The Complexity Trap: Skepticism, Denialism and the Political Epistemology of Climate Science

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Abstract The complexity trap snaps and gives rise to misconceptions and even denialism when scientists leave their narrow field of expertise and uncritically use their well-trained epistemological concepts in areas where they do not apply. This mechanism is rather universal and affects in similar ways non-climate scientists in their assessment of climate science results, specialists in a climate science subdiscipline in interdisciplinary controversies, and climate scientists participating in the complex socio-economic process of policymaking. Awareness of the complexity trap mechanism is the first step to avoid being caught in the trap.

Keywords Climate science · Global warming · Skepticism · Complex systems · Science–policy interaction

1 Introduction

Society's evolution in the last couple of centuries since the dawn of industrialization has largely been driven by scientific and technological advancement. Science and technology particularly enabled exponential growth of the global human population, historically unprecedented levels of energy consumption and per capita productivity. However, it was an unforeseen consequence that the industrial transition and the expansion of its fossil energy regime would reach a level of impact on the global ecosystem, even the entire Earth system, at which further growth endangers the future of our present civilization.

It becomes increasingly evident that only transformation toward a sustainable economy can secure high standards of living, which to this point, under circumstances created by the fossil energy regime of industrialism, has come at the cost of an increasing ecological footprint. Again, science is essential to provide society

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with guidance and orientation in the future transition. Today, climate science has achieved a leading role in steering our global society toward sustainability. In open, democratic societies, scientific knowledge and consensus must be communicated hoping to convince a large majority of people to support, or at least accept, measures toward sustainability and climate protection. Only then will effective policies be implemented. It is important to note that scientists, not only climate science experts, have a high responsibility in this communication process. Non-scientists expect that scientists, in general, will be able to expertly assess and communicate the findings of climate science. This expectation involves questions of reliability and public trust in scientific expertise. In the case of climate science, general trust in the scientific consensus on anthropogenic Climate Change, although well-established [1, 10, 48], has been under fire from lobbyists and "merchants of doubt". Contrarian scientists, conservative or right-wing think tanks and private corporations financially support pseudo-science and campaigns against climate science and scientists (for a list see the appendix to [21]).

A lot has been written about these campaigns and Climate Change denialism in general [21, 25, 44, 67]. Moreover, Naomi Oreskes and Eric Conway have published an account of the history of Climate Change denialism in the USA revealing who the merchants of doubts are and which private companies are supporting them [49]. The authors also showed convincingly that their strategies resemble the previous denial of the dangers of smoking. Like Oreskes's and Conway's, most studies on climate denialism focus on Anglo-American countries. This is also where Climate Change denialism is most common [4, 50]. It may not be fully explained by the success of "merchants of doubt" alone, there may be other reasons in the history of these countries as well [19: 138], about which we do not want to speculate here. In any case, there is evidence that scientists denying anthropogenic Climate Change were, in some cases, also paid by the fossil industry and other interest groups in Europe.[1]

From today's perspective, two decades of assertions by denialists that global warming is "a hoax" look like an early writing on the wall of the post-truth politics that has infected the American political system like a disease since the presidential elections of 2016. Unforeseeable in the 1980s and 1990s, the Republican Party has slipped deeply into the business of denying anthropogenic Climate Change following the millennium turn [9]. Recent statistics by the Yale Program on Climate Change Communication nevertheless suggests that denialists are losing ground,[2] despite a general declining trend in trusting scientific expertise [46]. Like in the USA under President Donald Trump, the rise of right-wing populism in Europe and Latin America might well lead to a new wave of denialist attacks on climate science [42]. It is a symptom of the current political atmosphere that fact-checking has become a

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[1] Recently, allegations that this was the case with the chemist Frits Böttcher (1915–2008), a former Club of Rome member, were published by investigative journalists working for the Dutch *Platform Authentieke Journalistiek* under the headline "Shell Papers", as was widely reported in international media in February 2020. See https://authentiekejournalistiek.org/portfolio-item/shell-papers-wob-naar-de-wob-want-overheid-zegt-nee/. Accessed 23 Feb 2020.

[2] See, in particular, the Climate Opinion Fact Sheets on https://climatecommunication.yale.edu/visualizations-data/factsheets/. Accessed 27 Feb 2020.

frequent occupation, if not an obsession, in the news media and beyond. A similar practice has long been established in the public debate on Climate Change. There are a number of webpages, some run by respected climate scientists, presenting climate science in accessible ways and refuting many of the standard arguments brought forward by climate denialists.[3] There are, on the other hand, various sources that promote these same arguments time and again, and there are scientists who support such efforts claiming they have the expertise and authority to challenge climate science.

