



COMMENTARY

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Crutzen +10: Reflecting upon 10 years of geoengineering research

Key Points:

- Foreseeable cuts in CO₂ and greenhouse gas emissions will not quickly and sufficiently forestall climate disruption and associated suffering
- Negative emissions and climate intervention, although difficult and even problematic, may well be necessary policy steps, as Crutzen foresaw
- Investigation and deployment of regional interventions may moderate severe impacts and provide insights about potential global intervention

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The rationale for accelerating regionally focused climate intervention research

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Abstract Ten years ago, Paul Crutzen asked whether the time had come to consider undertaking research into intentionally intervening in the climate system so that it might be considered a policy option comparable to reducing emissions for limiting human-induced climate change. Crutzen's article pointed out how little progress had been made in reducing emissions and suggested that resurrecting decades-old ideas for imitating volcanic eruptions as a possible intervention might be needed. Today, model-based simulations, optimistically assuming that nations fulfill their commitments for future emissions reductions, project global average temperature to increase to 3–4°C above its preindustrial level by 2100, a level that Crutzen envisioned as likely to meriting active intervention. While research has begun to explore the means for intervening globally, such interventions raise challenging issues of governance, unintended consequences, intergenerational equity, and more. Initially, focusing research on potential tropospheric and surface-based approaches to altering energy flows as a means for moderating adverse regional impacts might well pose less difficult governance challenges and more regionally constrained evaluations of intended outcomes and unintended consequences. Because natural processes would tend to dissipate most types of tropospheric interventions, adjustments, and even termination, would be possible over periods of weeks to months. In addition to serving their particular purpose, regional interventions would also provide an opportunity for learning more about Earth system behavior and the potential effectiveness and risks of global-scale interventions, if such interventions might eventually be needed to counter-balance especially severe global warming.

1. Progress Over the Past Decade in Slowing the Growth of Warming Influences

Ten years ago, as a result of the slow international progress at that time in reducing emissions of carbon dioxide (CO₂), Crutzen [2006] called for research to explore the possibility that enhancement of the Earth's albedo could serve as a useful complement to reducing greenhouse gas emissions as an approach to slow and eventually limit or reverse global warming. Since that time, annual emissions of CO₂ and other greenhouse gases in nations with relatively high per capita emissions have started to decline, now roughly balancing the increases in emissions from nations with relatively low per capita emissions that are rising due to population growth and the need for more energy to raise the standard-of-living in these nations [Timmer, 2015; Le Quéré et al., 2016]. As a result, despite overall good intentions, global annual emissions of CO₂ are now ~20% higher than in 2006 and the atmospheric CO₂ concentration has increased from ~380 ppmv to over 400 ppmv. There are also increasing indications that natural carbon feedbacks (including release of soil carbon in low latitudes and oxidation of thawing permafrost and methane clathrates in high latitudes) are being stimulated [Stocker et al., 2013], amplifying the ongoing warming influences of anthropogenic greenhouse gas emissions. Given the long persistence time of the atmospheric CO₂ increase, the commitment to future warming will thus continue to increase at least as long as global emissions are above a very small fraction of their current level [Clark et al., 2016].

That climate change is occurring in response to the increasing CO₂ and greenhouse gas concentrations has also become more evident since 2006. The continuing increase in global average temperature, thinning, and retreat of snow cover and Arctic sea ice, increased rate of mass loss from the Greenland and Antarctic ice sheets, increased ocean heat content, rising sea level, and more all indicate ongoing climate change [Blunden and Arndt, 2016]. As the statistical distribution of the weather is being altered, departures from the traditional statistical norm are reaching three to four standard deviations and more [e.g., Hansen et al., 2012]. As a result, regions of the world are experiencing, for example, more intense precipitation and flooding,

more intense and frequent periods of drought and consequent wildfire, greater and faster retreat of sea ice and snow cover, greater uptake of heat by the oceans, faster ice sheet loss, rising rates of sea level rise, and other conditions unprecedented in historical times. With the ongoing increase in global population, the increasing risks of severe impacts on grain and food production and on human health, the increasing occurrence of coastal inundation and storm damage, and the likelihood of severe environmental and societal disruption and dislocation are going up and already starting to impact particular regions [*Intergovernmental Panel on Climate Change (IPCC)*, 2014].

