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William C. G. Burns

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GEOENGINEERING THE CLIMATE: AN OVERVIEW OF SOLAR RADIATION MANAGEMENT OPTIONS

William C.G. Burns*

1. INTRODUCTION

Until recently, climate change geoengineering, broadly defined as "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change,"[1] was viewed as outside the mainstream, or as David G. Victor has put it less charitably, "a freak show in otherwise serious discussions of climate science and policy."[2] However, events on the ground have dramatically changed the landscape in the past few years. The parties to the United Nations Framework Convention on Climate Change[3] (UNFCCC) acknowledged at the 15th Session of the Conference of the Parties (COP) that increases in global temperatures should be held below 2° Celsius above pre-industrial levels to avoid dangerous anthropogenic interference with the climate system,[4]

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* Visiting Professor of International Environmental Policy, Graduate School of International Policy & Management, Monterey Institute of International Studies of Middlebury College, Monterey, Cal.

[1] ROYAL SOC'Y, *Geoengineering the Climate: Science, Governance and Uncertainty* (Sept. 2009), at 11, http://royalsociety.org/Geoengineering-the-climate/ (last visited Mar. 28, 2011.)

[2] David G. Victor, *On the Regulation of Geoengineering*, 24(2) OXFORD REV. ECON. POL. 322, 323 (2008). The concept of climatic geoengineering extends back to at least the 1830s when American meteorologist J.P. Espy suggested that lighting huge fires could stimulate convective updrafts and alter the intensity and frequency of precipitation. Philip J. Rasch et al., *An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols*, 366 PHIL. TRANACTIONS ROYAL SOC'Y. 4007, 4008 (2008). For a thorough historical treatment of weather and climate modification initiatives, see James Rodger Fleming, *The Pathological History of Weather and Climate Modification: Three Cycles of Promise and Hype*, 37(1) HIST. STUD. PHYSICAL SCI. 3-25 (2006), http://www.colby.edu/sts/06_fleming_pathological.pdf (last visited Nov. 30, 2010).

[3] U.N. Conference on Environment and Development: Framework Convention on Climate Change, May 9, 1992, 31 I.L.M. 849.

[4] United Nations Framework Convention on Climate Change, Conference of the Parties, Fifteenth Session, Copenhagen, Den., Dec. 7-19, 2009, *Copenhagen Accord*, ¶ 1, FCCC/CP/2009/L.7 (Dec. 18, 2009). The world's major economies also adopted this target in 2009 at the G8 Summit. Michel Den Elzen & Niklas Höhne, *Sharing the Reduction Effort to Limit Global Warming to 2°C*, 10 CLIMATE POL'Y 247, 248 (2010). At both the 15th and 16th Conferences of the Parties to the United Nations Framework Convention on Climate Change, the Parties also agreed to review the long-term global temperature goal, with a view to perhaps ultimately agreeing to a goal of limiting temperature increases to 1.5°C above pre-industrial levels. *Copenhagen Accord*, *supra*, ¶12; United Nations Framework Convention on Climate Change Secretariat, *Outcome of the Work of the Ad Hoc Working Group on Long-Term Cooperative Action under the Convention*, Sixteenth Session, Cancun, Mexico, ¶139(a), Draft decision -/CP.16, http://unfccc.int/files/meetings/cop_16/application/pdf/cop16_lca.pdf (last visited Dec. 15, 2010). This reflects the belief of many scientists that even temperature increases of 1.5°C above pre-industrial levels will have serious negative impacts for some of the world's most vulnerable regions. Suzanne Goldenberg, John Vidal & Jonathan Watts, *Leaked UN Report Shows Cuts Offered at Copenhagen Would Lead to 3C Rise*, GUARDIAN.CO.UK, Dec. 17, 2009, http://www.guardian.co.uk/environment/2009/dec/17/un-leaked-report-copenhagen-3c; KATHERINE RICHARDSON, ET AL., CLIMATE CHANGE: GLOBAL RISKS, CHALLENGES & DECISIONS 13 (2009).

affirming the scientific consensus that temperature increases of 1.5-2° Celsius will visit serious harms on natural systems and human institutions.[5]

Yet at "the dismal COP 15,"[6] the Parties to the UNFCCC were unable to agree to a binding post-2012 agreement, or even pass a binding resolution to effectuate a long-term response to climate change. Rather, following protracted and acrimonious negotiations, the COP merely took note of a non-binding accord[7] that put the world on pace for temperature increases of between 2.5-4.2° Celsius by 2100, with further increases thereafter.[8] Moreover, the failure of governments to make substantive progress at Copenhagen toward a "legally binding and ambitious agreement" has undermined domestic efforts to implement effective climate change policies.[9] While there were some positive developments at the Sixteenth Session of the Conference of the Parties/Sixth Session of the Meeting of the Parties to the Kyoto Protocol,[10] the world is still on pace

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[5] SIMON BULLOCK, MIKE CHILDS & ASAD REHMAN, RECKLESS GAMBLING 12 (Friends of the Earth, 2009), http://image.guardian.co.uk/sys-files/Environment/documents/2010/12/15/CarbonBudgetsReportdec14final.pdf (last visited Dec. 26, 2010); CAROLYN KOUSKY ET AL., RESPONDING TO THREATS OF CLIMATE CHANGE MEGA-CATASTROPHES 11 (The World Bank Development Research Group, Environment and Energy Team) (2009); M.J.C. Crabbe, *Modeling Effects of Geoengineering Options in Response to Climate Change and Global Warming: Implications for Coral Reefs*, 33 COMPUTATIONAL BIO. & CHEMISTRY 415, 416 (2009); Goldenberg, *supra* note 4.

[6] Hans Joachim Schellnhuber, *Tragic Triumph*, 100 CLIMATIC CHANGE 229, 229 (2010).

[7] *Copenhagen Accord*, *supra* note 4. At least four Parties to the UNFCCC objected to the Accord being adopted as a Conference of the Party (COP) decision. Because the Chair held that decisions by the COP could only be adopted by consensus, which he construed as unanimity among the parties, this scuppered adoption of the Accord as a Decision of the Parties. As a consequence, the Conference of the Parties merely 'took note' of the Accord, which was a way for the Parties to the UNFCCC to formally acknowledge its existence. Parties in support of the Accord are able, however, to immediately operationalize those parts of the Accord that do not require a COP decision, including emissions targets by Annex I Parties and mitigation actions by non-Annex I Parties. Jacob Werksman, *"Taking Note" of the Copenhagen Accord: What It Means*, WORLD RESOURCES INSTITUTE (Dec. 20, 2009), http://www.wri.org/stories/2009/12/taking-note-copenhagen-accord-what-it-means. *See also* Harald Winkler & Judy Beaumont, *Fair and Effective Multilateralism in the Post-Copenhagen Climate Negotiations*, 10 CLIMATE POL'Y 638, 639 (2010).

[8] INTERNATIONAL ENERGY AGENCY, WORLD ENERGY OUTLOOK 2010 EXECUTIVE SUMMARY 11 (2010), http://www.worldenergyoutlook.org/docs/weo2010/WEO2010_ES_English.pdf (last visited Nov. 11, 2010) ("[T]rends are in line with stabilising the concentration of greenhouse gases at over 650 ppm CO_2-eq, resulting in a likely temperature rise of more than 3.5° C in the long term."); Joeri Rogelj et al., *Analysis of the Copenhagen Accord Pledges and its Global Climatic Impacts – A Snapshot of Dissonant Ambitions*, 5 ENVTL. RES. LETTERS 034013, 7 (2010). *See also* Kevin Anderson & Alice Bows, *Reframing the Climate Change Challenge in Light of Post-2000 Emission Trends*, 366 PHIL. TRANS. ROYAL SOC. A 3863, 3880 (2008) (limiting temperature increases to 4°C above pre-industrial levels may require a "radical reframing of both the climate change agenda, and the economic characterization of contemporary society"). Forebodingly, a recent study drawing upon observational evidence from past eras when atmospheric concentrations of carbon dioxide were as high as projected by the end of this century concluded that we may be underestimating the sensitivity of radiation forcing by a factor of two to four. Jeffrey Kiehl, *Lessons from the Earth's Past*, 331 SCI. 158, 159 (2011). Thus, future generation could "face another world, one that the human species has never experienced in its history." *Id.*

[9] William Hare et al., *The Architecture of the Global Climate Regime: A Top-Down Perspective*, 10 CLIMATE POL'Y 600, 609 (2010).

[10] At the 16th Session of the Conference of the Parties to the UNFCCC, the Parties "anchored" the "economy-wide emission reduction targets" of Annex I Parties made after Copenhagen, as well as the "nationally appropriate mitigation actions" by developing country Parties, in a formal decision of the Parties. *Outcome of the Work of the Ad Hoc Working Group on Long-Term Cooperative Action under the Convention, supra* note 4. Moreover, developed country Parties were urged to increase their targets to comport with the levels recommended by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Id.* ¶ 37. *See also* UNFCCC, *Outcome of the Work of the Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol at its Fifteenth Session*, Draft Decision -/CMP.6 (2010), ¶ 4, http://unfccc.int/files/meetings/cop_16/application/pdf/cop16_kp.pdf (last visited Dec. 21, 2010). However, as

for temperature increases substantially above dangerous thresholds.[11]

The feckless response of the global community to climate change has led to increasingly serious consideration of the potential role of geoengineering as a potential means to avert a "climate emergency,"[12] such as rapid melting of the Greenland and West Antarctic ice sheets,[13] or as a stopgap measure to buy time for effective emissions mitigation responses.[14] The overarching purpose of climate geoengineering proposals is

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Gallagher observed, "most of the difficult decisions were deferred to the future." Kelly Sims Gallagher, *Spotlight Cancún: The Road to Rio*, TRIPLECRISIS: GLOBAL PERSPECTIVES ON FINANCE, DEVELOPMENT, AND ENVIRONMENT, http://triplecrisis.com/spotlight-cancun-the-road-to-rio/, (last visited Dec. 21, 2010).

[11] Claudine Chen et al., *Cancun Climate Talks – Keeping Options Open to Close the Gap*, CLIMATE ACTION TRACKER (Dec. 11, 2010), http://www.climateactiontracker.org/briefing_paper_cancun.pdf (last visited Dec. 19, 2010) (lowest ambition proposals by the Parties to the UNFCCC and Kyoto Protocol could lead to warming of 3.2°C above pre-industrial levels by 2100, and even high end of ambitions would leave a substantial gap in terms of what needs to be done to limit temperature increases to 2°C). Moreover, a recent study indicates that models may be substantially underestimating the long-term sensitivity of the Earth to radiative forcing, and thus potential increases of temperature in the future. Under a business as usual scenario of energy use, atmospheric concentrations of carbon dioxide could reach 900-1100ppmv by the end of this century. When concentrations reached this level during the warm mid-Cretaceous period, temperatures rose more than 16°C higher than pre-industrial levels. Jeffrey Kielhl, *Lessons from Earth's Past,* 331 SCI. 158, 159 (2011).