In this chapter, we refrain, for the most part, from involving ourselves in controversies about truth and facts. Even where we touch such controversies, our guiding question is why (some) scientists have become collaborators in the denialist agenda, for example: by participating in conferences such as the "International Conference on Climate Change" organized by the Heartland Institute, one of the fossil industry-financed conservative think tanks mentioned above, between 2008 and 2015. Many of these scientists are claiming an expert position on Climate Change, while they have no proven record supporting that claim. Without doubt, one reason is that climate science today is rooted in Earth system science, which means that it combines physics, chemistry and biology. This makes climate science accessible and open to critical assessments from these traditionally separated spheres of knowledge. At the same time, this epistemic openness involves the danger of overconfidence and misjudgment on the part of outsiders resulting from a lack of familiarity with methodologies and common practices in climate science that these outsiders are either unaware of or ignore willingly. While it is true that climate science is an inter-discipline, it is a widespread misconception that scientists with an expertise in any of the contributing disciplines are a apriori qualified to talk climate science.

In order to show what may go wrong in such cases, we will delve deeper into the *epistemology* of climate expertise, which has been somewhat neglected in the debate. In other words, our reflections will be more about the *conditions of knowledge production in climate science*, not so much about specific knowledge or claims of scientific truth attached to it. The *character* of climate science—its interdisciplinarity, its complexity, its relevance for the future and its unique level of politicization—is more important for our argument than questions about facts and truth. This is not at all to dismiss such questions and theories of scientific truth as irrelevant. They are extremely important! It is merely that we seek to shed light on some of the dangers that scientific expertise is exposed to, because climate science is a highly complex system of scientific knowledge production with many disciplines involved and depending on high-level technological infrastructures. Hence, our question is not "Why to trust science?" [51], but why to *mistrust* non-expert scientists raising their voice authoritatively on issues of Climate Change. Matters are further complicated, because the consensus on Climate Change and its predominant anthropogenic character translates into demanding profound changes in economy and society to mitigate global warming. This defines the transformative character of climate science and adds

[3] Best known is Stefan Rahmstorf's webpage *Realclimate*, http://www.realclimate.org Accessed 14 Feb 2020.

a political dimension to it, which is much more than a mere side-effect. No matter if considered desirable or not, it is, in fact, a cornerstone in the epistemology of climate science that cannot be ignored. The political dimension has posed enormous challenges to climate scientists, not least because it exposes them to a lot of criticism.

We will argue in the first part of this chapter that some scientists become Climate Change denialists, or at least openly oppose (some of) the findings of climate science, because they are falling into what we call the "complexity trap". This is partly due to diverging scientific cultures in dealing with uncertainties, which we will illustrate using the examples of high-resolution spectroscopy of simple systems and the investigations of complex chaotic systems. As we shall see, misconceived methodological approaches may distort the conception of scientific results for non-climate scientists, giving rise to over-skeptical or denialist positions. Another way of falling into the complexity trap, which we will discuss in the second part of this chapter, is by making sweeping generalizations about how the Earth system works. In the past, a lot of the denialist potential was generated from such generalizations based on specialized expertise in some climate-related field, for example: solar physics. While this type of argument has lost much of its power today, it survives from a period when climate science transformed into the kind of multidisciplinary field that it is today. Unsurprisingly, it is most often repeated by a group of elderly scientists who have failed to keep up with this process. Climate scientists are sometimes criticized as well, often by denialists, for their political efforts and direct collaboration with policymakers. In the final section, we address the political dimension, which adds another level of complexity compared with questions of scientific methodology and specialization that dominate the first two sections.

2 The Complexity Trap

Scientific expertise from outside climate science is one of the main sources of climate denialism. For the "merchants of doubt"—think tanks funded by companies for the purpose of discrediting climate science, political parties or representatives supporting denial etc.—scientists publicly expressing that they are skeptical about the consensus on anthropogenic Climate Change create references that lend authority to denialist policies. Of course, it is legitimate for scientists to publicly express their skepticism, and there is little doubt that this is honest in a lot of cases, or often was in the past. That said, it is just as legitimate to ask if non-expert scientists are indeed a reliable source? Are there, maybe, intrinsic mechanisms or possible pitfalls that might affect in particular scientists leading to failures in perceiving and communicating the results of climate science correctly? It might indeed be particularly tricky for non-expert scientists to correctly convey the results of climate science research. From the personal experience of one of the coauthors (Walter Pfeiffer), related problems are surprisingly common among physicists, that is: within a discipline that historically has acted as a blueprint for the scientific method itself [32]. One major pitfall is directly related to skepticism. The birth of modern science intimately relates to enlightenment traditions of skepticism. It is all about asking critical questions—any question that comes to mind, and if this does not receive a satisfying answer, a scientist might be inclined to dismiss a certain research area or at least to see it very critically. As we discuss in the following, this, in general, vital approach in science is prone to failure if misconceptions about an unfamiliar field of research come into play. Well-trained strategies or conventions might then be projected uncritically into that other field of research. We exemplify this possible failure for the case of physicists working in fundamental science and who are in their domestic field of research not dealing with complexity-related phenomena, such as criticality, self-organization or chaos. But note, this is only one possible example, similar mechanisms and pitfalls may well affect scientists from other disciplines as well.

