AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE

10.1002/2016EF000447

Development of geopolitically relevant ranking criteria for geoengineering methods

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Special Section:

Crutzen +10: Reflecting upon 10 years of geoengineering research

Key Points:

- Events such as the Pinatubo eruption provide richly textured data sets that reveal multifaceted Earth System responses to perturbation
- Despite governance impasses to advancing geoengineering research, natural events such as Pinatubo help to broaden ranking criteria
- Development of geopolitical ranking criteria reveals a diverse range of diagnostics to intercompare geoengineering approaches

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Citation:

Boyd, P. W. (2016), Development of geopolitically relevant ranking criteria for geoengineering methods, *Earth's Future*, *4*, 523–531, doi:10.1002/2016EF000447.

Received 29 AUG 2016
Accepted 20 OCT 2016
Accepted article online 31 OCT 2016
Published online 24 NOV 2016

Abstract A decade has passed since Paul Crutzen published his editorial essay on the potential for stratospheric geoengineering to cool the climate in the Anthropocene. He synthesized the effects of the 1991 Pinatubo eruption on the planet's radiative budget and used this large-scale event to broaden and deepen the debate on the challenges and opportunities of large-scale geoengineering. Pinatubo had pronounced effects, both in the short and longer term (months to years), on the ocean, land, and the atmosphere. This rich set of data on how a large-scale natural event influences many regional and global facets of the Earth System provides a comprehensive viewpoint to assess the wider ramifications of geoengineering. Here, I use the Pinatubo archives to develop a range of geopolitically relevant ranking criteria for a suite of different geoengineering approaches. The criteria focus on the spatial scales needed for geoengineering and whether large-scale dispersal is a necessary requirement for a technique to deliver significant cooling or carbon dioxide reductions. These categories in turn inform whether geoengineering approaches are amenable to participation (the "democracy of geoengineering") and whether they will lead to transboundary issues that could precipitate geopolitical conflicts. The criteria provide the requisite detail to demarcate different geoengineering approaches in the context of geopolitics. Hence, they offer another tool that can be used in the development of a more holistic approach to the debate on geoengineering.

1. Legacy of Paul Crutzen

The publication in 2006 of an editorial essay in the journal *Climatic Change* by Paul Crutzen was both seminal and controversial [as evidenced by the concurrent publication of five Commentaries on the Crutzen essay; see *Bengtsson*, 2006; *Kiehl*, 2006]. The groundbreaking aspect of his Commentary was to explore the somewhat nebulous idea of stratospheric geoengineering [*Fleming*, 2007, 2010] with a large-scale natural analogue—the 1991 Pinatubo eruption. Crutzen's ideas both complemented and advanced the debate on geoengineering; other researchers had already advocated the use of natural analogues (the role of iron supply on the ocean carbon cycle) to explore the alteration of Earth's climate in the geological past [*Martin*, 1990]. Martin's iron hypothesis [*Martin*, 1990] resulted in a debate on the potential for ocean geoengineering to mitigate climate change (see discussion in *Chisholm and Morel* [1991] and *Boyd* [2008a]).

Pinatubo provided the platform to explore a wide range of issues surrounding stratospheric geoengineering [now referred to as solar radiation management, SRM *Shepherd et al*., 2009]. These issues included confounding concerns of atmospheric pollution of the troposphere with aerosol particles and the short tropospheric residence time of aerosol particles [*Crutzen*, 2006]. The subsequent monitoring of the stratospheric dispersal of aerosols from the Pinatubo eruption provided a "proof-of-concept" of the role of this stratum for cooling the planet. Pinatubo also made available estimates of how much aerosol load was required, the stratospheric residence time of these aerosols, and how the 1991 eruption altered the radiative budget of the upper atmosphere [*Crutzen*, 2006].

By pointing the spotlight onto the natural laboratory of Pinatubo, *Crutzen* [2006] brought much needed rigor to the debate about geoengineering, which had gained momentum due to insufficient political progress in global climate mitigation. However, based on the wide-ranging responses to his Commentary, including how SRM ignored the CO_2 problem [*Bengtsson*, 2006] and that SRM was treating the symptom not the cause [*Kiehl*, 2006], it was clear that this was the onset of a complex debate that would not be settled readily [see *NAS* (*National Academy of Sciences*, *U.S.*), 2015; *National Research Council*, 2015]. Hence, it initiated a dialogue about the benefits and drawbacks of geoengineering the planet and enhanced the quality of the discussion on this topic, such that not long afterward, the UK Royal Society had published a detailed report in 2009 on geoengineering [*Shepherd et al*., 2009]. In my view, the legacy of *Crutzen* [2006] is twofold—first, by placing this large-scale natural event in the context of geoengineering, he stimulated researchers to look for other well-founded analogues, such as the study of the cloud signatures linked to aerosol emissions (associated with ship tracks) and how they might inform the study of cloud brightening [*Christensen and Stephens*, 2011; *Robock et al*., 2013], which could be used to provide a comparison with modeling studies of large-scale perturbations. Second, Crutzen motivated closer scrutiny of the rich wellspring of other related data sets from the Pinatubo eruption [such as *Randel et al*., 1995; *Herber et al*., 1996]. Here, I use such scrutiny to explore the side effects from the 1991 eruption, their wider geopolitical ramifications, and how they can be employed to formulate ranking criteria for other key factors needed to provide a holistic viewpoint of the range of geoengineering approaches [see *NAS* (*National Academy of Sciences*, *U.S.*), 2015].

