Rethinking climate engineering categorization in the context of climate change mitigation and adaptation

Olivier Boucher, Piers M. Forster, Nicolas Gruber, Minh Ha-Duong, Mark G. Lawrence, Timothy M. Lenton, Achim Maas, Naomi E. Vaughan

Accepted as “Opinion” article in WIREs Climate Change

Rethinking climate engineering categorization in the context of climate change mitigation and adaptation

Olivier Boucher[a], Piers M. Forster[b], Nicolas Gruber[c], Minh Ha-Duong[d], Mark G. Lawrence[e], Timothy M. Lenton[f], Achim Maas[g] and Naomi E. Vaughan[h]

[a] Laboratoire de Météorologie Dynamique, IPSL / CNRS, Université P. et M. Curie, Paris, France. E-mail: olivier.boucher@lmd.jussieu.fr

[b] University of Leeds, Leeds, United Kingdom

[c] Institute of Biogeochemistry and Pollutant Dynamics and Center for Climate Systems Modeling, ETH Zürich, Zürich, Switzerland

[d] Centre International de Recherche sur l'Environnement et le Développement, CNRS, Nogent-sur-Marne, France

[e] Institute for Advanced Sustainability Studies, Potsdam, Germany

[f] College of Life and Environmental Sciences, University of Exeter, Exeter, United Kingdom

[g] Institute for Advanced Sustainability Studies, Potsdam, Germany

[h] Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, United Kingdom

Abstract: The portfolio of approaches to respond to the challenges posed by anthropogenic climate change has broadened beyond mitigation and adaptation with the recent discussion of potential *climate engineering* options. How to define and categorize climate engineering options has been a recurring issue in both public and specialist discussions. We assert here that current definitions of mitigation, adaptation and climate engineering are ambiguous, overlap with each other and thus contribute to confusing the discourse on how to tackle anthropogenic climate change. We propose a new and more inclusive categorization into five different classes: anthropogenic emissions reductions (of short-lived climate agents and long-lived greenhouse gases, abbreviated AER, territorial or domestic removal of atmospheric CO_2 and other greenhouse gases (D-GGR), trans-territorial or trans-boundary removal of atmospheric CO_2 and other greenhouse gases (T-GGR), regional to planetary targeted climate and environmental modification (TCM), and climate change adaptation measures (including local targeted climate and environmental modification, abbreviated CCAM). Thus, we suggest that techniques for domestic greenhouse gas removal might better be thought of as forming a separate category alongside more traditional mitigation techniques that consist of emissions reductions. Local targeted climate modification can be seen as an adaptation measure as long as there are no detectable remote environmental effects. In both cases, the scale and intensity of action are essential attributes from the technological, climatic and political viewpoints. Whilst some of the boundaries in this revised classification depend on policy and judgement, it offers a foundation for debating on how to define and categorize climate engineering options and differentiate them from both mitigation and adaptation measures to climate change.

1. Introduction

The concept of large-scale environmental engineering is not new and a number of ideas have been proposed over the last century (see Ref. 1 for a historical perspective). The idea to engineer the environment to specifically counter anthropogenic climate change can be traced back at least to the 1960s with a US report calling for research on "possibilities to deliberately bringing about countervailing climatic changes" to that of carbon dioxide[2]. The term "geoengineering" itself was coined by Marchetti[3] to discuss the idea of injecting CO_2 into the ocean to reduce its atmospheric burden. Since then, the term has evolved and now encompasses a broad and ill-defined set of approaches that aim to deliberately alter the climate system on a large scale in order to alleviate the impacts of climate change[4]. Due to the strong emphasis on the climate modification aspect, we favor the use of "climate engineering" (CE), which we use throughout this study (with the exception of a brief revisiting of the term "geoengineering").

The Royal Society[5] categorized climate engineering methods into two broad classes. Solar Radiation Management (SRM) refers to the intentional modification of the Earth's shortwave radiative budget to reduce anthropogenic climate change. Injection of stratospheric aerosols[6] and cloud brightening[7] are two examples. Carbon Dioxide Removal (CDR) refers to approaches that aim to reduce atmospheric CO_2 concentration by either increasing natural or engineering new carbon sinks. CDR methods can involve ocean, land, and technological systems, examples include iron fertilization, large-scale afforestation, and direct capture of carbon dioxide[8]. However, this classification does not capture all CE methods which have been proposed, for example, the proposal to increase outgoing longwave radiation by seeding cirrus clouds with ice nuclei[9]. Nor does it provide a clear distinction between climate engineering and other policy responses like climate mitigation and adaptation.

There has been considerable attention on CE since the publication by Crutzen[6]. Various studies have compiled and assessed CE schemes[4,8,10,11], and several national assessments have also been conducted[5,12,13]. Yet there is a lack of common understanding of what CE refers to and existing studies do not provide an up-to-date and complete taxonomy of climate engineering methods. How to define and categorize climate engineering options has indeed been a recurring issue in both public and specialist discussions of climate engineering[14,15]. This study will i) critically discuss how climate engineering fits into the wider portfolio of responses to anthropogenic climate change and ii) develop a more robust taxonomy to categorize these responses. It should be viewed as an opinion article whose role is to initiate and foster debate on the subject.

We stress that any such categorization will depend on its aim – here we attempt a primarily climate-science-based categorization focusing on spatial and temporal scales and Earth system processes impacted. We recognize, however, that our categorization involves non-universal cultural attitudes, as well as certain norms, value judgement and political choices. We only address peaceful applications of climate engineering and omit any potential military dimension of climate engineering. Neither do we attempt to rank the effectiveness or appropriateness of climate change responses in any manner.