That the 2015 Paris Agreement [*UN Framework Convention on Climate Change (UNFCCC)*, 2015] was so widely agreed to reflects increasing international recognition that climate change has already started to have serious impacts, that substantial further impacts lie ahead, and that efforts to reduce CO₂ and other greenhouse gas emissions must be urgently undertaken. Indeed, the Paris Agreement committed the signatories to phasing out all emissions of fossil-fuel-generated CO₂ by no later than the latter part of the 21st century. With fossil fuels presently providing ~80% of the world's energy and with the demand for energy for transportation growing in developing nations, however, the near complete transformation of the global energy system seems unlikely to occur rapidly enough to avoid very disruptive impacts [*IPCC*, 2014] and to "prevent dangerous anthropogenic interference with the climate system," as called for in 1992's Framework Convention on Climate Change [*UN Framework Convention on Climate Change (UNFCCC)*, 1992]. Indeed, analyses based on current national commitments project a warming of roughly 3–3.5°C by 2100 and indicate that considerably greater reductions in emissions, including achieving negative emissions of CO₂ over many decades, will be needed to bring long-term warming below the proposed ceiling of 1.5–2°C above preindustrial temperatures [*Jones et al.*, 2016].

For sea level rise, the situation is even more threatening. Analyses of paleoclimatic records from the most recent deglaciation and from much more distant periods that were 4–6°C warmer than present suggest that the sensitivity of sea level to changes in global average temperature must be roughly 10–20 m per degree Celsius. While the response time for the ice loss to occur is not well understood, it is not implausible that the rate of future sea level rise could reach a few meters per century and that such a high rate could, on average, persist for many centuries, even if global CO₂ emissions are pushed to zero before 2100 [*Hansen et al.*, 2016].

2. The Prospects for Additional Steps to Limit Changes in Atmospheric Composition

Impressive initiatives being undertaken by many cities around the world to reduce their fossil-fuel footprints and the rapidly declining costs of non-CO₂ emitting energy technologies suggest the potential for a strong ratcheting up of the national commitments for emissions reductions under the Paris Agreement [*Rogelj et al.*, 2016]. The societal and environmental co-benefits of healthy forests and grazing lands are also increasing the prospects for reducing CO₂ emissions resulting from land clearing and forest mismanagement [*World Bank*, 2015]. There is also emerging research indicating that reforestation, afforestation, and even burial of biochar and similar measures could lead to a useful increase in terrestrial, or perhaps even ocean, carbon storage, which would also help to limit ocean acidification [*Houghton et al.*, 2015; *National Research Council (NRC)*, 2015a].

The UNEP/WMO *Integrated Assessment of Black Carbon and Tropospheric Ozone* [*United Nations Environment Programme (UNEP)/World Meteorological Organization (WMO)*, 2011; *Shindell et al.*, 2012] made clear that near-term reductions in positive radiative forcing could most rapidly be achieved by reducing the atmospheric loadings of short-lived species (particularly methane, black carbon, and tropospheric ozone). The Assessment estimated that, using existing technologies, feasible emission reductions could cut the projected global warming from the present to 2050 by ~0.5°C, so roughly halve their estimate of the projected warming over that period. And negotiations under the Montreal Protocol to reduce hydrofluorocarbon emissions have led to an agreement that is projected to reduce global warming in 2100 by as much as ~0.5°C when both direct (i.e., reduced hydrofluorocarbon emissions) and indirect factors (e.g., opportunities and incentives for improved efficiency) are considered [*Climate and Clean Air Coalition*, 2016].

