

Nanotechnology Geoengineering
An Upstream Technology Assessment of Two Converging Technologies

A Plan B Paper

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1 ABSTRACT

Geoengineering, the large-scale and intentional manipulation of climate, is under consideration to counteract anthropogenic climate change by keeping the Earth's temperature from departing from the historically normal level. To reduce solar radiation incident upon the Earth's surface, sulfate aerosols could be injected into the stratosphere, increasing the atmosphere's albedo. Manufactured "designer" particles of 100 nm or less ("nanoparticles") have emerged recently as a potentially more benign alternative to sulfate aerosols. Geoengineering research papers and news stories show increasing references to nanotechnology, a field many scientists and authors see as offering certain tools which may be useful replacements or supplements to existing geoengineering techniques. No literature is currently available that truly explores the marriage of these two novel and rapidly developing fields, in what this paper calls *Nanotechnology Geoengineering* (NanoGeo).

This paper's goal is to explore the convergence of nanotechnology and geoengineering, examine societal issues pertaining to NanoGeo, and assess the relevance of existing international regulatory frameworks. This paper conducts the analysis by first looking at how references to the nanotechnology have emerged in geoengineering literature and media. Next, societal issues are explored as they pertain to economics, risk, and ethics. From there, existing international governance mechanisms are identified and examined, then judged based upon criteria to determine their applicability for NanoGeo. Finally, a determination is made on the adequacy of these existing mechanisms and what future steps for appropriate international governance of NanoGeo, if any, might be needed or advisable.

Economic issues likely encountered by NanoGeo are its low cost compared to GHG emission reductions and the unequal distribution of societal benefits and costs. Health risks likely to emerge include human ingestion, inhalation, and dermal contact. Additionally, environmental risks may include altered rainfall patterns, continued oceanic acidity increases, sudden ecological collapse in the event of NanoGeo failure or cessation, and other unknown, unintended consequences. Ethically, NanoGeo may present a moral hazard, thereby reducing the urgency of reducing GHG emissions. Additionally, NanoGeo presents a powerful dual-use technology, has distributive and procedural justice issues, fails to address the root cause of climate change, and may lead down a slippery slope of increasing and potentially unwarranted climate modification.

The world community is likely to look to international law to control this emerging technology. The Rio Declaration on the Environment and Development, the United Nations Framework Convention on Climate Change, the Convention on Long-range Transboundary Air Pollution (CLRTAP), and the Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques (ENMOD) were identified as pertaining to NanoGeo and judged based upon economic, risk, ethical, relevancy, effectiveness, and enforcement criteria.

From the analysis, it appears that CLRTAP and ENMOD are better suited to address the criteria than the other international mechanisms based on relevancy. However, CLRTAP and ENMOD do not score highly on all criteria, making them likely candidates for revisions or additional protocols for NanoGeo applicability. The possibility exists that ENMOD could be used to prohibit nefarious use of NanoGeo, while a CLRTAP protocol could regulate limited use or experimentation. Instead of treaties in this early stage of NanoGeo technological development, a possible path forward is a limited international research program. Norms are likely to develop

among researchers and sponsoring organizations which will dictate responsible development and testing of NanoGeo and other geoengineering forms. This controlled research and development approach is a balance between skepticism of NanoGeo's potential concerns and the very real possibility that it might be desperately needed to stave off climate catastrophe. This paper is a starting point to what needs to be a larger, more inclusive international societal effort to anticipate and prepare for NanoGeo.

2 INTRODUCTION

2.1 Climate Change

As the world continues to warm as a result of anthropogenic climate change, many question whether the international community possesses the will and the means to address this serious issue. Largely due to greenhouse gas (GHG) emissions from human activities that have led to atmospheric CO₂ concentrations 40% higher than preindustrial levels, the Earth's temperature has already risen 0.7°C. According to the United Nation's Intergovernmental Panel on Climate Change (IPCC), if human activity and world development continue unimpeded, average surface temperatures could rise as much as 6.4°C by 2100. Even under the most optimistic scenarios, temperatures are expected to rise by 1.1-2.9°C before the century's end (Core Writing Team, Pachauri, R.K and Reisinger, 2007).

In the face of perilous climate changes, more severe storms, rising sea levels, and other unknown threats, international attempts to slow global warming have largely proven ineffective. The international agreement with the most global influence is the Kyoto Protocol, a result of the 1992 UN Framework Convention on Climate Change (UNFCCC) that allowed for the implementation of future protocols that address the prevention of global warming. Unfortunately, emissions continue to increase, despite the promises made by the ratifying nations (Victor, et al., 2009). The agreement was further endangered by the unwillingness of the US to participate in what the Bush Administration considered a flawed framework. Additionally, some enthusiastically participating countries have found themselves lacking the appropriate internal policy tools to turn reduction targets into reality. The European Union's Emissions Trading Scheme proved impotent when more emissions allowances were issued than required. As a result

of virtually no cost being attached to the superfluous amount of traded allowances, the market mechanism collapsed (Bales & Duke, 2008).

