Deep Time Perspectives on Climate Change: How to Use the Paleoclimatic Record to Find Analogues and Solutions

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In April of 2018, the concentration of carbon dioxide in the Earth's atmosphere reached 410 ppm. This is the highest in over 3 million years, and a 45% increase over the 280 ppm recent average, which held from the end of the last major glaciation until the start of the industrial revolution. **The last time CO_2 levels were this high, in the middle Pliocene epoch, the average global temperature was 5C greater than today, and sea levels were 25 meters higher.** In the early Miocene, 20 mya, atmospheric CO_2 again exceeded 400 ppm, at which time sea level exceeded today's by nearly 100 meters.

A temperature rise of 4-5C is on the high end of estimates of warming by the end of the century under a "business as usual" scenario, where we are for whatever reason unable to take meaningful action to address CO_2 buildup. Atmospheric CO_2 concentrations in these models range between 600 and 800 ppm by 2100. In our most optimistic projections, emissions quickly peak and begin to decline within the next 20 years. This results in concentrations remaining steady at roughly 400 ppm throughout the 21st century, giving a projected temperature increase of 2℃. The Paris Agreement considers this to represent a limiting value before truly catastrophic consequences take hold (although the Intergovernmental Panel on Climate Change has since revised this downward to 1.5℃). But this rise is less than half of that observed in the paleoclimatic record for the CO_2 concentration already in the atmosphere.

Most models assume that, under a best case scenario, we will avoid this degree of warming due to a steady decline in atmospheric CO_2 after 2100, due to a residence time of CO_2 in the atmosphere of roughly a century.

Slow CO_2 Absorption:

But the concept of a set residence time for CO_2 is highly misleading. CO_2 is removed either through sequestration and burial, or by dissolving into the ocean. Absorption through photosynthesis without sequestration of the biomass produced is carbon neutral. While the living and dead biomass in forests does represent a short to medium term sequestration of carbon, in order for the carbon to remain out of the atmosphere it is necessary that dead material not decompose. In boreal forests, cool temperatures and the resistance of conifer leaves and wood to decomposition allows longer term sequestration than in tropical forests, where the diversity of decomposers and efficiency of nutrient cycling ensures that much absorbed carbon is quickly re-emitted. But the sequestration capability of forests has been greatly overestimated. It is far easier to measure the CO_2 absorbed by a forest than the percentage of that carbon that is re-emitted. Recent increases in wildfires and insect damage, in addition to general human degradation, have caused many tropical forests in recent years to emit more CO_2 than they absorb. Misleading estimates of forest absorption of 10 to 20% of annual emissions ignore the distinction between absorption, short term storage, and long term sequestration. The same considerations apply in the case of carbon storage in soils. While a huge quantity of carbon is contained in terrestrial soils, and conservation of environments conducive to buildup of organic matter in soils is certainly beneficial, by conserving storage capacity, and restoring degraded environments, we are preventing further emissions more than we are creating an effective sequestration mechanism.

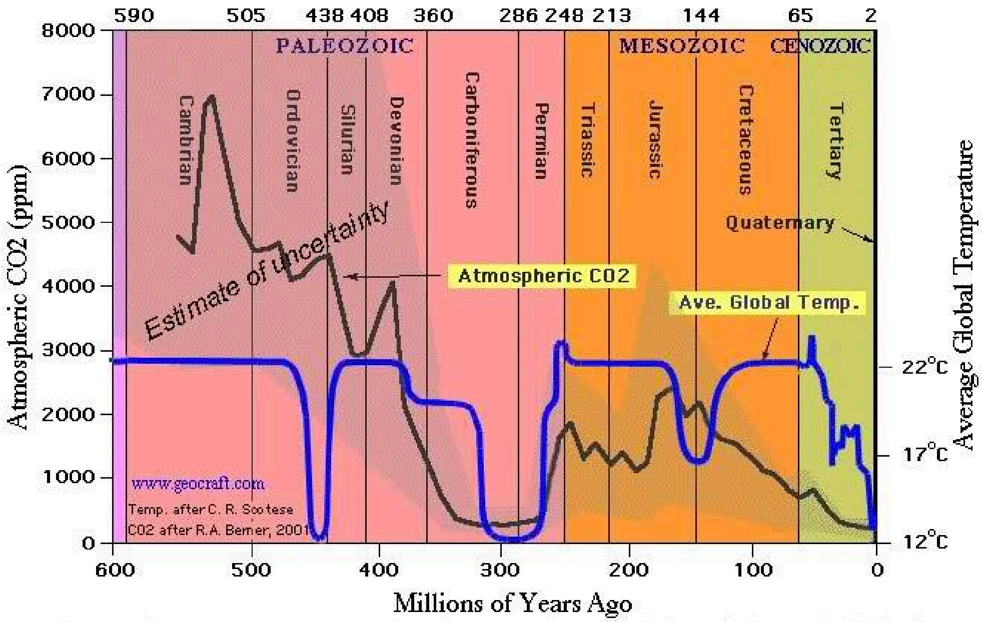
Ocean Acidification

Dissolution of C02 into the oceans, while reducing atmospheric concentration, causes ocean acidification, which reduces the potential for biological sequestration by ocean organisms, and generally has negative environmental consequences equal to those of warming itself. The average pH of the world ocean has decreased from 8.25 to 8.14 since 1750, the fastest rate observed in geological history. CO_2 is far more soluble in cold than warm water, and much of the dissolved CO_2 accumulates in cold deep water. This mechanism removes roughly 20% of annual human CO_2 emissions, but deep ocean water is now becoming saturated. CO_2 outgasses during upwelling of cold water toward the surface, and the shells of marine organisms are becoming prone to dissolution in increasingly shallow waters. In addition to degrading shallow water ecosystems, this prevents the storage of calcium carbonate as chalk and limestone on the seabed. Given the complexity of these processes in both the terrestrial and oceanic environments, determinations of residence time based on sequestration rates become question begging without including careful justifications for whatever sequestration rate they assume.

A simple explanation of the discrepancy between our projected levels of warming and those observed in the paleoclimatic record is the delayed response of the climate system to forcing events such as rising CO_2 concentration. This would suggest that if we reduce emissions CO_2 will steadily decline on its own due to the processes described above, even if we accept that we cannot use these to determine a set residence time for CO_2 in the atmosphere. To understand why this conclusion is dangerously erroneous we must understand the contingent and unusual nature of our current global climate in the context of geological history.