Fundamental theories in natural science rely on simplicity (Ockham's razor). Accordingly, simple explanations are favored over more complex models or theoretical concepts. Nicolaus Copernicus's heliocentric model of the solar system was simpler, while it had no improved predictive power compared with the model of planetary motion in epicycles around the Earth. According to Ockham's razor, the simpler explanation wins. Later, the heliocentric model was rapidly improved and gained tremendous predictive power. In this respect, physics is a paradigm discipline where rather simple fundamental laws in mechanics, quantum mechanics, or special relativity have proved highly efficient and versatile to develop and control technologies that largely reshaped our society compared with its pre-industrialized state. So, it appears that the reductionism to simple fundamental concepts is highly successful.

Skepticism is one of the paths toward simplicity. By asking fundamentally "simple" questions, i.e., disregarding dogmas and conventions, natural sciences have reached their present, rather advanced status quo. People trained in these areas, in particular physicists, have learned from the beginning of their socialization in their discipline that asking simple critical questions, in other words: being skeptical, is vital, both for better understanding the basic concepts, and for advancing our scientific knowledge in general. In a scientist's domestic field of expertise, this skepticism is moderated by the scientific community as a community of established practices. We know whom to ask, which book or journal to read, or which alternative theoretical concepts to study in case we struggle to find answers to our "simple" questions. In rare but exciting cases, we experience that such a question then indeed leads to new scientific insight. More often, we realize that others had the same question before us, and it was answered a long time ago. It is exactly our ability to deal with these "simple" fundamental questions and answers that make us experts in a particular field.

Now, what happens when we leave the comfort zone of our domestic field of expertise and start applying our well-trained strategies of skepticism in a different, albeit somehow related field of research or disciplines? In this case, we lack familiarity with the different community and practices, and there is the danger that we might not even be aware of this. We would struggle to know which books or journals to read to get straight answers to simple questions. One rather safe solution would be to become an expert also in the new field. Realistically, achieving this goal is time-consuming, and, unless we spend a lot of time, we will reach it only on a rather superficial level. Without reflecting on these limitations, we might be tempted to insist on procedures that proved successful in our own field of expertise. As we discuss and exemplify in greater detail below, this is a risky approach and the resulting assessment might be based on unquestioned biases and premises. The misconceptions arising from this approach will likely harm our personal judgment. In the worst-case, sound skepticism turns into denialism. A third option, for those who have no time to become (part-time) experts or would like to spend their spare time differently, is to become aware of the underlying mechanisms that affect one's own judgments. This might help to be especially careful in the assessment of results from a different discipline. This chapter might help rising awareness for this third and maybe less time-consuming option.

Assessing uncertainties and communicating them to society is essential in climate science. If there are different strategies for dealing with uncertainties in different disciplines, this might be a case where non-expert scientists fail when they comment on climate science.

Dealing quantitatively with uncertainties is a key element of the scientific method. This should, however, not be understood in the sense that there is a universal way of doing so in all disciplines. In many cases where observations can be repeated, statistical uncertainties can be minimized. This can lead to truly surprising accuracies of scientific statements. The applied statistical method is based on the high-frequency approach [2], i.e., uncertainties are almost eliminated by massive averaging. Whereas this strategy is reliable and highly successful in the area of fundamental research and for developing technologies, it has severe shortcomings when the complexity of a research subject increases. Note, for example, that to the best of our knowledge, none of our present technologies relies on chaotic dynamics, i.e., one example for dynamical behavior of a complex system. Presently and maybe forever, there won't be complete theoretical models that fully capture the behavior of complex systems. Therefore, any scientific model of a complex phenomenon will have to deal with qualitatively different statistical and fundamental uncertainties. These go beyond uncertainties related for instance to the statistical interpretation of quantum mechanics that still allow a complete description of simple enough systems. In these cases, the theoretical predictions can be verified in experiments to ultimate precision and vice versa. For example, the spectroscopy of optical transitions in hydrogen atoms is today performed with relative uncertainties of about 10^{-12} and similarly, the theoretical description reaches the same accuracy [3]. Great care is taken to assess the statistical and systematic uncertainties of both experiment and theory. Consequently, any significant deviation immediately raises big concerns. For example, the recently encountered highly significant discrepancy in proton radius measurements [65] initiated, both an intense effort to better specify systematic experimental uncertainties and a reconsideration of the theoretical premises required for modeling the experimental results. Presently, the race is open, i.e., it might be that we are experiencing a significant glitch in the foundations of physics or maybe the systematic errors in the measurements are not yet well enough understood.