[12] Ken Caldeira & David W. Keith, *The Need for Climate Engineering Research*, 27 ISSUES SCI. & TECH. 57, 57 (Fall 2010). *See also* Working Group Commissioned by the Pontifical Academy of Sciences, *Fate of Mountain Glaciers in the Anthropocene* 14 (2011), http://www.vatican.va/roman_curia/pontifical_academies/acdscien/2011/PAS_Glacier_110511_final.pdf (site visited on May 13, 2011).

[13] JASON J. BLACKSTOCK ET AL., CLIMATE ENGINEERING RESPONSES TO CLIMATE EMERGENCIES 1-2 (NOVIM 2009). A complete melting of the Greenland Ice Sheet could occur with temperature increases of 2-3°C. Stephen Schneider, *The Worst-Case Scenario*, 458 NATURE 1104, 1104 (2009). This could raise global sea level by approximately seven meters and trigger a slowdown or collapse of the ocean thermohaline circulation, which could result in significant cooling over much of the northern hemisphere. Jason A. Lowe et al., *The Role of Sea-Level Rise and the Greenland Ice Sheet in Dangerous Climate Change: Implications for the Stabilisation of Climate, in* AVOIDING DANGEROUS CLIMATE CHANGE 29, 30 (Hans Joachim Schellnhuber ed., 2006); Julian A. Dowdeswell, *The Greenland Ice Sheet and Global Sea-Level Rise*, 311 SCI. 963, 963 (2006). Global average temperature increases of 1-4°C relative to 1990-2000 could result in sea level rise of 4-6 meters. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, WORKING GROUP II CONTRIBUTION, CLIMATE CHANGE 2007: CLIMATE CHANGE IMPACTS, ADAPTATION AND VULNERABILITY 64 (Martin Parry, ed., Cambridge University Press 2007). Even a five-meter rise in sea level could affect five percent of the world's population and threaten $2 trillion of Gross Domestic Product. United Nations Framework Convention on Climate Change, *Mechanisms to Manage Financial Risks from Direct Impacts of Climate Change in Developing Countries*, FCCC/TP/2008/9, Nov. 21, 2008, at 35.

[14] Martin Bunzl, *Research Geoengineering: Should Not or Could Not?*, 4 ENVTL. RES. LETTERS 045104 (2009), http://iopscience.iop.org/1748-9326/4/4/045104/fulltext (last visited Sept. 27, 2010); Christopher Mims, *"Albedo Yachts" and Marine Clouds: A Cure for Climate Change?*, SCI. AM., Oct. 21, 2009, at 3. Evidence of the increasing legitimacy of geoengineering options in the climate change policy realm include a series of hearings by the U.S. House Committee on Science and Technology and a recommendation by the Chair for a geoengineering research agenda. U.S. H. COMM. ON SCIENCE AND TECHNOLOGY, 111TH CONG., ENGINEERING THE CLIMATE: RESEARCH AND STRATEGIES FOR INTERNATIONAL COORDINATION, 44 (2010), http://science.house.gov/publications/caucus_detail.aspx?NewsID=2944 (last visited Nov. 13, 2010). The U.K. House of Common Science and Technology Committee held similar hearings, leading to its issuance of a report calling for a regulatory framework for geoengineering research. SCIENCE AND TECHNOLOGY COMMITTEE, THE REGULATION OF GEOENGINEERING, REPORT, 2009-10, H.C. 221 (U.K.) http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/221.pdf (last visited Nov. 13, 2010). This has led to the development of a risk assessment framework for ocean fertilization. *See Information on Work on Carbon Capture and Storage in Sub-Seabed in Geological Formation and Ocean Fertilization under the London Convention and London Protocol*, Sixteenth Session, Cancun, Mexico, -/CP.16, Nov. 2010, http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Documents/COP%2016%20Submissions/IMO%20note%20on%20LC-LP%20matters.pdf (last visited March 30, 2011), as well as the cautious endorsement of research by several prestigious scientists. Ken Caldeira & Lowell Wood, *Global and Arctic Climate Engineering: Numerical Model Studies*, 366 PHIL. TRANSACTIONS ROYAL SOC'Y 4039, 4053 (2008); Paul Crutzen, *Albedo Enhancement By Stratospheric Sulfur Injections: A Contribution to Resolve a Policy*

to intervene in the climate system by deliberately modifying the Earth's energy balance to reduce potential temperature increases and ultimately stabilize temperatures at levels lower than currently projected. A number of recent studies have concluded that geoengineering schemes could potentially mitigate the climatic impacts associated with a doubling of atmospheric carbon dioxide levels from pre-industrial levels.[15]

Climate geoengineering options can be divided into two broad categories: solar radiation management (SRM) methods and carbon dioxide removal (CDR) methods.[16] SRM methods focus on reducing the amount of solar radiation absorbed by the Earth by an amount sufficient to offset the increased trapping of infrared radiation by rising levels of greenhouse gases.[17] In more popular parlance, these schemes "essentially put a dimmer switch on the sun."[18] SRM schemes can be subdivided into two categories: those that seek to "reduce the amount of solar radiation reaching the top of the atmosphere" and those that reflect solar radiation within the atmosphere (tropospheric-based or in the tropopause and above) or at the surface.[19]

CDR methods seek to reduce carbon dioxide levels in the atmosphere, facilitating the escape of more outgoing long-wave radiation, thus, exerting a cooling effect.[20] There are three subcategories of CDR schemes, those that seek to: enhance uptake and storage by terrestrial biological systems, those that enhance uptake and storage by oceanic biological systems, and those that use physical, chemical, or biochemical engineered

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Dilemma, 77 CLIMATIC CHANGE 211612 (2006); Tom M.L. Wigley, *Low-Intensity Geoengineering Should be Seriously Considered*, BULLETIN OF THE ATOMIC SCIENTISTS, May 21, 2008, http://www.thebulletin.org/web-edition/roundtables/has-the-time-come-geoengineering (last visited on Nov. 20, 2010) (peak load of 5 Tg.S/year required between 2050 and 2060, declining back to zero by 2090). Additionally, several scientific organizations, including the American Meteorological Society, the American Geophysical Union and the National Academy of Sciences in the United States have endorsed this research. *Getting Serious About Geoengineering*, UCAR MAGAZINE, Nov. 18, 2010, http://www.ucar.edu/magazine/features/getting-serious-about-geoengineering (last visited Nov. 18, 2010). The Intergovernmental Panel on Climate Change also plans to address the risks, benefits, and feasibility of climate geoengineering in its Fifth Assessment Report, due to be released in 2013-14. The three working groups of the IPCC are also coordinating meetings of experts in the field in the interim. Ottmar Edenhofer, *IPCC Yet to Assess Geoengineering*, 468 NATURE 508 (2010), http://www.nature.com/nature/journal/v468/n7323/full/468508a.html (last visited Dec. 15, 2010). At the same time, it should be emphasized that there has been substantial pushback to the prospect of climate geoengineering. The parties to the Convention on Biological Diversity at the 10th meeting of the Conference of the Parties in Nagoya, Japan in 2010 passed a resolution calling for a moratorium on climate geoengineering activities "until there is an adequate scientific basis on which to justify such activities." Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity, ¶ 8(w), Oct. 29, 2010, http://www.cbd.int/doc/decisions/cop-10/cop-10-dec-33-en.pdf. Moreover, over sixty Civil Society groups also recently expressed their opposition to even climate geoengineering experiments. *Hands Off Mother Earth!: Civil Society Groups Announce New Global Campaign Against Geoengineering Tests*, ETC GROUP, Apr. 21, 2010, http://www.etcgroup.org/en/node/5131 (last visited Dec. 15, 2010).

[15] B. Govindasamy, K. Caldeira & P.B. Duffy, *Geoengineering Earth's Radiation Balance to Mitigate Climate Change from a Quadrupling of CO_2*, 37 GLOBAL & PLANETARY CHANGE 157, 158 (2003); Caldeira & Wood, *supra* note 14, at 4044.

[16] ROYAL SOC'Y, *Geoengineering the Climate* 1, at ix (Sept. 2009).

[17] Michael C. MacCracken, *Beyond Mitigation: Potential Options for Counter-Balancing the Climatic and Environmental Consequences of the Rising Concentrations of Greenhouse Gases*, 15 Policy Research Working Paper 4938, World Bank (2009).

[18] Andrea Thompson, *Raging Debate: Should We Geoengineer Earth's Climate?*, LIVESCIENCE, Feb. 10, 2010, http://www.livescience.com/environment/geoengineering-earth-climate-100210.html (last visited Dec. 21, 2010).

[19] T.M. Lenton & N.E. Vaughan, *The Radiative Forcing Potential of Different Climate Geoengineering Options*, 9 ATMOSPHERIC CHEMISTRY & PHYSICS 5539, 5540 (2009).

[20] ROYAL SOC'Y, *supra* note 16, at 9.

systems.[21]

This article will focus solely on SRM methods. The primary rationale for doing so is a personal belief that CDR schemes are less likely to prove viable as a response to climate change, and thus are far less likely to be deployed.[22] For example, some proponents of ocean iron fertilization (OIF),[23] one of the primary CDR options, have contended that it could reduce atmospheric concentrations of carbon dioxide by between 50-107 parts per million in 100 years.[24] However, a series of field trials in recent years have seriously undercut these estimates.[25] Another primary CDR option is carbon dioxide air capture, which would utilize filtering devices to capture substantial quantities of carbon dioxide.[26] However, the cost, at least in the short and medium term, may prove prohibitive. The Institution of Mechanical Engineers has estimated that as many as 10 million air-capture devices would be needed to absorb only 10% of current global emissions, at a cost of $20 trillion per 50ppm of carbon dioxide.[27] A third CDR option,

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[21] *Id.*

[22] Further, SRM options are marked by relative simplicity, rapid effects, and low cost. BLACKSTOCK, *supra* note 13, at 4-16.

[23] Ocean iron fertilization (OIF) techniques seek to stimulate the production of phytoplankton through the addition of iron to ocean regions that are allegedly deficient in this micronutrient. Phytoplankton takes up carbon dioxide from seawater to carry out photosynthesis and to build up particulate organic carbon (POC). Ultimately, part of the POC sinks to the deep ocean where it can be stored for a century or more. Christine Bertram, *Ocean Iron Fertilization in the Context of the Kyoto Protocol and the Post-Kyoto Process*, 38(2) ENERGY POL'Y 1130, 1131 (2010); Philip Boyd, *Ironing Out Algal Issues in the Southern Ocean*, 304 SCI. 396-97 (2004). Iron stimulates biological production chiefly in high nutrient low-chlorophyll (HNLC) regions. The Southern Ocean is the predominant high-nutrient low-chlorophyll region in the world, and thus the primary focus for proponents of OIF. Stéphane Blain et al., *Effect of Natural Iron Fertilization on Carbon Sequestration in the Southern Ocean*, 446 NATURE 1070, 1070 (2007).

[24] O. Aumont & L. Bopp, *Globalizing Results from Ocean In Situ Iron Fertilization Studies*, 20 GLOBAL BIOGEOCHEMICAL CYCLES 1, 1 (2006).