Emissions from coal-fired power plants are becoming a particular target for reductions because their generation of energy leads to relatively high emissions of CO₂ per unit of delivered electricity. However, because the typical lifetime of sulfate aerosols in the atmosphere is roughly a week or two, closing coal-fired power plants that are not already scrubbing out SO₂ will actually augment the net warming influence of human activities for several decades until offset by the long-term benefits of the associated reduction in CO₂ emissions [Wigley, 1991]. As a result, while clearly beneficial in the long-term, the closing of coal-fired power plants may need to be paired with reductions in emissions of methane and black carbon so that the net change in radiative forcing from all policy actions tracks downward as the coal-fired plants are closed.

Thus, while the decade since Crutzen's paper has seen the initiation of substantial local, regional, national, and international efforts, the predicament that concerned him remains at least as serious as it was then.

3. So What Is the Potential Role for Global Climate Intervention?

Crutzen [2006] specifically proposed that the potential for augmenting the sulfate loading of the stratosphere merited increased research as the most plausible intervention approach for counter-balancing greenhouse-gas-induced warming. He specified only taking this step, however, in the event rapid warming was overwhelming a strong global effort to limit greenhouse gas emissions. Unfortunately, this seems to indeed be the situation: warming and overall weather and climate disruption appear to be intensifying more rapidly than expected while the international community is moving more slowly away from fossil fuels than is needed to avoid potentially catastrophic and irreversible environmental and societal impacts [IPCC, 2014; Clark *et al.*, 2016].

While, as Crutzen encouraged, there has been a modest increase in research to understand the potential for undertaking global-scale climate intervention, most of the research remains largely exploratory with virtually no focus on practical implementation [National Research Council (NRC), 2015b]. To date, there has been no high-level interest among international decision-makers in organizing a mission-focused climate intervention research and deployment program aimed at *preventing* the global average temperature increase from exceeding the 1.5–2.0°C ceiling specified in the Paris Agreement, a ceiling that may well lead to quite severe consequences [e.g., Hansen *et al.*, 2016]. Nor has there been any movement toward the even larger global intervention [Irvine *et al.*, 2012] that would be needed to slow and then halt the rise in sea level, which may soon be on a path that will, over a few centuries, inundate many of the world's coastal cities and productive deltas and wetlands.

Instead, global climate intervention seems to be viewed as a potential emergency response that could be resorted to some decades in the future as a possible *remedy* after substantial impacts are widely evident and the consequences are becoming unacceptable. Although research is indicating that augmenting the stratospheric aerosol concentration could substantially cancel out the increase in global average temperature and associated broad-scale changes in precipitation over many regions of the world [Tilmes *et al.*, 2013; NRC, 2015b; Irvine *et al.*, 2016], comparable attention is not being given to the inability of a delayed intervention to reverse disruptions of the landscape, undo the irreversible losses of biodiversity, or substantially slow the accelerating pace of sea level rise from the loss of mass of the Antarctic and Greenland sheets.

Unless global climate intervention is started in the near term and gradually augmented with the intent of pushing the global average temperature (as a surrogate for global climate conditions) slowly back toward mid-to-late 20th century values, there is the possibility that the research to better understand the potential for global climate intervention may ultimately go unused even though a return to relatively recent conditions might prove optimal for long-term survival for most of the world's people [Robock, 2012]. The problem is that the greater the delay, the greater the speed of a transition from the much warmer conditions would likely be needed and therefore the greater the challenges of adapting to more rapidly changing conditions and the more likely that complex questions of equity and differential endpoints would arise. Thus, while scientific and technological questions that merit additional research [MacMartin *et al.*, 2016] and, while governmental efforts are needed that develop appropriate governance mechanisms for deciding how to optimally intervene, putting off initiation of actual climate intervention until there is much greater understanding might well lead to a situation where the transient conditions associated with restoring the past's milder conditions might themselves be unacceptably disruptive.