2. The Pinatubo Eruption: Lessons for Earth System Science

The publication of the Editorial essay by *Crutzen* [2006] was not the first to display the wide-ranging and interlinked effects of this 1991 event on the Earth System. The first suite of publications detailed the eruption and its subsequent alteration of radiative forcing and the knock-on effects on climate [*Hansen et al*., 1992; *Minnis et al*., 1993]. Other publications focused attention on the influence of Pinatubo on natural climate variability in the global carbon budget [*Sarmiento*, 1993] and on its potential role in fertilizing anemic (iron-poor) phytoplankton in the ocean with the fallout of iron-rich aerosols [*Watson*, 1997]. Subsequent papers detailed the longer-term effects of the eruption on land temperatures several years later [*Jones et al*., 2003] and the influence of Pinatubo on the moisture content of the troposphere [*Soden et al*., 2005]. The initial influence of Pinatubo, along with many lagged effects, on the ocean, land, stratosphere, and troposphere are summarized in Figure 1.

This summary of the short- and longer-term effects of the 1991 eruption reveal a complex suite of events, over and above the widely publicized natural stratospheric cooling (Figure 1). For example, Pinatubo may have had a pronounced effect on biologically mediated CO_2 drawdown in the ocean via iron fertilization from the aerosols associated with the eruption [*Sarmiento*, 1993; *Watson*, 1997]. Such an oceanic effect had to be inferred from global carbon budgets [*Sarmiento*, 1993] in the absence of any satellites with the relevant sensors (to detect enhanced ocean productivity) orbiting Earth in 1991. However, other more recent studies in the Gulf of Alaska have clearly linked vulcanism with enhanced ocean productivity and CO_2 drawdown [*Hamme et al*., 2010]. This oceanic fertilization effect of volcanic eruptions points to some fundamental differences between the physicochemical properties of naturally emitted aerosols (enriched in iron) and those proposed for stratospheric geoengineering [*Weisenstein et al*., 2015]. Hence, natural analogues do not mimic all of the effects of proposed stratospheric geoengineering [see discussion in *Rasch et al*., 2008; *Robock et al*., 2013].

In the upper atmosphere, as a result of the 1991 Pinatubo eruption, there was evidence of long-term radiative cooling and ozone reduction [*Minnis et al*., 1993], while in the lower atmosphere, there were reports of cooler tropospheric temperatures [*Jones et al*., 2003; Figure 1, this Commentary]. The lagged effects (i.e., months) significantly reduced the total water vapor in the atmosphere [*Soden et al*., 2005], causing widespread changes to Earth's hydrological cycle [*Trenberth and Dai*, 2007]. Specifically, there was less precipitation on landmasses (including South Africa, India, and South America, Figure 3 in *Trenberth and Dai*, 2007) and decreased riverine inputs into the ocean.

These wide-ranging processes triggered by Pinatubo pointed to the interlinked nature of the Earth System along with temporal lags and their potentially confounding influence (especially in the context of natural climate variability) on detection and attribution of the influence of this eruption (Figure 1). Perhaps most significantly, for the geoengineering debate, the Pinatubo eruption revealed that this local event had other "far-field" regional and global environmental consequences. In some cases, the aftereffects were detrimental (drought and its agricultural ramifications) and in others potentially beneficial (enhanced ocean productivity and consequent effects on fisheries). Observations of a complex suite of environmental effects from a natural event (Figure 1) resonated with other research into the complicated interlinked circuitry of