With the Kyoto Protocol set to expire in 2012, the international community is contemplating a successor agreement. Meetings in Copenhagen in December 2009 yielded no substantive consensus between nations for a successive protocol. The international community continues to ponder the feasibility of future GHG reduction agreements resulting from coming UN meetings over the next few years.

2.2 Geoengineering

What is to be done about the dire circumstances in which we find our planet and the seemingly impossible task of creating real international cooperation to reduce emissions in a meaningful manner? One proposed answer is the intentional, large-scale manipulation of the Earth's climate by 'geoengineering,' a concept recently given a high-profile introduction by the White House Science Advisor, John Holdren. In an April 2009 interview, Holdren said of geoengineering that, "It's got to be looked at. We don't have the luxury ... of ruling any approach off the table." Holdren elaborated by saying, "We're talking about all these issues in the White House. There's a very vigorous process going on of discussing all the options for addressing the energy climate challenge" (Borenstein, 2009). With Holdren's statements, the concept of geoengineering was suddenly propelled from fringe science into scientific and policy mainstream by a high-profile government official.

The seemingly strange notion of geoengineering isn't new; it was discussed as far back as 1965 when President Johnson received the first-ever presidential briefing on the dangers of climate change. The single suggestion given, considered the only feasible response, was geoengineering. Though this concept was disregarded in the context of climate change, research

continued to be done in other applications. Earlier in 1962, US government researchers under *Project Stormfury* tried to lessen hurricane intensity by cloud seeding, but their efforts met with no clear success. Then in the early 1970s, nations first began to see the environment as a weapon, an attractive tool in the Cold War. Soviet scientists openly discussed the possibility of damming both the Strait of Gibraltar and the Bering Strait as a way to warm the Arctic, thereby making Siberia more hospitable. At the Pentagon, *Project Popeye* attempted to use cloud seeding to increase the strength of monsoons over the Ho Chi Minh Trail. As a result of these early actions, international agreements were formed to prevent the use of climate and weather modification as a weapon of warfare (Keith, 2000).

More recently in 1996, the Air Force *2025* program issued a document entitled “Weather as a Force Multiplier: Owning the Weather in 2025,” a report that gained little traction (Fleming, 2007). Likewise, a US Department of Energy white paper entitled “Response Options to Limit Rapid or Severe Climate Change” was developed in October of 2001 which recommended a \$13 million/year national geoengineering research effort; however, the paper was never released to the public (Robock, 2008).

Geoengineering is now found in mainstream public discourse, as evidenced by a plethora of recent articles in *Foreign Affairs*, *Scientific American*, *Science*, and respected peer-reviewed journals. A 2008 article in *Scientific American* laid out three compelling reasons to contemplate geoengineering options seriously. First, despite the Kyoto Protocol, CO₂ emissions are rising faster than IPCC worst-case scenarios. Second, ice at both poles is melting faster than expected, increasing talk of nearing an environmental tipping point. Third, Paul Crutzen, an eminent Nobel Prize-winning atmospheric scientist, published a 2006 paper in the journal *Climate Change*, urging serious consideration of geoengineering options (Crutzen, 2006). With no end in sight to

increasing GHG emissions, dangerous climatic changes occurring at faster rates and perhaps approaching criticality, and the validation of well-respected minds behind the idea, geoengineering suddenly seems a serious option that begs consideration by the scientific community and world states (Kunzig, 2008). Additionally, some consider geoengineering an important tool to use hand-in-hand with mitigation techniques, in a short-term effort to wean the world off of carbon fuels in the long-term (Wigley, 2006); (Keith, 2009).

Perhaps the most standard and modern definition of geoengineering is provided by David Keith, one of the foremost scientists and thinkers behind this evolving field. According to Keith, “Geoengineering is defined as intentional large-scale manipulation of the environment” (Keith, 2000). By this definition, scale and intent play central roles in classifying actions as geoengineering or not. For instance, foresting a plot of private land is not considered geoengineering because it is small in scale. Likewise, climate change by anthropogenic greenhouse gas emissions is not considered geoengineering because altering the climate is not the intent; it is simply an unintended consequence (Keith, 2000). Thus, geoengineering as we shall consider it must be large-scale action by people with the express intent of changing the world’s current climate. In the realm of climate change and societal response, geoengineering techniques are under consideration to counteract human activities in an attempt to keep the Earth’s temperature from departing too far or perhaps at all from recent historic levels.