Recognizing that the technical approaches to actual intervention generally mimic natural influences and processes that have been studied and are being represented in existing climate models, it might well be that the uncertainties and consequences (both intended and unintended) associated with gradually intensifying global intervention starting in the near term would be less serious than the uncertainties and consequences associated with either not intervening at all or with waiting until impacts are substantial and intervention is viewed as the only remaining option for preventing global catastrophe. I suggest this because the conditions being returned to with near-term global intervention would likely be within or closer to the envelope of past conditions for which observational records, experience, and understanding exist than for the situation where warming continues to a level never experienced by society and not experienced by the planet in tens of millions of years.

Research to confirm these assertions using the traditional scientific hypothesis-testing framework, however, seems likely to take longer than the time for the global average temperature increase to exceed, even far exceed, 1.5–2°C. In addition, many of the ethical analyses have been primarily focused on evaluating the relative risks and benefits of climate intervention on its own rather than as compared to the risks of projected changes without climate intervention. I have no argument with those who would oppose climate intervention as conceived in the mid-20th century when it was to be directed, with considerable hubris, toward *improving* the climate for, for example, resource extraction from the Arctic [Fleming, 2010]. As now proposed, however, potential implementation is intended to reduce the severity of human-induced global warming by keeping the climate near to present or recently past conditions. With the prospects for the future now viewed with sufficient alarm and confidence to cause leaders of the world, despite all the uncertainties described in the IPCC Assessment Reports, to unanimously agree that the world's fossil fuel energy system must be replaced, the limitations of the present national commitments to emissions reductions would seem to favor serious international consideration of near-term global-scale intervention. In my view, unless international leaders insist on a framing the issue in terms of the relative risks of ongoing climate change with versus without intervention, it seems unlikely to me that international leaders will consider global-scale climate intervention as an option in the near term.

4. A Potential Interim Approach: Focusing Intervention First on Moderating the Most Severe Impacts

Assuming the international commitment to phasing out fossil-fuel emissions made in the Paris Agreement is real, a virtually unexplored option could be targeted interventions aimed at moderating at least some of the most severe, often regional, changes that can have strongly negative impacts [MacCracken, 2009]. The notion is that such targeted interventions might be able to moderate the worst impacts, including some that might otherwise be irreversible during the decades when the global average temperature increase is above the desired ceiling temperature, whether it be 2°C, 1.5°C, or, as, for example, Hansen *et al.* [2008] suggest, 0.5°C, and then phased out thereafter (i.e., there would be an “exit strategy”). While such efforts might be viewed as providing a bit more time for global emissions reductions, delays in reducing emissions would lengthen the time needed for such interventions and were emissions reductions not rapid enough, the regionally focused approaches would very likely be overwhelmed by the warming caused by delayed emissions reductions, negating their whole purpose.

A few potential interventions seem, on first glance, especially worthy of focused research attention, seeking to explore what might be possible in the laboratory and with limited field experiments, to identify associated and unintended consequences, to evaluate ecological and societal implications, to address governance, ethical, and other related issues, and ultimately to carry out comprehensive risk-benefit evaluations. While such efforts could potentially take many decades, the impacts being addressed are being felt now and so, to be useful and likely most effective, interventions, if technically feasible and the evaluations are favorable, are needed in the near term to moderate what are proving to be intensifying impacts.

Having been evaluating the natural and human-induced causes of climate change and their impacts over the past five decades, these are my suggestions for the most urgently needed potential climate interventions, each to be carefully researched, investigated, and evaluated:

1. *The potential for moderating amplified Arctic warming:* For a number of reasons, warming and associated impacts are occurring far more rapidly in the Arctic than in the rest of the world. The

impacts are already directly affecting the region's indigenous peoples, high-latitude flora and fauna, migrating species, Northern Hemisphere weather, and global sea level. Sharp reductions in snow and sea ice cover are also contributing to thawing of permafrost and clathrates, which has the potential to greatly amplify global warming [Whiteman *et al.*, 2013; Schuur *et al.*, 2015]. To the extent that focused regional intervention to moderate change in the Arctic would be possible without serious, unintended adverse outcomes, both the region and the world would seem to benefit.

