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Review

The Climate Change Crisis: A Review of Its Causes and Possible Responses

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Abstract: Anthropogenic climate change (ACC) has evolved into a set of crises due to society's deep economic dependency on fossil fuels. These multiple crises have been well documented and span diverse ecological, human health and economic settings. Given the scale and breadth of CC impacts, expert labeling of the issues has gradually changed from the somewhat benign sounding "global warming" to the more frightening description of a "climate emergency". Notwithstanding calls for transformative societal change, serious attempts to confront ACC have been hampered by decades of government policy inaction, various scientific debates, political conservatism and denial and public ignorance or apathy. Meanwhile, atmospheric greenhouse gas concentrations have increased inexorably and show no sign of plateauing. The impacts of ACC are becoming evident sooner than expected, and projections for the future of the planet's ecosystems and the human population which depends on them are dire. Proposals to geoengineer the climate are currently being hotly debated within the scientific community but may prove to be a last resort if the impacts of unmitigated warming become even more severe.

Keywords: climate change; fossil fuels; mitigation; nonlinearity; geoengineering; aerosols

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1. Introduction

The multiple threats due to impacts of ACC are now thought to constitute a global emergency [1], with potentially catastrophic consequences for humanity [2]. Notwithstanding decades of international research, political debate and increasingly ominous scientific warnings since the first IPCC assessment in 1990, the failure of mitigation through carbon emissions reduction is depressingly clear. In fact, the global increase in CO_2 emissions has been relentless, with emissions now 60% higher than they were in 1990 [3]. Monthly mean carbon dioxide measured at the Mauna Loa Observatory, Hawaii, constitutes the longest record of direct measurements of CO_2 in the atmosphere (see Figure 1). This monitoring program was started by C. David Keeling of the Scripps Institution of Oceanography in March 1958 at a facility of the National Oceanic and Atmospheric Administration [4]. Current CO_2 concentration (April 2023) at Mauna Loa is 423 ppm, which is an increase of about 108 ppm (or 35%) since the start of the monitoring program. The current emissions trajectory puts the world on track for a temperature rise of between 2.1 °C and 3.9 °C by the end of this century [5], with even the lower temperature bound implying severe disruption to many of the Earth's systems.

As an attempt to reduce our collective dependence on fossil fuels, various alternative energy sources such as renewables have been promoted and developed in recent decades. However, fossil fuels still accounted for 82% of primary energy in 2021, down from 83% in 2019 and 85% five years ago [6]. Notwithstanding photovoltaic, nuclear and hydroelectric sources, fossil fuels (primarily coal and gas) still dominate global electricity production, generating over 60% of today's global electricity supply (https://ourworldindata.org/fossil-fuels, accessed on 30 May 2023).