For complex systems such as a living organism or the global climate similarly rigorous testing of our model understanding is fundamentally impossible. Deterministic chaos might serve as an example. Deterministic chaos is defined by a rather striking behavior: however small the difference between two initial conditions is chosen the subsequent trajectories for both cases diverge exponentially, i.e., the difference between variables grows infinitely [56]. Note that this holds already for a classical system, i.e., intrinsic quantum mechanical uncertainties are not even playing a role here. In the case of deterministic chaos, predictions of the correct theoretical model and any observation deviate exponentially and it is actually a feature and not a shortcoming of the model. Not quite so obvious this holds also for complex systems that do not exhibit deterministic chaos. For a complex system singular deviating observations or partial discrepancies between model and observation cannot immediately falsify a given model for a complex system. However, for a non-expert, this is not always immediately evident. Being trained, for example, in fundamental physics relevant for high-resolution atomic spectroscopy possibly leaves one unaware of this limitation of the falsification strategy.

Note that there are numerous other pitfalls that follow the same mechanism besides the assessment of uncertainties. As another example, take oversimplification. If inadequate simple models from one discipline are applied for complex systems this leads to severe misconceptions. For example, applying a simple box model from combustion engineering [14] to the redistribution dynamics of the radiotracer ^{14}C introduced by nuclear weapons testing yields wrong carbon residence times, which can only be reliably identified in a more advanced model accounting for the complexity of the carbon cycle [33]. Hence, oversimplification here seemingly supports a denialist position. The lack of awareness about differences in other fields of research and its consequences form the *complexity trap*. This trap is not immediately obvious and seemingly many scientists working in fundamental or applied research are not aware of the associated pitfalls, in other words: they might get easily trapped. Why is that an issue?

In democratic societies, the opinion formation process in the present climate crisis is influenced, mediated and driven by different interest groups, with climate scientists, scientists from other research fields (in particular natural sciences), non-scientists and various other groups as relevant players. The non-expert scientists take an important and not always responsible role in the communication of climate research results to the general audience.[4] Non-scientists cannot easily differentiate between statements made by a climate scientist or a non-expert scientist, since the way how scientific knowledge is gathered and the inner workings of scientific communities are unfamiliar to them. Now, if a non-expert scientist makes skeptical remarks about some climate-related topic this is likely to be perceived by the non-experts as equally well-founded as a statement made by a climate science expert.

The complexity trap is most influential for non-expert scientists. Climate scientists have detailed knowledge of complex interdisciplinary climate research and

[4] Consider, for example, the impact of the 1973 Nobel Prize laureate in physics, Ian Giaever, https://en.wikipedia.org/wiki/Ivar_Giaever#cite_note-16 Accessed 27 Feb 2020.

established consensus among themselves about anthropogenic Climate Change and the most likely future climate developments. In contrast, non-expert scientists lack detailed insight but nevertheless perceive themselves as sufficiently well educated in the scientific method to assess and communicate the results of climate research. This potentially distorts the opinion formation in society and emphasizes unfounded controversies already settled among specialists. In this way, non-climate scientists can unintentionally become allies of denialist interest groups.

3 Sweeping Generalizations

Even experts from the disciplinary spectrum coming together in the interdisciplinary field of climate and Earth system science are exposed to the danger of falling into the complexity trap. This problem can be illustrated by denialist arguments that are based on sweeping generalizations founded on some deviating expert opinions related to climate science. For example, some scientists from the group of solar physicists have argued against anthropogenic Climate Change starting from the fact that solar radiation is the most important source of heat on the Earth's surface. However, this does not allow the conclusion that solar variability must be the dominant reason for Climate Change, as this simply ignores that there are multiple external and internal forcing factors driving the climate system. These forcing factors interact with each other and operate on a variety of timescales [20: 180]. Assessing the relationship between them requires Earth system modeling informed by historical data (reconstructions) on past climatic changes on various timescales.

Difficult and open to constant improvement as modeling efforts are, it is beyond rationality that some people doubt the validity of this approach and continue criticizing climate models for what they are by necessity—i.e., simplifications of an extremely complex system—, while, at the same time, holding on to monocausal theories of the solar type. The most obvious explanation for this stubbornness may be a lack of expertise in assessing alternative explanations or, in some cases, a narcissistic desire to place solar physics center stage no matter what. This may be human, but it is not very scientific. It looks even worse when the advocates of such theories ignore the data collected from satellite observations since 1978, which show a declining trend [18]. Denialist reports have frequently repeated false claims that solar activity dominates human influence from greenhouse gas emissions, founded on highly controversial statements that the global temperature record on the millennial timescale correlates with solar variability [27: 247]. The latter is a matter of some controversy between different studies (e.g. [55, 57]). However, even the boldest calculations of radiative forcing have failed to produce numbers anywhere near explaining global warming by means of solar physics. Logically, most solar physicists today define their role by improving solar modeling as an important part of climate models. But they do not doubt the dominance of anthropogenic forcing. Controversial questions are in other areas where scientific efforts are needed to improve modeling.