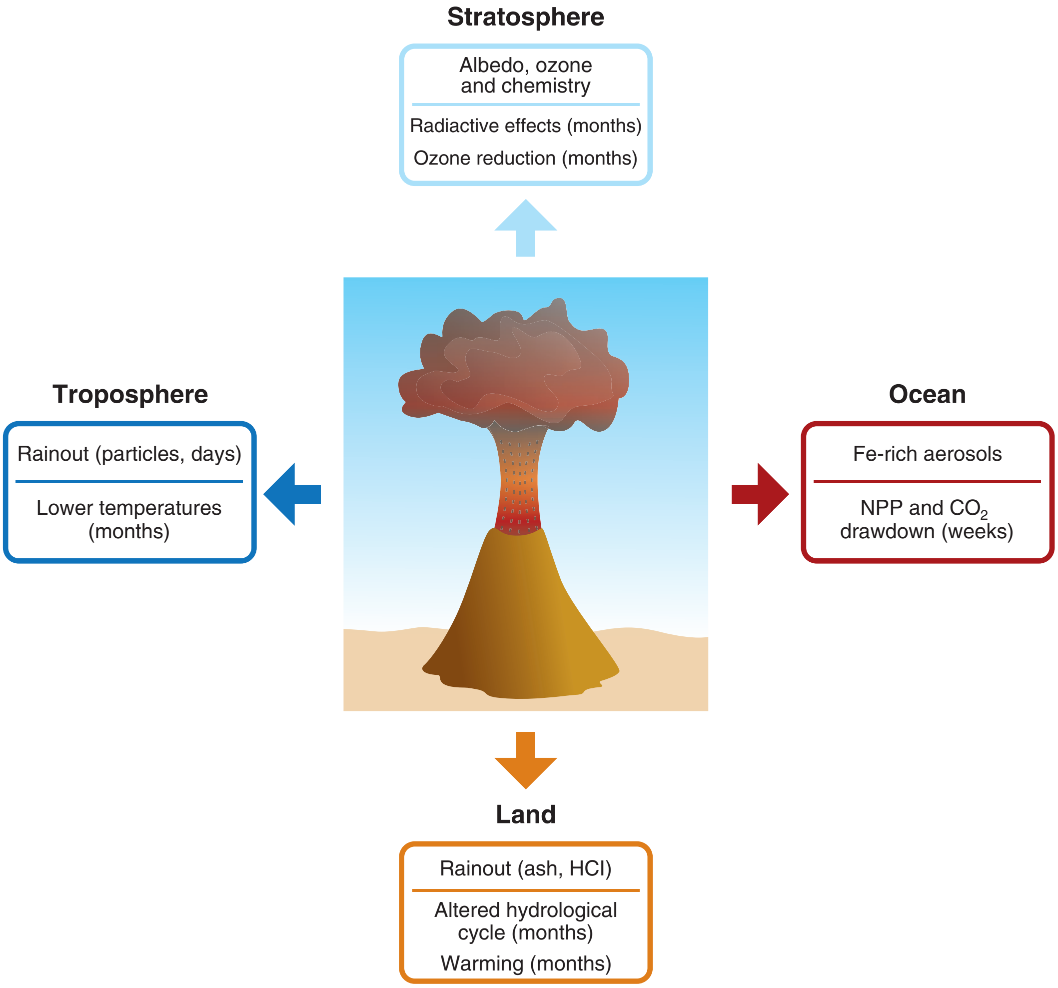

Figure 1. Summary of the widespread influence of the 1991 Pinatubo eruption on the lower and upper atmosphere, land, and ocean. The upper panel of each box describes the immediate effects of the eruption, and the lower panel lists the longer-term effects (i.e., months to years). NPP denotes Net Primary Productivity. CO_2 drawdown is the net transfer of atmospheric carbon dioxide into the ocean driven by iron-enhanced photosynthetic carbon fixation, as speculated by *Sarmiento* [1993] and *Watson* [1997], with respect to Pinatubo and as observed for another volcanic eruption by *Hamme et al*. [2010]. Note that unlike the Pinatubo eruption, the beneficial fertilization effects on the ocean may not occur with any proposed stratospheric engineering as the aerosols used would likely not contain iron. For data sources, see the discussion of this figure in the main text.

the Earth System [*Jickells et al*., 2005]. Pinatubo also catalyzed attempts to devise ranking criteria for geoengineering, including risks and side effects [*Boyd*, 2008b; *Shepherd et al*., 2009], and hence moved outside of the realm of the scientific effects of geoengineering.

3. Geopolitics and Geoengineering

This subheading comes from the title of Correspondence to the journal *Nature Geoscience* [*Boyd*, 2009],that was stimulated largely as a response to the wider ramifications of the Pinatubo eruption, above and beyond those summarized by *Crutzen* [2006]. Clearly, evaluating the individual implications of potentially beneficial and detrimental effects from this natural geoengineering analogue in relation to the well-publicized outcome [long-term cooling of the planet, *Hansen et al*., 1992] presented a significant challenge. Specifically, how can the opposing effects of this example of SRM geoengineering be reconciled. On one hand, there is the potential benefit of relatively rapid (within 1 year) global-scale cooling [*Crutzen*, 2006], albeit of a transient nature from this sole eruption. On the other hand, there are regionally uneven changes to the hydrological cycle [wetter in southern South America relative to northern South America, see Figure 3 in *Trenberth and Dai*, 2007]. The changes to the hydrological cycle, such as an increase in the drought index reported by *Trenberth and Dai* [2007], also probably influenced highly populated regions, such as the Indian subcontinent.

It is clear that a wide range of other pressing issues that cover many topics beyond the natural sciences—law, socioeconomics, ethics, and politics—are nested within these examples of regional-scale drought. *Boyd* [2009] comments that the geopolitical fallout of reduced precipitation in highly populated regions, driven by the potential side effects of a large-scale geoengineering project, could make prior transboundary disputes, such as on fisheries or water abstraction, seem like minor squabbles. Hence, Paul *Crutzen* [2006], by placing the Pinatubo eruption in the context of a natural SRM geoengineering analogue of sufficient scale, presented the unprecedented opportunity to evaluate a host of other issues that must be jointly considered in the geoengineering debate. This real-world example of SRM can be used to construct a framework of holistic check and balances that are embedded in the reality of Pinatubo (i.e., the global scope of geoengineering, regional “winners” and “losers”) as opposed to geoengineering “thought experiments” [*Lovelock and Rapley*, 2007] or based solely on scientifically orientated desktop studies [*Lenton and Vaughan*, 2009].

4. Developing Geopolitically Relevant Ranking Criteria

4.1. A Holistic Reappraisal of the Pinatubo Event

The 1991 eruption and its subsequent signature within the Earth system provided—at a scale sufficiently large to be detectable globally and attributable to a point-source event [*Hansen et al*., 1992; *Sarmiento*, 1993]—the first evidence of how a large-scale aerosol pulse alters radiative forcing that has been invaluable to modeling simulations [i.e., GEOMIP, *Kravitz et al*., 2011; *Robock et al*., 2013]. The transient nature of Pinatubo also provided a “scale bar” of how many such events would be required to drive sustained global cooling (e.g., of ~2C). From a geopolitical standpoint, it raised the pressing issue of how a point source perturbation rapidly becomes a globally distributed signature that alters key planetary services such as the water cycle in a regionally uneven manner [*Trenberth and Dai*, 2007]. This link between a sole perturbation (the Pinatubo eruption) and the consequent complex regional effects on the hydrological cycle underscores additional major uncertainties. If multiple SRM geoengineering projects are required for sustained planetary cooling, then how will each of them be detected, as they rapidly disperse in the upper atmosphere? In addition to detection, attribution of the influence of each event (how much cooling can they provide) is also needed not only for planetary accounting (are we cooling enough?) but also presumably for recompensation of the costs incurred in a geoengineering project [and also credits for cooling, carbon removed, see *NAS* (*National Academy of Sciences*, *U.S.*), 2015].