2. Discussion of existing definitions

Definitions of mitigation and adaptation

Mitigation is defined by the Intergovernmental Panel on Climate Change (IPCC) Fourth assessment report's glossary[16] as "technological change and substitution that reduce resource inputs and emissions per unit of output". It further specifies that "although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks". This definition is consistent with that from the IPCC Third assessment report[17] and implies that methods aiming at reducing natural sources or enhancing natural sinks of CO_2 and other greenhouse gases do qualify as mitigation policies. This definition is also consistent with the United Nations Framework Convention on Climate Change[18] (UNFCCC) which stipulates in its Article 4 that Parties "shall adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs". These definitions raise three important comments:

i) There is an ambiguity as to whether mitigation includes emission reductions through a voluntary reduction of production and/or consumption per capita, i.e., so-called "non-technical" measures. The above-mentioned definition and IPCC[14] refer to emissions reductions per unit of output or gross domestic product, but emissions reductions are often considered to contribute towards mitigation objectives irrespective of their origin. However, behavior changes can also contribute to emissions reductions and it is surprising that this is not made explicit in the definition. A related issue is whether emissions and emission reductions should be counted from a territorial (i.e., depending on their location) or a consumption (i.e., depending on who the "final user" is) perspective.

ii) Carbon Capture and Storage (CCS), as a technology which aims to capture and sequester waste CO_2 from large source points before it is emitted in the atmosphere, qualifies as a mitigation technology[19].

iii) The IPCC and the UNFCCC definitions include the enhancement of greenhouse gas sinks as a mitigation option. This was designed to include sustainable forms of agriculture and forest management, reforestation and afforestation within the scope of the UNFCCC and the Kyoto Protocol. It is unlikely that UNFCCC negotiators and IPCC authors had in mind the full spectrum of CE methods that have now been proposed to modify the carbon cycle when they crafted these definitions. Heyward[15] discussed this issue and concluded that there are advantages of specifying CDR as a separate category rather than a subset of mitigation.

Adaptation is defined as "initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects" [16]. The IPCC further specifies that "various types of adaptation exist, e.g. *anticipatory* and *reactive*, *private* and *public* and *autonomous* and *planned*" and provides some examples of adaptation measures such as "raising river or coastal dikes" and "the substitution of more temperature-shock resistant plants for sensitive ones". Central to the concept of adaptation is the idea to reduce the vulnerability of natural and human systems to climate change through a modification of these systems. It is not always clear, however, what the system boundaries are when talking about adaptation. For instance, one could adapt to the risk of fluvial flooding by building dykes, by diverting streams and rivers, increasing storage capacity, or theoretically if it were at all possible to, by preventing extreme rain events from occurring. There is potentially varying degrees of climate or environmental engineering in such adaptation options. It should also be noted that modifying natural and human systems may feedback on the local climate. For instance it is now well understood that the climate can be modified locally by increasing green spaces in cities[20], building large dams[21] by changing agricultural practices through irrigation[22] or the modification of land cover. The boundary between adaptation and climate engineering within current definitions can therefore be blurred. This was also noted by Heyward[15] who observes that SRM could be seen as preventative or responsive depending on "whether dangerous anthropogenic interference or dangerous climate change is taken as the referent". It is worth noting that the definition of adaptation considered here is very specific to addressing climate change; it is also possible to adapt our environment to better suit our individual and community needs as a habitat, as has been done already for millennia.

Definitions of climate engineering

As discussed above, there is no definition of "geoengineering" or "climate engineering" which is agreed on by the research, policy and civil society communities at large. The IPCC working group III defined it as "technological efforts to stabilize the climate system by direct intervention in the energy balance of the Earth for reducing global warming"[23] and later more generally as "a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change"[14], while the Royal Society[5] refers to as "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming". Recognising the lack of agreed definition, the Convention on Biological Diversity[24] stated in its decision X/33 that "Without prejudice to future deliberations on the definition of geo-engineering activities, understanding that any technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale that may affect biodiversity (excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released into the atmosphere) should be considered as forms of geo-engineering which are relevant to the Convention on Biological Diversity until a more precise definition can be developed".

There is a broader naming issue surrounding the concept of CE. Prior to the more recent usage of the term "geoengineering" in relation to counteracting global warming, the term has historically been used as an abbreviation for "geotechnical engineering", which is "a branch of civil engineering concerned with the engineering behavior of earth materials" (Wikipedia), or "a science that deals with the application of geology to engineering" (Merriam-Webster.com), or "the branch of engineering concerned with the analysis, design and construction of foundations, slopes, retaining structures, embankments, tunnels, levees, wharves, landfills and other systems that are made of or are supported by soil or rock" (*The Electronic Journal of Geotechnical Engineering*). There is also a *Journal of Geoengineering* (published by the Taiwan Geotechnical Society) which "covers various topics in geotechnical engineering." This is quite different from what is understood under "geoengineering" in the context of climate change.

Due to the imprecise nature of "geoengineering" and the potential for confusion with geotechnical engineering, many climate scientists have instead begun to use the term "climate engineering", which is more specific and for which the intent is immediately more apparent[8,11,12,13,25]. Climate engineering is the most widely used alternate terminology, although many other terms have been proposed, such as "climate intervention", "climate management", "climate remediation" and "novel options for addressing climate change". In the rest of this study we refer to the topic as climate engineering (sometimes abbreviated CE), for the reasons of greater precision, although we recognize that the term "climate engineering" is not without a past: it has sometimes been used to refer to air conditioning technologies, as opposed to the large scale climate control being considered here. The word “engineering” itself may also be misleading as we are considering here methods that try to influence one aspect of a complex system rather than control or "engineer" the full system.

Finally, there is considerable discussion within the community about whether an umbrella term should be used at all, given the vast range of techniques that it subsumes. We will not attempt to address this issue here. We rather develop an improved categorization for what generally falls under the umbrella term. We hope that our improved categorization will allow people to be more comfortable either addressing a specific category of climate engineering and using terminology which makes that clear, and also to be able to specify what categories they are subsuming under the umbrella term.

Issues and overlaps with existing definitions

There is also potential overlap with both mitigation and adaptation. Responses to climate change can be categorized according to where they take place in the chain of processes between anthropogenic drivers of climate change and the impacts of climate change[15,26]. This is not enough to resolve all the ambiguities.