[25] Crabbe, *supra* note 5, at 418 (OIF of 20% of world's oceans would only reduce atmospheric carbon dioxide by approximately 15 parts per million at expected levels of 700 parts per million in 2100 for business as usual scenarios of greenhouse gas emissions); R.S. Lampitt, *Ocean Fertilization: A Potential Means of Geoengineering?*, 366 PHIL. TRANS. R. SOC. A 3919, 3928 (2008) (OIF could only draw down atmospheric levels of carbon dioxide by 10 parts per million). There is also serious concerns about potential negative impacts from OIF deployment, including decreasing primary production in large regions of temperature oceans as a consequence of exportation of nutrients, S. Dutkiewicz; M.J. Follows, P. Parekh, *Interactions of the Iron and Phosphorous Cycles: A Three-Dimensional Model Study*, 19 Global Biogeochemical Cycles: GB1021 (2005), and potential production of harmful algal blooms, Ian S.F. Jones, *Contrasing Micro- and Macro-Nutrient Nourishment of the Ocean*, 425 MAR. ECO. PROGRESS SERIES 281, 291 (2011); C.G. Trick, et al., *Iron Enrichment Stimulates Toxic Diatom Production in High-Nitrate, Low-Chlorophyll Areas*, 107 PROC. NAT'L ACAD. SCI. 5887-92 (2010).

[26] Klaus S. Lackner, *Washing Carbon Out of the Air*, SCI. AM., June 2010, at 66. Air capture is an industrial process that captures carbon dioxide from ambient air, producing a pure stream of carbon dioxide that can be used or sequestered. Most potential technologies would use sorbent materials to capture carbon dioxide, such as solid amines, or highly or moderately alkaline solutions. ROYAL SOC'Y, *supra* note 16, at 15-16. *See also* K.S. Lackner, *Capture of Carbon Dioxide from Ambient Air*, 176 EUR. PHYSICAL J. 93, 96 (2009); Roger A. Pielke, Jr., *An Idealized Assessment of the Economics of Air Capture of Carbon Dioxide in Mitigation Policy*, 12 ENVTL. SCI. & POL'Y 216, 217 (2009).

[27] DAVID BIELLO, *Pulling CO_2 from the Air: Promising Idea, Big Price Tag*, YALE ENV'T 360, http://e360.yale.edu/feature/pulling_co2_from_the_air_promising_idea_big_price_tag/2197/ (last visited Dec. 23, 2010). *See also* Robert Socolow, et al., *Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*, American Physical Society, Apr. 28, 2001, at 3, http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=244407 (last visited May 20, 2011); Nicola Jones, *Sucking It Up*, 458 NATURE 1094, 1096 (2009) (cost of returning atmospheric concentrations of carbon dioxide to 380 ppm by 2100 using air capture technology, assuming substantial cuts in emissions during this century, would be approximately $60 trillion).

mineral sequestration, would seek to accelerate the natural weathering process, producing a reaction between silicate rocks and carbon dioxide that forms solid carbonate and silicate materials.[28] The reaction consumes one carbon dioxide molecule for each silicate molecule, with storage of carbon as a solid mineral.[29] While proponents contend that this approach could "store all the carbon that is available in fossil fuels,"[30] they also acknowledge the imposing costs of such schemes,[31] probably rendering this option unviable in all but the long term.[32] Another CDR option is biochar. Biochar (charcoal) is created when biomass, such as wood, leaves or manure, is heated to approximately 700°C in a limited oxygen environment, a process known as pyrolysis.[33] Because the carbon atoms in charcoal are bound together much more strongly than in plant matter, it can sequester carbon for a thousand years.[34] However, biochar is unlikely to make a substantial contribution to carbon sequestration absent a very substantial commitment to production of biofuels.[35]

The purpose of this article is to provide an overview of the primary SRM geoengineering options currently being discussed in the science and policy communities as a means of framing the remaining articles in this issue. In this pursuit, the article examines the potential effectiveness of the main schemes being discussed, and discusses potential negative impacts of these approaches in terms of specific technologies and more generally.

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[28] PHILIP GOLDBERG ET AL., CO_2 MINERAL SEQUESTRATION STUDIES IN US 3 (U.S. Dept. of Energy, Nat'l Energy Tech. Lab. 2010), http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/6c1.pdf (last visited Dec. 24, 2010); G. Montes-Hernandez et al., *Mineral Sequestration of CO_2 by Aqueous Carbonation of Coal Combustion Fly-Ash*, 161 J. HAZARDOUS MATERIALS 1347, 1348 (2009). The most commonly cited minerals to be used in this process are serpentine and olivine. GOLDBERG, *supra*, at 3. One option, for which research is being conducted currently, would transport carbon dioxide from an emissions source to a carbonation reactor, where it would be combined with crushed minerals to facilitate the desired degree of carbonation, with the carbonate materials than disposed of as mine tailings. *Id.* at 4. *See also* Sigurdur Reynir Gislason et al., *Mineral Sequestration of Carbon Dioxide in Basalt: A Pre-Injection Overview of the CarbFix Project*, 4(3) INT'L J. GREENHOUSE GAS CONTROL 537, 537 (2010). Another proposal calls for adding silicate minerals such as olivine to soil used for agriculture to immobilize carbon dioxide partly as carbonate minerals and partly bicarbonate ion in solution. The Royal Soc'y, *supra* note 16, at 13-14. A third option might be to inject carbon dioxide underground at a carefully selected site where it would react with local mineral rocks and form carbonates underground. *Air Capture and Mineral Sequestration: Tools for Fighting Climate Change*, *H. Comm. on Science and Tech.*, 111th Cong. 7 (2010) (Testimony of Klaus S. Lackner), http://democrats.science.house.gov/Media/file/Commdocs/hearings/2010/Energy/4feb/Lackner_Testimony.pdf (last visited Dec. 24, 2010) [hereinafter Lackner Testimony].

[29] ROYAL SOC'Y, *supra* note 1, at 13.

[30] Lackner Testimony, *supra* note 28, at 7; HOWARD HERZOG, *Carbon Sequestration via Mineral Carbonation: Overview and Assessment*, Mar. 14, 2002, at 5, http://sequestration.mit.edu/pdf/carbonates.pdf (last visited Dec. 25, 2010).

[31] Herzog, *supra* note 30, at 6.

[32] *Id.* at 7.

[33] Arezoo Taghizadeh-Toosi, et al., *Biochar Incorporation into Pasture Soil Suppresses in situ Nitrous Oxide Emissions from Ruminant Urine Patches*, 40 J. ENVTL. QUALITY 468-475 (2011); International Biochar Institute, *What is Biochar?*, http://www.biochar-international.org/biochar/faqs#question1 (last visited May 24, 2011).

[34] International Biochar Institute, *supra* note 33.

[35] ROYAL SOC'Y, *supra* note 1, at 12.

2. SRM OPTIONS AND THEIR POTENTIAL IMPACTS

2.1. Stratospheric Sulfur Dioxide Injection

2.1.1 Overview and Potential Effectiveness

Perhaps the most widely discussed climate geoengineering option is enhancement of planetary albedo (surface reflectivity of sun's radiation)[36] using stratospheric sulfate aerosols.[37] The genesis of this approach was a suggestion by Russian climatologist Mikhail Budyko in 1974 that potentially dangerous climate change could be countered by deploying airplanes to burn sulfur in the atmosphere, producing aerosols to reflect sunlight away.[38] While most of the focus of albedo enhancement research has been on the use of sulfur, other potential options include hydrogen sulfide (H_2S), carbonyl sulfide, ammonium sulfide,[39] soot[40], and engineered nanoscale particles.[41]

Sulfate aerosols are an important component of the troposphere and stratosphere, and can substantially reduce the incoming solar radiation reaching the Earth's system during powerful volcanic eruptions.[42] For example, the Mt. Pinatubo eruption in 1991 spewed out about 10 million tons of sulfur, reflecting enough sunlight back to space to cool the Earth by 0.5° Celsius for a year or two following the eruption.[43]

A recent study by A.V. Eliseev and others concluded that the amount of sulfur emissions required to compensate for projected warming by 2050 would be between 5-16 TgS/year, increasing to 10-30 TgS/year by the end of the century.[44] However, several other studies have indicated that the amount of requisite injections might be considerably less.[45] Potential delivery vehicles for stratospheric sulfur dioxide injection include

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[36] "Albedo is the fraction of incident sunlight that is reflected." Albedo is measured on a 0-1 scale. If a surface absorbs all incoming sunlight, its albedo is 0; if it is perfectly reflecting, its albedo is 1. ARCTIC COASTAL ICE PROCESSES, *Albedo*, http://www.arcticice.org/albedo.htm (last visited Dec. 1, 2010).

[37] Albert C. Lin, *Balancing the Risks: Managing Technology and Dangerous Climate Change*, 8(3) ISSUES IN LEGAL SCHOLARSHIP, art. 2 (2009), at 4.

[38] M.I. BUDYKO, CLIMATIC CHANGES 243 (American Geophysical Union, trans., Waverly Press, Inc. 1977). "Sulfur dioxide in the stratosphere oxidizes via the reaction with the hydroxyl radical to sulfuric acid . . . The sulfuric acid gas forms together with water vapor sulfate particles . . . . In the presence of aerosols sulfuric acid gas may condense onto pre-existing aerosol particles." J. Feichter & T. Leisner, *Climate Engineering: A Critical Review of Approaches to Modify the Global Energy Balance*, 176 EUR. PHYSICAL J. 81, 86 (2009).

[39] Ben Kravitz et al., *Sulfuric Acid Deposition from Stratospheric Geoengineering with Sulfate Aerosols*, 114 J. GEOPHYSICAL RES., D14109 (2009), at 2.

[40] ERIC BICKEL & LEE LANE, AN ANALYSIS OF CLIMATE ENGINEERING AS A RESPONSE TO CLIMATE CHANGE 17 (Copenhagen Consensus Center 2009), *available at* http://fixtheclimate.com/fileadmin/templates/page/scripts/downloadpdf.php?file=/uploads/tx_templavoila/AP_Climate_Engineering_Bickel_Lane_v.5.0.pdf (last visited Nov. 19, 2010).

[41] David W. Keith, *Photophoretic Levitation of Engineered Aerosols for Geoengineering*, 108(38) PROC. NAT'L ACAD. SCI. 16428-16431 (2010).

[42] Rasch et al., *supra* note 2, at 4010.

[43] Richard A. Kerr, *Pollute the Planet for Climate's Sake?*, 314 SCI. 401, 401 (2006).

[44] A.V. Eliseev, I.I. Mokhov & A.A. Karpenko, *Global Warming Mitigation by Means of Controlled Aerosol Emissions into the Stratosphere: Global and Regional Peculiarities of Temperature Response as Estimated in IAP RAS CM Simulations*, 22(4) ATMOSPHERIC & OCEANIC OPTICS 388, 390 (2009). 1 Tg = 10^{12} grams, or one million metric tons. Simone Tilmes, Rolf Müller & Ross Salawitch, *The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes*, 320 SCI. 1201, 1202 (2008).