Robock *et al.* [2008], MacCracken *et al.* [2012], and Tilmes *et al.* [2014], among others, have performed global model simulations that provide some, not particularly surprising, insights. Robock *et al.* [2008] found that high-latitude injection of sulfate aerosols into the stratosphere not only cooled the Arctic, but also, due to their roughly 1-year half-life, spread to sub-Arctic latitudes and depressed the summer monsoon. MacCracken *et al.* [2012] found that, just as high-latitude warming was amplified by albedo feedback, so was high-latitude cooling, making an intervention, on a per mass basis, more effective at high latitudes than at low latitudes. Tilmes *et al.* [2014] found that, due to increased heat transport into the region from lower latitudes, high-latitude cooling would be unable to reverse the effects on the Arctic of warming induced by a quadrupling of the atmospheric CO₂ concentration.

Together, these results suggest that an effective Arctic-cooling intervention needs to be carried out in a way that does not lead to the aerosols spreading out over the Northern Hemisphere and also to be carried out before global warming would overwhelm the limited cooling influence that can be induced. As part of an integrated approach, reducing emissions of black carbon, methane, and tropospheric ozone would certainly be a very useful supporting effort [Arctic Monitoring and Assessment Programme (AMAP), 2015a, 2015b], but intervention seems the only potential approach to keeping conditions in the Arctic similar to those of the past few decades. Potential approaches for contributing to the needed alteration in the region's energy balance, possibly used in combination, would seem to include brightening land, ocean, and clear and/or cloudy skies during the sunlit season [Latham *et al.*, 2014], reversing the warming influence caused by reducing air pollutant emissions flowing into the region [Acosta Navarro *et al.*, 2016], and, during the fall and winter seasons, cirrus thinning [Mitchell and Finnegan, 2009], bypassing the thermal barrier created by the sea ice (e.g., by using icebreakers), and ice thickening by pumping sea water up onto existing sea ice.

If it could be promptly initiated, stratospheric aerosol injection could suitably cool the Arctic as the world was cooled. For the Arctic-only injection, several unique factors moderate the need for scaling up the aerosol amount based simply on the areas over which the actions would be taken. For example, while the quantity of the injected sulfate and/or sea salt aerosol into the Arctic troposphere would need to be larger than for a global stratospheric injection due to the shorter lifetime of tropospheric as compared to stratospheric aerosols (~1 to 2 weeks in the relatively quiescent weather in the Arctic summer troposphere versus 1–2 years for the stratosphere), augmenting the tropospheric albedo would only need to be done for the few sunlit months when the surface albedo has dropped due to surface melting or total ice loss. Focusing on increasing cloud albedo would also create a larger change in albedo than simply injecting the aerosol into clear skies in the stratosphere. In addition, during this period, the increased albedo would be reducing incoming solar flux for up to 24 h per day instead of for about half that time over the world as a whole. Further, injections to increase the albedo could be modulated in time based on sea ice condition and be timed and located based on forecast weather to achieve maximum direct effects as well as maximum amplification by snow and ice albedo feedbacks. That at least some of the injections could be made from elevated terrain rather than requiring stratospheric injection could also help to reduce the cost of the intervention. In addition, because the desired effect would be substantially less than trying to fully reverse a doubling of the CO₂ concentration, the amount of salt or sulfate aerosol, while needing careful evaluation because some cancellation would result from additional heat that would be carried into the region, would likely not be so much as to cause the hemispheric wide adverse effects of global stratospheric aerosol injection described in Robock *et al.* [2008].

Of course, recognizing that this analysis is largely qualitative, substantial research is needed, especially of how combinations of approaches could be used together. That the affected processes are already included in the most advanced models, substantial upgrading and testing of the available models is

likely no more critical than the need to improve model simulations of ongoing climate change without intervention, especially recognizing that benefits and unintended consequences would largely be concentrated in the region and the proposed tropospheric intervention approaches could be rapidly terminated if substantial unintended consequences arise.