4.2. Modes and Time Scales of Detection and Attribution

In the geopolitical context, particularly based around evidence from Pinatubo of the enhancement of drought indices as a side effect [*Dai et al*., 2004; *Trenberth and Dai*, 2007], there is also the need to detect and attribute in a timely manner (i.e., within 1 year) any causes of such side effects. This is not trivial given the rapid dispersal (months, Figure 1) of a point source large-scale SRM perturbation. Such detection and attribution may also be confounded, as pointed out by *Boyd* [2009], by shifting baseline conditions due to natural climate variability and the influence of climate change on climate variability [*Boyd et al*., 2016]. Examples of shifting baselines driven by natural variability include warming [El Niño and La Niña; *Sumner*, 2015], cooling (another large-scale eruption akin to Pinatubo or El Chichón), cryptic shifts in natural carbon sinks [Southern Ocean, *Landschützer et al*., 2015], or oxygen inventories [*Chan et al*., 2007], which in some cases could negate or exacerbate the signatures from geoengineering [either SRM or CDR, see *Boyd and Bressac*, 2016]. *Bürger and Cubasch* [2015] have recently employed data sets from CMIP5 [*Taylor et al*., 2012] and GeoMIP [*Kravitz et al*., 2011] to reveal difficulties in detecting and attributing (years to decades) the climatic effects of geoengineering against a background of “nonstationary” gradual warming.

Detection and attribution will also be made more difficult given the likelihood that if we as a society in the future have permitted multiple SRM approaches, then we will also probably have allowed multiple CDR [carbon dioxide reduction, *Shepherd et al*., 2009] geoengineering approaches to proceed [as SRM cannot mitigate ocean acidification, *Orr et al*., 2005; *National Research Council*, 2015]. The geopolitical consequences of large-scale geoengineering, involving multiple players, are particularly important to transboundary issues, such as compensation for any damage to regional resources [see *Horton et al*., 2015]. If a catastrophic regional event occurred, this could ratchet up geopolitical tensions, particularly if there was equivocal evidence of the environmental driver(s), including the possibility that some geoengineering agency (who were receiving benefit financially from their project(s)) was inadvertently complicit in such an event [*Dalby*, 2015]. Clearly, any future governance of geoengineering [ranging from research to adaptive governance, *Banerjee*, 2009; *Parson and Ernst*, 2013; *Foley et al*., 2015; *Horton et al*., 2015] must take geopolitically relevant detection and attribution into account on an equal footing with those for SRM and/or CDR detection and attribution for planetary accounting.

4.3. The Power of Ranking Criteria

Ranking criteria have played a key role in teasing apart the many different characteristics of proposed geoengineering approaches that enable them to be intercompared in a structured manner across a range of properties, such as efficacy or cost [*Keith and Dowlatabadi*, 1992; *Boyd*, 2008b; *Shepherd et al*., 2009]. It is clear from the outcome of a natural analogue of geoengineering such as Pinatubo, along with the executive summaries from natural science academies such as the U.S. *National Research Council* [2015], that we need to expand these criteria to make them encompass all of the major issues, including geopolitics. Such criteria help to reveal major points of difference between geoengineering approaches—including safety or rapidity—that permit comprehensive discussions to take place prior to any future decision making about the future of geoengineering research and any consequent large-scale geoengineering projects. One of the problems with the development of such ranking criteria is how to also include the effects, in this case geopolitical consequences, of business-as-usual anthropogenic CO_2 emissions. For example, climate change-mediated regional effects are projected to differ from those of the global mean effects [*Boyd et al*., 2015]. Hence, anthropogenic climate change could cause regional transboundary effects of comparable (or greater, we simply do not know) magnitude to some geoengineering approaches.

Here, I amplify some of the concepts outlined in *Boyd* [2009] along with ideas introduced in more recent geopolitical appraisals of geoengineering [*Yusoff*, 2013; *Dalby*, 2015; *Horton and Reynolds*, 2016] to put forward geopolitically relevant ranking criteria. The ranking criteria are presented in a "paint chart" format employed by *Boyd* [2008b] as a means of representing qualitative, or at best semiquantitative, information used to rank the criteria. In the absence of data from large-scale geoengineering studies, this information is largely based on natural analogues (such as Pinatubo and ocean basin-scale iron fertilization events in the geological past [*Boyd*, 2008a; *Martinez-Garcia et al*., 2014]), other analogues (cloud whitening and ship stack emissions [*Latham et al*., 2012; *Robock et al*., 2013]), or detailed small-scale CDR studies [*Lackner*, 2009; *Matter et al*., 2016]. Two proposed methods from SRM geoengineering are considered along with three from CDR approaches. The examples were chosen to illustrate a wide range of scoring estimates, in a geopolitical context, to stimulate further discussion around this issue.

4.4. Geopolitically Relevant Ranking Criteria

The ranking criteria have been initially split into four categories, the first two—spatial scale and dispersal—provide details, across a series of subcategories, into the initial size required by a particular geoengineering method and whether dispersal (e.g., in the ocean or atmosphere) is also part of the required strategy for measurable success as a geoengineering approach. These two categories provide the platform to inform how inclusive (or exclusive) each of these methods are, which relates to wider issues, covered by category three, of participation, governance, and democracy across geoengineering [*Boyd*, 2009; *Yusoff*, 2013]. The final category builds on the three previous ones and considers the intersection of geopolitical characteristics and tradeoffs in the context of what each of the five geoengineering approaches has to offer. I will use illustrative examples from each of these geoengineering approaches to guide the reader through the ranking criteria.