Defining climate engineering as “engineering the climate system” requires one to specify what one means by climate system. It is usual to define the climate system as the sum of and the results of the interactions between the atmosphere, the ocean, the cryosphere and the biosphere. It is sometimes considered to include the crustal lithosphere and the “anthroposphere” of human population, technology, activities and consciousness. Normally the definition excludes sediments and other geological reservoirs that are nevertheless known to play a role on long climatic timescales. This justifies a posteriori why CCS[19] is usually not considered as CE as it reduces CO_2 emissions at the source (i.e., capturing CO_2 from flue gases of power plants or other CO_2-emitting industry) rather than removing CO_2 from the atmosphere. However CCS is required for some forms of carbon dioxide removal from the atmosphere, notably biomass energy with CCS (BECCS) and direct capture through chemical engineering and storage[8,27]. BECCS has the potential to remove CO_2 from the atmosphere and will have an impact on the biosphere if performed on a large scale. It can therefore be considered as climate engineering even though bio-energy and CCS on their own are usually considered as mitigation options as they individually contribute to reduce atmospheric emissions of CO_2.

Some climate engineering proposals may be considered as adaptation options. For instance, using more reflective roofs or road surfaces is sometimes presented as a climate engineering method[28,29]. Yet this technique is also an adaptation method to mitigate the urban heat island effect[30]. Highly reflective building surfaces were already a common architectural feature in countries with a hot climate long before anthropogenic climate change started to be an issue. Likewise, changes in cropland management practices such as increasing irrigation[22] or increasing crop albedo[31] may also help to adapt to a changing climate by cooling the Earth's surface locally and maintain crop productivity in a warmer climate.

While the distinction between SRM and CDR[5] is useful, it does not cover all potential climate engineering schemes that have been proposed to date. For instance, it has been suggested that the terrestrial radiation budget could also be artificially modified through changes in cirrus clouds[9]. Such a technique aims to increase outgoing longwave radiation but shares a lot of characteristics with SRM techniques in that it is non-permanent, quasi-reversible and is only meant to “mask” the warming effect due to greenhouse gases. Carbon dioxide is not the only long-lived greenhouse gas in the atmosphere, and removal or destruction of methane can also be envisaged either in the atmosphere[32] or before emissions from natural reservoirs take place[33,34].

3. What characterizes and distinguishes climate engineering?

We now discuss a number of attributes of CE techniques, which can help to classify these techniques, and differentiate such techniques from mitigation and adaptation.

Intent. There is general agreement in the scientific literature that climate engineering is *per se* an intentional attempt to counteract climate change by a method that does not seek to reduce anthropogenic emissions of warming agents. For instance, the emission of sulphate aerosols from burning fossil fuels, although responsible for a cooling effect, is not considered to be climate engineering because it is a by-product rather than a deliberate human action to cool the climate. Although in most cases, it is clear if an action is or is not a deliberate attempt to modify the climate, there are situations where this criterion may not apply clearly. A particularly poignant example is the emission of sulphur dioxide (SO_2) from ocean-going ships. A putative deliberate decision to continue burning high-sulfur fuel over the open oceans to maintain the cooling effect of sulphate aerosols could be considered a form of climate engineering, if such a decision is made despite the availability of low-cost, low-sulfur fuel and known adverse air quality impact.

Scale and/or intensity. Climate engineering implies a certain scale and/or intensity of action and/or impact. Below some spatial scale a deliberate environmental change should not be considered as climate engineering. Planting trees on a small plot of land or whitening roofs in a small urban area do not constitute CE as their impact on the climate system will be negligible. Scale and intensity clearly distinguish climate engineering from weather modification or other sorts of ecological or environmental engineering that usually attempt to modify the environment on a fairly small scale. CE can be considered to start when there is a measurable climate impact at the regional or global scale. What constitutes a 'measurable climate impact' is subject to judgement although analyses of past events, such as the eruption of Mount Pinatubo, and model simulations could be used to quantify this. We envisage that a typical scale relevant to regional climate impact could be of the order of 300 km x 300 km $\approx 10^5$ km^2. Conversely any action that mainly aims at modifying the climate at the local scale should be considered as an adaptation measure rather than as CE per se, as long as there is no measurable or detectable remote effect. Again this is subject to judgement and we envisage that a typical scale relevant to local climate impact could be that of a small city or approximately 30 km x 30 km $\approx 10^3$ km^2. There is a scale or intensity beyond which it is no longer possible to affect the climate locally without having a measurable effect remotely. For instance Jones et al.[35] showed that a rather intense cloud brightening applied on a fairly small fraction of the world's ocean would have significant remote impacts in terms of surface temperature and precipitation. Such options therefore qualify as climate engineering. We recognize though that the border between local and regional climate modification is likely to be fuzzy and will require additional research and public debate conceivably on a case-by-case basis. For example a small scale intervention in the wrong place could have a larger impact than a large intervention in a less sensitive area.

Impact on global commons and remote effects. Climate engineering techniques may also be categorized according to whether they intervene within "territorial" regions and/or intervene in the global commons. By global commons we refer here to the Earth's non-owned natural resources, such as the atmosphere and the oceans, but purposely leave the global climate out of this concept. Global commons are therefore resources that are beyond national jurisdictions whose ownership is subject to interpretation (Antarctica) or held jointly (e.g., the atmosphere because it is perpetually in motion and crosses borders). SRM by stratospheric aerosols and marine cloud brightening are examples of climate engineering techniques based on the global commons, for which some remote effects are known and understood[35,36]. The CE medium (e.g., stratospheric aerosols) will travel in the atmosphere and cross national boundaries. Likewise ocean fertilization[37,38], increased ocean alkalinity[39] and SRM by ocean foam or hydrosols[40,41] rely on using the ocean and can hardly be contained to territorial waters; they should therefore be considered as trans-territorial. Land-based CDR methods can be considered as territorial in that they operate within or at least from within national boundaries. They are unlikely to have any measurable trans-boundary impact (beyond that due to decreasing atmospheric concentrations of CO_2) if performed on a small scale. However, such methods should be considered as trans-territorial when their intensity or scale are such that they have significant trans-boundary impacts. For instance land-based biological CDR techniques will have a regional impact on the hydrological cycle if they are performed on a large scale. Likewise SRM by whitening roofs or increasing desert reflectivity can be considered as territorial as long as they do not have any measurable remote, trans-boundary impact. There is, however, an intensity beyond which such techniques will have remote effects[42]. An important characteristic of climate engineering therefore relates to the existence of remote side-effects.