[45] Paul J. Crutzen, *Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?*, 77 CLIMATIC CHANGE 211, 213 (2006) (stratospheric loading of 1-2 TgS/year required); Wigley, *supra* note 14 (peak load of 5 TgS/year required between 2050 and 2060, declining back to zero by

aircraft, artillery shells, stratospheric balloons, and hoses suspended from towers.[46]

Supporters of stratospheric aerosol injection tout the fact that it could prove to be an extremely cheap option, perhaps costing only a few billion dollars annually.[47] This is at least a hundred times less than the projected costs for emissions cuts.[48] However, serious questions exist both in terms of the potential effectiveness of injection schemes and potentially disastrous side effects.

In moving beyond the results derived from models, many uncertainties exist in terms of how an artificial sulfate layer would operate in the stratosphere. It is unclear if nozzles and injection strategies can be designed that will produce clouds with droplet sizes that would be effective for scattering sunlight.[49] Other potential problems associated with this option include accurately calculating the residence time of aerosols at twenty kilometers, meteorological dynamics, and photodissociation of sulfuric acid in the stratosphere.[50]

2.1.2 Potential Adverse Impacts

2.1.2.1 Potential Precipitation Impacts

Sulfur injection could also have serious ramifications globally and regionally. Injection schemes that seek to block the sun would almost invariably reduce global rainfall because evaporation is approximately twice as sensitive to sunlight as temperature.[51] The consequent reductions in evaporation could substantially weaken Asian and African monsoons,[52] "threatening the food and water supplies of billions of people."[53] The Mt. Pinatubo eruption in 1991 provides empirical evidence for this threat.

2090).

[46] Alan Robock et al., *Benefits, Risks and Costs of Stratospheric Geoengineering*, 36 GEOPHYSICAL RES. LETTERS L19703 (2009), at 4-7.

[47] Scott Barrett, *The Incredible of Economics of Geoengineering*, 39 ENVTL. RES. ECON. 45, 49 (2008); Robock et al., *supra* note 46, at 1-9. However, it should be emphasized that the costs of monitoring systems would likely substantially increase the cost of deploying such systems. Caldeira & Keith, *supra* note12, at 60.

[48] David Keith, Edward Parson & M. Granger Morgan, *Research on Global Sun Block Needed Now*, 463 NATURE 426, 426 (2010); Charles Eccleston, *Can Geo-engineering Reverse Climate Change?*, ENVTL. QUALITY MGMT. 21, 26 (Winter 2009). However, the costs associated with monitoring, including the deployment of satellite, atmosphere, and ground-based systems would substantially increase costs. Caldeira & Keith, *supra* note 12, at 60.

[49] Geoengineering: Assessing the Implications Large-Scale of Climate Intervention, H. Comm. on Science and Tech., 11th Cong. 8 (2009) (Testimony of Alan Robock) http://democrats.science.house.gov/Media/file/Commdocs/hearings/2009/Full/5nov/Robock_Testimony.pdf (last visited Nov. 20, 2010) [hereinafter Robock Testimony].

[50] A.F. Tuck, et al., *On Geoengineering with Sulphate Aerosols in the Tropical Upper Troposphere and Lower Stratosphere*, 90 CLIMATIC CHANGE 315, 328 (2008).

[51] Robert B. Jackson & James Salzman, *Pursuing Geoengineering for Atmospheric Restoration*, ISSUES SCI. & TECH. 67, 70 (Summer 2010).

[52] Robock Testimony, *supra* note 49, at 9; Victor Brovkin, et al., *Geoengineering Climate by Stratospheric Sulfur Injections: Earth System Vulnerability to Technological Failure*, 92 CLIMATIC CHANGE 243, 252 (2009).

[53] Alan Robock, Luke Oman & Georgiy L. Stenichov, *Regional Climate Responses to Geoengineering with Tropical and Arctic SO_2 Injections*, 113 J. GEOPHYSICAL RES., D16101 (2008), at 13; *Testing Times for Geoengineering*, ENVIRONMENTAL RESEARCH WEB (Feb. 8, 2010), http://environmentalresearchweb.org/cws/article/opinion/41651 (last visited Nov. 22, 2010). Sulfur dioxide injection could result in approximately a 10% decline in global precipitation relative to the mean value for 2000-2010, with the greatest declines in the tropics and Southern Hemisphere storm tracks. Eliseev, et al., *supra* note 44, at 78. Precipitation declines in the

The year following the eruption saw the lowest amount of global rainfall on record, a striking 50% lower than the previous low of any year,[54] triggering a drought in Southeast Asia.[55] The flow rates of the Ganges and Amazon Rivers were also the lowest on record in the year following the eruption.[56]

2.1.2.2 Potential Impacts on the Ozone Layer

Anthropogenic ozone depleting substances, primarily chlorofluorocarbons, may ultimately result in a 7% reduction in the stratospheric ozone layer within sixty years.[57] In the United States alone, this may translate into 60 million additional cases of skin cancer, resulting in one million deaths.[58] Depletion of the ozone layer also is associated with cataracts, as well as potential adverse impacts on marine ecosystems, agricultural production, forest productivity, and biogeochemical cycles.[59]

The Montreal Protocol on Substances that Deplete the Ozone Layer,[60] designed to ultimately phase out most ozone depleting substances, could effectuate the recovery of the Antarctic ozone layer by 2050.[61] However, there is substantial concern that injection of sulfur particles into the stratosphere could imperil recovery of the ozone layer by catalyzing chemical reactions that deplete ozone.[62] Recent studies indicate that geoengineering schemes that would enhance aerosol loads in the stratosphere could result in global annual mean decreases of the ozone column of 4.5%, more than the annual global mean decreases associated with ozone depleted substances in the early part of this century.[63] This could delay recovery of the ozone layer in the Antarctic by between thirty and seventy years.[64]

However, adverse impacts in this context are by no means certain to transpire. Some researchers believe that damage to the ozone layer associated with sulfur dioxide

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Amazon and Congo valleys associated with sulfur injection could result in a dieback of tropical forests, decreasing carbon uptake from the atmosphere, triggering additional warming that would place additional stress on ecosystems in these regions. *Id.* at 79.

[54] Kevin Bullis, *The Geoengineering Gambit*, TECH. REV., Jan./Feb. 2010, at 53, *available at* http://www.technologyreview.com/energy/24157/. *See also* Gabriele C. Hegerl & Susan Solomon, *Risks of Climate Engineering*, 325 SCI. 955, 955-56 (2009).

[55] Brovkin, *supra* note 52, at 255.

[56] Caldeira & Keith, *supra* note 12, at 61. *See also* Kevin E. Trenberth & Aiguo Dai, *Effects of Mount Pinatubo Volcanic Eruption on the Hydrological Cycle*, 34 GEOPHYSICAL RES. LETTERS L15702 1 (2007).

[57] *Ozone Depletion*, CLIMATE INSTITUTE, http://www.climate.org/topics/ozone-depletion.html (last visited Nov. 27, 2010).

[58] *Ozone Depletion – Effects*, ORACLE EDUCATION FOUNDATION, http://library.thinkquest.org/26026/Environmental_Problems/ozone_depletion.html (last visited Nov. 27, 2010).

[59] *Health and Environmental Effects of Ozone Layer Depletion*, U.S. ENVIRONMENTAL PROTECTION AGENCY, http://www.epa.gov/ozone/science/effects/index.html (last visited Nov. 27, 2010).

[60] Montreal Protocol on Substances that Deplete the Ozone Layer, Sept. 16, 1987, 26 I.L.M. 1541 (1987).

[61] CLIMATE INSTITUTE, *supra* note 57.

[62] Cold liquid sulfate aerosols in the stratosphere provide surfaces that facilitate efficient chlorine activation from anthropogenic halogens, the cause of severe ozone loss in the Arctic and Antarctic. Tilmes et al., *supra* note 44, at 1201. Additionally, cooling of the surface and troposphere associated with aerosol loading would result in warmer temperatures in the tropic lower stratosphere, resulting in an increase in the temperature gradient between the tropics and polar regions. This would strengthen the polar vortex and make it colder, accelerating polar ozone depletion. Rasch, *supra* note 2, at 4027.

[63] P. Heckendorn et al., *The Impact of Geoengineering Aerosols on Stratospheric Temperature and Ozone*, 4 ENVTL. RES. LETTERS 1, 7 (2009).

[64] Tilmes et al., *supra* note 44, at 1203; ROYAL SOC'Y, *supra* note 16, at 31.1

injection would be "modest."[65] Other researchers contend that sulfate aerosols could increase light extinction and attenuation, compensating for diminution of the ozone layer, or even resulting in a net decrease in UV-B impacts.[66]

2.1.2.3 Potential Increase in Tropospheric Sulfate Pollution

As indicated above, sulfur injection schemes could require emissions of between 5 and 30 TgS/year during this century.[67] The requisite emissions in the middle of the century could be 10 TgS/year, which could cause sulfate emissions in the troposphere to increase by about 14% from its current levels.[68] This could have serious health implications given the fact that sulfate particle pollution is responsible for over 500,000 premature deaths annually.[69] Moreover, the "wash-out" from the stratosphere of sulfate particles is likely to be concentrated in the polar regions, potentially threatening ecosystems and livelihoods in these regions.[70] On the other hand, some researchers, including Paul J. Crutzen, have argued that the requisite amount of sulfur emissions that would need to be released in a geoengineering scheme would be far less, translating into only 2-4% of current annual anthropogenic emissions.[71]

2.2 Cloud Albedo Enhancement

2.2.1 Overview and Potential Effectiveness

Low-level marine stratiform clouds cover approximately one quarter of the oceanic surface and possess albedos[72] of 0.3-0.7, thus exerting a substantial cooling effect on the Earth's radiative balance.[73] Cloud albedo enhancement geoengineering schemes contemplate dispersing seawater (NaCl) droplets approximately one micrometer in size in marine stratiform clouds. These droplets would be sufficiently large to act as cloud condensation nuclei[74] "when they rise into the bases of stratiform clouds" and shrink through evaporation to about half their original size.[75] According to the seminal work of S. Twomey, increases in cloud condensation nuclei increases cloud droplet numbers and decreases cloud droplet size.[76] This enhances overall droplet surface area and results in

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[65] Barrett, *supra* note 47, at 48.

[66] Rasch et al., *supra* note 2, at 4031-32; Caldeira & Wood, *supra* note 14, at 4050.

[67] Eliseev et al., *supra* note 44, at 390.

[68] *Id.*

[69] Crutzen, *supra* note 45, at 211.

[70] John Virgoe, *International Governance of a Possible Geoengineering Intervention to Combat Climate Change*, 95 CLIMATIC CHANGE 103, 108 (2009).

[71] Crutzen, *supra* note 45, at 213.

[72] *See supra* note 36 for an explanation of albedo.

[73] John Latham et al., *Global Temperature Stabilization via Controlled Albedo Enhancement of Low-Level Maritime Clouds*, 366 PHIL. TRANSACTIONS ROYAL SOC'Y 3969, 3970 (2008).