Examining the Historical Global Climate Record

Global Temperature and Atmospheric CO2 over Geologic Time



Late Carboniferous to **Early Permian** time (315 mya -- 270 mya) is the only time period in the last 600 million years when **both** atmospheric **CO2** and **temperatures** were as low as they are today **(Quaternary Period).**

Temperature after C.R. Scotese http://www.scotese.com/climate.htm

As noted above, the last time CO_2 concentration was above 400 ppm was the Mid-Pliocene, 3 mya. This however was a short term event bounded by lower concentrations both before and after, and we are currently in an interglacial period of an ice age which has lasted for the past 2.6 mya. If we go back 20 mya, to the Miocene, CO_2 again reaches current levels, and prior to this, was significantly above them for most of Earth's history. In both the Miocene and Pliocene the Arctic Ocean was ice free in the summer, and the Northern margins of the surrounding continents were clothed in temperate forest. The Antarctic Ice Sheet covered only a small area around the pole, the rest of the continent supporting mixed forests of conifers and southern beeches. The coastlines of the continents were many miles further inland than today.

In contrast to some current apocalyptic narratives, the tropics were not scorched barren wastelands, instead being covered with luxuriant rainforests, containing up to 100 species of ape, including the first members of the lineage that would later lead to humans. As recent observations are beginning to show, warming is concentrated in high latitudes, causing reduced seasonal variation in the Northern and Southern hemispheres. Tropical temperatures were about 4℃ higher than todays, contrasting with 10℃ at the poles.

The climate in the previous epoch, the Oligocene, fluctuated around conditions similar to the Miocene, interspersed with slightly cooler periods, but without significant glaciation compared to modern levels. In the Eocene, about 33 mya, the climate was extremely warm and wet, with much reduced seasonality. Rainforests covered most continents, extending almost to the poles.

The last time the climate was similar to today's was during the Carboniferous period, 300 mya, when repeated glaciations occurred over a period of 60-100 mya. Before this, the Ordovician glaciation, 450 mya (but likely lasting only 1 ma) is the only remaining ice age since the evolution of multicellular organisms. A simple calculation will show that our current conditions are highly anomalous in Earth history. The Earth has been in conditions conducive to polar ice caps for at most 20% of the last 540 mya. The remaining 80%, including the entire Mesozoic era, saw what are often described as greenhouse conditions. The greenhouse state is the default, and climatic excursions tend to be counteracted by negative feedbacks that return the system to this equilibrium. Glacial or icehouse periods are in contrast metastable and highly vulnerable to slight perturbations. They are comparatively short term events occuring because of particular sets of contingent conditions.

Paleohistorical Causes of Climate Change

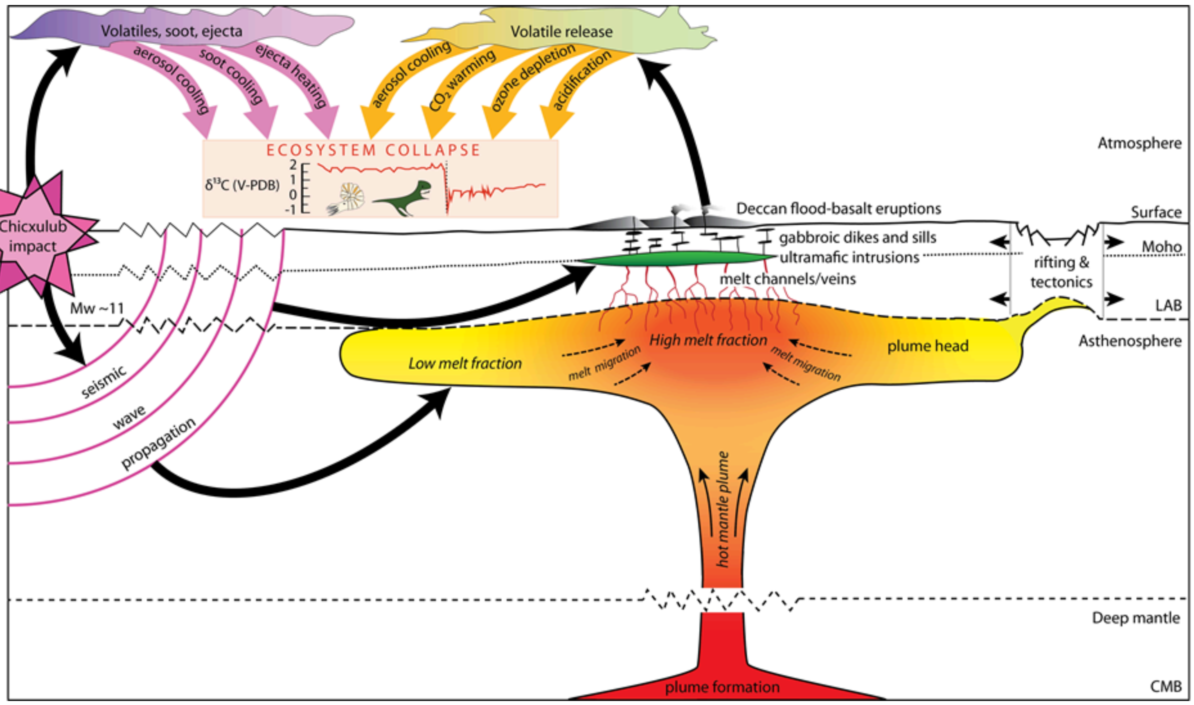
Historical changes in climate equilibria are closely correlated with addition and removal of CO_2 from the atmosphere.

Flood Basalt Eruptions cause Mass Additions of Atmospheric CO_2

Atmospheric CO_2 additions are usually associated with massive and sustained volcanic activity on a scale unseen in human history. For example, large areas of Siberia and Northern India are covered with the remains of lava flows extending hundreds of miles, from eruptions which continued for tens of millenia, known as flood basalts or traps.

The Siberian Traps were formed simultaneously with the Permian-Triassic mass extinction, the worst in history, where 95% of marine and 70% of terrestrial species were wiped out. Coming close on the heels of this extinction event, the Wrangellia eruptions in the Carnian stage of the early Triassic caused a further mass injection of CO_2 into the atmosphere, and another episode of sudden warming. This increased evaporation from the oceans to such an extent that the resulting extreme weather patterns caused a huge increase in precipitation over the continents. This was sufficient to leave signatures of almost continuous flooding in the geological record across the entire planet. Current evidence suggests that average global rainfall reached the levels now seen in temperate rainforests on the Pacific Coast of the United States and Canada, for a period of 2 million years. This is known as the Carnian Pluvial Event, and caused another large scale turnover in the biosphere, instrumental in the evolution of the dinosaurs.