However, it is not in the interest of denialists or merchants of doubt to cooperate in such efforts.

Even for historical epochs of Climate Change, such as the so-called Medieval Warm Period and the Little Ice Age, the sun has lost its previously almost undisputed explanatory power. The role of solar minima like the Maunder Minimum (1645–1715) as dominant force during the Little Ice Age (c. 1300–1850) is no longer common sense as it used to be 30 or 40 years ago [40: 76–84]. The influence of increased volcanic activity, particularly in the last phase of the Little Ice Age [6], and internal forcing [66] have emerged in recent decades as parts of a more complex pattern of forcing factors, which is also applied to earlier historical periods of significant climate variability [8]. Moreover, recent millennial scale temperature reconstructions that include the southern hemisphere have found no evidence for global cold or warm epochs during the preindustrial Common Era. Global warming in the twentieth century was the warmest period for more than 98% of the globe, which makes it spatially as exceptional in the last 2,000 years as it is temporally, that is: with regard to the speed of warming [45].

Sweeping generalizations about the sun as the dominant natural force driving all climate variability are scientifically obsolete. Today, only very few scientists continue to collaborate in the denialist effort to obscure this fact. Yet, the solar myth is remarkably persistent in public discourse. This is probably best explained by the historical longevity of solar explanations for climatic variability in popular science—a tradition that apparently has survived in public memory. Perhaps in more than one way, this resembles the equally persistent belief in astrology and horoscopes in popular culture. Sunspots became subject to telescopic observation from 1610 onwards. Speculations about sunspots as indicators of solar variability started soon afterward, but it took some time before this relationship was confirmed by astronomy. Once it was, sunspots precipitated into popular culture and were frequently discussed in context with economic cycles (e.g. [30]) and other social and economic phenomena. It is the tradition of this kind of speculation and its popularization that defines the seductive potential of the "solar argument" and, therefore, suits denialist intentions particularly well. The psychology they can count on by playing down the unknown and, instead, reducing it to the supposedly well-known is a desire to ease our conscience and concerns about anthropogenic Climate Change.

A different version of a sweeping theory is that the Earth is too big to be harmed by any human action. The most general version of this theory about "nature" or the "Earth" has almost disappeared nowadays. But well into the 1980s, a number of scientists still underestimated the speed of anthropogenic Earth system change, despite a much longer history of early warnings against the obvious trends of industrial growth. There is a long tradition of such warnings starting from George Perkins Marsh's book *The Earth as Modified by Human Action* [37, 38]. Reports published in 1956 and 1990 provided surveys of human impacts on all parts of the Earth system [62, 63], decades before Paul Crutzen proposed to define a new geological epoch called the Anthropocene [11, 12]. Earth system science has substantiated the diagnosis behind this proposal that human activities have become the dominant force of Earth system change—not only of Climate Change but also biodiversity loss, ocean acidification, atmospheric aerosol loading, profound modifications of the phosphorus and nitrogen cycles, land-use change and stratospheric ozone depletion. Recent history itself is the power behind this shift. This is what the "Great Acceleration" graphs suggest, introduced by Earth scientist Will Steffen to describe exponential socio-economic growth after World War II and its impact on the Earth system [58, 59, 61]. More recently, the concept of planetary boundaries has been introduced, which is basically an attempt to measure the speed of change of critical Earth system indicators against the background ratio of change during the Holocene [52, 60]. This approach is open to further improvement. Collecting reliable information on all the critical indicators for the entire Holocene epoch remains one of the challenges. In any case, constant improvement in methodology and data collection is key to the advancement of science. In contrast to such efforts, sweeping generalizations look like bad excuses for protecting one's opinions rather than exposing them to be challenged by others.

Some arguments frequently repeated by denialists of anthropogenic Climate Change are variations on the theme of supposed human insignificance. For example, CO_2 is only a small proportion of the whole mix of atmospheric gases; that in Earth's history, CO_2 has always lagged behind rising temperatures rather than being the driving force [27] that the amount released from anthropogenic sources, mostly the burning of fossil fuels, is relatively small compared with the masses of CO_2 stored in soils, forests and oceans. These statements have been disproven in many ways. Most of them are mere *ad hominem* appeals with no scientific value, because the proportions chosen for comparison allow no conclusions whatsoever about the effectivity of CO_2 as a greenhouse gas. To put CO_2 concentrations into perspective, climate scientists prefer more meaningful comparisons, particularly those between industrial and pre-industrial concentrations of CO_2, which can be traced back hundreds of thousands of years based on the analysis of air bubbles in ice cores. Such comparisons show how far industrial concentrations have moved beyond natural variability over this entire period [29: 201]. However, in order to assess the contribution of industrial increase in atmospheric greenhouse gases to global warming, scientists calculate how greenhouse gas concentrations affect the radiative balance of the Earth (radiative forcing), which is the difference between incoming (insolation from the sun) and outgoing radiation. Radiative forcing and, more recently, effective radiative forcing, which includes temperature response, have become the gold standards in comparing different forcing factors. It is precisely such comparisons by which climate science came to conclude that anthropogenic greenhouse forcing has dominated natural forcing during the industrial era (since 1750), with a clear accelerating trend in the decades after 1970 [28: 649–740].