Geoengineering is considered one of three possible responses to the climate problem. If humans are unable to mitigate actions that ultimately create climate change, and we as a society wish to avoid any level of climate change that requires adaptation, the remaining course of action is geoengineering of the climate system, as illustrated in Figure 1.

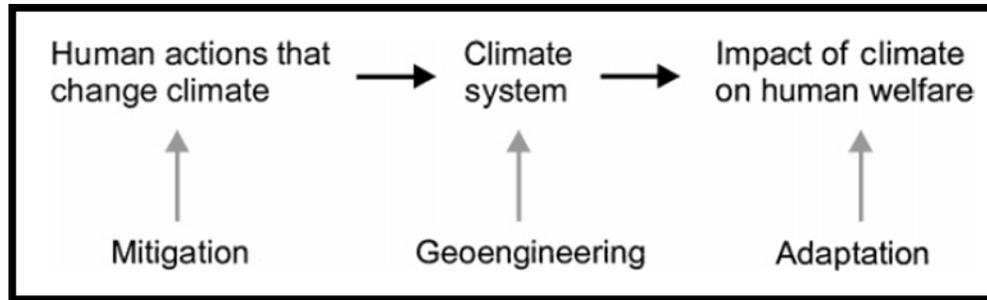


Figure 1 - Climate Problem Responses (Keith, 2008)

Multiple existing and emerging ideas for geoengineering fall into two categories. Broadly, all actions are either: (1) Carbon Dioxide Removal (CDR) methods that reduce CO₂ in the Earth's atmosphere through natural or man-made mechanisms, or (2) Solar Radiation Management (SRM) methods that modify the Earth's radiation balance on land, water, or atmosphere (The Royal Society, 2009). The more frequently discussed of the CDR methods include: enhancing land carbon sinks, using biomass for carbon sequestration, enhancing natural weathering processes that remove CO₂ from the atmosphere, directly capturing CO₂ from ambient air, and fertilization of the ocean with nutrients to enhance uptake of CO₂ by biological processes. The more frequently discussed of the SRM methods include: increasing surface land and man-made structures reflectivity, enhancing marine cloud reflectivity, reducing radiation by injecting sulfur aerosols into the lower stratosphere, and placing reflective or deflective solar shields in space between the Sun and Earth (The Royal Society, 2009).

A comprehensive study of geoengineering and the science, governance, and uncertainty surrounding the field was published by The Royal Society in late 2009. This work provides one of the most cohesive and comprehensive assemblages of broad issues in the field to date. Though no science was conducted exclusively for the report, it did address many issues pertaining to geoengineering and rated each one of the geoengineering methods previously listed for: Effectiveness, Affordability, Timeliness, and Safety. Based upon these judgments, stratospheric

aerosols were determined to provide a large degree of effectiveness, a large degree of affordability, a large degree of timeliness, and a small degree of safety, as indicated by the dashed box in Figure 2 (The Royal Society, 2009). By this composite score, methods using stratospheric aerosols are determined to be one of the most desirable and eventual tools, perhaps even being the best when all issues are taken into account. It is for this reason that this paper focuses exclusively on this particular method.