Degree of (perceived) "naturalness". Some proposed climate responses to climate change may be seen as more natural than others, such as planting trees even if on a large scale, and it has been suggested that "unnaturalness" and/or the recourse to technology should be a characteristic of climate engineering methods[43]. Indeed, this issue also surfaced in the public perception of climate engineering[44,45]. Notwithstanding that what constitutes a technology is ill-defined, especially when technology attempts to reproduce or enhance some natural processes, this raises the issue of the relationship between humans and nature, which is value-laden. Furthermore, humanity has interacted with nature in a number of ways, e.g., through large-scale forest clearing, development of mono-cultures and breeding of animal and plant species for commercial purposes, thus it is debatable to what extent "nature" exists independently of human influence, or is just socially constructed as such[46-47]. Overall, the degree of "naturalness" or the reliance on "technology" do not really help to differentiate climate engineering from mitigation and adaptation[15]. However, it might be helpful to consider if a climate engineering approach removes warming climate agents or instead adds cooling climate agents (e.g., stratospheric aerosols). When removing climate agents, it may often be constructive to make a distinction between whether this is done by a) decreasing anthropogenic emissions to the atmosphere, b) increasing "natural" sinks, c) decreasing "natural" emissions, or d) creating new engineered sinks. While approaches under a) definitely fall under a strict definition of mitigation and approaches under d) are forms of climate engineering, those under b) and c) could be one or the other, depending on what other attributes are considered.

Degree of permanency. This relates to the timescale at which the system will come back to its initial state after the action stops. The permanence of climate engineering methods (but also mitigation and adaptation actions) can vary greatly. It can be either a positive or a negative trait of particular climate engineering methods depending on their mode of action and side effects.

Speed. Related to but distinct from the previous attribute, is whether the impact of a particular method occurs slowly or rapidly. This relates both to the characteristics of the method and to its potential rate of deployment. This can again by either a positive or negative trait depending on mode of action and side effects.

Leverage. High leverage is when a rather small effort (e.g., in terms of energy input or financial investment) results in a rather large climate engineering effect. It is generally the case that high-leverage climate engineering methods (such as stratospheric aerosol injection) can be rapid but have a fairly low degree of permanency, while methods with a greater degree of permanency have much lower leverage.

4. Categorization of climate engineering in relationship to mitigation and adaptation

These considerations lead us to propose a more general categorization of responses to climate change (Table 1). In doing so, it is important to be clear about our aim and motivation. As a group of climate scientists, we seek to clarify the wider societal discourse and action on responses to climate change by distinguishing methods according to the processes in the Earth system being altered and the corresponding spatial and temporal scales of action and effects. However, our categorization is also aware of the political context in that it distinguishes territorial and trans-boundary actions/effects, rather than speaking purely in terms of numerical metrics of scale. In other words, it is a primarily scientific categorization that is also somewhat rooted in political reality. Alternative approaches to categorization could be technology-based or more policy-oriented.

Though our categorization scheme was developed independently, it shares some aspects of the typology recently put forward by Heyward[15]. However, it goes beyond Heyward[15] in that it broadens the SRM and CDR categories and revisits the boundaries of both mitigation and adaptation. The categorization proposes five main categories. A preliminary version of this categorization has been tested against a list of 47 possible responses to climate change by 10 scientists from the European Framework Programme 7 EuTRACE project involved in CE research. Because of the small sample of responses considered here, we did not seek to interpret the responses in a statistical sense but rather as expert elicitation to guide our study. Results from the questionnaire showed that in about one third of the cases, responses were unanimously attributed to a particular category by all 10 researchers, and in about two thirds of the cases it was unambiguous, with 8 out of 10 agreeing; however, there were cases with multiple answers and/or some spread in the answers, with only about half of the responses agreeing on the “best” choice. Most of the time the spread in answers was because of some ambiguity on the scale of the climate change response or because the primary intention of the method was not necessarily to address climate change. This exercise led to further improvements and refinements of the definitions and attributes of the five categories. We present the new categorization that resulted from these improvements in Table 1.

The first category, anthropogenic emissions reductions (AER), includes initiatives and measures to reduce or prevent anthropogenic emissions of warming agents into the atmosphere. This encompasses most of what IPCC and UNFCCC regard in their definition as mitigation, including CCS from fossil fuel combustion. AER excludes, however, CO_2 sink enhancement techniques that are considered as mitigation by IPCC and UNFCCC. This category could be further divided into the mitigation of emissions of well-mixed (long-lived) greenhouse gases and the mitigation of emissions of short-lived radiative forcing agents such as black carbon.

The second and third categories, domestic and trans-boundary greenhouse gas removal (D-GGR and T-GGR, respectively), encompass all techniques aiming at removing CO_2 from the atmosphere (i.e., CDR) as well as potential techniques to remove other long-lived greenhouse gases from the atmosphere. D-GGR includes techniques that are territorial, do not involve the global commons and are unlikely to have any significant trans-boundary impact (i.e., those techniques originally envisaged as being part of mitigation in a UNFCCC sense), while other, potentially more disruptive techniques belong to T-GGR. Whether the carbon is stored in national jurisdictions (e.g., in forests, soils or geological reservoirs) or outside such national jurisdictions (e.g., in the ocean) matters as this would raise very different cultural, political and legal issues (e.g., for verification purposes).