The five approaches selected straddle fundamentally different approaches to geoengineering in the context of geopolitics. For example, atmospheric [artificial trees, *Lackner*, 2009] and geochemical [geological reservoirs, *Matter et al*., 2009, 2016] carbon capture (Figure 2) are constrained spatially (artificial trees, size of basaltic rock sites for subsequent carbon storage) and hence must rely on a large number of units [trees, sites, see *Goldberg and Slagle*, 2009] to provide a sufficiently large cumulative effect to have a measurable influence on atmospheric carbon dioxide (Figure 1). Hence, each has a relatively small spatial scale, and thus a readily detectable provenance, and does not require dispersal to boost their geoengineering potential; as each of these issues influence attribution, transboundary, and interference effects, they are given high scores as they will have relatively few geopolitical ramifications. Proposals that describe cloud whitening

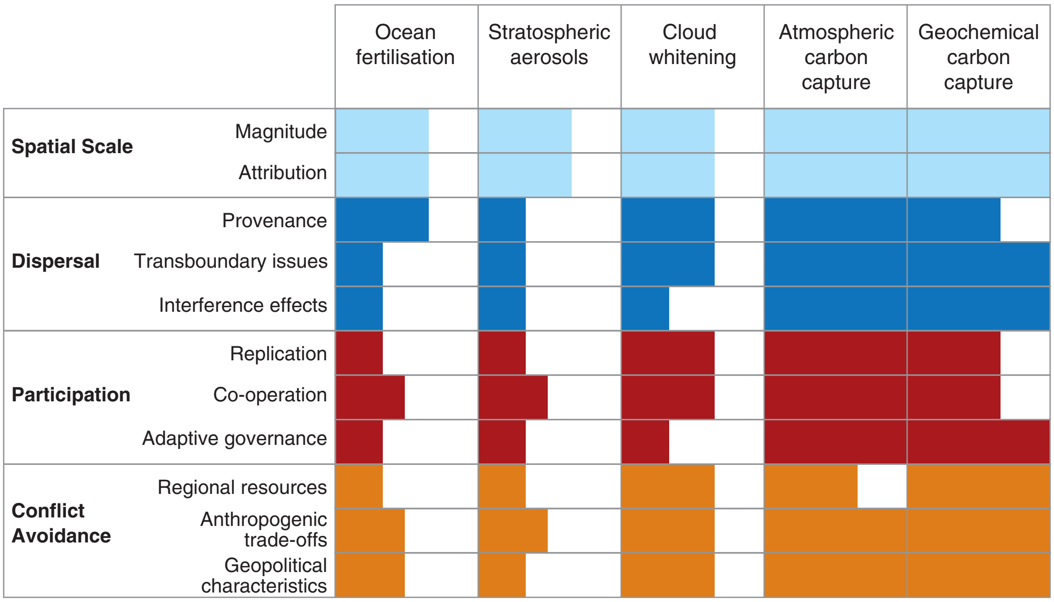

Figure 2. An appraisal of five geoengineering methods (two SRM [stratospheric aerosols and cloud whitening] and three CDR) using four categories of geopolitically relevant ranking criteria. Each category has several subcategories, and more color within a panel of the figure represents less geopolitical risk for a particular method for a particular subcategory. The layout of the figure follows that used by *Boyd* [2008b] to assess the efficacy, risk, cost, and rapidity of these five geoengineering methods. Note that this ranking is viewed as preliminary, and not definitive, due to the many unknowns in the field of geoengineering and how they might mesh with geopolitical concerns. Furthermore, it is problematic to incorporate the effects of anthropogenic climate change (i.e., business-as-usual CO_2 emissions) onto many of these metrics, such as participation and dispersal.

[*Latham et al*., 2012] also largely appear to rely on relatively small/intermediate spatial scales but would also require some atmospheric dispersal to maximize their geoengineering potential; hence, they attain intermediate scores under the first two categories (Figure 2). In contrast, stratospheric geoengineering and ocean fertilization require intermediate scales (which may influence confirmation of their provenance) but then require widespread dispersal to stratospheric [*Kravitz et al*., 2011] and ocean basin [*Gnanadesikan et al*., 2003] scales, respectively, to maximize their geoengineering potential for SRM and CDR, respectively. Hence, ocean fertilization and stratospheric aerosols and their required modes of delivery and fate receive lower scores (reflecting more potential for geopolitical risks) as they are more likely to lead to transboundary effects [e.g., Pinatubo and increased drought indices, *Trenberth and Dai*, 2007] and/or interference (i.e., regional or even global due to globalization of trade) effects on other resources [fisheries, *Gnanadesikan et al*., 2003; regional climate, *Kravitz et al*., 2014; agriculture, *Liu and Chen*, 2015].

The wide range of characteristics for each of the five selected geoengineering approaches is also reflected in the scoring for the third subcategory, Participation. As stated, the two carbon capture approaches, if they are to have any significant effect regionally or globally on CDR, must be scaled up by increasing the number of sites for carbon storage (e.g., geological sites with low potential for CO_2 leakage or artificial trees). This replication approach is largely amenable to widespread participation [*Yusoff*, 2013] across nations that may help foster collectivism and cooperation (Figure 2). Moreover, this upscaling of multiple small-scale units (versus regional or global dispersion of fewer large-scale units) is conducive with the development of adaptive governance, which requires periods of lead-in time to develop adaptation [*Parson and Keith*, 2013; *Foley et al*., 2015].