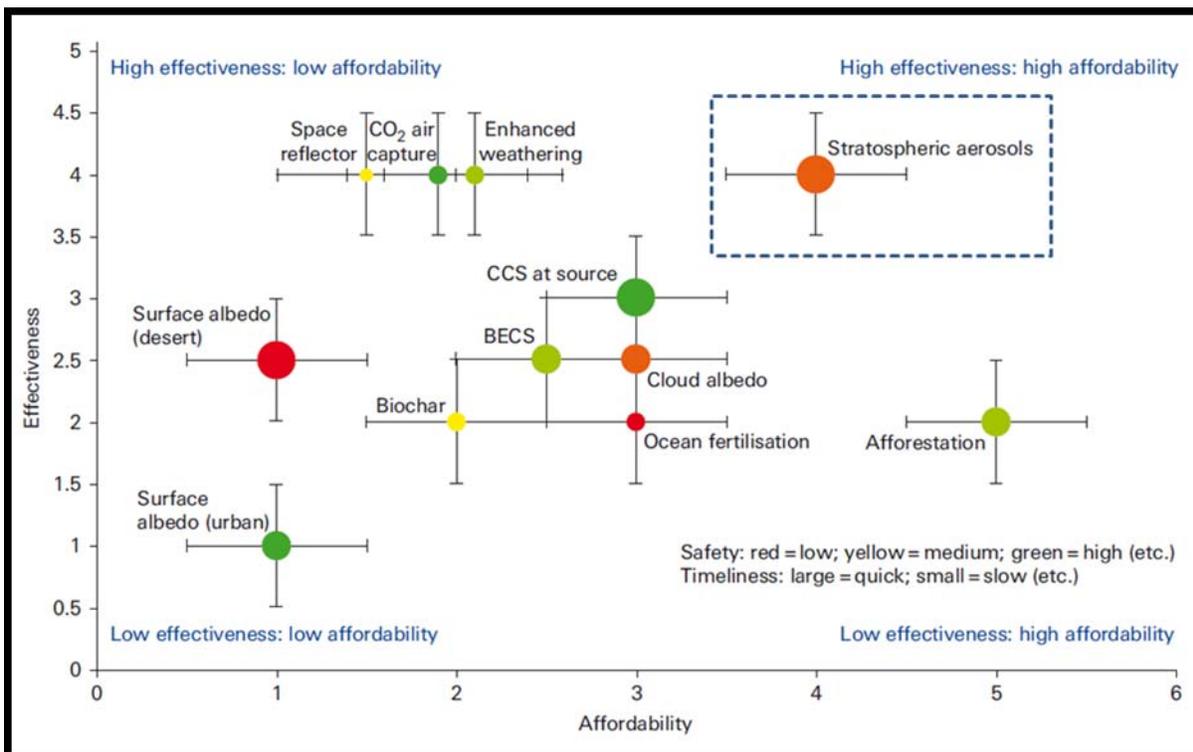


Figure 2 - Summary of Geoengineering Techniques (The Royal Society, 2009) As Modified

To reduce radiation incident upon the Earth's surface, relatively small amounts of sulfate aerosols, like SO₂ gas, can be injected into the stratosphere. Recent climate models indicate that a radiation decrease of approximately 2% can balance a doubling of atmospheric CO₂ concentrations from preindustrial levels (The Royal Society, 2009). Seen in Figure 3 below, is a model indicating global temperature increases as a result of a doubling of CO₂ to 560 ppm.

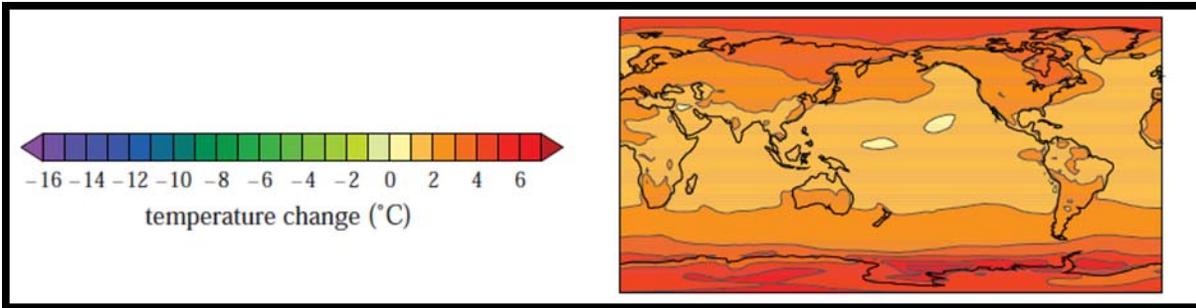


Figure 3 - Global temperature changes from 2xCO₂ to 560 ppm. (Caldeira & Wood, 2008)

Compare Figure 3 to Figure 4 below, where CO₂ concentrations remain doubled but radiation intensity upon the Earth is uniformly reduced by 1.84%, resulting in much less temperature change across the globe.

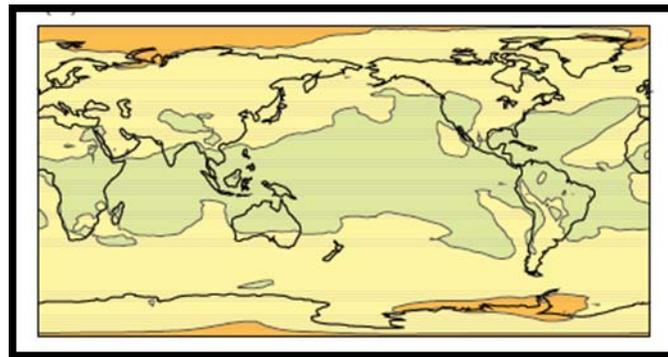


Figure 4 - Global temperature changes from 2xCO₂ to 560 ppm and a uniform reduction in radiation intensity of 1.84%. (Caldeira & Wood, 2008)

The study focuses on a hypothetical reduction in solar intensity, not by any particular method (Caldeira & Wood, 2008). The most widely proposed aerosol, sulfur dioxide, is known to increase the Earth's albedo by reflecting or diffracting a small portion of sunlight. SO₂ aerosols have other harmful effects including increased rain acidity and ozone depletion, amongst even greater concerns about the moral hazard of a "quick fix" (Robock, 2008). Despite the risks, this concept is widely considered the most promising use of geoengineering for a few key reasons. First, a relatively small amount of sulfur aerosols could completely negate the effects of anthropogenic GHG emissions. Second, to position sulfur aerosols appropriately in the

atmosphere, relatively simple means such as high-flying aircraft, naval guns, and giant balloons could be employed.