It is almost impossible to conceive that any serious scientist him- or herself believes typical denialist statements about CO_2 of the type we have quoted above. These arguments are obviously designed for making use of some kind of seeming plausibility for the purpose of seducing a non-scientific audience into believing that no harm will come from the unhampered release of greenhouse gases from all kinds of human activities. Just like in the case of the solar argument, expert as well as non-expert denialists can count psychologically on a collective desire to be relieved from concerns and responsibilities related to global warming. There is another psychological element that denialists can count on when making sweeping generalizations of the type we discussed in this section. Sweeping generalizations are always founded on simplifications that are scientifically unsound, because they reduce complexity in a way already falsified by science. In a scientific context, the burden of proof would clearly be on the part of denialists. But this burden may be turned against science in case denialists succeed in placing misleading conceptions in public discourse. In the public arena, the complexities of climate science pose the challenge to turn specialized knowledge into comprehensible concepts and arguments, which may easily work against science.

4 Transformative Science

Today, climate science has achieved a very high level of public visibility, which is predominantly a symptom of its level of politicization. It has become pretty common practice for climate scientists to translate scientific findings into calls for, and advice on, political action. Recommendations for policymakers have become a built-in element of press releases on scientific expert meetings or as part of scientific reports. These practices are by no means restricted to the IPCC framework. However, the level of science–policy cooperation on Climate Change is unique in the history of science. Today, as the Earth system interacts with the social system, the inter-discipline that is Earth system science also involves the social sciences and humanities. Since science-based calls for political action affect society, and action as well as non-action on Climate Change will affect the Earth system in one way or another, the whole system forms a complex network with multiple feedback mechanisms giving rise to nonlinear dynamics reaching from the local to the global scale. Dealing with this historically unprecedented level of complexity is clearly among the greatest challenges for society today.

Climate scientists are sometimes questioned for their proximity to politics, for making recommendations to policymakers, for predicting planetary disaster if anthropogenic Climate Change remains unchecked, and for arguing for major socio-economic transformations based on the urgent need for massive greenhouse gas emission reductions. Criticism has been voiced by sceptics and denialists to publicly discredit climate science. However, it would be too simple to identify this kind of criticism as merely denialist. The circle of critics includes scientists and researchers from various disciplines, politicians, journalists and other people, who are not necessarily doubting the findings of climate science and the predominant anthropogenic causes of Climate Change. Their criticism is rooted in (traditional) normative expectations of scientific neutrality and objectivity. From a political point of view, there are also concerns regarding the lack of democratic legitimation for political action based on the expertise of climate scientists. Political scientists have criticized top-down approaches in global climate governance for their supposedly "technocratic" attitudes [35, 36]. Climate science experts are also criticized for giving far-reaching political advice on socio-economic or technological change representing these as effective pathways to emission reductions without providing alternatives and without fully considering the cultural, social, political and economic complexities of transformative processes [26].

Diverse as this criticism is regarding its underlying motives and intentions, it is particularly interesting for us as it opens up a completely new perspective on the issue of complexity. To this point, we have discussed climate science in the context of an epistemic environment struggling, mostly for its disciplinary fragmentation, to deal with complexity. Hence the danger of some of the scientific criticism coming from other disciplines falling into what we have named the complexity trap. As we move forward to the implications of anthropogenic Climate Change for society, we reach a new level of complexity—the complexity of a transformative science. Transformative science more or less claims that there is a need for major socio-economic changes that should be politically implemented [54]. This is the case with climate science diagnosing that the cause of potentially dangerous Climate Change is anthropogenic.

The logical consequence of this diagnose is that, to conquer Climate Change, we need to control its anthropogenic causes, in other words: greenhouse gas emissions. This looks straightforward and simple enough. But it is not, as, both, scientists and politicians were to find out quickly following the foundation of the Intergovernmental Panel on Climate Change (IPCC) in 1988. The late 80s of the twentieth century produced an enormous level of optimism on solving all kinds of complex international issues dynamically, peacefully and efficiently, particularly when the Cold War ended rather suddenly and unexpectedly with the dissolution of the Eastern Bloc and the Soviet Union. This optimism also applied to environmental problem-solving. The Montreal Protocol to protect the stratospheric ozone layer, ratified in 1987, served as the model to international cooperation on controlling global warming. However, expectations that the international community of states would agree, in a binding treaty, to reduce greenhouse gas emissions just as easily as it agreed to phase out the production and consumption of ozone-depleting substances proved erroneous [34]. The difference is best explained by the universality of greenhouse gas emissions (in contrast with emissions effecting the ozone layer), meaning there is practically no human activity that does not produce them.