These qualities for the two carbon capture and storage approaches (and to a lesser extent for cloud whitening) again resulted in higher scores due to less perceived geopolitical risk offered by the potential buffer of widespread participation. In contrast, ocean fertilization and stratospheric aerosols were ranked lower as their underlying need for widespread dispersal minimizes participation, and a single SRM release (unilateral implementation, see *Horton and Reynolds*, 2016) can attain stratospheric coverage. Moreover, rapid stratospheric dispersal (months) of aerosols was evident following the Pinatubo eruption (Figure 1), leaving little lead-in time for regulators to refine adaptive governance. Furthermore, point source SRM or

CDR releases by multiple players (potentially using different agents, including wide-ranging aerosol types [*Weisenstein et al*., 2015] or release strategies [*Arino et al*., 2016], would also raise a wide range of detection and attribution issues, as discussed earlier.

The cumulative influence of the scores for categories 1–3 is reflected in the scores for the final category, conflict avoidance. The three subcategories for conflict avoidance reflect some of the issues that are evident from the example of the 1991 Pinatubo eruption [*Trenberth and Dai*, 2007; *Boyd*, 2009] but are largely the preserve of the International Relations literature [*Horton and Reynolds*, 2016]. For example, the hypothetical richness of regional resources [agriculture, fisheries, environmental services, see *Liu and Chen*, 2015] and how they might be compromised by different modes of geoengineering (in these cases, mainly by transboundary and interference effects) is reflected in the rankings (Figure 2). In some cases, such as low-lying territories and states, there may be tradeoffs between the partial loss of a regional resource and the benefit from arresting sea-level rise through SRM and/or CDR geoengineering (Figure 2). The final subcategory, geopolitical characteristics, encapsulates the first two subcategories but also takes into account whether a region or nation is developing, industrialized, militarized, or populous, and hence, this subcategory attempts to capture the range of responses to geopolitical tensions arising from inadvertent effects of large-scale geoengineering. For example, overlaying Figure 3 from *Trenberth and Dai* [2007] on changes in drought potential, following the 1991 Pinatubo eruption, with maps of the above geopolitical characteristics would provide a vivid illustration of this category on conflict avoidance.

5. The Utility of Natural Analogues in the Geoengineering Debate

In the last decade, the discourse on the benefits, drawbacks, and challenges of geoengineering—from individual research papers to the comprehensive reports from national academies—would have been vacuous without a series of natural analogues to draw upon. The upscaling provided by such large-scale (Pinatubo) and long-term events (basin-scale ocean iron fertilization over centuries to millennia) has both opened our eyes and broadened our imagination to the inextricable linkages across the Earth System. This planetary circuitry reveals unanticipated side effects and timescales of change that are wide-ranging in response to natural large-scale events (Figure 1). When this dynamic environment is placed in the context of a planet with an ever-growing population, diminishing resources [*Rockström et al*., 2009; *Steffen et al*., 2015], and an unprecedented rate of climate change [*IPCC*, 2013], then geopolitical concerns regarding any form of geoengineering must be front and center of any discussion on this topic. Paul Crutzen, by linking a natural event with the debate on geoengineering, has done both the scientific and wider communities an immense service—he has both animated the debate and grounded it in a real-world analogue that provides a cutting edge into the many facets of this discussion, from the science to other wider concerns.

Acknowledgments

We thank Andreas Oschlies and an anonymous reviewer for constructive comments that helped to improve this manuscript. PWB was supported by an Australian Research Council Australian Laureate Fellowship (project number FL160100131). The data used in this study are from the cited references.

References

Arino, Y., K. Akimoto, F. Sano, T. Homma, J. Oda, and T. Tomoda (2016), Estimating option values of solar radiation management assuming that climate sensitivity is uncertain, *Proc. Natl. Acad. Sci. U. S. A.*, *113*, 5886–5891.

Banerjee, B. (2009), The limitations of geoengineering governance in a world of uncertainty, *Stanford J. Law Sci. Policy*, *4*, 16–35.

Bengtsson, L. (2006), Geo-engineering to confine climate change: Is it at all feasible? *Clim. Change*, *77*, 229–234, doi:10.1007/s10584-006-9133-3.

Boyd, P. W. (2008a), Implications of large-scale iron fertilization of the oceans, *Mar. Ecol. Progr. Ser.*, *364*, 213–218, doi:10.3354/meps07541.

Boyd, P. W. (2008b), Ranking geo-engineering schemes, *Nat. Geosci.*, *1*, 722–724, doi:10.1038/ngeo348.

Boyd, P. W. (2009), Geopolitics of geoengineering, *Nat. Geosci.*, *2*(12), 812, doi:10.1038/ngeo710.

Boyd, P. W., and M. Bressac (2016), Developing a test-bed for robust research governance of geoengineering: The contribution of ocean iron biogeochemistry, *Philos. Trans. R. Soc. A*, *374*, 20150299, doi:10.1098/rsta.2015.0299.

Boyd, P. W., S. T. Lennartz, D. M. Glover, and S. C. Doney (2015), Biological ramifications of climate-change mediated oceanic multi-stressors, *Nat. Clim. Change*, *5*, 71–79, doi:10.1038/NCLIMATE2441.