While we focus here on the potential trans-boundary effects on climate and global commons, we also recognize that other trans-boundary transfers may be involved (e.g., fibres or financial flows).

The fourth category, targeted climate modification (TCM), encompasses all techniques aiming to affect the climate on the regional to global scale through a direct modification of radiative or energy fluxes, rather than indirectly through the removal of long-lived greenhouse gases. It includes but is not restricted to SRM techniques. Most of the proposed techniques that fall in this category are likely to operate rather rapidly, but they lack permanency, i.e., the climate system will return rapidly to its initial state if this type of climate engineering is stopped. We tentatively define the regional scale as covering an area of the order of 300 km x 300 km ≈ 10^5 km^2 but recognize there is a judgement involved here.

Finally, the fifth category, climate change adaptation measures (CCAM), covers traditional adaptation measures, but broadens the concept to also include those relying on local targeted cooling, as long as they have no measurable remote effects. We tentatively define the local scale as being of the order of 30 km x 30 km ≈ 10^3 km^2. The broadening of the adaptation concept does not necessarily require any changes in the currently accepted definition, but we nevertheless propose the new acronym CCAM to designate this expansion, and also to make clear that it is referring to adaption to climate change (since adaptation can also apply to other environmental and also social changes).

Figure 1 provides a flowchart that helps classify a particular action into the categories defined above. The question of "significant trans-boundary (remote) effects" is likely to be the one that is most difficult to answer and where some fuzziness may arise between categories D-GGR and T-GGR, as well as between TCM and CCAM. Analyses of past events and regional climate modelling can be used to inform what the threshold scale/intensity of a particular method is for remote effects to become detectable. For completeness we can mention a sixth possible category, introduced and labelled as "rectification" by Heyward[15], which covers financial compensation and symbolic measures.

Although not universal, the new five-class categorization maps naturally on current usage. The combination of AER and D-GGR corresponds to the definition of mitigation by UNFCCC and IPCC. The combination of D-GGR and T-GGR encompass all methods of atmospheric removal of carbon dioxide (CDR) along with other long-lived greenhouses gases. Categories T-GGR and TCM collectively correspond to the more 'disruptive' forms of interventions, which corresponds to what is often envisioned under the term "climate engineering," and are likely to be the most controversial. Finally categories TCM and CCAM have in common that they do not attempt to reverse the anthropogenic modification of the atmospheric composition, which is the main cause of climate change.

There remain some overlaps in our classification, for example BECCS can both offset fossil fuel emissions (AER), achieve territorial removal of CO_2 (D-GGR), potentially range across territories by involving import of biomass in the global economy (T-GGR), and create a land-use change carbon source (thus adding to the anthropogenic causes of climate change)[48]. Such overlaps are inevitable in any attempt to fit the world into simple categories. They can be beneficial in the sense of encouraging broader thought about the consequences of particular actions. We suggest that particular methods such as BECCS can be assigned to a primary category in our classification, with the possibility of secondary categories where these are clearly identifiable.

5. Conclusion

The large and growing number of CE methods that have been proposed, irrespective of their feasibility, is causing ambiguity in the current definitions of mitigation and adaptation. The definition of climate engineering itself is unclear and has been a recurring issue in discussions. We have proposed a simple categorization of the strategies to respond to anthropogenic climate change in five distinct classes that alleviates some of the issues associated with the existing terminology.

In particular we recommend that CDR techniques (except CCS directly at power and industrial plants) should no longer be considered as part of mitigation, but should instead form separate categories of responses to climate change. We also suggest that localized climate modification can be seen as an adaptation measure, as long as there are no measurable remote environmental effects. In both cases the scale and intensity of action are essential attributes from technological, climatic and political viewpoints. Differentiating territorial or domestic removal of greenhouse gases (D-GGR) from trans-territorial or trans-boundary removal (T-GGR), and differentiating local adaptation via targeted climate and environmental modification (a component of CCAM) from regional and global modification (TCM) will require further work.

Our aim is to progress the debate on how climate engineering should fit (or not) in the portfolio of existing climate change policies. We hope that our proposed revisions to the terminology and necessary definitions of the boundaries between categories can help to foster a debate among stakeholders such as the research, policy and civil society communities at large. We invite in particular further feedback from social scientists and policymakers on our preliminary categorization.

Finally we have not tried to rank or assess policy responses to climate change, either within a category, or between categories. Multiple factors have to be considered when comparing these policy responses, including their technological maturity, affordability, effectiveness, scalability, timescale for implementation, risk, residual climate change, unintended consequences, degree of interference with the climate system, intergenerational and trans-regional ethical implications, the policy and governance challenges they pose.

6. Acknowledgements

This opinion article has benefited from discussions held at the IPCC Expert Meeting on Geoengineering that took place in Lima, Peru on 20-22 June 2011, which four of the authors attended. PMF and NEV would like to acknowledge support from the EPSRC/NERC for the IAGP project. OB, ML, TML, AM, and NEV would like to acknowledge partial support from the FP7 EuTRACE project grant agreement (306395). AM and ML would additionally like to thank the German Ministry for Education and Research (BMBF), the Brandenburg Ministry for Science, Research and Culture (MWFK) and the Research for Sustainability Platform (FONA). OB acknowledge supports from the Agence Nationale de la Recherche under the REAGIR project. NG acknowledges the financial support of ETH Zurich. The authors would also like to thank Jim Haywood, Thomas Leisner, Helene Muri, Rodrigo Riestein, Simon Shackley, Harald Stelzer for useful discussions and for responding to the questionnaire. Bénédicte Fisset helped with formatting the manuscript and references. We thank three anonymous reviewers for their insightful comments that have contributed to improve this opinion article.

7. References

1. Fleming JR. Fixing the sky: The checkered history of weather and climate control, New York, Columbia University Press, 2010. 325 pp.

2. President's Science Advisory Committee. *Restoring the Quality of Our Environment*, Report of the Environmental Pollution Panel, Washington, DC, 1965.