2. *The potential for moderating ocean warming in the tropical cyclone intensification zones:* While there remain uncertainties, ocean warming is likely increasing the intensity and/or frequency of the most intense tropical cyclones [Intergovernmental Panel on Climate Change (IPCC), 2013]. The horrific damage from especially severe typhoons in the Philippines has been one manifestation; the intensification of Superstorm Sandy was another. Even reducing the increasing warmth of the Philippine Sea, the Gulf of Mexico, the Caribbean, or other intensification areas by a degree or two would tend to reduce the supply of energy to transiting tropical cyclones.

While a vertical ocean-mixing approach to cooling waters ahead of particular tropical cyclones has been patented [Bowers *et al.*, 2009], intervening so as to create persistent, but more modest, reductions in annual ocean heat uptake and summertime sea surface temperature by cloud and/or clear sky brightening, surface brightening, and/or inducing vertical mixing of ocean waters would seem a more feasible alternative [Latham *et al.*, 2014]. In that tropical cyclones seem to move, other influences being equal, toward warmer ocean waters because of the greater energy these waters provide, research seems worthwhile to explore if regionally focused interventions aimed at a degree or two cooling might be a means for moderating intensification across the set of storms that occur in any particular year.

While theoretically plausible, observational confirmation would be difficult because of storm-to-storm variability, but with the ongoing improvement of storm models, statistical analyses of the effectiveness of such interventions might be possible. Evaluation would also be needed of the possibility that a storm path might be altered in ways that might create unintended consequences (or might just be perceived as doing so), creating potential legal liabilities. Unless global warming is separately counter-balanced by global climate intervention [as modeled by Moore *et al.*, 2015], the intent would be to moderate the intensification effect of warmer ocean waters in just a few specific regions, so the amount of sea salt and/or sulfate aerosols needed to brighten clouds would likely remain within achievable bounds.

3. *The potential for slowing mass loss from the Greenland and Antarctic Ice Sheets:* Irvine *et al.* [2012] lay out what would be required to slow climate change through global intervention. While the likelihood of success of regional approaches is likely low with only temporary effects, failing to explore all possible approaches to reducing the increasing and seemingly inevitable loss of mass by the Greenland and Antarctic Ice Sheets and consequent sea level rise seems to be too early a concession. In addition to approaches involving physically blocking the exits of ice streams (which may well be unworkable), approaches to consider might include cloud brightening, injection of reflective bubbles, and vertical mixing to lower the temperature of the waters that are observed to be inducing melting at the faces of ice streams.
4. *The potential for a regional replacement for the loss of global sulfate cooling:* Over the past 50 years, the centroid of the 0.5–1.0°C cooling influence resulting from SO₂ emissions has moved from the North Atlantic basin to southern and eastern Asia, a region where the per-ton-of-emission influence of SO₂ emissions is likely larger due to the higher amounts of incoming solar radiation [Kaufmann *et al.*, 2011]. As China and India clean up or close their coal-fired power plants, the present SO₂ cooling offset will be diminished, likely contributing a net positive forcing for at least several decades, even with the expanded effort to reduce CO₂ emissions.

One possible alternative to the loss of the global sulfate offset of ~0.5°C would be to inject SO₂ into the stratosphere, an approach that would likely require global political agreement, create very challenging governance questions regarding who decides how much, and be the start of what would likely become a prolonged effort to offset global warming. Might there be an alternative, regional substitute capable of providing a comparable, regionally focused cooling offset that might pose less challenging governance and equity considerations than jumping to potential global-scale intervention?