The Indian flows, or Deccan Traps, correspond to the Cretaceous-Paleogene mass extinction and the demise of the non-avian dinosaurs (these eruptions were possibly intensified by the simultaneous impact of a six mile asteroid into the Gulf of Mexico). This was followed by a warming period leading to the Paleocene-Eocene Thermal Maximum, an event much studied as a possible analogue of current climate change. The volcanic hotspot underlying Yellowstone National Park is a likely source of a future flood basalt event.



Effects of Deccan eruptions and Chicxulub impact on the atmosphere and biosphere

The climatic effects of these eruptions show a distinct signature of initial global cooling followed by a large degree of warming. This likely represents the dimming effect of immense releases of sulfur dioxide and aerosols into the upper atmosphere, followed by rebound warming as these dissipate. The close temporal correlation of flood basalts with mass extinctions is likely due to the particular effects on the biosphere that result from large concentrations of CO_2 coupled with lower light levels and cooler conditions, followed by sudden warming. The CO_2 cannot be removed sufficiently quickly by plant growth, and dissolves into the oceans, causing ocean acidification and the extinction of marine life, including phytoplankton that otherwise is extremely efficient in carbon sequestration. The later rebound warming therefore occurs in the context of a biosphere already disrupted by previous cooling and ocean acidification, and is increased in intensity by the lack of effective mechanisms of CO_2 removal. Often several million years are required to return CO_2 to baseline levels in a slow drawdown through photosynthesis and sequestration of biomass. Over longer timescales, weathering of rocks exposed by the uplift of mountain ranges also removes carbon from the atmosphere, and long term warming and cooling trends correlate with mountain building activity and continental drift. In recent times, the isolation of Antarctica from the rest of the global climate system, due to its position over the

South Pole and the corresponding circumpolar current, coupled with the continuing uplift of the Himalayas, have contributed to Antarctic glaciation and CO2 drawdown through weathering.

Historical Mass Extractions of Atmospheric CO_2 due to Biological Sequestration

Historically, massive CO_2 addition to the atmosphere has generally been caused by volcanic eruptions, and slow carbon drawdown has occurred through the response of the biosphere to this addition, returning conditions to a hothouse equilibrium. In contrast, sudden CO_2 removal is caused by distinctive and contingent biological events, rather than a common geophysical mechanism, and results in a metastable icehouse state. Our current addition of CO_2 differs from this pattern by being caused by biological activity (our extraction and burning of fossil fuels), and occurring on a far shorter timescale and higher rate than is typical, although with a lower potential total addition.

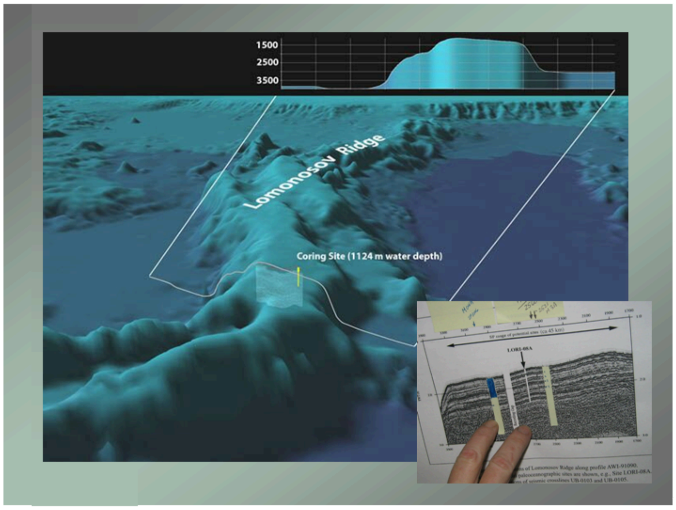
Natural mass extraction of CO_2 from the atmosphere is associated with events where unusual and contingent factors enable the removal of large quantities of plant material from circulation, through burial before the biomass either decomposes or is consumed by herbivorous animals. Once icehouse conditions are established, they are maintained until the sequestration mechanism ceases to operate, or by physical changes, such as aridity through the reduction in ocean evaporation, or reflection of solar radiation by ice. In the early history of the Earth, this happened multiple times, and these ice ages are termed Snowball Earth events. The earliest one was likely caused by the disruption to the biosphere caused by the injection of large quantities of oxygen into the atmosphere by early photosynthetic organisms, coupled with the oxidation and removal of methane, a powerful warming gas which at that time was a major constituent of the atmosphere. Much of the unicellular life at the time was adapted to extremely low oxygen concentrations, and was poisoned, with the result that algae could continue the CO_2 drawdown until levels became so low that nearly the entire surface of the planet was covered by ice sheets. While the causes of the second two events are more uncertain, carbon sequestration likely played a major role. These events, as in other ice ages, were probably ended by the injection of CO_2 through eruption of flood basalts through the ice cover.

For comparison, the most intense phase of the Deccan volcanic eruptions 66 mya released several tens of thousands of gigatons of CO_2 into the atmosphere, over a period of about 30,000 years (and estimates of total CO_2 injection have been steadily increasing). Since 1750, we have emitted about 550 gigatons, half of this in the last 40 years. We have roughly 3000 gigatons of potential emissions from easily accessible fossil fuels remaining in the ground, although to release this we would have to extract and burn all the world's coal, which is unlikely. So, even assuming these figures to be underestimates, and factoring in CO_2 equivalents in methane and other warming gases, total realized and potential anthropogenic emissions are unlikely to exceed 4000 gigatons. This is many times less than the total CO_2 released in the largest Deccan eruptions, and realistically, given that we will not use all available coal reserves, and carbon intensity of economic growth is either flat or on a slowly declining trend, we will only ever emit about a tenth of the CO_2 released in a flood basalt volcanic event. However, our emissions are occuring over a period of centuries, rather than tens of millenia. If we emit, say, a total of 2000 gigatons over 400 years, we average about 5 gigatons per year, vs. about 1 gigaton per year for even the most extreme natural events, and in 2017 global CO_2 emissions were about 32.5 gigatons.