[74] "Cloud condensation nuclei (CCN) are a subset of the atmospheric aerosol population, which undergo rapid growth into cloud droplets at a specified supersaturation." Gregory C. Roberts et al., *Cloud Condensation Nuclei in the Amazon Basin: 'Marine' Conditions Over a Continent?*, 28(14) GEOPHYSICAL RES. LETTERS 2807, 2807 (2001).

[75] Keith Bower et al., *Computations Assessment of a Proposed Technique for Global Warming Mitigation via Albedo-Enhancement of Marine Stratocumulus Clouds*, 82(1-2) ATMOSPHERIC RES. 328, 329 (2006).

[76] R.D. Borys, D.H. Lowenthal & M.A. Wetzel, *Chemical and Microphysical Properties of Marine Stratiform Cloud*, 103 J. GEOPHYSICAL RES. ATMOSPHERES, No. D17 (1998), at 22,073.

an increase in cloud albedo.[77] Moreover, it can extend the longevity of clouds, increasing the time-mean albedo of a region.[78]

Studies indicate that a 50-100% increase in droplet concentration of all marine stratiform clouds by mechanical generation of sea salt spray could increase top-of-cloud albedo by 0.02 (approximately 10%), which could offset warming associated with a doubling of atmospheric carbon dioxide.[79] Stephen Salter and others have proposed the development of a fleet of approximately 1,500 remotely controlled spray vessels, drawing upon the motion from the vessels to drive underwater propellers to generate the energy for spray production.[80] As is the case with sulfur dioxide injection schemes, the cost of this approach could be extremely low, perhaps no more than $2 billion.[81] One commentator concluded that this expenditure could provide benefits of up to $20 trillion in terms of avoided damages associated with climate change.[82]

However, there are many uncertainties associated with this technology that leave its viability in question.[83] Some recent numerical simulations revealed that increasing cloud condensation nuclei might not increase surface albedo, or could even decrease it.[84] Moreover, the addition of cloud condensation nuclei would suppress the growth of large cloud droplets that fall out of the cloud as precipitation. This could increase the intensity of circulation in the upper part of the boundary layer, which in turn could draw in dry air from above that would increase evaporation. As a consequence, clouds might be thinned and disrupted, degrading their albedo.[85]

Also, we currently do not have spray generators capable of generating the necessary quantity and size of droplets to achieve the requisite whitening of clouds, and serious issues remain in developing methods for sea water filtration and spray generation.[86] Moreover, T.M. Lenton and N.E. Vaughan recently concluded that the requisite top-of-cloud albedo needed to offset the warming associated with a doubling of

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[77] Bower et al., *supra* note 75, at 329.

[78] Andy Jones, John Latham & Michael H. Smith, *Radiative Forcing Due to Modification of Marine Stratocumulus Clouds*, NATIONAL CENTER FOR ATMOSPHERIC RESEARCH, http://www.mmm.ucar.edu/people/latham/files/cloud_albedo_gcm_modelling_paper.pdf (last visited Dec. 6, 2010), at 1.

[79] Lenton & Vaughan, *supra* note 19, at 5548; Philip Rasch, Chih-Chieh (Jack) Chen & John Latham, *Global Temperature Stabilisation via Cloud Albedo Enhancement: Geoengineering Options to Respond to Climate Change*, RESPONSE TO NATIONAL ACADEMY CALL, http://americasclimatechoices.org/Geoengineering_Input/attachments/LathamNationalAcademyGeoengineering090615.pdf (last visited Dec. 11, 2010). *See also* John Latham, *Amelioration of Global Warming by Controlled Enhancement of the Albedo and Longevity of Low-Level Maritime Clouds*, ATMOSPHERIC SCI. LETTERS (2002), at 2, *available at* http://www.mmm.ucar.edu/people/latham/files/Latham%20Atmospheric%20Sciences%20%282002%29.pdf.

[80] Stephen Salter, Graham Sortino & John Latham, *Sea-Going Hardware for the Cloud Albedo Method of Reversing Global Warming*, 366 PHIL. TRANSACTIONS ROYAL SOC'Y 3989, 3994 & 4004 (2008).

[81] Oliver Morton, *Great White Hope*, 458 NATURE 1097, 1099 (2009).

[82] Bjorn Lomborg, *Climate Engineering: It's Cheap and Effective*, THE GLOBE AND MAIL (Aug. 14, 2009), http://www.theglobeandmail.com/news/opinions/climate-engineering-its-cheap-and-effective/article1252644/.

[83] H. Wang, P.J. Rasch, G. Feingold, *Manipulating Marine Stratocumulus Cloud Amount and Albedo: a Process-modeling Study of Aerosol-cloud-precipitation Interactions in Response to Injection of Cloud Condensation Nuclei*, 11 ATMOSP. CHEM. PHYS. DISCUSSION 885-916 (2011).

[84] Philip J. Rasch, John Latham & Chih-Chieh (Jack) Chen, *Geoengineering by Cloud Seeding: Influence on Sea Ice and Climate System*, 4 ENVTL. RES. LETTERS 045112 (2009), at 2.

[85] Morton, *supra* note 81, at 1099.

[86] The Royal Soc'y, *supra* note 16, at 28.

carbon dioxide levels from pre-industrial levels would be markedly greater than estimated in previous studies.[87] This could potentially make this option technologically impossible to achieve if the proportion of added aerosols to new cloud condensation nuclei falls below a critical threshold.[88]

2.2.2 Potential Adverse Impacts

While cloud albedo enhancement would have insignificant impacts on precipitation over most land areas, there may be several significant exceptions.[89] Sub-Saharan Africa and eastern Australia, areas of extremely low precipitation, could benefit from precipitation increases of 0.2-0.6 mm day^{-1} (a 10-30% increase) compared to the A1B scenario[90] of the Intergovernmental Panel on Climate Change.[91] However, cloud enhancement could also potentially "help turn the Amazon rainforest into a desert" by cooling the South Atlantic and reducing evaporation from the ocean.[92] The Amazonia and Nordeste regions of South America could see declines of precipitation of more than 50% in some places.[93] Moreover, net primary productivity in the north of South America could be reduced by 50-100% in some areas.[94]

However, a more recent study questions these conclusions. G. Bala and others contend that a cloud albedo enhancement scheme could result in fairly substantial declines in precipitation over oceans, but only 0.23% over land.[95] Moreover, the study concluded that runoff over land with smaller marine cloud droplets would actually increase, leading to a moistening of soils.[96] This could have significant implications for projections of productivity impacts.

2.3 Space-Based Systems

2.3.1.Overview and Potential Effectiveness

Space-based methods seek to reduce the amount of solar radiation reaching the Earth by positioning sun-shields in space to reflect or deflect radiation. As is true with several other SRM options, it may be possible to reduce solar radiation inflows by 1.8%, offsetting greenhouse effects associated with a doubling of atmospheric carbon dioxide

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[87] Lenton & Vaughan, *supra* note 19, at 5548.

[88] *Id.*

[89] Andy Jones, Jim Haywood & Olivier Boucher, *Climate Impacts of Geoengineering Marine Stratocumulus Clouds*, 114 J. GEOPHYSICAL RES., D10106 (2009), at 5.

[90] For a description of IPCC scenarios, see Intergovernmental Panel on Climate Change, *IPCC, Working Group I: The Scientific Basis*, http://www.ipcc.ch/ipccreports/tar/wg1/029.htm#storya1 (last visited Dec. 12, 2010).

[91] *Id.* at 5. Northern India, another area of low precipitation, could see even larger increases of up to 0.8 mm day^{-1}. *Id.*

[92] Mims, *supra* note 14.

[93] Jones et al., supra note 74, at 5.

[94] *Id.*

[95] G. Bala et al., *Albedo Enhancement of Marine Clouds to Counteract Global Warming: Impacts on the Hydrological Cycle*, 6 CLIMATE DYNAMICS (2010), published online first, June 10, 2010, http://www.springerlink.com/content/95691724151 50486/fulltext.pdf, site visited on Dec. 11, 2010.

[96] *Id.* at 7.

concentrations.[97] Several proposals involve placing reflectors in near-Earth orbits, including placement of 55,000 mirrors in random orbits, or the creation of a ring of dust particles guided by satellites at altitudes of approximately 1,200 to 2,400 miles.[98] An alternative approach could be to establish a "cloud of spacecraft" with reflectors in a stationary orbit near the Inner Lagrange point (L1),[99] a gravitationally stable point between Earth and the sun.[100] Proponents argue that this approach would ensure stability of sunshades, whereas shields positioned in near-orbit could be pushed out of orbit by sunlight.[101]

Supporters of space-based schemes tout these technologies on several grounds. First, it is argued that while it would take decades to deploy such systems, atmospheric temperatures would respond within a few years after they were in place.[102] Moreover, some proponents contend that the potential side effects would be less significant and more predictable than alternative geoengineering options.[103] Finally, space-based systems could be the optimal approach if the world community feels "the need to construct systems that would deflect sunlight for many centuries."[104]

However, deployment of space-based systems could prove extremely challenging. As indicated earlier, some configurations of sunshades could prove unstable and thus ultimately sail out of orbit.[105] Low Earth orbit systems could also face tracking problems, posing the threat that mirrors could collide.[106] Space-based systems would also present imposing logistical challenges. Estimates of the number of flyers that would need to be produced range from 5 to 16 trillion.[107] This would require an "unprecedented" scale of production,[108] and could "take a century to produce."[109]

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[97] Takanobu Kosugi, *Role of Sunshades in Space as a Climate Control Option*, 67 ACTA ASTRONAUTICA 241, 242 (2010).

[98] ROYAL SOC'Y, *supra* note 16, at 32.1

[99] Roger Angel, *Feasibility of Cooling the Earth with a Cloud of Small Spacecraft Near the Inner Lagrange Point (L1)*, 103(46) PROC. NAT'L ACAD. SCI. 17184, 17184 (2006).

[100] Katharine Ricke et al., *Unilateral Engineering*, Non-technical Briefing Notes for a Workshop at the Council on Foreign Relations Washington, D.C., May 5, 2008, at 6, http://d1027732.mydomainwebhost.com/articles/articles/cfr_geoengineering.pdf (last visited on Dec. 17, 2010). The Lagrange L1 point is about 900,000 miles from the Earth. ROYAL SOC'Y, *supra* note 16, at 32. The plan, developed by Roger Angel at the University of Arizona, contemplates the production of silicon discs about 60 centimeters across and a few micrometers thick; the discs would be studded with holes that would scatter incoming light. David L. Chandler, *Global Shades*, NEW SCI., July 21, 2007, at 44.

[101] David W. Keith, *Geoengineering the Climate: History and Prospect*, 25 ANN. REV. ENERGY ENV'T 245, 263 (2000).

[102] ROYAL SOC'Y, *supra* note1, at 32.

[103] Keith, *supra* note 101, at 263.

[104] Caldeira & Keith, *supra* note 12, at 60.

[105] Keith, *supra* note 101, at 263.

[106] Govindasamy, Caldeira & Duffy, *supra* note 15, at 167.