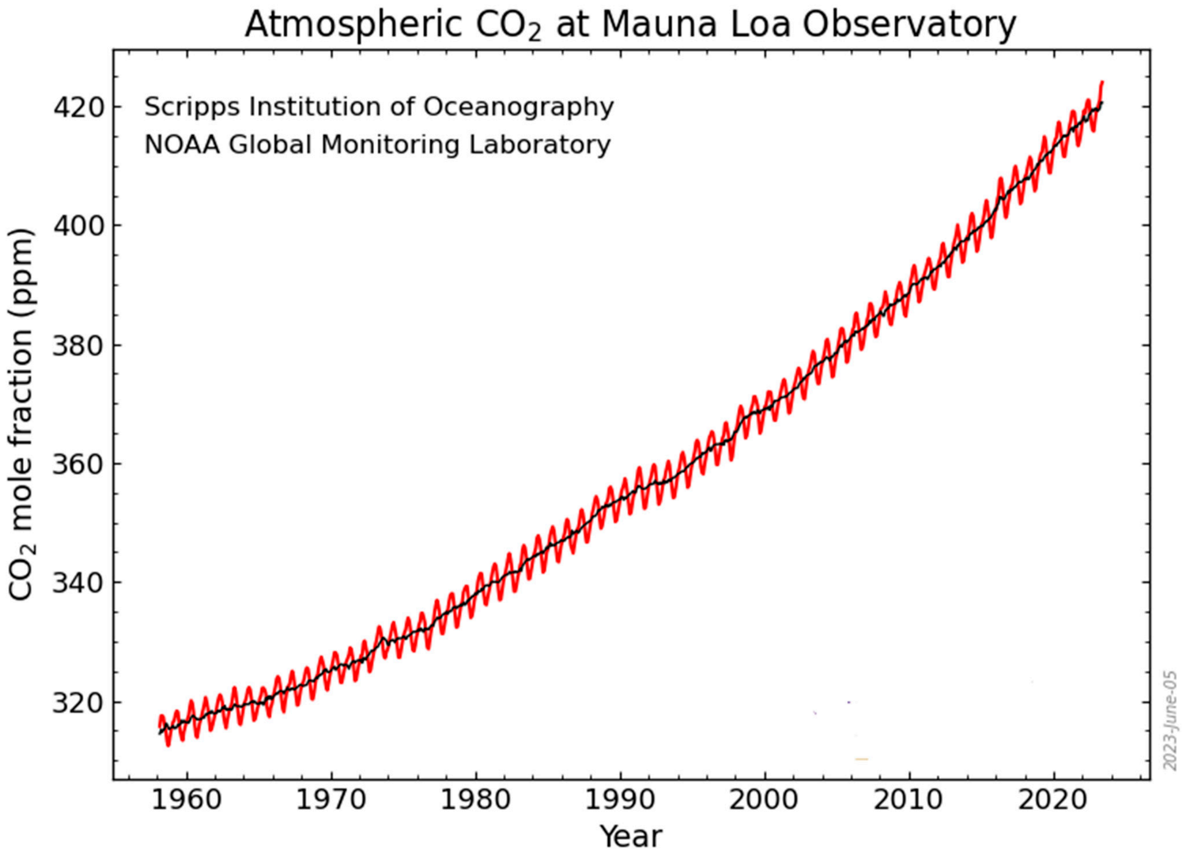


Figure 1. The so-called "Keeling curve". Data retrieved from NOAA Global Monitoring website https://gml.noaa.gov/ccgg/trends/, accessed on 5 June 2023.

Against this background of climate policy inaction, multiple biophysical and human health impacts are already evident or predicted to increase in the near future. These impacts include: changes in the growth and distribution of plants [7], animals and insects [8]; ocean acidification [9] and poleward shifts in the distribution of marine species [10] with effects on global fisheries; and increases in marine heatwaves and coral bleaching [11].