However, the world of greenhouse gas emissions is not flat. Industrial countries have developed high-emission economies based on the burning of fossil fuels. Therefore, this group of countries is historically most responsible for global warming, while developing countries have had lower emissions and less responsibility. This inequality in terms of causation adds socio-economic complexity to the scientific complexity of climate science and modeling; moreover, political complexity is added on top of this, as there are different states with different political regimes and emission profiles cooperating in a United Nations framework, which treats mitigation of Climate Change and adaption to it as one political issue among a mix of others such as development, trade, health etc. After all, solving the problem of anthropogenic Climate Change is not, what the United Nations (UN) were founded for in 1945. The declared ends of the UN were the maintenance of international peace and security, protection of human rights and socio-economic advancement.[5] Creating a United Nations framework for international cooperation on Climate Change resulted from an evolutionary process, which added the fields of developmental and environmental policies to the mix by connecting them with those ends. In other words, scientists and politicians argued that Climate Change (like other global environmental problems) poses threats to peace, international security, human rights and welfare.

The level of politicization of climate science today is, more than anything else, due to an institutional framework created by the IPCC and the United Nations Framework Convention on Climate Change (UNFCCC). The IPCC was founded in 1988, the UNFCCC ratified by 197 signatory states at the Rio Earth Summit in 1992. The latter has fulfilled the role of a United Nations Charter for climate protection. With it, regular conferences of the parties (COP) were established, which have kept climate negotiations going ever since and have guaranteed climate politics frequent public attention [13, 22]. This may be considered an upside for a field of research concerned with the future of the Earth and the existence of human life on its surface. However, the experience of three decades of constant public attention has also shown the downside of exposing science to unpredictable trends in political discourse and changes in the media landscape, for which scientists have no training to be prepared. "Merchants of doubt" and private media companies with a certain political agenda have frequently attempted to use this exposure as an opportunity to discredit climate science [49].

Looking back at the period of institutionalization and the bigger picture of world politics, it is easily discernible that international climate governance reached a new level of institutionalization precisely when the Cold War was about to come to an end. However, this should not blind us to the fact that this period was preceded by a state in the politicization of anthropogenic Climate Change very much influenced by the forces and interests of the Cold War superpowers. The Cold War with its characteristic competition between the USA and the Soviet Union is, in fact, key to the political epistemology of climate science, in particular its technological infrastructures and its political networks. This is crucial, because it explains why it was relatively easy for scientists to make their early warnings against anthropogenic Climate Change heard and bring this subject to high-level political attention.

One of the ways meteorology and climatology got involved in the Cold War is "weather warfare," which uses atmospheric circulation and precipitation for military purposes. We know from a number of historical studies published in the last decade or two that both superpowers became interested in it even before the end of World War II [16, 17, 23: 165–188]. A wide range of weather modification technologies were patented, few were used. For example, the US military applied cloud seeding in Vietnam between 1967 and 1972 to enhance the monsoon season and provoke flooding [24: 218–225]. The New York Times reported about these secret operations on July 3, 1972, and afterward they became subject to Congressional hearings in 1974 [64]. The USSR used silver iodide seeding in April 1986, after the accident at the Chernobyl nuclear power plant, to make highly radioactive clouds rain over

[5] See the UN Charter as it was ratified in San Francisco 1945, https://treaties.un.org/doc/publication/ctc/uncharter.pdf (last accessed February 25, 2020).

Belarus before they would reach Moscow [7: 40–45]. In the Soviet case, these were the fruits of scientific efforts that had started in 1941 and precipitated in Stalin's plans for the transformation of nature [5, 47]. In the American case, ideas of weather and climate modification have an even longer tradition reaching as far back as the colonial period [15, 41, 53].

These examples and historical contexts must suffice here to illustrate some of the ambiguities surrounding the use of weather modification technology, be it for military purposes, or be it in the context of a state executing power over its own territory and people. Climate and Earth system scientists were involved in "cold war business" by the superpowers in many more ways than this. For example, atmospheric scientists and oceanographers did a lot of research on radioactive isotopes in nuclear testing areas and beyond. Geological knowledge informed the military sector in constructing missiles that would reach even distanced targets with enormous precision. Climate and Earth scientists learned how to use the extraterrestrial infrastructures provided by satellites for their purposes. In sum, following World War II climate science became a Cold War science. It is not at all surprising that this context guaranteed anthropogenic Climate Change a significant level of political attention. In the USA, it climbed the political ranks quickly once Charles Keeling's measurements, carried out at the Mauna Loa observatory since 1958, confirmed that CO_2 was indeed accumulating in the atmosphere. Warnings against the implications of these measurements entered the political sphere through the veins of the President's Science Advisory Committee (PSAC) in 1965, created in 1957 by President Dwight D. Eisenhower. This is how President Lyndon B. Johnson became the first Commander in Chief to mention Climate Change in a "Special Message to the Congress on Conservation and Restoration of Natural Beauty" [31, 39]. From then on, anthropogenic Climate Change became a frequent subject of scientific reports on behalf of the US federal administration and several of its institutions. Under the impression of the 1973 Oil Crisis, concerns about future energy supplies and the need to transform the energy system became the dominating framework for discussing Climate Change. Throughout the 1970s, and well into the 1980s, the energy question framed the early debate on anthropogenic Climate Change and helped increasing its political and socio-economic relevance [43]. The nuclear age continued to give political leverage to climate science, both, in the energy context and beyond, particularly through discussions of the threat of nuclear winter.