[107] Oliver Morton, *Is This What It Takes to Save the World?*, 447 NATURE 132, 136 (2007); Bickel & Lane, *supra* note 40, at 48.

[108] Bickel & Lane, *supra* note 40, at 48. *See also* C.R. McInnes, *Space-Based Geoengineering: Challenges and Requirements*, 224 PROC. OF THE INSTITUTION OF MECHANICAL ENGINEERS, PART C: J. MECHANICAL ENGINEERING & SCI., Special Issue Paper 571, 578-579 (2009). The deployment of these schemes would also be imposing. For example, the "cloud of spacecraft" approach would require the use of twenty electromagnetic rail guns, an untested propulsion method, "working round the clock and launching one bundle of discs every 5 minutes for 10 years." Chandler, *supra* note 100, at 44.

[109] Morton, *supra* note 107, at 136.

Moreover, deflectors "would have to be replaced at the end of their useful lives."[110] The cost of deployment would also be extremely high, pegged at approximately $5 trillion by one major proponent;[111] some commentators believe this is far too conservative,[112] while others have contended that modification could reduce the mass of shields, thus substantially reducing the costs of deployment.[113] Nevertheless, some studies have emphasized that the scheme could prove to be highly cost effective compared to the reference case of projected climate change damages without deployment.[114]

2.3.2. Potential Negative Impacts

As is the case with other SRM approaches, sunshade schemes would likely lead to precipitation declines, with a 5% decrease in the tropics due to cooling that leads to a less evaporative tropical ocean surface.[115] However, one recent study found that the lowered surface temperature associated with the deployment of sunshades would translate into a small increase in soil moisture. As a consequence, it was concluded the tropics would not likely experience a decline in agricultural production.[116] Sunshades might also lead to increased precipitation "north of the equator in the Atlantic and eastern Pacific."[117] There might also be ecosystem implications from altering "atmospheric CO_2 content and photosynthetically active radiation."[118]

Moreover, it would be impossible to collect and remove trillions of flyers potentially spread over 60,000 miles or more in space when they reached obsolescence. This debris that could interfere with Earth-orbiting spacecraft.[119] The failure of rockets, or collisions, could also produce huge orbital debris clouds that would circle the Earth.[120]

3. SRM OPTIONS AND THE TERMINATION EFFECT

Beyond the concerns outlined above about specific SRM options, all of these options could sow the seeds of major peril for future generations. Imagine a scenario in which a single nation,[121] or group of nations, deploys an SRM scheme and it proves

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[110] Lin, *supra* note 37, at 5.

[111] Angel, *supra* note 99, at 17,189.

[112] Bickel & Lane, *supra* note 37, at 48.

[113] E. Teller, L. Wood & R. Hyde, *Global Warming and Ice Ages: I. Prospects for Physics Based Modulation of Global Change* 20, UNIV. OF CAL. LAWRENCE LIVERMORE NAT'L LABORATORY (Aug. 15, 1997), *available at* http://www.chemtrails911.com/docs/scatteringEdTellerwithnotes.pdf.

[114] Kosugi, *supra* note 97, at 245-247.

[115] D.J. Lunt et al., *'Sunshade World': A Fully Coupled GCM Evaluation of the Climatic Impacts of Geoengineering*, 35 GEOPHYSICAL RES. LETTERS L12710, at 4 (2008); *See also* Feichter & Leisner, *supra* note 38, at 86 ("Lower precipitation is simulated particularly over the continents at mid- and low latitude.").

[116] Lunt, *supra* note 109, at 4.

[117] *Id.*

[118] Govindasamy, Caldeira & Duffy, *supra* note 15, at 167.

[119] Angel, *supra* note 94, at 17,188-89.

[120] Dan Vergano, *Can Geoengineering Put the Freeze on Global Warming?*, USA Today, Feb. 25, 2011, http://www.usatoday.com/tech/science/environment/2011-02-25-geoengineering25_CV_N.htm, (last visited May 16, 2011)

[121] The cost of many geoengineering options might be "well within the budget of almost all nations," as well as a handful of wealthy individuals. Ricke, *supra* note 100, at 4.

successful in abating temperature increases and other phenomena associated with climate change. Many analysts believe successful deployment of geoengineering technologies would severely undermine development of effective mitigation responses to climate change. As The Royal Society concluded:

> The very discussion of geoengineering is controversial in some quarters because of a concern that it may weaken conventional mitigation efforts, or be seen as a 'get out of jail free' card by policy makers . . . . This is referred to as the 'moral hazard' argument, a term derived from insurance, and arises where a newly-insured party is more inclined to take risky behavior than previously because compensation is available. In the context of geoengineering, the risk is that major efforts in geoengineering may lead to a reduction of effort in mitigation and/or adaptation because of a premature conviction that geoengineering has provided 'insurance' against climate change.[122]

Beyond empirical evidence of moral hazards in the context of insurance,[123] there is ample cause for concern that deployment of geoengineering technology could seriously undermine society's commitment to reducing greenhouse gas emissions and ultimately decarbonizing the world's economy. This is true for several reasons. First, while accurate cost assessments of geoengineering technologies are difficult at this protean stage, several studies have indicated that some SRM options could cost as little as "one percent (or less) of the cost of dramatically cutting emissions,"[124] exerting a potentially very powerful pull away from mitigation initiatives. Moreover, because geoengineering options "leave[] powerful actors and their interests relatively intact,"[125] they are likely to be backed by influential constituencies going forward. Indeed, there are growing advocacy initiatives for geoengineering by think tanks funded by fossil fuel interests.[126] Finally, there would likely be substantial public support for geoengineering options because they would not require fundamental changes in lifestyles.[127]

Unfortunately, while a commitment to SRM geoengineering approaches in lieu of effective mitigation responses might prove effective and politically palatable for our generation, future generations may not feel the same way. Such a strategy would create a Sword of Damocles for Earth's future inhabitants, with the potential climatic impacts of very high atmospheric concentrations of greenhouse gases masked only by the ongoing

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[122] ROYAL SOC'Y, *supra* note 1, at 37. *See also* Keith, *supra* note 104, at 276.

[123] Dianne Dumanoski, *Resisting the Dangerous Allure of Global Warming Technofixes*, YALE ENV'T 360 (Dec. 17, 2009), http://e360.yale.edu/feature/the_dangerous_allure_of_global_warming_technofixes/2224/ (last visited Sept. 30, 2010). *See also* Howard Kunreuther, *Disaster Mitigation and Insurance: Learning from Katrina*, 604 ANNALS AM. ACAD. POL. & SOC. SCI. 208 (2006).

[124] David W. Keith et al., *Research on Global Sun Block Needed Now*, 463 NATURE 426, 426 (2010); David G. Victor, et al., *The Geoengineering Option: A Last Resort Against Global Warming?*, 88(2) FOREIGN AFF. 64, 69 (2009); Graeme Wood, *Re-Engineering the Earth*, THE ATLANTIC (July/Aug. 2009), http://www.theatlantic.com/magazine/archive/2009/07/re-engineering-the-earth/7552/.

[125] Jay Michaelson, *Geoengineering: A Climate Change Manhattan Project*, 17 STAN. ENVTL. L.J. 73, 113 (1998).

[126] Alan Robock, *Geoengineering Shouldn't Distract from Investing in Emissions Reduction*, BULLETIN OF THE ATOMIC SCIENTISTS (May 29, 2008), http://www.thebulletin.org/web-edition/roundtables/has-the-time-come-geoengineering (last visited Oct. 7, 2010). *See also* Bjønar Egede-Nissen & Henry David Venema, *Desperate Times, Desperate Measures: Advancing the Geoengineering Debate at the Arctic Council*, International Institute for Sustainable Development, 9-10 (Aug. 2009), http://www.iisd.org/pdf/2009/desperate_times_desperate measures.pdf (last visited Oct. 10, 2010).

[127] Virgoe, *supra* note 70, at 107; Michaelson, *supra* note 125, at 113.

use of SRM technology. This is termed the "termination effect."[128]

Should the use of SRM technology cease in the future, the implications of the termination effect could be "catastrophic."[129] As one study recently concluded:

> [S]hould the engineered system later fail for technical or policy reasons, the downside is dramatic. The climate suppression has been only temporary, and . . . the now CO_2-loaded atmosphere quickly bites back, leading to severe and rapid climate change with rates up to 20 times the current rate of warming of ≈0.2°C per decade . . . .[130]

As a consequence, temperatures could increase 6-10°C in the winter in the Arctic region *within 30 years of termination of the use of SRM technology*, with northern landmasses seeing increases of 6°C in summer.[131] Moreover, temperatures could jump 7°C in the tropics in 30 years.[132] Projected temperature increases after termination would occur more rapidly than during one of the most extreme and abrupt global warming events in history, the Paleocene-Eocene Thermal Maximum.[133] It is beyond contention that climatic changes of this magnitude "would trigger unimaginable ecological effects"[134] and also imperils many human institutions.[135]

A compelling case can be made that the specter of the termination effect would contravene the international legal principle of intergenerational equity. Intergenerational equity is a principle of distributive justice[136] that calls for "fairness in the utilization of resources between human generations past, present and future."[137] It is ultimately grounded in the premise that human survival is a salutary goal, and the correlated moral obligations to support human continuity by sound stewardship of the resources essential for life, as well as to ensure the dignity and well-being of Earth's inhabitants.[138] As

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[128] *The Regulation of Geoengineering*, United Kingdom, House of Commons, Science and Technology Committee, 2009-10 Session Fifth Report, HC 221 at 14 (Mar. 18, 2010), *available at* http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/221/221.pdf.

[129] B. Govindasamy, et al., *Impact of Geoengineering Schemes on the Terrestrial Biosphere*, 29(22) GEOPHYSICAL RES. LETTERS 18-1, 18-4 (2002).

[130] Peter G. Brewer, *Evaluating a Technological Fix for Climate*, 104(24) PROC. NAT'L ACAD. SCI. 9915, 9915 (2007). *See also* Arnold van Vliet & Rik Leemans, *Rapid Species' Response to Changes in Climate Require Stringent Climate Protection Targets, in* AVOIDING DANGEROUS CLIMATE CHANGE, 135-141 (Hans Joachim Schellnhuber et al. eds., 2006) (To put this rate of temperature increase in perspective, a recent study concluded that even a warming rate of greater than 0.1°C per decade could threaten most major ecosystems and decrease their ability to adapt); Rik Leemans & Bas Eickhout, *Another Reason for Concern: Regional and Global Impacts on Ecosystems for Different Levels of Climate Change*, 14 GLOBAL ENVTL. CHANGE 219, 226 (2004) (Should temperatures increase at a rate of 0.3°C per decade, only 30% of all impacted ecosystems and only 17% of all impacted forests would be able to adapt.); J.C. Moore, S. Jevrejeva & A. Grinstad, *Efficacy of Geoengineering to Limit 21st Century Sea-Level Rise*, 107(36) PROC. NAT'L ACAD. SCI. 15699, 15702 (2010).

[131] Brovkin, *supra* note 48, at 254.