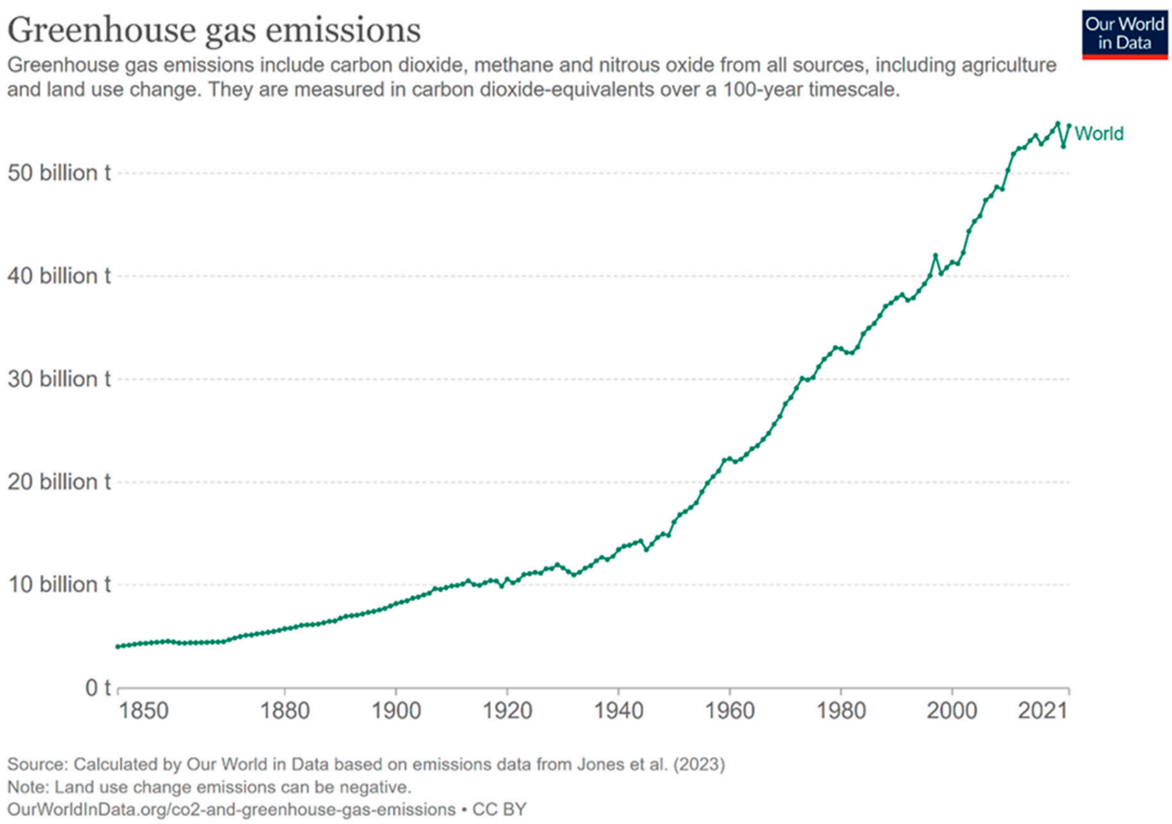
It is likely that ACC has increased the frequency and intensity of daily temperature extremes [12] and has also contributed to a widespread intensification of daily precipitation extremes [13]. These extreme weather events have increased human morbidity and mortality [14,15] and contributed to forced human migration [16], especially in the world's poorer regions. There is also some evidence of a temporal increase in economic damages from extreme weather events, particularly in temperate climate zones [17].

Although consistent with the warming of the troposphere, it is still uncertain whether *specific* extreme weather events—such as floods, droughts and heat waves—are partially or totally the result of anthropogenic climate change. A closely related question is how ACC affects the statistical probability of a particular extreme weather event occurring. Resolving this attribution question is not straightforward and involves the analysis of often-limited observational data and the use of climate model(s), thus often taking some time to resolve. Given the increasing number of extreme weather events (https://www.undrr.org/quick/50922, accessed on 30 May 2023), the field of "event attribution" science has grown during the last decade but is still an evolving field of research [18,19]. For a good overview of event attribution, the reader is referred to van Oldenborgh et al. [20].

Given the immense scope of the climate change issue, in this review, we examine some important selected facets of the current crisis, especially the progress in the field since the historic COP21 meeting. These include the continuing failure to mitigate emissions at the global scale, and, although complex, we attempt to succinctly discuss some of the reasons for the poor societal response. Often forgotten in discussion of climate futures is the essential nonlinear nature of the Earth system and the possible dangers of abrupt or irreversible change to the climate system, which are briefly discussed. In light of the many urgent calls for transformative action, we outline possible remedial options that society can practically take to minimize damage from the impacts of CC. We conclude the review with a brief overview of proposals for geoengineering interventions, which, in the absence of effective mitigation, will likely need to be considered. For reasons of brevity, it is not possible to include discussion of the very rich field of climate change adaptation. However, we note that there is a very close nexus between the scale and speed of mitigation of climate change and the feasibility and overall cost of adaptation responses [21,22].