3. Marchetti C. On geoengineering and the CO2 problem. Climatic Change 1977, 1:59-68. doi: 10.1007/BF00162777

4. Keith D. Geoengineering the climate: History and prospect. Annual Review of Energy and the Environment 2000, 25:245-284. doi: 10.1146/annurev.energy.25.1.245

5. Royal Society, Geoengineering the climate: Science, governance and uncertainty. Report 10/09, 2009, 82 pp.

6. Crutzen PJ. Albedo Enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? Climatic Change 2006, 77:211-220. doi: 10.1007/s10584-006-9101-y

7. Latham J. Control of global warming? Nature 1990, 347:339–340. doi: 10.1038/347339b0

8. Vaughan NE, Lenton TM. A review of climate engineering proposals. Climatic Change 2011, 109:745-790. doi: 10.1007/s10584-011-0027-7

9. Mitchell DL, Finnegan W. Modification of cirrus clouds to reduce global warming. Environmental Research Letters 2009, 4:04510. doi: 10.1088/1748-9326/4/4/045102

10. Boyd PW. Ranking geo-engineering schemes. Nature Geoscience 2008, 1:722-724. doi: 10.1038/ngeo348

11. Feichter J, Leisner T. Climate engineering: A critical review of approaches to modify the global energy balance. The European Physical Journal 2009, 176:81-92. doi : 10.1140/epjst/e2009-01149-8

12. GAO, Technology assessment: Climate Engineering: Technical status, future directions and potential responses, U.S. Government Accountability Office, GAO-11-71, Washington, USA, 2011, 121 pp.

13. Rickels W, Klepper G, Dovern J, Betz G, Brachatzek N, Cacean S, Güssow K, Heintzenberg J, Hiller S, Hoose C, Leisner T, Oschlies A, Platt U, Proelß A, Renn O, Schäfer S, Zürn M. Large-Scale Intentional Interventions into the Climate System? Assessing the Climate Engineering Debate. Scoping report conducted on behalf of the German Federal Ministry of Education and Research (BMBF), Kiel Earth Institute, Kiel, 2011.

14. IPCC, IPCC Expert Meeting Report on Geoengineering, [Edenhofer O, Field C, Pichs-Madruga R, Sokona Y, Stocker T, Barros V, Dahe Q, Minx J, Mach K, Plattner GK, Schlomer S, Hansen G, Mastrandrea M (eds.)] IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 2011.

15. Heyward C. Situating and abandoning geoengineering: A typology of five responses to dangerous climate change. PS: Political Science & Politics 2013, 46:23-27. doi: 10.1017/S1049096512001436

16. IPCC, Climate Change 2007, Synthesis Report, Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, [Core writing team, Pachauri RK, Reisinger A (eds.)], IPCC, Geneva, 2007, 104 pp.

17. IPCC, Climate Change 2001, Synthesis Report, Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, [R. T. Watson and the Core writing team (eds)], Cambridge University Press, Cambridge, UK, 2001, 398 pp.

18. UNFCCC, United Nations Framework Convention on Climate Change, 1992, 33 pp.

19. IPCC, Special report on carbon dioxide capture and storage, Intergovernmental Panel on Climate Change, [Metz B, Davidson O, de Coninck H, Loos M, Meyer L (eds.)], Cambridge University Press, Cambridge, UK, 2005.

20. Gill SE, Handley JF, Ennos AR, Pauleit S. Adapting cities for climate change: The role of the green infrastructure. Built Environment 2007, 33:115-133. doi : 10.2148/benv.33.1.115

21. Miller NL, Jin J, Tsang CF. Local climate sensitivity of the Three Gorges Dam. Geophysical Research Letters 2005, 32:L16704. doi: 10.1029/2005GL022821

22. Boucher O, Myhre G, Myhre A. Direct influence of irrigation on atmospheric water vapour and climate. Climate Dynamics 2004, 22:597-603, doi: 10.1007/s00382-004-0402-4

23. IPCC, Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds.)], Cambridge University Press, Cambridge, UK, 2007.

24. CBD, Decisions adopted by the conference of parties to the Convention on Biological Diversity at its tenth meeting, Decision X/33 on Biodiversity and Climate Change, Nagoya, 18-29 October 2010. Available from http://www.cbd.int/cop10/doc/

25. Caldeira K, and Wood L. Global and Arctic climate engineering: numerical model studies. Philosophical Transactions of the Royal Society A, 2008, 366:4039-4056. doi: 10.1098/rsta.2008.0132

26. Boucher O, Gruber N, Blackstock J. Summary of the Synthesis Session, In: IPCC Expert Meeting Report on Geoengineering. [Edenhofer O, Field C, Pichs-Madruga R, Sokona Y, Stocker T, Barros V, Dahe Q, Minx J, Mach K, Plattner GK, Schlomer S, Hansen G, Mastrandrea M (eds.)] IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 7 pp., 2011.

27. APS Direct air Capture of CO2 with Chemicals. A Technology Assessment for the APS Panel on Public Affairs. 1 June 2011. Available from http://www.aps.org/policy/reports/assessments/upload/dac2011.pdf

28. Oleson KW, Bonan GB, Feddema J. Effects of white roofs on urban temperature in a global climate model. Geophysical Research Letters 2010, 37:L03701. doi: 10.1029/2009GL042194

29. Akbari H, Matthews HD, Seto D. The long-term effect of increasing the albedo of urban areas. Environmental Research Letters 2012, 7:024004. doi: 10.1088/1748-9326/7/2/024004

30. Akbari H, Konopacki S, Pomerantz M. Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. Energy 1999, 24:391-407. doi: 10.1016/S0360-5442(98)00105-4

31. Ridgwell A, Singarayer J, Hetherington A, Valdes P. Tackling regional climate change by leaf albedo bio-geoengineering. Current Biology, 2009, 19(2):146-150. doi: 10.1016/j.cub.2008.12.025