For example, inducing modest clear and cloudy sky brightening in the troposphere over the vast Pacific Ocean that would cause changes in the global energy balance comparable to those induced by the present highly concentrated, health-damaging sulfate loading presently centered over China, India, and downwind would seem to be possible as a conceptual alternative global-scale climate intervention. Might such a brightening approach, one that could be strengthened or weakened on a several week basis, also be a way to moderate the intense periods of warming that are apparently being brought on when the Interdecadal Pacific Oscillation reinforces rather than counters greenhouse gas-induced warming [Meehl *et al.*, 2013]? Might decision-makers be interested in such an alternative approach to global intervention and/or an approach that could conceivably be available to moderate the effects of regional variability [e.g., Bond *et al.*, 2015]? Research on the levels, timings, and distributions of alternative patterns and amounts of aerosol loadings and cloud brightening that would minimize adverse influences on weather, monsoon, biological systems, and more over various time scales would seem merited as a way to have more control over what could be done with the much less adjustable approach of injecting aerosols into the stratosphere, and, as an added benefit, would provide potentially useful experience for later global-scale intervention, if needed.

A common feature of these examples is that the proposed interventions would be tropospheric- and/or surface-based. Because the persistence time for the perturbing materials would be only days to weeks, testing, implementation, and termination would all have similarly short time scales, potentially allowing design of nuanced detection strategies. In addition, because of the need for ongoing injections, the interventions could be modulated and readily terminated if needed, for example, following a volcanic eruption or if adverse seasonal variations resulted or were forecast. Such interventions could also be adjusted through the year, responding to seasonal conditions, rather than dealing with the longer timescales that would necessarily be associated with global stratospheric interventions. In addition, specific metrics of success could be developed, providing the basis for adjustments to optimize the overall outcome. Because only limited offsets are likely to be possible, termination would not be likely to substantially worsen the situation nearly as much as foregoing proposed global interventions.

5. Is It Time to Create a Stepping Stone on the Path to Potential Global Intervention?

At present, the policy alternatives seem to all focus on mitigation (with a decreasing likelihood that adaptation will be sufficient to deal with the projected consequences). Global-scale climate intervention is seen as a potential emergency backstop, even though the impacts from initiating melting of the polar ice sheets and biodiversity loss may well be irreversible and even though proposals to test steps in the intervention process outside the laboratory are controversial, at best.

As an alternative to jumping from undertaking no intervention to initiating full global intervention and, in essence, imposing human control of the complex global climate system, establishing a research program to explore potential regionally focused, tropospheric interventions might serve as a useful interim step between not intervening at all and jumping straight to global-scale intervention. Naming it the Regional Impact Protection through Co-Ordinated Research and Development (RIPCORDER) program would appropriately be a reminder that the world is presently in a free fall that will need to be greatly slowed if a soft landing is to be the result. With global climate intervention viewed as the last resort to avoiding exceedingly disruptive, even life shattering, consequences from uncontrolled warming, the RIPCORDER program could investigate a number of sub-global regionally focused approaches to intervening in ways that would seek to counteract the most severe impacts, basically serving as a "pilot chute" if the political decision is later made to deploy them while also providing a more gentle transition to a full climate intervention effort, if ultimately needed. With efforts to reduce global emissions not yet on a clear pathway toward lower and then zero CO₂ emissions, preparing, demonstrating, and learning from the types of interventions and analyses that global-scale climate intervention would involve seems to me a far better alternative than allowing the projected warming to continue upward on a temperature path that will likely not be moderated by current actions until the second-half of the century, at best.

Ten years ago, Crutzen [2006] foresaw the possible need for global-scale climate intervention and encouraged stepped up research. Given the still limited international response to controlling emissions, this paper

suggests that a mission-oriented research program initiated as early as possible to investigate and explore the potential for early deployment of regionally focused interventions could be an important complement to enhancing the resilience of particularly vulnerable areas. Such an effort would thus offer the prospect for both moderating the most damaging and imminent impacts and the opportunity for learning more about Earth system behavior and the potential effectiveness of global-scale interventions, if they are needed in the decades ahead.

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