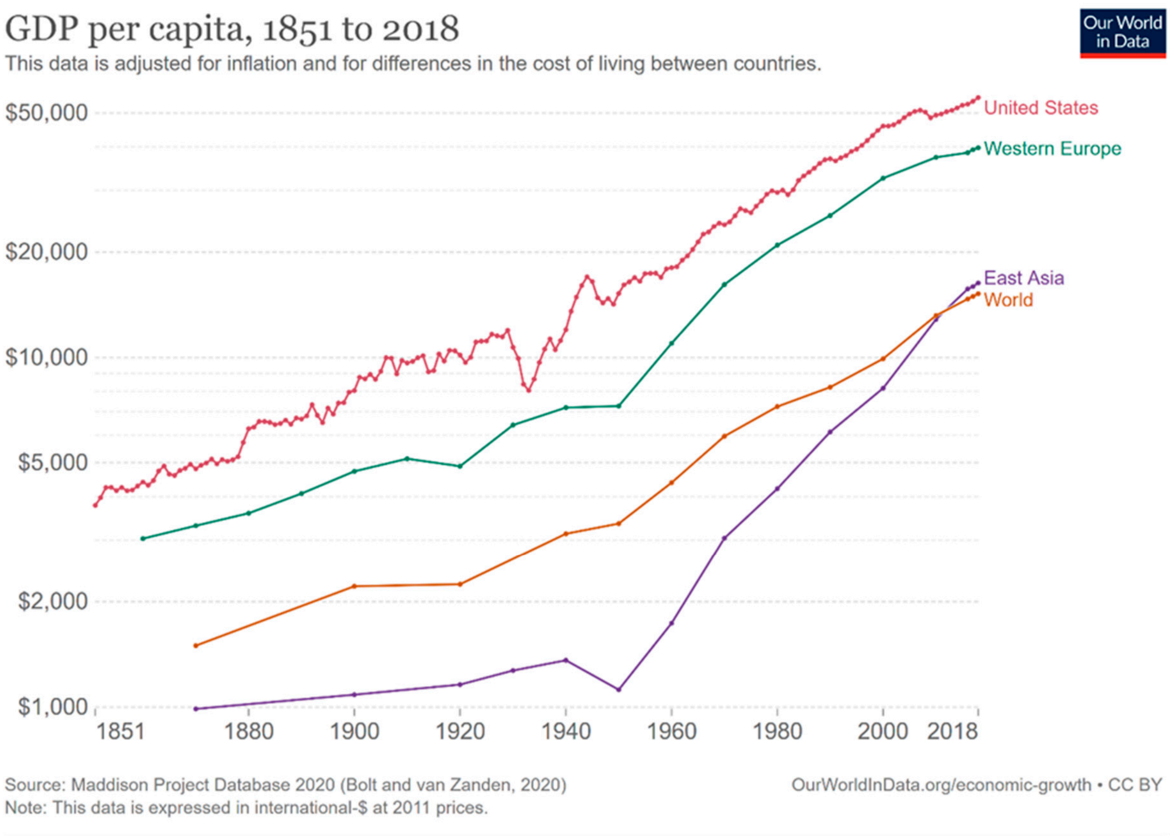
2. Mitigation Failure

Global carbon emissions increased rapidly from the mid-20th century (see Figure 2a), coinciding with a sharp upturn in a multitude of global socio-economic indicators at that time (See Figure 2b), a phenomenon termed the 'Great Acceleration' [23]. It is important to note that per capita GDP has increased faster than global population, with the "average person" in the world now being 4.4 times richer than in 1950, during which time the world population has increased 3-fold, from around 2.5 billion to almost 7.5 billion today [24]. It is pertinent to reflect on what the number of impoverished people would have been without this increase in GDP, largely enabled by the combustion of fossil fuels. This highlights the ethical and social justice dimensions of attempts at emissions reduction, where the remaining carbon budget (to avoid catastrophic CC) needs to be allocated amongst countries in a fashion that is deemed fair to all parties (see Zhou and Wang [25] and Williges et al. [26] for reviews of this contentious field).



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. (**a**) Global CO_2-equivalent emissions data retrieved from Ritchie et al. [27], source data from Jones et al [28] (**b**) GDP per capita in selected regions, data retrieved from https://ourworldindata.org/economic-growth#gdp-growth-since-1950, accessed on 2 May 2023 based on Bolt and Van Zanden [29].