With minimal material needed and readily accessible means for deployment, it is estimated that the sulfur aerosol method could be implemented globally for as little as a few billion to a hundred billion dollars per year. At either end of this range, the method is likely just a fraction of the cost of dramatically reducing GHG emissions. Geoengineering with sulfur aerosols might soon emerge as the “low-cost backstop,” advocated by some as the optimal economic choice when dealing with climate change (Nordhaus, 2008).

Though the long-term consequences of this form of geoengineering are unknown, it is nearly certain to be effective in decreasing average global temperatures in the short-term. The eruption of Mount Pinatubo in 1991 ejected 20 million tons of SO₂ into the atmosphere, blocking out a small fraction of the Sun’s rays across the globe. Over the course of a year, the resulting effect was an average reduction in global temperatures of .5°C. Greater eruptions, such as Mount Krakatau in 1883, caused global cooling of an even larger magnitude. Volcanic events provide an example of the cause-and-effect relationship implemented in geoengineering; in fact, many researchers call sulfur aerosol geoengineering the “Pinatubo Option” as it so closely mimics natural phenomena (Victor, et al., 2009).

2.3 Emergence of Nanotechnology in Geoengineering

Like geoengineering, the basic concepts and potential applications of nanotechnology are surprisingly old. The original concept was introduced in the now famous 1959 lecture by Richard Feynman, “There’s Plenty of Room at the Bottom.” Feynman predicted that eventually we could arrange and manipulate individual atoms at minute scales. This idea was famously realized in 1989 when IBM researchers manipulated 35 individual Xenon atoms to write out the company’s

name. Throughout the 1980s and 1990s, researchers began to create nanostructures and refine the field with the introduction of buckminsterfullerene (buckyballs), carbon nanotubes, nanowires, and quantum dots (Lane, 2005).

Over its development, a definition specifying what exactly nanotechnology is has emerged. The National Nanotechnology Initiative (NNI), the federal program designed to coordinate US research and development in the field provides the following definition:

“Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale.” (NNI, 2010)

Within the US, NNI is the primary clearing house of nanotechnology federal funding, with a 2011 budget of \$1.8 billion passing through to 15 federal agencies; DOE, NSF, NIH, DOD, and NIST being the largest. Private industry in the US is estimated to spend at least this much annually as well. Furthermore, many other areas of the world are increasing their nanotechnology funding efforts, with the European Union (EU) investing \$1.05 billion and Japan investing \$950 million in 2005 estimates. Many other Asian countries are increasing investments in parallel with the US, EU, and Japan; prominent among them are Korea, China, and Taiwan (NNI, 2010).

With this greatly increasing amount of funding, products containing nanotechnology are expected to significantly increase market share over the coming years. In 2004, nanotechnology products had less than 0.1% of the manufacturing market share, but estimates project an increase to 14% by 2014, totaling \$2.6 trillion (United Nations Environment Programme, 2007). The

reason for increased usage of nanotechnology in products is due to the unique properties – color, conductivity, elasticity, strength, explosivity, reactivity, toxicity, penetrability, etc. – of materials at the nanoscale (Hallstrom, 2008). The breadth of applications for nanotechnology is also impressive, with uses in drug delivery, cancer treatment, sporting equipment, computers, food and agriculture, and a variety of other basic consumer products (Hallstrom, 2008). Despite the promises of nanotechnology, our knowledge of the environmental and human health effects of nanomaterials is limited, creating uncertainty about the risks our society could face with greater adoption of nanotechnology alone and also in the convergence of nanotechnology with other emerging fields such as biotechnology (Lane, 2005).

A close observation of academic papers and news stories relating to geoengineering in the last couple of years shows the emergence of references to “nanoparticles”, “carbon nanotubes”, and “structures 100 nm in size.” As will be discussed, many scientists and authors see that the field of nanotechnology offers certain tools which may be useful replacements or supplements for existing geoengineering techniques. However, the use of nanotechnology affects the consequences, risks, and rewards that geoengineering by itself offers. Unfortunately, no literature is currently available that truly explores the marriage of these two novel and rapidly developing fields, in what this paper will call *Nanotechnology Geoengineering* (NanoGeo).