Boyd, P. W., C. E. Cornwall, A. Davison, S. C. Doney, M. Fourquez, C. L. Hurd, I. D. Lima, and A. McMinn (2016), Biological responses to environmental heterogeneity under future ocean conditions, *Global Change Biol.*, *22*, 2633–2650, doi:10.1111/gcb.13287.

Bürger, G., and U. Cubasch (2015), The detectability of climate engineering, *J Geophys. Res. Atmos.*, *120*, 11,404–11,418, doi:10.1002/2015JD023954.

Chan, F., J. A. Barth, J. Lubchenco, A. Kirincich, H. Weeks, W. T. Peterson, and B. A. Menge (2007), Emergence of anoxia in the California current large marine ecosystem, *Science*, *319*, 920.

Chisholm, S. W., and F. M. M. Morel (Eds) (1991), What controls phytoplankton production in nutrient rich areas of the open sea? *Limnol. Oceanogr.*, *36*, 1232–1239, doi:10.4319/lo.1991.36.6.1232.

Christensen, M. W., and G. L. Stephens (2011), Microphysical and macrophysical responses of marine stratocumulus polluted by underlying ships: Evidence of cloud deepening, *J. Geophys. Res.*, *116*, D03201, doi:10.1029/2010JD014638.

Crutzen, P. J. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? *Clim. Change*, *77*, 211, doi:10.1007/s10584-006-9101-y.

Dai, A., K. E. Trenberth, and T. Qian (2004), A global data set of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, *5*, 1117–1130.

Dalby, S. (2015), Geoengineering: The next era of geopolitics? *Geogr. Compass*, *9*(4), 190–201, doi:10.1111/gec3.12195.

Fleming, J. R. (2007), The climate engineers, *Wilson Q.*, *31*, 46–60.

Fleming, J. R. (2010), *Fixing the Sky: The Checkered History of Weather and Climate Control (Columbia Studies in International and Global History)*, Columbia Univ. Press, New York, 325 pp. ISBN 978-0-231-14412-4.

Foley, R. W., D. H. Guston, and D. Sarewitz. (2015), Toward the anticipatory governance of geoengineering. Working Paper, *Geoengineering Our Climate Working Paper and Opinion Article Series*, Earthscan, Oxford, U.K. [Available at http://wp.me/p2zsRk-c8].

Gnanadesikan, A., J. L. Sarmiento, and R. D. Slater (2003), Effects of patchy ocean fertilization on atmospheric carbon dioxide and biological production, *Global Biogeochem. Cycles*, *17*(2), 1050, doi:10.1029/2002GB001940.

Goldberg, D., and A. L. Slagle (2009), A global assessment of deep-sea basalt sites for carbon sequestration, *Energy Proc.*, *1*, 3675–3682.

Hamme, R. C., et al. (2010), Volcanic ash fuels anomalous plankton bloom in subarctic northeast Pacific, *Geophys. Res. Lett.*, *37*(19), L19604, doi:10.1029/2010GL044629.

Hansen, J., A. Lacis, R. Ruedy, and M. Sato (1992), Potential climate impact of Mount Pinatubo eruption, *Geophys. Res. Lett*, *19*, 215–218, doi:10.1029/91GL02788.

Herber, A., L. W. Thomason, K. Dethloff, P. Viterbo, V. F. Radionov, and U. Leiterer (1996), Volcanic perturbation of the atmosphere in both polar regions: 1991–1994, *J. Geophys. Res.*, *101*(D2), 3921, doi:10.1029/95JD02462.

Horton, J. B., and J. L. Reynolds (2016), The international politics of climate engineering: A review and prospectus for international relations, *Int. Stud. Rev.*, *18*, 438–461.

Horton, J. B., A. Parker, and D. Keith (2015), Liability for solar geoengineering: Historical precedents, contemporary innovations, and governance possibilities, *N. Y. Univ. Environ. Law J.*, *22*, 268–269.

IPCC (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge, U. K.

Jickells, T. D., et al. (2005), Global iron connections between desert dust, ocean biogeochemistry, and climate, *Science*, *308*, 67–71, doi:10.1126/science.1105959.

Jones, P. D., A. Moberg, T. J. Osborn, and K. R. Briffa (2003), Surface climate responses to explosive volcanic eruptions seen in long European temperature records and mid-to-high latitude tree-ring density around the Northern Hemisphere, in Volcanism and the Earth's Atmosphere, Geophys. Monogr. Ser., vol. 139, edited by A. Robock and C. Oppenheimer, pp. 239–254, AGU, Washington, D. C.

Keith, D. W., and H. Dowlatabadi (1992), A serious look at geoengineering, *EOS Trans. AGU*, *73*, 289–293, doi:10.1029/91EO00231.

Kiehl, J. T. (2006), Geoengineering climate change: treating the symptom over the cause? *Clim. Change*, *77*, 227–228, doi:10.1007/s10584-006-9132-4.

Kravitz, B., A. Robock, O. Boucher, H. Schmidt, K. E. Taylor, G. Stenchikov, and M. Schulz (2011), The Geoengineering Model Intercomparison Project (GeoMIP), *Atmos. Sci. Lett.*, *12*(2), 162–167, doi:10.1002/Asl.316.

Kravitz, B., et al. (2014), A multi-model assessment of regional climate disparities caused by solar geoengineering, *Environ. Res. Lett.*, *9*, 7, doi:10.1088/1748-9326/9/7/074013.

Lackner, K. S. (2009), Capture of carbon dioxide from ambient air, *Eur. Phys. J.*, *176*, 93–106, doi:10.1140/epjst/e2009-01150-3.