Various multi-faceted reasons for our collective failure to bend the global emissions curve have been identified [3]. These include, inter alia, economic, geo-political, psychological and sociological factors, all combining to create an almost immutable status quo. In addition, the last three decades have seen a concerted effort to either deny the reality of CC [30,31] or, through the use of more nuanced arguments, to seek to delay climate action [32]. These denialist strategies have been successful, as shown by recent analyses of public opinion in the USA, where public understanding of global warming is improving but remains low and perceived personal risk is still very low [33]. In the highly polarized and politicized USA population, the expression of skeptical opinions appears to have more influence on public perceptions than factual science [34]. Likewise, studies of public opinion in Europe suggest that climate change experiences (e.g., extreme weather events) can increase support for climate action, but only under favorable economic conditions [35]. A similar relationship was found in Australia, where climate change skepticism was shown to be negatively associated with the annual global temperatures the previous year [36].

Some authors point to a breakdown of the science–society contract, referring to the tragedy of climate change science—namely, that despite compelling evidence and fresh warnings issued ever more frequently, greenhouse gas (GHG) emissions and other indicators of adverse climate impacts have risen steadily. This lack of societal action has led some to suggest a moratorium on further CC research [37]. The only momentary slowing of emissions occurred during the 2008–09 GFC, with a rapid rebound in subsequent years [38], underscoring the tight coupling of global economic growth and fossil fuel usage. This multi-faceted complexity emphasizes the "wicked" nature of the CC problem which underpins the difficulty in addressing the climate change threat through efforts at societal decarbonization. As first discussed by Rittel and Webber [39], wicked problems always occur in a social context—the wickedness of the problem reflects the diversity among the stakeholders affected by the problem. In the context of climate change, all of us are arguably stakeholders, which underscores both the complexity of the problem and the difficulty of reaching international consensus on ways forward.

Carbon capture and storage (CCS), once thought to be a central technology to offset present and future GHG emissions while continuing societal use of fossil fuels, has proved to be expensive and difficult to deploy at the required rate due to the limited availability of storage sites [40,41]. At current rates of deployment, CO_2 storage capacity by 2050 is projected to be around 700 million tons per year, just 10% of what is required [42]. Oreskes [43] describes CCS as a technology that does not yet exist—in other words, despite many attempts, it has not been shown to be a way to store carbon in the ground safely, permanently and affordably.

3. Calls for Transformative Change

It is evident that the rate of mitigation needs to increase and that the international community must urgently reduce GHG emissions. What is also clear is that this implies nothing less than wholesale societal changes, without which CC impacts will continue and likely accelerate. This will only happen through deep changes to our energy, industry, transport, food and financial systems. In the context of widespread global environmental degradation (of which CC is only one, albeit important, part), Diaz et al. [44] urge transformative change that tackles the root causes: the interconnected economic, sociocultural, demographic, political, institutional and technological indirect drivers behind the direct drivers. A call for just such a societal transformation was made in the papal encyclical “Laudato Si” by Pope Francis [45]. More recently, faith leaders representing the world’s major religions joined scientists at the Vatican to call on the international community to raise their ambition and step up their climate action ahead of the UN Climate Change Conference COP26 in November 2021 in Glasgow. The faith leaders’ appeal stated: “We must address these challenges using the knowledge of science and the wisdom of religion. We must think long-term for the sake of the whole of humanity. Now is the time to take transformative action as a common response”.

As CC impacts become more common and extreme [46], civil society is calling for urgent action that addresses the drivers of climate vulnerability. Transformative change (TC) is defined as a fundamental, system-wide reorganization across technological, economic and social factors [47]. TC is understood to be quite different to incremental change, which is likely to maintain the status quo and so be too slow to redress the rapidly evolving impacts of CC [48,49]. However, the very notion of societal transformation still lacks clarity in terms of its scope, scale and pace [50,51]. Although increasingly discussed, the suggested pathways to TC are not well defined and sometimes divergent [52]. As noted by Sachs et al. [53], TC can only succeed if it has societal legitimacy, so political processes should engage the public in participatory decision making and promote transparency and accountability. However, such changes cannot be driven solely by governments and emerge instead from dialogues and learning processes between stakeholders. New ways for decision making to engage social movements will therefore be crucial [53].