2.4 Paper Goals

It is the intent of this paper to explore the important convergence of the fields of nanotechnology and geoengineering and the relevance of existing international legal frameworks for related technologies. With evidence of the emergence of NanoGeo references and a series of societal issues pertaining to economics, risk, and ethics, the international community is likely to turn to international law and governance mechanisms to regulate this field. Also addressed in this

paper is the need for international oversight of NanoGeo. As such, it presents an assessment pertaining to this currently upstream technology which is likely to have global ramifications as inferred from the individual fields of nanotechnology and geoengineering.

This paper will conduct the analysis on this novel topic by first looking at how references to nanotechnology have emerged in geoengineering literature and media. Next, societal concerns will be explored as they pertain to economics, risk, and ethics. From there, existing international governance mechanisms will be identified and examined, judging them based upon criteria to determine their applicability to NanoGeo. Finally, a determination will be made on the adequacy of these existing mechanisms and what future steps for appropriate international governance of NanoGeo, if any, might be needed or advisable.

3 METHODOLOGY

An upstream technology assessment (UTA) was performed in an attempt to anticipate major issues and concerns pertaining to a novel technology containing two complicated, convergent fields: geoengineering and nanotechnology. A UTA is suited particularly for fields and applications like NanoGeo where research and development are currently wedding two dynamic fields “coming down the pipeline” that are yet to see any scale of testing or deployment. A UTA can include an upstream oversight assessment (UOA) in that its primary goal is to be an anticipatory tool for emerging technology issues to prepare for oversight by examining case studies (Kuzma, et al., 2008). However, UTA for this paper differs from UOA in that case studies are not the primary mode of anticipatory analysis, as only a few relevant case studies exist. The particular approach in performing UTA in this paper entails:

1. An anticipation of features and types of the emerging technology;
2. An inspection of societal issues pertaining to human and environmental health risk, economics, and ethics;
3. An examination of existing international law and governance structures which may bear to some degree on NanoGeo or elements of it;
4. An assessment regarding the applicability of the identified existing international policy systems to NanoGeo in particular; and
5. An analysis of likelihood that international structures are robust and applicable enough to suitably address NanoGeo.

The first step in this UTA, anticipating the types and features of NanoGeo, required the accumulation and analysis of several sources of information to determine potential short- and

long-term applications. Information was gathered through a literature and media search, consisting primarily of academic papers, reports, and publications which discuss the maturing dialogue on geoengineering and contain references either directly to nanotechnology or allude to nanoscale principles and features. As with many emerging and novel technologies, the breadth of information is small, and a rather small group of academics and researchers were found to be discussing NanoGeo formally and, more often, informally during small group presentations and briefings. From this research, Table 1 (page 25) illustrates the references to applications of nanotechnology in geoengineering.

The second step of the UTA process was to investigate and anticipate societal issues likely to emerge from NanoGeo. This was accomplished by a literature review focused largely on nanotechnology and geoengineering independently, as a quality of one parent field is likely to remain present in a combined application. This evaluation of societal issues is broken down into three broad criteria for simplicity of analysis, which have previously been used for assessment of more traditional geoengineering techniques (Keith, 2000):

- Economics
- Risk
- Ethics

A summary of issues contained within these three categories was created and is illustrated in Table 2 (page 37).

To address the societal issues raised, the world community is likely to look to international politics and law to control this emerging technology. To examine the international law and governance structures that may pertain to NanoGeo, an exhaustive search of legal and policy literature on international governance was conducted as the third step. As no formal,

binding international legal and regulatory structure currently exists for nanotechnology, the search focused on the field of geoengineering and similarly related fields such as short-term weather modification, transnational air pollution, international territory experimentation, and so on. The search began with legal, policy, and scientific literature found through Google, Google Scholar, and University of Minnesota online library systems.

As UTA is anticipatory, a limited amount of literature in peer-reviewed publications is available, requiring a large amount of analysis based upon news publications, periodicals, trade publications, and history. Primary sources were discovered through keyword searches, including terminology pertaining to “nanotechnology”, “geoengineering”, “weather modification”, and “international environmental treaties.” The search scope expanded by analyzing secondary documents discovered through citations in the primary sources. This technique was used extensively in all literature review contained within this entire report. The international governance structures that may pertain to NanoGeo are listed and summarized in Table 3 (page 40).

For the fourth step, determining applicability of existing international governance mechanisms to NanoGeo, the structures discovered previously in this report were judged based upon multiple criteria:

- Economics: How does the governance address concerns relating to costs and any financial reparations?
- Risk: How does the governance structure address health and ecological risks associated with geoengineering deployment?
- Ethics: How does the governance system address and abide by common ethical norms?