The unprecedented rate of anthropogenic emissions is likely to cause significant instability in the global climate system, which is already precariously balanced in an unusual ice house state. Such short term instability has been seen in the transitions between glacial and interglacial periods in the current ice age, although not directly caused by CO_2 emissions. The climatic transition from the last glacial maximum to our present interglacial was not gradual or stable. Temperatures rose and fell multiple ℃ within decades. In the Younger Dryas event, only 13,000 years ago, global temperatures declined 2-6℃ from values similar to the present, within about 30 years, after having risen on a similar timescale. The colder climate lasted 1000 years, causing glaciers to advance once more across Eurasia and North America, and then ended as abruptly as it started. There is evidence that the sudden increase in aridity caused during this time disrupted and postponed early development of agriculture in the Levant. Our economic systems and patterns of settlement are not equipped to deal well with this degree of instability, or with its possible result of a return to the hothouse equilibrium. To understand how we can intervene in the global climate system to maintain current conditions, we need to examine some of the historical mechanisms of mass carbon removal from the atmosphere. The two most relevant events here occurred during the Carboniferous and Eocene periods.

Evolution of Land Plants before Effective Decomposers

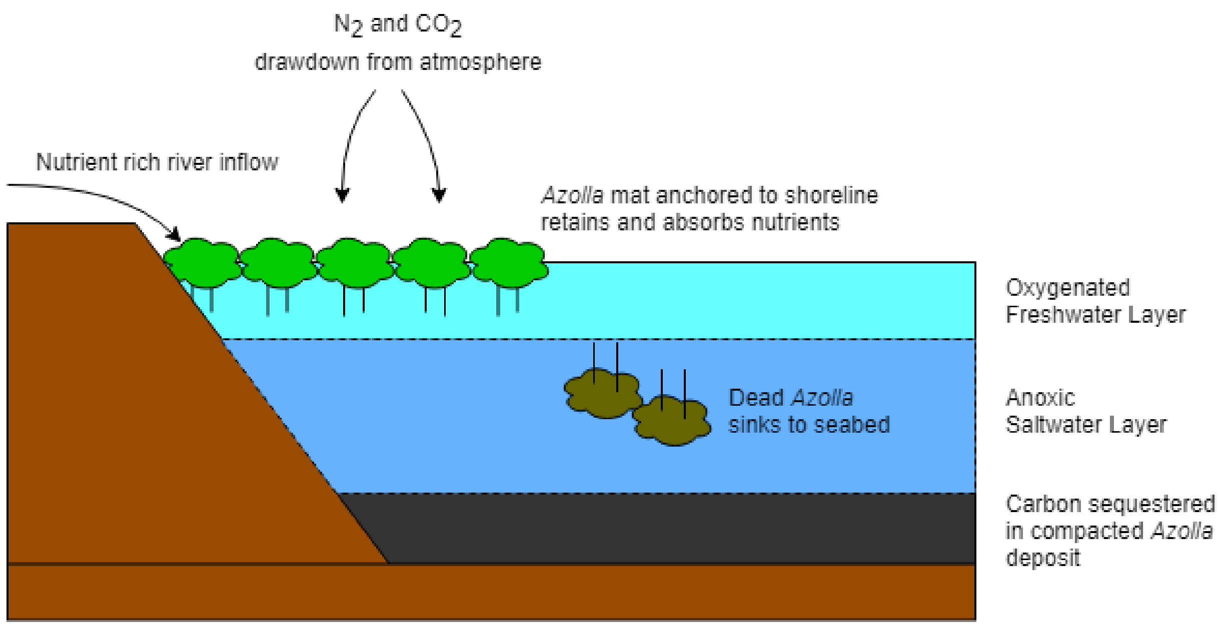
In the Carboniferous, 320 mya, CO_2 concentration suddenly declined tenfold from over 2000 ppm to about 200 ppm, similar to levels at the last glacial maximum, and the only other time they have fallen this low in the last 600 million years. Unsurprisingly, this also resulted in an ice age, a particularly long and deep one lasting over 60 million years. The carbon drawdown was caused by the evolution of land plants before terrestrial herbivores, and before fungi became adept at digesting wood. Huge forests proliferated across the continents, and dead trees simply lay where they fell, without decomposing efficiency, until eventually buried by subsequent vegetation. Millions of years of this process sequestered enough carbon to raise the oxygen concentration of the atmosphere to 35% (today it is 20%). This allowed the evolution of giant insects, whose respiratory system depended on this elevated oxygen, and terrifyingly destructive firestoms, where even wet wood would burn. When fungi, termites, and herbivorous vertebrates evolved and proliferated enough to end the sequestration process, and start returning carbon trapped in dead vegetation to the atmosphere, the ice age ended. Glaciation did not occur on Earth for another 270 million years. Much of the coal we burn now represents carbon removed from the atmosphere during this ice age.




Drill core from the Lomonosov Ridge composed of compacted Eocene Azolla

The Azolla Event

The second example, the [*Azolla* event], was only discovered in the last 20 years, and was extremely specific in its mechanism. In the early Eocene global surface temperatures were 8℃ higher than today. Tropical forests extended almost to the poles, and atmospheric CO_2 concentration was 3500 ppm in contrast to today's 400 ppm. 49 million years ago, the global climate cooled 6℃, with a simultaneous drop of atmospheric CO_2 to 650 ppm. The cause of this drop in temperature and CO_2 was unknown until a convincing hypothesis was proposed in 2004. At this time, the Arctic Coring Expedition took advantage of reduced ice cover to take core samples from the Lomonosov Ridge, in the Northern Arctic Ocean. To their surprise, they discovered huge deposits of the freshwater aquatic fern *Azolla* locked under the seabed. These deposits, up to 20 meters deep, were laid down 49 mya, sustained over 800,000 years, and exactly coinciding with the observed drop in temperature and CO2. Noting this correlation, the researchers proposed a causal link, now widely accepted, between the growth of *Azolla* and the massive drawdown in atmospheric carbon dioxide, accounting for the sudden global cooling in the late Eocene.