An additional dilemma is that the time needed to implement large-scale societal changes is likely to exceed the time left to constrain warming to safe levels [54]. It is notable that major fossil fuel companies have indicated that they expect to be pumping oil and gas out of the ground beyond 2050 [55]. This scenario will likely eventuate in the absence of major national government policy interventions. Unfortunately, current policy approaches have failed to generate change at anywhere near the rate of mitigation that is needed [56,57]. This is despite three decades of climate negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) and associated policies and actions at national and sub-national levels [58]. The Paris Agreement at the COP21 to keep warming at or below 1.5–2 °C is estimated to correspond to at least halving global emissions by 2030 and reaching net-zero CO_2 emissions by the middle of the century. However, as indicated by the Climate Action Tracker project (an independent scientific consortium that tracks government climate action), *no* countries are yet on track to comply with the Paris Accord [59]. This inertia in government policy response on decarbonization is made all the more risky by the inherent nonlinearity and complexity of the climate system.

4. Nonlinearity in the Climate System

The nonlinearity of the climate has been recognized for quite some time [60] and may lead to abrupt and dangerous perturbations to the climate [61]. Nonlinear dynamical systems are characterized by several important differences from linear systems. These differences include:

- The possibility of the system undergoing sharp transitions, even in the presence of steady forcing;
- A small change in some parameters can cause great qualitative differences in the resulting behavior (e.g., chaos);
- The response of a nonlinear system to oscillatory external forcing usually exhibits frequencies not present in the external forcing.

Nonlinear dynamical systems are challenging to model and can harbor surprises or manifest periods of abrupt change (or even persistent catastrophic shifts), notwithstanding only gradual change in external forcings, e.g., increasing GHG emissions [62]. Abrupt change in the climate system has been identified in the paleoclimatic ice core record even during the otherwise relatively stable Holocene epoch [63,64]. Indeed, various potential "climate tipping points" have been identified in the Earth's climate system [65]. Examples of these tipping points include, inter alia, triggering polar ice sheet collapses, polar permafrost thawing, monsoon disruptions and forest and coral reef diebacks. If triggered, these could cause rapid, and perhaps irreversible, planetary change [66]. Although the timing of such possible changes is uncertain, their occurrence will likely be a function of the degree of warming [67]. Armstrong Mackay et al. [68] note that even a global warming of 1 °C, a threshold that we already have passed, puts us at risk by triggering some tipping points. Limiting global warming to 1.5–2 °C—as agreed upon in the Paris Accord—could still mean exceeding the best estimates for several tipping points, causing the loss of mountain glaciers and the disruption of key ocean currents. This finding underscores the urgency of limiting additional warming as much as possible.

To avoid the potential of such cataclysmic futures (e.g., a "hothouse" Earth scenario), Steffen et al. [69] suggest three possible categories of societal response: (i) reducing GHG emissions (mitigation), (ii) enhancing or creating new carbon sinks, i.e., enhancing negative emissions and (iii) modifying the Earth's energy balance (for example, via solar radiation management). It is unlikely that any one of these categories of response will be sufficient on its own, and a combination will provide the best pathway to addressing the threats of ACC.

5. Enhancing Natural Carbon Sinks

Agricultural land use practices have historically been a major contributor to GHG emissions and are still responsible for up to a third of total anthropogenic GHG emissions [70]. Poor land management has caused between 1 and 6 billion hectares of global soils to be considered degraded to varying degrees [71], having lost much of their soil organic carbon (SOC) through the historical expansion of agriculture [72]. The main land-based mechanisms to enhance emissions sinks (so-called 'negative emissions technologies') are through improving the SOC of degraded agricultural lands and through afforestation or reforestation. For context, it is useful to note that, during the last decade (2011–2020), the net global increase in anthropogenic CO_2 emissions, after accounting for ocean and land sinks, was 4.9 GtC yr^{-1} [73]. If land management practices are improved, it is estimated that sequestering organic carbon in soil could potentially remove up to 1.54 GtC yr^{-1} from the atmosphere, while afforestation and reforestation could remove up to 0.98 GtC yr^{-1} [74].