- Relevancy: How does the governance structure pertain to NanoGeo or components contained within? To what degree does the structure invoke certain aspects or circumstances of NanoGeo?
- Effectiveness: How has the governance structure proven to be effective in addressing, or preventing if necessary, the issue it is intended to target? Historically, were experiments and actions prevented or ceased in response to the prevention structure put in place for just such circumstances?
- Enforcement: How does the governance structure have the proper deterrent to prevent unwarranted action or punishment and enforcement if action was or is taken? Does it apply to different actors, such as nations, companies, and individuals, who may use NanoGeo?

These criteria were derived from the policy analysis approach suggested by Bardach (Bardach, 2000) and the NanoGeo literature described above. Additionally, the criteria were also vetted with peers in the field of science and technology policy. An assessment of the six judging criteria for each international governance mechanism addressed is summarized in Table 4 (page 53).

Based upon the results of step 4, it was determined whether existing governance structures could be applied to NanoGeo. Three overall policy possibilities were considered in looking at all international governance regimes:

- A. Existing international governance structures are adequate to address the particular novel and emerging technology of NanoGeo;
- B. Existing international governance structures require certain revisions because they only partially address NanoGeo or constituent components; or

- C. Entirely new international laws, treaties, or governance structures are needed, as the existing systems do not address NanoGeo and are not suitable for revision.

4 ANALYSIS

4.1 Emergence of NanoGeo

As was explored in the Introduction, this paper will focus on the use of NanoGeo specifically related to planetary albedo enhancement by stratospheric nanoparticle aerosols for two primary reasons. First, The Royal Society concluded that stratospheric aerosols such as SO₂ provided a large degree of effectiveness, affordability, and timeliness, though with little safety. Comparing this method of geoengineering versus others, Figure 2 illustrated that stratospheric aerosol geoengineering is likely to emerge from the menu of options as a strong potential tool (The Royal Society, 2009). Second, the literature and media search in the first phase of UTA yielded a variety of sources with references to both geoengineering and nanotechnology. More importantly, the majority of identified sources referenced nanotechnology specifically related to aerosols. Because of these two reasons, it was reasonable to focus exclusively on NanoGeo stratospheric aerosols, as this method seems likely to emerge as a frontrunner amongst others for research, trials, and use.

The concept of manufacturing “designer” particles at the 100 nm scale or less has emerged recently in scientific literature and academia as a potentially more benign alternative to sulfate aerosols (Teller, et al., 1997). Though not always referred to specifically as “nanotechnology” or “nanoparticles,” papers and presentations within the scientific community have increasingly cited “engineered” particles of a radius of approximately 100 nm (Koonin, et al., 2009) (Fleming, 2007). Five core control variables have been identified as significant factors in aerosol-based stratospheric albedo modification. Of the five, aerosol material composition, size and shape, and geographical and vertical location of dispersion can be largely affected by

nano-scale properties (Koonin, et al., 2009). By taking advantage of the fact that nanomaterials of a very small size have unique properties of color, conductivity, elasticity, strength, toxicity, and explosivity, scientists are looking at nanotechnology as a way to create optimal aerosols and structures that maximize benefits and reduce risks in geoengineering applications (Hallstrom, 2008).

As an example, material droplets of a radius of 100 nm are optimal for the preferred interaction with incoming solar radiation (The Royal Society, 2009). At this scale, *mass scattering efficiency* is optimized, as scattering theory of uniform spherical particles dictates that the most mass-efficient scatterers have radii of ~ 0.1 of the wavelength of the scattered radiation. For the solar spectrum in particular, this means particles on the order of 100 nm. By minimizing particle size to an optimum mass-efficiency, geoengineers could inject the least amount of particles into the atmosphere while achieving the greatest effect (Koonin, et al., 2009) (Wigley, 2006).

Other than spherical particles, studies also suggest that mesh microstructures and micro-balloons could be used to increase the atmosphere's albedo, with the potential to be even more mass-efficient than spheres (Teller, et al., 1997) (Teller, et al., 1999). Though the accumulated size of these structures and balloons may be on the micro-scale, individual components are likely to be even smaller, such as mesh wire thicknesses of 20 nm (Keith, 2000). Ultra-thin metallic walled balloons have also been proposed and are expected to have very long stratospheric residence time, likely only limited by micrometeoritic punctures that may punch micro-scale holes in vulnerably thin walls. The balloons are envisioned to have an aluminum wall thickness of ~ 20 nm, an overall radius of 4 mm, and a lifting gas of hydrogen (H_2) (Teller, et al., 1997). All

of the above structures are likely to have individual nanoscale components of C₆₀ buckyballs, graphite nanotubes, or any number of other emerging structures (Teller, et al., 1997).