32. Boucher O, Folberth G. New Directions: Atmospheric methane removal as a way to mitigate climate change? Atmospheric Environment 2010, 44:3343-3345. doi: 10.1016/j.atmosenv.2010.04.032

33. Krey V, Canadell JG, Nakicenovic N, Abe Y, Andruleit H, Archer D, Grubler A, Hamilton NTM, Johnson A, Kostov V, Lamarque JF, Langhorne N, Nisbet EG, O'Neill B, Riahi K, Riedel M, Wang W, Yakushey V. Gas hydrates: entrance to a methane age or climate threat? Environmental Research Letters 2009, 4:034007. doi: 10.1088/1748-9326/4/3/034007

34. Stolaroff JK, Bhattacharyya S, Smith CA, Bourcier WL, Cameron-Smith PJ, Aines RD. Review of methane mitigation technologies with application to rapid release of methane from the Arctic. Environmental Science & Technology 2012, 46:6455-6469. **doi:** 10.1021/es204686w

35. Jones A, Haywood J, Boucher O. Climate impacts of geoengineering marine stratocumulus clouds. Journal of Geophysical Research 2009, D10106, doi: 10.1029/2008JD011450

36. Bala G, Duffy PB, Taylor KE. Impact of geoengineering schemes on the global hydrological cycle. Proceedings of the National Academy of Sciences of the USA 2008, 105:7664–7669. doi: 10.1073/pnas.0711648105

37. Lampitt RS, Achterberg EP, Anderson TR, Hughes JA, Iglesias-Rodriguez MD, Kelly-Gerreyn BA, Lucas M, Popova EE, Sanders R, Shepherd JG, Smythe-Wright D, Yool A. Ocean fertilisation: a potential means of geoengineering? Philosophical Transactions of the Royal Society A 2008, 366:3919-3945. doi: 10.1098/rsta.2008.0139

38. Watson AJ, Boyd PW, Turner SM, Jickells TD, Liss PS. Designing the next generation of ocean iron fertilisation experiments. Marine Ecology Progress Series 2008, 364:303-309. doi: 10.3354/meps07552

39. Kheshgi HS. Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. Energy 1995, 20:915-922. doi: 10.1016/0360-5442(95)00035-F

40. Evans JRG, Stride EPJ, Edirisinghe MJ, Andrews DJ, Simons RR. Can oceanic foams limit global warming? Climate Research 2010, 42:155-160. doi: 10.3354/cr00885

41. Seitz R. Bright water: hydrosols, water conservation and climate change. Climatic Change 2011, 105:365-381. doi: 10.1007/s10584-010-9965-8

42. Irvine PJ, Ridgwell A, Lunt DJ. Climatic effects of surface albedo geoengineering. Journal Geophysical Research 2011, 116: D24112. doi: 10.1029/2011JD016281

43. Schelling T. The economic diplomacy of geoengineering. Climatic Change 1996, 33:303-307. doi: 10.1007/BF00142578

44. Croner AJ, Parkhill K, Pidgeon NF, Vaughan NE. Messing with nature? Exploring public perceptions of geoengineering in the UK. Global Environmental Change 2013, in press. doi: 10.1016/j.gloenvcha.2013.06.002

45. Hiller S, Renn O. Public perception of geoengineering. Security and Peace 2012, 4:215-220.

46. Rolston III H. A managed Earth and the end of nature? Research in Philosophy and Technology 1999, 18:143-164.

47. Demeritt D. What is the ‘social construction of nature’? A typology and sympathetic critique. Progress in Human Geography 2002, 26:766-789. doi:10.1191/0309132502ph402oa

48. Powell TWR, Lenton TM. Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. Energy and Environmental Science 2012, 5:8116-8133. doi: 10.1039/c2ee21592f