These approaches would provide significant environmental co-benefits, such as improving soil health and food security, apart from addressing ACC [75]. However, as noted above, the period left to implement change at the scale required is short, and improved land management practices need to be rapidly scaled up and implemented to contribute effectively to climate change mitigation [76,77]. Unfortunately, accurate estimates of land use emissions are still being assessed, and uncertainties in land use emissions are very high [78].

6. Geoengineering of Climate

It is now evident that our current efforts at reducing emissions are not sufficient to arrest the impacts of ACC [79]. In recent years, a variety of geoengineering proposals have been suggested to counteract the impacts of ACC, most of which have been highly controversial [80]. No geoengineering proposal has yet been implemented, although small-scale experiments have been conducted [81]. These proposals are not suggested as replacements for mitigation, but rather as supplementary actions that may reduce the overall severity and impacts of ACC. These include ocean fertilization to stimulate primary production and hence draw down atmospheric carbon dioxide [82] and modification of the planetary albedo by various means [83].

Ocean iron fertilization (OIF) has had a long and checkered history since the initial hypothesis that the addition of iron (a micro-nutrient limiting algal growth) could stimulate CO_2 drawdown in certain parts of the world's oceans, as first posited over 30 years ago [84]. Several experiments tested the iron fertilization hypothesis between 1993 and 2009 with varying degrees of success, as measured by the amount of carbon sequestration [85]. However, uncertainties such as the possible out-gassing of CO_2 as the phytoplankton decompose and the risk of major undesirable marine ecosystem impacts have resulted in the almost universal rejection of OIF as a climate intervention [81].

6.1. Solar Radiation Management (SRM)

This technique consists of a set of approaches that aims to modify the Earth's shortwave radiative budget and hence reduce the warming due to climate change. This class of methods aims to block or reflect a small portion of incoming sunlight and consequently cool the planet but will not reduce other ACC impacts such as ocean acidification. A controversial proposal to inject aerosols into the stratosphere is perhaps the best-studied and -understood SRM technique.

The role of natural and anthropogenic atmospheric aerosols in shaping climate has been a subject of extensive research over several decades [86–89]. Most aerosol particles cool the planet via the direct scattering of incoming shortwave radiation and through indirect changes in cloud microphysical properties, such as cloud albedo. This aerosol negative radiative forcing effect is significant [86] and similar to up to half the positive radiative forcing due to GHGs. However, compared to the long residence times of GHGs, aerosols are short lived in the troposphere, with lifetimes in the order of weeks [90].

It has been understood for some time that anthropogenic aerosols are co-emitted with GHGs during the combustion of fossil fuels, and it has been posited that they are masking the warming due to GHGs to some degree [91]. Because of the short atmospheric residence time of aerosols in the troposphere, and the adoption of more stringent air pollution standards (especially in Europe), the decline in anthropogenic aerosol concentration may be removing a significant cooling effect that has masked the underlying GHG warming [92–94].

In contrast, aerosols introduced into the stratosphere, for example, by explosive volcanic eruptions, may have residence times of several months to a few years [95,96]. Analysis of the recent massive Tongan eruption in January 2022 suggests the mean downward surface net shortwave radiative flux was reduced by 2.45–11.9 Wm^{-2} on different regional scales, and the surface temperature decreased by 0.16–0.42 K [97]. Radiation equilibrium model analyses of the same event suggest that the global average surface temperature will decrease by about 0.032–0.112 °C over the next 1–2 years [98].

The leading SRM method attempts to mimic the cooling effect of volcanic eruptions by artificially injecting aerosols into the stratosphere [99–101]. However, caution is required as cooling is not the only impact of volcanic eruptions; they have been shown to also cause significant changes to regional hydrology through decreases in precipitation [102,103].