Landschützer, P., et al. (2015), The reinvigoration of the Southern Ocean carbon sink, *Science*, *349*, 1221–1224, doi:10.1126/science.aab2620.

Latham, J., et al. (2012), Marine cloud brightening, *Philos. Trans. R. Soc. A*, *370*, 4217–4262, doi:10.1098/rsta.2012.0086.

Lenton, T. M., and N. E. Vaughan (2009), Radiative forcing potential of climate geoengineering, *Atmos. Chem. Phys.*, *9*, 5539–5561, doi:10.5194/acp-9-5539-2009.

Liu, Z., and Y. Chen (2015), Impacts, risks, and governance of climate engineering, *Adv. Clim. Change Res.*, *6*, 197–201.

Lovelock, J. E., and C. G. Rapley (2007), Ocean pipes could help the Earth to cure itself, *Nature*, *449*, 403, doi:10.1038/449403a.

Martin, J. H. (1990), Glacial-interglacial CO_2 change: The iron hypothesis, *Paleoceanography*, *5*, 1–13, doi:10.1029/PA005I001P00001.

Martinez-Garcia, A., D. M. Sigman, H. Ren, R. F. Anderson, M. Straub, D. A. Hodell, S. L. Jaccard, T. I. Eglinton, and G. H. Haug (2014), Iron fertilization of the Subantarctic ocean during the last ice age, *Science*, *43*, 1347–1350, doi:10.1126/science.1246848.

Matter, J. M., et al. (2016), Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions, *Science*, *352*, 1312–1314, doi:10.1126/science.aad8132.

Matter, J. M., W. S. Broecker, M. Stute, S. R. Gislason, E. H. Oelkers, A. Stefánsson, D. Wolff-Boenisch, E. Gunnlaugsson, G. Axelsson, and G. Björnsson (2009), Permanent Carbon dioxide storage into basalt: The CarbFix Pilot Project, Iceland, *Energy Proc.*, *1*(2009), 3641–3646.

Minnis, P., et al. (1993), Radiative climate forcing by the Mt. Pinatubo eruption, *Science*, *259*, 1411–1415.

NAS (National Academy of Sciences, U.S.). (2015), Climate intervention: Reflecting sunlight to cool earth. [Available at http://www.nap.edu/catalog.php? record_id¼18988].

National Research Council (2015), *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*, The National Academies Press, Washington, D. C.

Orr, J. C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos (2005), Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, *437*, 681–686.

Parson, E. A., and D. A. Keith (2013), End the deadlock on governance of geoengineering research, *Science*, *339*, 1278–1279, doi:10.1126/science.1232527.

Parson, E. A., and L. N. Ernst (2013), International governance of climate engineering, *Theor. Inquir. Law*, *14*, 307–338, doi:10.1515/til-2013-015.

Randel, W. J., F. Wu, J. M. Russell, J. W. Waters, and L. Froidevaux (1995), Ozone and temperature changes in the stratosphere following the eruption of Mount Pinatubo, *J. Geophys. Res.*, *100*(D8), 16753–16764, doi:10.1029/95JD01001.

Rasch, P. J., S. Tilmes, R. P. Turco, A. Robock, L. Oman, C.-C. Chen, G. L. Stenchikov, and R. R. Garcia (2008), An overview of geoengineering of climate using stratospheric sulphate aerosols, *Philos. Trans. R. Soc. A*, *366*, 4007–4037, doi:10.1098/rsta.2008.0131.

Robock, A., D. G. MacMartin, R. Duren, and M. W. Christensen (2013), Studying geoengineering with natural and anthropogenic analogs, *Clim. Change*, *121*, 445–458, doi:10.1007/s10584-013-0777-5.

Rockström, J., et al. (2009), A safe operating space for humanity, *Nature*, *461*, 472–475, doi:10.1038/461472a.

Sarmiento, J. L. (1993), Atmospheric CO_2 stalled, *Nature*, *365*(6448), 697–698, doi:10.1038/365697a0.

Shepherd, J., K. Caldeira, P. Cox, J. Haigh, D. Keith, B. Lauder, G. Mace, G. MacKerron, J. Pyle, and S. Rayner (2009), Geoengineering the climate: Science, governance and uncertainty. U. K. R. Soc. Policy Document 10/09, RS1636, ISBN: 978-0-85403-773-5.

Soden, B. J., D. L. Jackson, V. Ramaswamy, D. Schwarzkopf, and X. Huang (2005), The radiative signature of upper tropospheric moistening, *Science*, *310*, 841–844.

Steffen, W., K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit (2015), Planetary boundaries: Guiding human development on a changing planet, *Science*, *347*(6223), 736, doi:10.1126/science.1259855.

Sumner T. (2015) Warming could nearly double rate of severe La Niña events. *Science News Online*, 26 Jan.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, 486–498, doi:10.1175/BAMS-D-11-00094.1.

Trenberth, K. E., and A. Dai (2007), Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering, *Geophys. Res. Lett.*, *34*, L15702, doi:10.1029/2007GL030524.

Watson, A. J. (1997), Volcanic iron, CO_2 ocean productivity and climate, *Nature*, *385*, 587–588, doi:10.1038/385587b0.

Weisenstein, D. K., D. W. Keith, and J. A. Dykema (2015), Solar geoengineering using solid aerosol in the stratosphere, *Atmos. Chem. Phys.*, *15*, 11835–11859, doi:10.5194/acp-15-11835-2015.

Yusoff, K. (2013), The geoengine: Geoengineering and the geopolitics of planetary modification, *Environ. Plann. A*, *45*, 2799–2808, doi:10.1068/a45645.