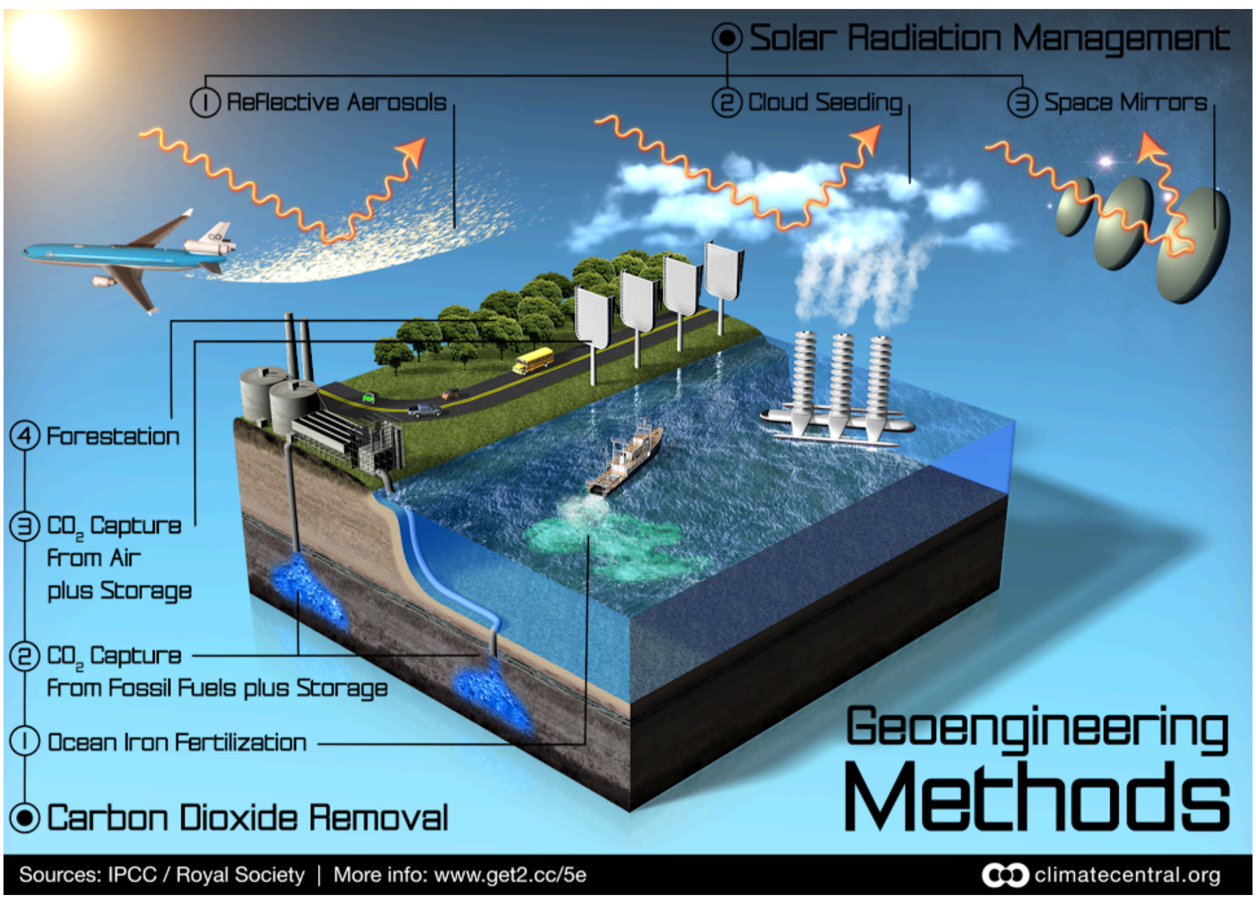


Azolla is incapable of growth in salt water, and was only able to grow in huge volumes in the Arctic Ocean due to a set of contingent and unusual factors. These factors also ensured that the carbon absorbed by the fern through photosynthesis was sequestered on the seabed rather than being returned to the atmosphere when the plants decomposed. During the Eocene, the Arctic Ocean had limited water exchange with the rest of the world ocean, and received the flow of a number of large rivers. The lower density freshwater from these rivers pooled on the surface, causing a low salinity layer to form. This layer prevented mixing of the water column, and caused the seabed to become highly anoxic, while also enabling *Azolla* to proliferate across the surface. As a floating plant with leaves above the water, *Azolla* had direct access to atmospheric CO_2. Additionally, and unusually among ferns, *Azolla* is able to fix nitrogen directly from the atmosphere using a bacterial symbiosis, removing a further limitation to growth. Most decomposing organisms require oxygen for their metabolism, and this was severely depleted on the seabed. Therefore, when the ferns died and sank, they were preserved intact until buried by sediment, and the carbon they had absorbed in life was locked into the sedimentary rock under the sea. The oil and natural gas resources in the Arctic National Wildlife Refuge are primarily composed of these *Azolla* deposits.

As shown above, previous episodes of warming have only ended when specific events in the biosphere caused mass drawdown of CO_2. The cessation of emissions alone, and the background rate of carbon extraction from the atmosphere, have never been sufficient to reduce atmospheric CO_2 on a sufficiently short timescale to be relevant to human civilization. Also, by not taking action to drawdown CO_2 in the near term, we risk either dramatic climatic instability, or a phase transition into a stable hothouse equilibrium, where the factors maintaining the equilibrium are powerful enough to exceed our efforts to return to prior baseline. Active intervention in the climate system is therefore necessary, and would be no different in principle to previous examples such as the *Azolla* event, which is particularly informative as it shows how specific conditions obtaining in the physical environment can cause a self-sustaining biological process with a favorable ratio of carbon extraction to energy investment. Regardless of debates on moral permissibility and unforeseen consequences, active CO_2 extraction, or geoengineering, is a practical imperative if we are to be able to stabilize the global climate in the short term. While previous examples of biological carbon drawdown have mostly occurred over timescales of at minimum several millennia, any human effort would need to be effective on a much shorter timescale.

Four Realistic Geoengineering Options

There are four dominant candidates for realistically practicable geoengineering methods. These are 1) direct air capture (DAC), 2) bioenergy with carbon capture and storage (BECCS), 3) injection of aerosols into the high atmosphere, and 4) oceanic iron fertilization.



Direct Air Capture

Direct air capture is the simplest, but currently has major problems of economic viability. Right now, the cost of extracting a ton of CO_2 from the atmosphere is approximately $100, as estimated by the Canadian company Carbon Engineering. In common with other existing DAC startups, Carbon Engineering does not plan to sequester the CO_2 pulled from the air. In order to make the process profitable in the near term, they intend to use the captured carbon to produce emissions neutral fuels. Their model is therefore at best carbon neutral, if powered by renewable energy sources. While government funding could enable such companies to remove captured CO_2 from circulation, problems of scalability have not yet been solved, and Carbon Engineering's pilot plant removes only 1 ton of CO_2 per day. While DAC is likely to be a component of long term CO_2 drawdown strategies, the technology is unlikely to be mature and economically viable in the short term.