The potential deployment of SRM has triggered an unprecedented response from scientists—both cautiously for and completely against its use. In January 2022, more than 60 scientists and scholars launched a global initiative calling for a "non-use agreement on solar geoengineering" with the aim of stopping the development and potential use of planetary-scale solar geoengineering technologies (https://www.solargeoeng.org/non-use-agreement/, accessed on 20 May 2023). This prompted a vigorous debate within the scientific community focused on these issues, and, in February 2023, a carefully worded contrary response came from an even larger group of scientists (https://climate-intervention-research-letter.org/#add-your-name, accessed 20 May 223). Their response stated, " . . . affirms the importance of proceeding with responsible research to objectively evaluate the potential for SRM to reduce climate risks and impacts, to understand and minimize the risks of SRM approaches, and to identify the information required for governance".

6.2. Marine Cloud Brightening (MCB)

This related SRM technique was first proposed by Latham [104] and involves seeding low-level marine stratocumulus clouds with sea salt aerosol generated at or near the ocean surface. In contrast to the injection of aerosols into the stratosphere, MCB aims to affect cloud characteristics by enhancing existing cloud droplet particle albedo and lifetime to produce a cooling effect. Since the lifetime of salt particles in the troposphere is less than 10 days (versus up to 2 years in the stratosphere), MCB is argued to be a safer method than stratospheric aerosol injection, with the possibility of finer control of climate and faster reversal in the case of problems developing. However, there is a range of issues around MCB that require further clarification [105]. To fully explore the potential benefits and dangers of MCB, the risks to ecosystems and coastal communities from such a climate intervention would need to be assessed against the risks from unmitigated warming [106].

7. Conclusions

The current climate crisis manifests through a set of complex and interconnected issues and is the result of global society's continuing dependence on fossil fuels for its main energy supply. This dependence shows no sign of diminishing, even in the rich economies of the global north. Notwithstanding many decades of discussion and debate, progress on addressing the issue of mitigation through decarbonization has been slow and ineffective, with the result that emissions and baseline GHG concentrations continue to increase. Frustration with such slow climate action has led to several contemporary calls for transformational societal change, but ways of implementing such deep change still appear elusive. However, as the impacts of ACC accelerate and become even more serious, TC remains one of the few options to slow catastrophic futures.

Despite international enthusiasm at the time, it is now unlikely that the landmark 2015 Paris Accord will be adhered to in the short time available to prevent a warming of >1.5 °C. As the global temperature exceeds the 1.5-degree threshold, the nonlinearity inherent in the climate system may beget dangerous surprises which current climate models cannot accurately predict and for which humanity is likely ill prepared. The increasingly dire impacts of overshooting this limit are of immense concern, and many have described them as being an existential threat to humanity.

Although every effort to decarbonize through reducing emissions must continue, the slow progress in mitigating emissions means that other technological approaches to remove carbon from the atmosphere will also be necessary. Moving forward, innovative methods of carbon dioxide removal must be developed into climate change strategies to avoid dangerous levels of warming. For example, the improvement of land management practices offers many other co-benefits and few disadvantages, but the scale of the changes required is formidable, and, in many poorer countries, the maintenance of agricultural yields will still be the primary consideration to sustain local food security.

There are numerous uncertainties in both the large-scale implementation and governance of geoengineering proposals such as OIF or SRM. Of major concern is the possibility that, instead of serving as an adjunct to decarbonization efforts, geoengineering could be used to circumvent mitigation commitments and maintain a business-as-usual emissions scenario. Due to the possibility of causing more harm than good, geoengineering "solutions" are currently best seen as a last resort. Notwithstanding these concerns, however, the prudent approach would seem to be to continue to carefully examine and increase the research effort on the potential use of geoengineering as it may be the only effective method to reduce global temperature increases in the short-to-medium term.

8. Dedication

To the memory of Emeritus Professor Des Connell (1938–2023), Griffith University, Brisbane, Australia.

Des was a fine educator, passionate conservationist, and leading ecotoxicologist, as well as a much-valued friend.

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