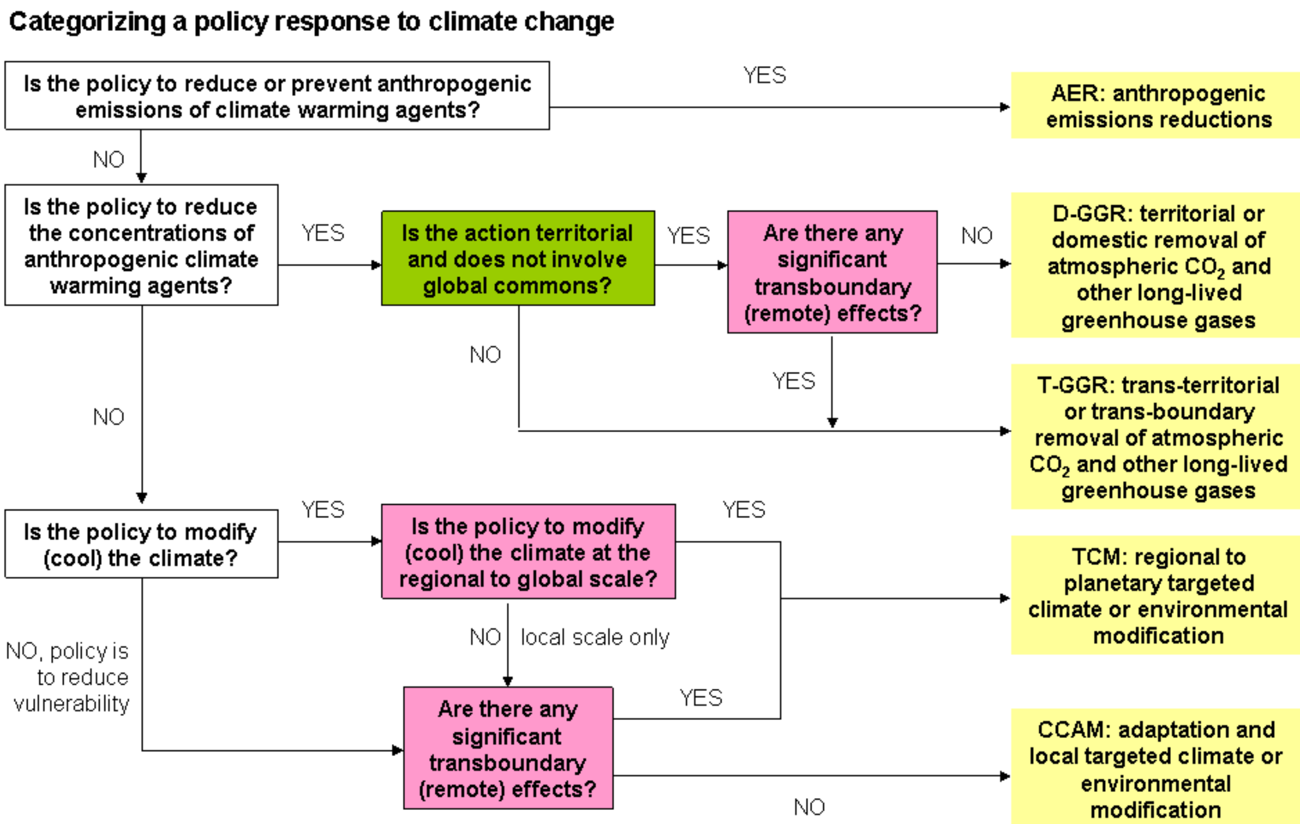

Figure 1: Flowchart of the proposed categorization of climate change responses. Text in white boxes corresponds to policy questions; text in the green box corresponds to a legal question; text in pink boxes corresponds to questions that involve value judgements but can be informed by climate and related sciences. Yellow boxes to the right side list the five categories.

Proposed name and acronym	Short definition	Mapping onto previous terminology	Examples	Scale of action	Scale of impacts	Impact on the global commons (*)	Trans-boundary or transnational side effects (*)	Permanence of the effect
Anthropogenic emissions reductions (AER)	Initiatives and measures to reduce or prevent anthropogenic emissions of warming agents into the atmosphere	Includes most forms of mitigation but excludes human-induced CO_2 sink enhancement	Improved energy efficiency, reduction in production and/or consumption of goods and services, introduction of renewable energies, nuclear energy, fossil fuel energy with CCS, reducing emissions from deforestation and forest degradation, emission reductions of BC and ozone precursors	Generally a localised action or a sum of localised actions	Global through a decrease in the global-mean RF by greenhouse gases and other warming agents	None expected. Expected to slow down the depletion of fossil fuel resources (except for CCS). Expected to slow down ocean acidification for CO_2 measures	Generally none	Commensurate to the atmospheric lifetime of the species being mitigated, longer if emission reduction is sustained
Territorial or domestic removal of atmospheric CO_2 and other long-lived greenhouse gases (D-GGR)	Removal of CO_2 and long-lived greenhouse gases from the atmosphere operating within national jurisdictions and little consequences outside	Includes territorial CO_2 sink enhancement previously labelled under mitigation, with environmental side effects if any occurring within national jurisdictions	Reforestation, biochar and other means of increasing storage of C in soils, small-scale afforestation, BECCS, CO_2 air capture and storage in territorial (geological) reservoirs, enhanced weathering (without input of by-products into rivers or the oceans)	Generally a localised action or a sum of localised actions	Global through a decrease in the global-mean RF by greenhouse gases	None in the strict sense. May not slow down the depletion of fossil fuel resources. Expected to slow down ocean acidification for CO_2 measures	Possible (e.g., through changes in evaporation, runoff, river flow, changes in biodiversity) but limited	Commensurate with the permanence of the storage medium
Trans-territorial or trans-boundary removal of atmospheric CO_2 and other long-lived greenhouse gases (T-GGR)	Removal of atmospheric CO_2 and long-lived greenhouse gases from the atmosphere operating or having consequences partly or fully across or beyond national jurisdictions	Includes the more environmentally disruptive CDR techniques	Large-scale afforestation, ocean alkalinity, enhanced weathering (with input of by-products into rivers or the oceans), iron fertilization, injection of CO_2 into the ocean.	Localised but with significant remote effects and/or diffuse with diffuse effects	Global through a decrease in the global-mean RF by greenhouse gases	Expected (e.g., through changes to the water cycle, rivers and/or the global ocean). Expected to slow down ocean acidification in the case of CDR methods not involving iron fertilization or ocean injection	Trans-boundary or transnational side effects expected	Commensurate with the permanence of the storage medium

Regional to planetary targeted climate or environmental modification (TCM)	Intentional modification of the Earth’s energy fluxes in order to offset climate change at the regional to global scale	Essentially what used to be defined as SRM, but excludes small-scale SRM. Excludes removal of long-lived greenhouse gases but includes other large-scale changes to the Earth's energy budget that do not involve long-lived greenhouse gases	Injection of stratospheric aerosols, marine cloud brightening, cirrus suppression, desert brightening on a large scale, ocean heat mixing, modification to Arctic sea ice	Large-scale and/or diffuse (even though the initial action can be local)	Regional to global cooling	Yes (e.g., through the atmosphere and remote climate effects). Does not slow down ocean acidification	Measurable trans-boundary or transnational side effects	Short as this happens through rapidly-responding components of the climate system
Climate change adaptation measures including local targeted climate or environmental modification (CCAM)	Initiatives and measures to reduce the vulnerability of natural and human systems to the effects of climate change. Local risk management.	Essentially what is usually considered as adaptation, but also includes small-scale SRM that only has small if any remote climate impacts	Relocating urban or rural settlements, building dykes, air conditioning, agricultural crop choices, reflective crops, whitening of human settlements on a small scale, irrigation	Local with no or little remote effects	Local	None expected	None, limited to the local scale, or not detectable (i.e., "within the noise"). Some measures may however affect river flow	Commensurate to the lifetime of the adaptation measure (typically months to decades)

(*) beyond any direct effects due to decreasing concentrations of greenhouse gases and other warming agents.

Table 1: A possible categorization of responses to anthropogenic climate change along with their attributes.