Bioenergy with Carbon Capture and Storage

BECCS is usually categorized as an elaboration of the existing biofuel industry rather than a method of geoengineering. This has enabled it to be recognized as a mainstream approach for achieving the levels of negative emissions required to meet the goals of the Paris Agreement, and included in roadmaps provided by the Intergovernmental Panel on Climate Change, which have now become reliant on the large scale roll out of BECCS to limit warming to 1.5℃. However, the basic methodology of BECCS involves active technological intervention in the biosphere, and does not differ substantially from a geoengineering approach. In BECCS, biomass is cultivated and used as feedstock to create biofuels, such as ethanol, replacing fossil fuels in the same roles, or directly burned to generate electrical power. The CO_2 released in the process is captured by scrubber systems and injected deep underground, usually into porous rock formations. This enables a portion of the CO_2 collected by the plants in photosynthesis to be sequestered, while the rest is used to create carbon neutral biofuel and electricity.

In theory, this enables a BECCS system to achieve net negative emissions, while remaining economically viable from the sale of biofuels and electrical power. BECCS is an elaboration of simple carbon capture and storage (CCS), where scrubbers are used to capture exhaust gases from fossil fuel burning. CCS can also function using biomass, which is burnt in the absence of oxygen to create charcoal (biochar), which is buried deeply or used as a soil amendment. These methods are already in operation where carbon credits act as an economic incentive for emitting industries.

Because of its close integration with existing technologies and emissions sources, BECCS is currently the favored method for achieving net negative emissions, but like DAC, suffers from problems of scalability. Also, in order to achieve negative emissions status, a BECCS project must be able to economically support both its fuel and power production, and its method of carbon sequestration, using the sale of the commodities produced. This is unlikely to be viable in the near term without carbon taxation, or significant and sustained increases in fossil fuel prices, which have been rendered unlikely by the advent of fracking and other techniques of extraction of oil and gas from shales.

Using current methods, removing 10 gigatons of CO_2 annually using BECCS would require a land area the size of India to be brought under cultivation for this purpose alone, which would entail an expansion of agricultural land without compare in recent history, and be ecologically disastrous in itself. If BECCS projects replaced existing agriculture, this would displace the cultivation of food on arable land. BECCS will almost certainly be a component of future strategies to effect carbon drawdown, but cannot be rolled out on the scale required within a short time frame. Reliance on BECCS as a sole solution would also be extremely environmentally destructive, and endanger the global food supply, unless near term and large scale efficiency gains could offset the loss of land.

High Atmosphere Aerosol Injection

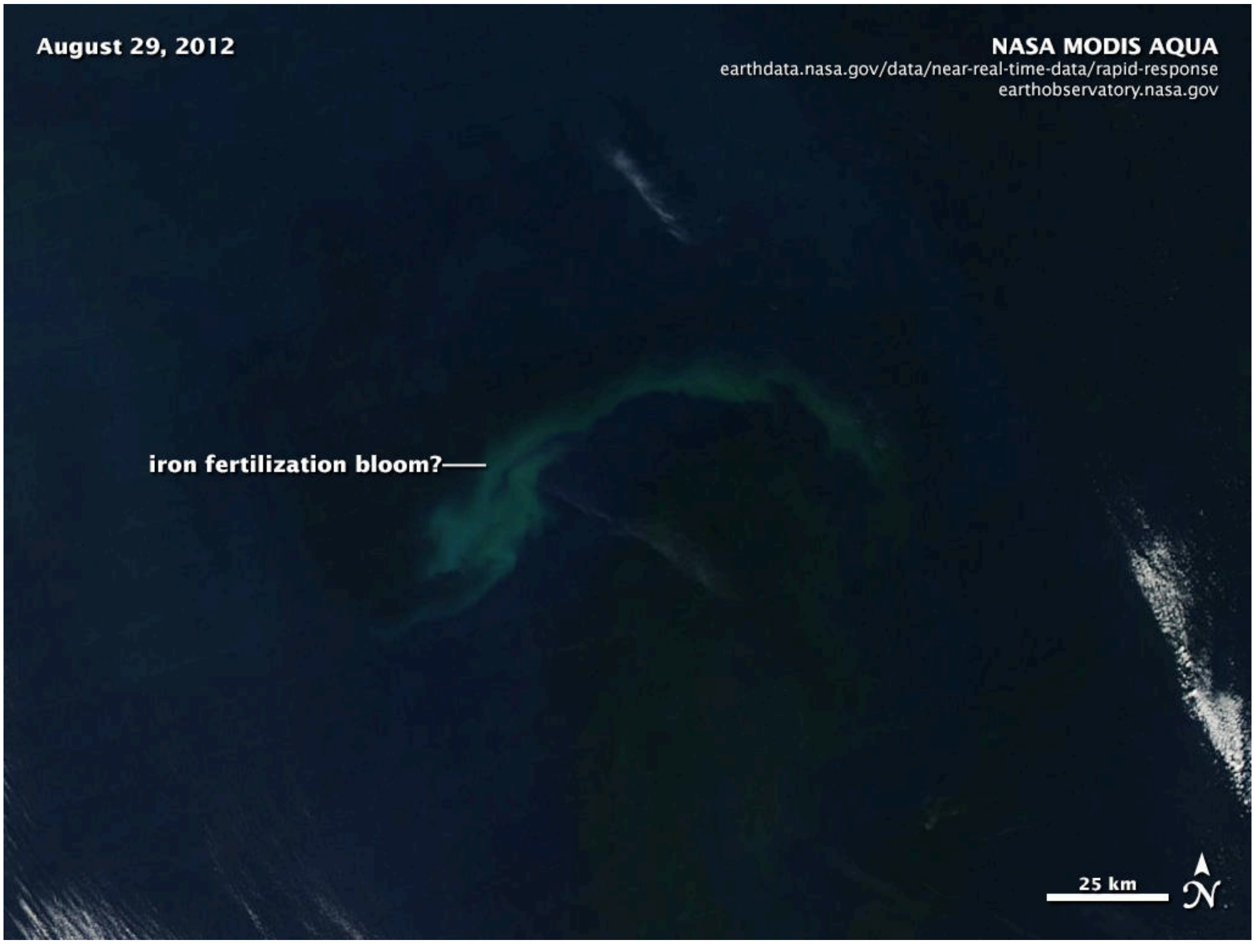
The next method, injecting aerosols (most models suggest SO_2) into the stratosphere to act as a sunshade, is not included in mainstream models or roadmaps, but would be extremely economical and deceptively efficient. By directly reducing incoming solar radiation, causing global dimming, SO_2 injection mimics the short term effects of a large volcanic eruption, and enables the prevention of warming without addressing CO_2 emissions. Aerosol pollution from industry likely masked some of the impact of increasing CO_2 levels during the 20th century, and warming has accelerated as this pollution has decreased in many areas in recent decades. While SO_2 causes acid rain if released at low altitude, if injected into the upper atmosphere it would have little to no effect at ground level, and would provide effective cooling if continuously replenished. SO_2 could be injected through large hoses attached to tethered balloons, from pressurized canisters aboard aircraft (one proposal suggests outfitting airliners with distribution systems), or through artillery guns. Addition of a few million tons of SO_2 yearly would be sufficient to offset the warming effect of doubled CO_2 concentrations. This is a comparatively small quantity, and could be distributed by a fleet of modified 747 airliners for a cost of 1 or 2 billion dollars yearly. This would provide effective mitigation of climate change within months, and with costs comparable to those of operating a small airline, could be implemented by most states, or even by wealthy individuals.