We stop our brief historical account here. For our purposes, it suffices to hint at the historical roots of the politicization of anthropogenic Climate Change, which we can trace back to the Cold War. There are many implications, which may follow from this; various conclusions are possible. While this largely depends on perspective, it would be too simplistic to consider climate science "contaminated" by the nuclear age and, therefore, discredited. Against the temptation of such moralistic simplifications, one could argue that the unprecedented dangers of the nuclear age required scientific reliability and increased the demand for (applied) scientific knowledge. The competition between the superpowers of the Cold War fostered technological innovation, which required high levels of control of complex and often dangerous technologies. This strengthened the ties between policymaking, the economy and science, which are essentially modern. In the nuclear era, it was logical for science to move beyond the framework of applied science and get involved in direct cooperation with policymakers.

It is in this context that we need to consider the evolution of science–policy cooperation on anthropogenic Climate Change as well as the meaning of high-level political Climate Change denialism. The withdrawal of the USA from the Paris Agreement based on publicly more-than-once declared denial of anthropogenic Climate Change by Donald Trump was a revocation of the standard, reached during the Cold War, that, for the welfare of all people, policymakers acknowledge scientific rationality. The significance of this rupture in modern history remains, even though President Biden has once again revoked his predecessor's decision.

5 Conclusions

There is a danger for highly specialized scientists to fall into what we have called the complexity trap—a mechanism rooted in the epistemology of complex systems which exposes scientific expertise to the danger of unnoticed lack of competence. In other words, (often) based on general attitudes such as skepticism, scientists tend to misconceive their competence in the unfamiliar environment of complexity science. The examples we gave in the first part of this paper were related to the disciplinary framework of physics; and we exemplified the complexity trap for experts and non-experts in climate science. However, it needs to be emphasized that similar mechanisms are relevant whenever interdisciplinary knowledge and discourse become relevant. Scientists are inclined to trust their disciplinary expertise, even in cases where their expertise is limited. To some extent, this is the historical heritage of long-lasting trends in scientific specialization. The effects, however, go beyond the realm of science and leave their traces in the wider public and political disputes about Climate Change.

Science–policy collaboration is a logical consequence of diagnosing that the global climate is warming due to anthropogenic emissions of greenhouse gases. Mitigating Climate Change requires global participation of all countries, particularly all major emitters of greenhouse gases. At some point in the process of diagnosing anthropogenic Climate Change, scientists have asked for political action, and politicians have then asked for scientific expertise to inform that action. As we have shown, science–policy cooperation on global warming emerged from the historical arena of the Cold War. In other words, the politicization of climate science is as much a *historical* fact as it is a logical consequence of the consensus that Climate Change is predominantly anthropogenic. Scientists both in- and outside the field of climate science need to recognize this fact and deal with it rather than complain about it or criticize climate scientists for a historical path taken by climate science, which is not a matter of choice and cannot be changed retrospectively. Radical "conclusions" from our awareness of this history, such as: that climate scientists should practice political abstinence, would not merely be unrealistic; they would be irresponsible.

That said, contributing in a responsible way to solving the problem of global warming is a permanent challenge to every scientist involved. The complexity of the problem, its economic, social and political dimensions, overwhelm the scientific expertise of any individual scientist involved. In a political environment, climate scientists themselves are in danger of underestimating this complexity, if only occasionally. Hence, Mike Hulme's warnings against the danger of "climate reductionism" might emerge from subordinating all governance issues to the priority of mitigating Climate Change [26]. Being a climate science expert does not necessarily qualify for assessing unforeseeable feedbacks on future developments of the socio-economic and political spheres. This is why the concerted expertise from multiple disciplines is required and needs to be integrated with a co-creative process that includes policymakers, stakeholders and other groups on all levels of governance. This is by no means a ready-made answer, but a current field for further explorations and experiences with newly designed political processes. Science–policy cooperation on anthropogenic Climate Change will continue to explore new pathways and participative processes to counter the dangers of reductionism. It is crucial for scientists participating in these processes to responsibly reflect their expertise and its limits.

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