[132] Eli Kintisch, *Scientists Say Continued Warming Warrants Closer Look at Drastic Fixes*, 318 SCI. 1054, 1055 (2007).

[133] Brovkin, *supra* note 48, at 254.

[134] Kintisch, *supra* note 132, at 1055.

[135] *Id.*; Dumanoski, *supra* note 123.

[136] Brett M. Frischmann, *Some Thoughts on Shortsightedness and Intergenerational Equity*, 36 LOY. U. CHI. L.J. 457, 460 (2005). "Distributive justice is concerned with sharing the benefits and burdens of social cooperation." Lawrence B. Solum, *To Our Children's Children's Children: The Problems of Intergenerational Ethics*, 35 LOY. L.A. L. REV. 163, 174 (2001).

[137] G.F. Maggio, *Inter/intragenerational Equity: Current Applications under International Law for Promoting the Sustainable Development of Natural Resources*, 4 BUFF. ENVTL. L.J. 161, 163 (1997).

[138] Dinah Shelton, *Intergenerational Equity, in* SOLIDARITY: A STRUCTURAL PRINCIPLE OF INTERNATIONAL LAW 131 (Rüdiger Wolfrum & Chie Kojima eds., 2010); Edith Brown Weiss, *Climate*

such, it "demands that present generations should not create benefits for themselves in exchange for burdens on future generations."[139]

There are several rationales that can support an obligation of intergenerational equity. From a social contract perspective, we can view all generations as partners in an open-ended social contract which defines their rights, duties and obligations. As Burke contended, because society's objectives cannot be achieved in a single generation, it is imperative that each generation protect the interests of those to come.[140]

Another basis for imposing intergenerational obligations is grounded in the equitable notions that underpin the "original position" theory formulated by John Rawls. As Brown Weiss contends:

> In order to define what intergenerational equity then means, it is useful to view the human community as a partnership encompassing all generations, the purpose of which is to realize and protect the well-being of every generation and to conserve the planet for the use of all generations. Although all generations are members of this partnership, no generation knows in advance when it will be living, how many members it will have, nor even how many generations there will be.
>
> It is appropriate to adopt the perspective of a generation which is placed somewhere on the spectrum of time, but does not know in advance where . . . Such a generation would want to receive the planet in at least as good condition as every other generation receives it and to be able to use it for its own benefit. This requires that each generation pass on the planet in no worse condition than received and have equitable access to its resources.[141]

The notion of unjust enrichment is another rationale that has been advanced as a basis of duties toward future generations. Our generation is indebted to past generations for endowing us with the resources that ensure our well-being. In turn, it can be argued that we hold these resources in trust and have a responsibility to pass them on in no worse condition than we received them. To not do so would constitute a form of unjust enrichment.[142] Finally, intergenerational equity can be viewed as an extension of the public trust doctrine, mandating that this generation protect the interests of future generations in the Earth and its resources.[143]

The equitable considerations that support the principle of intergenerational equity mandate that "later generations [should] not be worse off than previous generations."[144] In the context of environmental resources, this includes both the form of

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Change, Intergenerational Equity and International Law: An Introductory Note, 15 CLIMATIC CHANGE 327, 330 (1989) ("Each generation is both a trustee and a beneficiary, or a custodian and user, of the planet").

[139] Marlos Goes, Klaus Keller & Nancy Tuana, *The Economics (or lack thereof) of Aerosol Engineering*, at 1, http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.144.446 (last visited Mar. 27, 2011).

[140] "[A]s the ends of such a partnership cannot be obtained in many generations, it becomes a partnership not only between those who are living but between those who are living, those who are dead, and those who are to be born." Edmund Burke, *Reflections on the Revolution in France (1790)*, *in* 2 WORKS OF EDMUND BURKE 130-40 (1854). *See also*, Robin Attfield, *Environmental Ethics and Intergenerational Equity*, 41(2) INQUIRY 207, 219 (1998).

[141] Edith Brown Weiss, *Climate Change, Intergenerational Equity and International Law: An Introductory Note*, 15 CLIMATIC CHANGE 330, 335 (1989).

[142] Shelton, *supra* note 138, at 132.

[143] E.B. Weiss, *Intergenerational Equity: A Legal Framework for Global Environmental Change*, *in* E.B. WEISS, ENVIRONMENTAL CHANGE AND INTERNATIONAL LAW 395 (1992); Donna R. Christie, *Marine Reserves, The Public Trust Doctrine and Intergenerational Equity*, 19 J. LAND USE 427, 434 (2004), http://www.law.fsu.edu/journals/landuse/vol19_2/1achristie.pdf (last visited Feb. 12, 2011).

[144] Edith Brown Weiss, *What Obligation Does Our Generation Owe to the Next? An Approach to Global*

resource stocks and the shape of environmental problems that current generations bestow on future generations.[145] More broadly, intergenerational equity also requires that future generations are accorded freedom of choice as to their political, economic and social systems.[146]

Edith Brown Weiss outlines three basic obligations of intergenerational equity:

> **Conservation of options.** "[E]ach generation should be required to conserve the diversity of the natural and cultural base, so that it does not unduly restrict the options available to future generations in solving their problems and satisfying their own values . . .";
> **Conservation of quality.** "[E]ach generation should be required to maintain the quality of the planet so that it is passed on in no worse condition than that in which it was received . . .";
> **Conservation of access.** "[E]ach generation should provide its members with equitable rights of access to the legacy of past generations and should conserve this access for future generations."[147]

These three categories of "Planetary Obligations" are further disarticulated into five duties of use: (i) the duty to conserve resources; (ii) the duty to ensure equitable use; (iii) the duty to avoid adverse impacts; (iv) the duty to prevent disasters, minimize damage, and provide emergency assistance; and (v) the duty to compensate for environmental harm.[148]

Intergenerational equity is a binding principle of international law with broad application.[149] Most pertinent in the context of climate change policy making, the United Nations Framework Convention on Climate Change,[150] which has 194 Parties,[151] incorporates the principle in Article 3(1), providing that "The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity . . ."[152] It can also be argued that intergenerational equity is a binding principle of customary international environmental law given its incorporation in a wide array of treaties,[153] domestic and international case law,[154] domestic law,[155] and soft

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Environmental Responsibility: Our Rights and Obligations to Future Generations for the Environment, 84 AM. J. INT'L L. 198, 200 (1990).

[145] Lars Osberg, *Meaning and Measurement in Intergenerational Equity* (1997), at 4, http://myweb.dal.ca/osberg/classification/book%20chapters/Meaning%20and%20Measurement%20in%20Intergenerational%20Equity/Meaning%20and%20Measurement%20in%20Intergenerational%20Equity.pdf (last visited Oct. 2, 2010).

[146] UNESCO, *Declaration on the Responsibilities of the Present Generations Towards Future Generations*, http://portal.unesco.org/en/ev.php-URL_ID=13178&URL_DO=DO_PRINTPAGE&URL_SECTION=201.html (last visited Oct. 3, 2010.

[147] Weiss, *supra* note 143, at 201-02.

[148] E. BROWN WEISS, IN FAIRNESS TO FUTURE GENERATIONS: INTERNATIONAL LAW, COMMON PATRIMONY, AND INTERGENERATIONAL EQUITY 51-60 (1989).

[149] Maggio, *supra* note 137, at 161.

[150] United Nations Framework Convention on Climate Change, May 9, 1992, 31 I.L.M. 849 (hereinafter UNFCCC).

[151] UNFCCC Secretariat, *Status of Ratification of the Convention*, http://unfccc.int/essential_background/convention/status_of_ratification/items/2631.php (last visited Oct. 3, 2010.

[152] UNFCCC, *supra* note 150, at art. 3(1).

[153] Convention on International Trade in Endangered Species of Wild Fauna and Flora, 12 I.L.M. 1086 (1973), pmbl.; Amazonian Co-operation Treaty, 17 I.L.M. 1045 (1978), pmbl.; Convention on Biological Diversity, 31 I.L.M. 818 (1992), pmbl, para. 23; Convention on the Conservation of Migratory Species of Wild Animals, 19 I.L.M. 15 (1980), pmbl.; Convention on the Conservation of European Wildlife and Natural Habitats, UKTS no. 56 (1982), cmnd. 8738, pmbl.; Convention on Access to Information, Public Participation

law instruments.[156] Moreover, the principle has been characterized as "a fundamental principle of sustainable development,"[157] a concept that many believe has now emerged as a principle of customary law.[158]

A future generation would face the grave implications of the termination effect if an SRM scheme failed, or as a consequence of unforeseen negative impacts that

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in Decision-Making, and Access to Justice in Environmental Matters (Aarhus, 25 June 1998), pmbl. *See also* North—East Atlantic Fisheries Commission, *Information on the Protection of Biodiversity and Mitigating Impact of Fisheries in the North East Atlantic* 2 (2010) ("Fishing communities and societies have the right to pursue their legitimate business of establishing economic development that meets the needs of the present generation without compromising the ability of future generations to meet their needs"). It should be noted, however, that the UNFCCC is the only treaty that includes intergenerational equity considerations in non-preambular provisions. Intergenerational equity principles are also incorporated into the first paragraph of the United Nations Charter ("We the peoples of the United Nations, determined to save future generations from the scourge of war), United Nations, The Charter of the United Nations, pmbl.

[154] *Denmark v. Norway*, 1993 ICJ 38, 274 (Separate Opinion of Judge Weeramantry); Minors Oposa v. Secretary of the Dept. of Environment and Natural Resources, 33 I.L.M. 173, 185 (1994); *Legality of the Threat or Use of Nuclear Weapons Case*, Advisory Opinion, [1996] I.C.J. Rep. 226, at 243-44; State of Himachal Pradesh and Others (Appellants) v. Ganesh Wood Products and Others (Respondents), AIR 1996 Supreme Court 149, 158 (1995), *available at* http://www.ecolex.org/server2.php/libcat/docs/COU/Full/En/COU-143787E.pdf (last visited Oct. 28, 2010).

[155] "The domestic Constitutions of twenty-two countries explicitly recognize the environmental interests of future generations." Lynda Collins, *Revisiting the Doctrine of Intergenerational Equity in Global Environmental Governance*, 30 DALHOUSIE L.J. 79, 136. For example: France ("in order to secure sustainable development, the choices made to meet the needs of the present should not jeopardize the ability of future generations and other peoples to meet their own needs," Article 2 Constitutional Amendment on the Environment Charter); Sweden ("public institutions shall promote sustainable development leading to a good environment for present and future generations," Article 2 Constitution of Sweden); Switzerland (Swiss people and cantons "conscious of their common achievements and their responsibility towards future generations," Preamble Constitution of Switzerland); Ukraine (Parliament "aware of our responsibility before God, our own conscience, past, present and future generations," Preamble to Constitution of Ukraine); Poland ("bequeath to future generations all that is valuable from our [...] heritage," Preamble to Constitution of Poland); South Africa (right of South African citizens "to have the environment protected, for the benefits of future and present generations," Article 24 Constitution of South Africa). *See also* J. C. Tremmel, *Establishing Intergenerational Justice in National Constitutions*, *in* HANDBOOK OF INTERGENERATIONAL JUSTICE 187-214 (J.C. Tremmel ed., 2006).