The ease of implementation of this method makes it almost inevitable that it will at some point be employed unilaterally. For example, if a strong heat wave occurs in a city in Southern Asia during a period of high humidity, as likely will happen at some point in the next few decades, and wet bulb temperatures rise above 35℃, this will cause mass casualties obviously attributable to climate change. Currently, the impacts of heatwaves are seen as an increase in the background death rate, and mainly affect the very old, very young, and people with existing health problems. But in this case, previously healthy people will start dying in the streets without access to air conditioning. This level of obvious impact will create an imperative for the government of the country concerned to do something, anything, to mitigate the situation. Given the low cost of aerosol injection, and its immediate effects, there is a strong possibility that injecting SO_2 into the stratosphere will be their response, with easy justification using the argument that the tragedy was the result of centuries of emissions by large wealthy nations. This could have complex geopolitical consequences, given that aerosol injection will modify the global climate quickly and obviously, and cause easily observable whitening of the sky.

At first glance, aerosol injection seems to be the ultimate “get out of jail free card” for climate change, and it does have a place in preventing immediate catastrophic consequences of runaway warming. I do not doubt that it will be employed at some point. It does not however provide a long term solution. Shading the planet will not affect the rate of ocean acidification, which creates severe problems in its own right. Any aerosol injection system requires continuous management and calibration to give the right degree of cooling. Successful short term management of climate using this method will likely reduce the rates of emissions reductions and employment of negative emissions technologies. If CO2 concentrations continue to increase during a period of effective solar radiation management, an unstable situation will result, where any interruption or miscalibration in aerosol injection will result in sudden extreme warming. This is the same mechanism that caused previous mass extinctions after flood basalt events, as noted above. While mass extinction is unlikely due to the compensatory abilities of human societies, an unnecessary vulnerability is certainly created if longer term solutions are not pursued.

Oceanic Iron Fertilization

The ideal geoengineering method would mimic a naturally occurring process which has been shown to mitigate past episodes of global warming, would not be prohibitively expensive or environmentally destructive, would have beneficial effects beyond those of reducing climate change, would not create dependency on continuous careful management, and would have self-limiting negative consequences if misapplied. Such a method exists, has been demonstrated experimentally for decades, and does not require the creation of any massive infrastructure or technological innovation. This method is oceanic iron fertilization.



Possible Phytoplankton bloom resulting from the 2012 Haida Salmon Restoration Corporation iron fertilization experiment

Iron fertilization takes advantage of the fact that the growth of marine phytoplankton is primarily limited by micronutrient availability, specifically that of iron, and that repletion of available iron in the photic zone of the oceans is able to induce massive algal blooms, which then sink into the abyss, sequestering vast quantities of carbon dioxide. Iron fertilization has been experimentally demonstrated twelve times since 1993, most notably in 2007 in the South Atlantic by an Indo-German consortium (project LOHAFEX, 2007), and in the North Pacific in 2012, by the Haida Salmon Restoration Corporation. In both cases the addition of ferrous sulfate in quantities between 10 and 100 tons resulted in massive plankton blooms visible from space, with an estimated production of up to 100 000 tons of algae per ton of added iron. Even assuming that much of the carbon contained in this algae is eventually returned to the atmosphere, this is a most favorable ratio. Oceanographer John Martin was aware of this as early as 1988, when he stated “give me half a tanker of iron, and I will give you an ice age.”

Several iron fertilization experiments have been of doubtful legal status, and societal reactions to them have been polarized both in the popular press and academic contexts. The HSRC release was organized by the HSDC in collaboration with Russ George, founder of the San

Francisco based company Planktos Inc.. George was subsequently described in much of the media as a "rogue geoengineer" and "Pacific Ocean hacker," and accused of manipulating the Haida into supporting his scheme. In reality the project was collaborative and the Haida were fully equal partners. In the case of the HSRC project, there was a correlated increase of the 2013 year class of sockeye salmon by up to 400% due to increased food fish availability. While a causal relationship cannot be proven, a similar increase in salmon population occurred in the years following the 2008 eruption of the Kasatochi volcano in Alaska, which introduced a large quantity of iron-rich dust into the atmosphere, providing strong evidence that iron fertilization in general increases fish stocks.

Currently, the majority of iron input to the deep oceans originates from desert dust storms over the Sahara and Central Australia, which also contribute to the fertility of the Amazon rainforest, due to their global transport by wind currents in the high atmosphere. There is evidence that the increased input of windblown iron rich dust into the oceans due to aridity in the last glacial maximum was partly responsible for maintaining low CO_2 and cold temperatures. The quantity of this windblown dust has been decreasing in recent decades, and this is correlated with a decline in ocean fertility. Another major source of iron and other nutrients is whale feces. Whales distribute nutrients throughout the world ocean by feeding on krill and small fish in productive regions of upwelling, and spreading nutrients throughout their migrations by defecating in surface waters. Krill contain so much iron that the feces of whales become red, containing 10 million times the concentration of iron in ocean surface waters. The global population of large whales is still only 20-30% of that before industrial whaling, despite a decades old ban. Studies of average water transparency suggest that there has been an annual decline of 1% in ocean phytoplankton populations throughout the 20th century.

While one ton of iron can theoretically fix roughly 83,000 tons of CO2, the actual sequestration efficiency is reduced by several factors. As noted above, the HSDC project was associated with a large increase in salmon population, and this represents the transfer of carbon into the bodies of these fish. Some were caught and eaten, and others returned to the rivers of their birth to spawn. None of this carbon was sequestered, but the increased productivity of the salmon fishery and transfer of nutrients to Pacific coast forests are beneficial in themselves. Sequestration is dependent on downwelling currents separating phytoplankton from surface nutrient cycling. Because of this, choosing the right location to fertilize is of paramount importance. The Antarctic circumpolar current and areas of the Central Pacific with sustained downwelling are currently the leading candidates. Estimates of sequestration from recent iron fertilization experiments average about 20%, with the Southern Ocean giving the higher reported values. Additionally, some species of algae produce dimethyl sulfide, which has been shown to outgas into the atmosphere, assisting cooling by the same mechanism as atmospheric SO_2 injection.

While a huge amount of work remains to be done in determining sequestration efficiency, and the degree to which depletion of other nutrients affects the phytoplankton response to added iron, a quick calculation is possible at this point. Assuming a 20% near term sequestration efficiency in optimal sites, and accounting for inevitable inefficiencies in distribution of iron, and emissions incurred in transport to the site of release, a sequestration of 10,000 tons of CO_2 per ton of iron is reasonable. Global anthropogenic emissions in 2017 were 32.5 gigatons. Were we to entirely offset these emissions with iron fertilization, 3.25 megatons of iron would be required. Global crude steel production in 2017 was about 1.7 gigatons, so this represents the diversion of roughly 0.2% annual iron production, although using scrap and recycled iron would be preferable. Drawing down this quantity of carbon would not actually be possible because other nutrients in the oceans would be depleted long before this point, there are not enough downwelling areas in the oceans to remove such massive quantities of carbon from circulation, and global marine ecosystems would be heavily disrupted by such a massive ongoing fertilization campaign. In a real world scenario including ongoing emissions reductions and limitations to fertilization efforts, 25% at most of this quantity of iron would be used, about 800,000 tons. This is equivalent to the capacity of 2 large oil tankers. If we assume the use of an easily soluble iron source, such as iron sulfate, this brings us up to 2.2 megatons, about 6 tankers per year. While this is economically non-trivial, it could be done for less than 10 billion dollars, comparing favorably with BECCS and DAC, which require human intervention at all stages of the sequestration process, and would cost at minimum several hundred billion in order to offset a significant fraction of current emissions.

More work is required is delineating the possible negative effects of phytoplankton blooms. These blooms are a natural occurrence, occurring yearly in several areas of the oceans, so we already have a good idea of what these could be. A particularly concerning example is in stimulating the growth of algae which produce toxic compounds, chiefly among these the production of domoic acid by *Pseudo-nitzschia* diatoms. Domoic acid is neurotoxic to birds and mammals, causing damage to the hippocampus and memory loss (known as amnesic shellfish poisoning), and can reach high concentrations in marine organisms. The dungeness crab fishery on the California coast has been recently affected by the concentration of domoic acid in crabs, with mandatory testing now required before areas are opened to fishing.

Pseudo-nitzschia produces domoic acid in order to scavenge iron in depleted environments (the substance attracts and chelates dissolved iron), enabling it to monopolize the supply, but ceases production when iron is in good supply. There is some evidence from recent iron fertilization experiments that *Pseudo-nitzschia* growth increased, and this was associated with domoic acid production, most plausibly through the stimulation of a bloom which subsequently depleted the added iron and produced the compound in order to monopolize what was left. Natural and artificial iron addition from volcanic eruptions and the HSRC experiment have however not shown increases in domoic acid in food fish. Concerns such as this can be partially mitigated by avoiding fertilization of coastal areas, which is in any case inefficient in terms of carbon sequestration, but more experimentation is needed into this and other possible negative consequences.

In practice, stabilizing global climate will require a combination of emissions reductions and negative emissions technologies. We do not need to choose one method to the exclusion of all others. Examining historical analogues is vital to predicting the future consequences of different methods, while noting that these often occurred at a slower rate but for much longer time periods. For example, the closest analogue to BECCS is the mass burial of terrestrial vegetation in the Carboniferous. Aerosol induced global dimming mimics the effects of large volcanic eruptions, without the associated CO_2 injection. DAC is a form of accelerated weathering. Iron fertilization has analogues in both the *Azolla* event and more directly in the addition of iron rich wind borne dust to the oceans during recent glacial periods. While insights from paleoclimatology and empirical research will continue to improve our characterization of the costs and efficacy of all of these, presently iron fertilization appears a leading candidate, due to its economy in comparison to BECCS and DAC, and significant associated benefit of increasing ocean productivity and improving fisheries. The possibility of injecting SO_2 into the atmosphere in order to prevent the worst consequences of rapid warming remains, but this method does not address CO_2 levels and therefore ocean acidification, and should only be considered as a stop-gap measure while other technologies are brought online.

Emissions Reductions Alone are Not Enough

What is clear is that a focus on emissions reductions alone is untenable. Projecting climate impacts in terms of arbitrarily defined residence times of CO_2 in the atmosphere ignores the fact that ocean dissolution is not an acceptable long term means of removing CO_2, and that natural sequestration is not a process occurring independently from human activity at a constant rate. Whatever our intentions, and independently of our fossil fuel emissions, humans now exert a dominating influence on the carbon cycle. We appropriate roughly 30% of the primary production of the terrestrial biosphere to grow food and produce raw materials such as wood, paper, and textiles. Very little of the carbon contained in these products is likely to be sequestered. We cannot expect the biosphere to continue to function as though 7.7 billion humans are not present, simply because we reduce or eliminate fossil fuel use.

Unlike any previous organism which has caused global disruptions in climate simply by doing too well (and there have been many), we have the ability to intervene deliberately to ameliorate the worst consequences of our sudden dominance for the rest of the biosphere, and to maintain the planet indefinitely in a habitable state for ourselves. We can also stumble blindly toward extremely unpleasant climate scenarios while desperately trying to minimize our impact, and descending into accusatory but practically useless political infighting. There is a clear choice here, and while the first will require unprecedented global coordination and unity of purpose, in the long term it is our only tenable option.

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