[156] *See* European Parliament, *The Charter of Fundamental Rights of the EU* (2000/C 364/01, 7 December 2000), para. 6, *available at* http://www.ec.europa.eu/justice_home/unit/charte/index_en.html (last visited Oct. 28, 2010); IUCN Draft International Covenant on Environment and Development, Environmental Policy & Law Paper No. 31 Rev. 2 (2004), at art. 5, *available at* http://www.i-c-e-l.org/english/EPLP31EN_rev2.pdf (last visited Oct. 4, 2010); UNEP, *Proposal for a Basic Law on Environmental Protection and the Promotion of Sustainable Development*, Document Series on Environmental Law No. 1, UNEP Regional Office for Latin America and the Caribbean, Mexico D.F. (1993); *Goa Guidelines on Intergenerational Equity adopted by the Advisory Committee to the United Nations University Project on International Law, Common Patrimony and Intergenerational Equity*, Feb. 15, 1988. *See also* United Nations Commission on Sustainable Development, *Report of the Expert Group Meeting on Identification of Principles of International Law for Sustainable Development, Geneva, Switzerland, 26-28 September 1995*, para. 38.

[157] OECD, *National Strategies for Sustainable Development: Good Practices in OECD Countries*, SG/SD(2005)6, para. 16, *reviewed in* UNDSD, *Expert Group Meeting on Reviewing National Sustainable Development Strategies New York* 10-11 (Oct. 2005). *See also* United Nations Conference on Environment and Development, Rio de Janeiro, Brazil, June 13, 1992, *Report of the United Nations Conference on Environment*, U.N. Doc. A/CONF.151/26 (vol. 1) (Aug. 12, 1992); U.N. Environment Programme, *Final Report of the Expert Group Workshop on International Environmental Law Aiming at Sustainable Development*, UNEP/IEL/WS/3/2 (1996) 13-14, para. 30, 44-45.

[158] P. SANDS, PRINCIPLES OF INTERNATIONAL ENVIRONMENTAL LAW 254-55 (2003); Hari M. Osofsky, *Defining Sustainable Development After Earth Summit 2002*, 26 LOYOLA L.A. INT'L & COMP. L. REV. 111, 112 (2003).

compelled suspension of its deployment.[159] This would contravene the second obligation of intergenerational equity outlined by Brown Weiss, conservation of quality, because the failure of our generation to substantially reduce its greenhouse gas emissions would result in greatly degraded planetary conditions for future generations under such a scenario.

Alternatively, even if a future generation was not compelled to forego or terminate deployment of an SRM scheme, it might deem it judicious to do so on policy or ethical grounds. For example, as indicated earlier in this article, atmospheric sulfur dioxide injection might result in adverse regional impacts on precipitation, undermining the interests of inhabitants in Asia and Africa.[160] Also, while another SRM scheme, marine cloud seeding, might substantially reduce incoming solar radiation, it could also result in sharp declines in precipitation in South America, including particularly serious impacts on the Amazon rain forest.[161]

While our generation might deem such "collateral effects" acceptable, a future generation might not, especially if regional impacts were exacerbated by other factors, such as rising populations or declines in food production attributable to other causes, or if affected States threatened war.[162] However, leaders might feel that their hands were tied given the potentially catastrophic global implications of suspending the use of SRM technologies. Indeed, some of the proponents of geoengineering strategies even tout the threat of the rebound effect as a way to ensure "policy continuity" in the future.[163] Placing a future generation on the horns of such a dilemma would violate the first obligation of intergenerational equity outlined by Brown Weiss, conservation of options, because it would severely circumscribe its ability to make policies that reflects its values and its options to address climate change.

It should also be emphasized that SRM technologies would have to be deployed for 500-1,000 years unless we can find a way to remove carbon dioxide from the atmosphere.[164] As a consequence, the intergenerational implications of SRM geoengineering would extend for a breathtaking period of time, threatening the interests of tens of billions of future inhabitants of this planet.

Proponents of SRM geoengineering might contend that a geoengineering governance regime could condition deployment of an SRM scheme on a scheduled reduction in greenhouse gas emissions to ensure that future generations would not face the threat of the termination effect. Unfortunately, this approach could prove problematic for several reasons. First, it is by no means clear that SRM geoengineering would be governed by any current international regime. For example, the UNFCCC,[165] the most

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[159] Andrew Ross & H. Damon Matthews, *Climate Engineering and the Risk of Rapid Climate Change*, 4 ENVTL. RES. LETTERS 045103, 6 (2009).

[160] *See supra* notes 89-95, 115-117 and accompanying text.

[161] G. Bala et al., *Albedo Enhancement of Marine Clouds to Counteract Global Warming: Impacts on the Hydrological Cycle*, 6 CLIMATE DYNAMICS, DOI 10.1007/s00382-010-0868-1, at 2 (2010), *available at* http://www.springerlink.com/content/956917241515 0486/fulltext.pdf; Jones, *supra* note 84, at 4.

[162] Bullis, *supra* note 50; Robock, *supra* note 46.

[163] Bickel & Lane, *supra* note 40, at 27.

[164] Brovkin, et al., *supra* note 52, at 255; Dumanoski, *supra* note 123.

[165] U.N. Conference on Environment and Development, *supra* note 3.

logical locus for international regulation of geoengineering, likely could not currently assert jurisdiction over SRM deployment. As provided for under Article 2, "[t]he ultimate objection of this Convention . . . is to achieve . . . *stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*."[166] Thus, the focus is on controlling atmospheric levels of greenhouse gases, whereas SRM approaches focus on reducing the amount of solar radiation incident on the surface of the Earth. This conclusion is reinforced by Article 4, which delimits the commitments of Parties under the UNFCCC to "measures to mitigate climate change *by addressing anthropogenic emissions by sources and removals by sinks* of all greenhouse gases not controlled by the Montreal Protocol . . . .[167] Thus, while the Parties to the UNFCCC arguably could assert jurisdiction over CDR schemes since they would enhance carbon dioxide sinks,[168] SRM schemes would fall outside the ambit of Article 4 because these technologies would neither enhance sinks or contribute to reduction of greenhouse gas emissions.[169] While the UNFCCC could potentially be amended to assert jurisdiction over SRM deployment, it is difficult to be sanguine about the prospects given the very high bar for passage of amendments to the treaty,[170] as well as the resistance of many of the States that would most likely develop geoengineering systems to accept binding international mandates to address climate change.[171]

Second, even if there was authority under the UNFCCC to condition deployment of SRM technology on a commitment to reduce greenhouse gas emissions, it is far from clear that the political will exists to operationalize such a mandate. As indicated in the introduction to this article, the very impetus for geoengineering has been the abject failure of the world's major greenhouse gas emitting States to curb their emissions.[172]

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[166] *Id.* at art. 2 (emphasis added).

[167] *Id.* at art. 4(1)(b) (emphasis added).

[168] Under the UNFCCC, a "sink" "means any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere." *Id.* at art. 1(8).

[169] *See also* Virgoe, *supra* note 66, at 109-110; U.N. Conference on Environment and Development, *supra* note 3, at art. 4(1)(f) (In support of this proposition it cites a provision of the treaty that requires the Parties to minimize "adverse effects on the economy, on public health and on the quality of the environment, of projects or measures undertaken by them to mitigate or adapt to climate change."); William R. Travis, *Geo-Engineering the Climate: An Emerging Technology Assessment*, 1 INSTITUTE OF BEHAVIORAL SCIENCE, ENVIRONMENT AND SOCIETY PROGRAM, Working Paper ES2008-0002 (2009), *available at* http://www.colorado.edu/ibs/pubs/eb/es2008-0002.pdf (last visited Oct. 14, 2010) (again rendering 4(1)(f) non-applicable); American Meteorological Society, *Proposals to Geoengineer Climate Require More Research, Cautious Consideration, and Appropriate Restrictions*, AMS NEWS (July 21, 2009), http://www.ametsoc.org/policy/2009geoengineeringclimate_amsstatement.html (last visited Oct. 14, 2010) (However, as indicated before, SRM technologies could not be construed as measures to "mitigate" climate change under the UNFCCC since Article 4 restricts such measures to those that address sources or sinks. Moreover, most commentators and policymakers draw a distinction between geoengineering responses and adaptation responses); ROYAL SOC'Y, *supra* note 16, at 41 (The Royal Society contends that any geoengineering scheme would be subject to UNFCCC jurisdiction).

[170] "The Parties shall make every effort to reach agreement on any proposed amendment to the Convention by consensus. If all efforts at consensus have been exhausted, and no agreement reached, the amendment shall as a last resort be adopted by a three-fourths majority vote of the Parties present and voting at the meeting." U.N. Conference on Environment and Development, *supra* note 3, at art. 15(3).

[171] For example, China, the United States, and India have not ratified the Kyoto Protocol nor committed themselves to binding long-term commitments. *Id.*

[172] *See supra* notes 4-9 and accompanying text.

This is despite the fact that there is nearly universal recognition by States of the serious impacts that climate change will visit upon nations throughout the world.[173] Despite this fact, the latest "International Energy Outlook" assessment by the U.S. Energy Information Administration projects that energy-related carbon dioxide emissions may rise 43% by 2035 from 2007 levels.[174] If the world community has not been willing to make a meaningful commitment to reduce emissions in the face of a looming threat of extremely serious climatic impacts, why would it do so merely because the threat of those impacts could be reduced by deployment of geoengineering technologies?[175]

CONCLUSION

As one commentator noted recently, geoengineering "has hubris written all over it."[176] Indeed, it seems paradoxical, and perhaps even a bit tragic, that society would now contemplate the deployment of technological options with potentially serious negative climatic side effects to respond to the impacts of technologies with serious negative climate impacts. The articles that follow in this issue discuss some of the critical ethical and moral dilemmas that the global community must grapple with in determining if geoengineering should have a role to play in long-term climate policy, and the role of legal institutions in this decision making process. While tremendous uncertainties abide in both the potential effectiveness and negative ramifications of geoengineering schemes, it is virtually certain that the debate will only intensify in the decades ahead.

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[173] *See* Copenhagen Accord, *supra* note 4, ¶ 1.

[174] U.S. Energy Information Administration, *International Energy Outlook 2010 – Highlights* (May 25, 2010), http://www.eia.doe.gov/oiaf/ieo/pdf/highlights.pdf.

[175] *See* Chuck Greene, Bruce Monger & Mark Huntley, *Geoengineering: The Inescapable Truth of Getting to 350*, 1(5) SOLUTIONS 57-66, (Oct. 5, 2010), *available at* http://www.thesolutionsjournal.com/node/771 ("First, given a rapidly growing global population and the desire of most developing nations to achieve an improved standard of living, society currently lacks the sense of urgency and political willpower necessary to alter its energy consumption habits in the short amount of time available.").

[176] Rachel Armstrong, *Geoengineering – A Project for the People*, E2 MAGAZINE (Nov. 28, 2010), http://earth2channel.com/magazine/article/19 (last visited Dec. 21, 2010).