Perhaps the most extensive exploration of nanotechnology utilization in geoengineering is being performed by David Keith, professor and director of the ISEEE Energy and Environmental Systems Group at the University of Calgary (The University of Calgary, 2009). Geoengineering and nanoscale issues were presented to a large audience – in attendance and through online video later – at the annual TED (Technology, Entertainment, Design) Conference in 2007 (TED, 2007). In subsequent presentations to the academic community, Keith explored the possibility of releasing man-made designer particles and devices into the stratosphere specifically as geoengineering devices. In addition to the benefits of nanostructures, Keith imagined designing particles to harness photophoretic levitation, the process by which an object with unequally heated sides is acted upon by a force in a particular direction due to more energetic collisions with atmospheric particles on the warmer side of the object. Photophoretic levitation and the inclusion of a magnetic component would hypothetically allow devices to maintain their individual elevation, orientation, and geospatial location for an extended period of time once released within the atmosphere (Keith, 2008). Engineered particles could possibly be deployed into the mesosphere as well, even higher above the Earth's surface than the stratosphere (Keith, 2009). This technique would likely allow geoengineers to artificially design particles or objects that provide the greatest albedo increase with the least amount of mass and the longest atmospheric lifetime.

One of the keys to concept fruition is the ability to fabricate nanodevices at an extremely minute scale. In conversations, manufacturers told Keith that not only is this fabrication possible,

but it is likely to become cheaper, more efficient, and safer upon further maturation of the nanotechnology field (Keith, 2008).

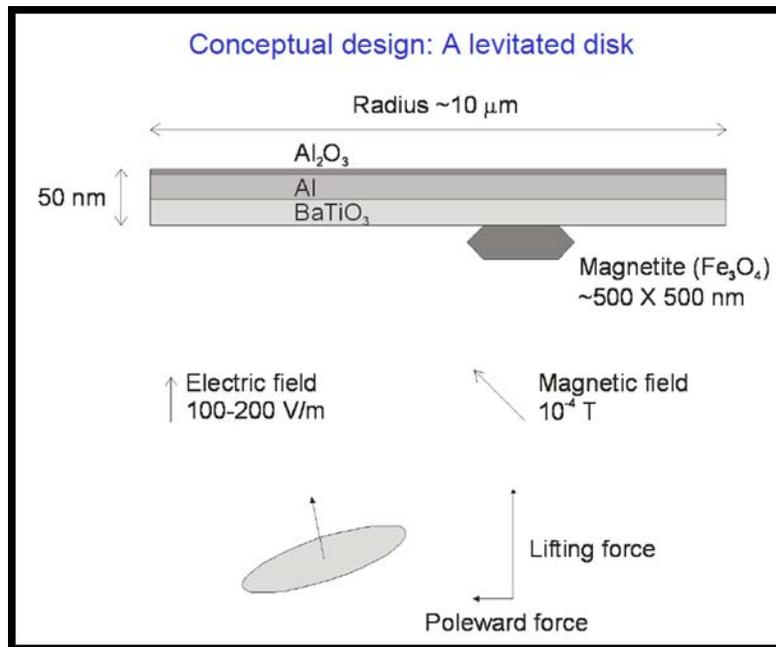


Figure 5 - Keith's conceptual design for a nanoscale, self-levitating reflective disc (Keith, 2008)

The conceptual design in Figure 5 above incorporates a highly reflective aluminum coating built upon a manufactured substrate of BaTiO_3 for rigidity. At an overall thickness of $\sim 50\ \text{nm}$, wafer layers would need to be deposited and manufactured using nanotechnology and nanoparticles.

A variety of references to the use of nanotechnology in geoengineering have occurred since 1997, as summarized in Table 1 below. Given the continuing maturation of both fields, it is likely this trend will continue into the future with greater occurrence.

Table 1 - Summary of references to Nanotechnology in Geoengineering media

Year	References	Media	Source
1997	“nano-droplets”, “nanometer-scale poly-carbon structures with fully enclosed interiors (e.g., C ₆₀ buckyballs, graphitic nanotubes, etc.)”, “ultra-thin metallic-walled balloons”	Report	(Teller, et al., 1997)
1999	“sub-microscopic...mass-economized metallic-surfaced balloons”	Report	(Teller, et al., 1999)
2000	“thickness of the mesh wires...(about 20 nm)”	Journal Article	(Keith, Geoengineering the Climate: History and Prospect, 2000)
2006	“Smaller diameter aerosols would have longer lifetimes and require still smaller injection rates.”	Journal Article	(Wigley, 2006)
2007	“specially engineered nanoparticles”	Periodical	(Fleming, 2007)
2007	Presentation Slide Images Audio: “I think it’s almost certain we will eventually think of cleverer things than just putting sulfur in [the atmosphere]. That if engineers and scientists really turned their minds to this, it’s amazing how we can affect the planet.”	Presentation	(TED, 2007)
2008	“metal nanoparticles in the stratosphere”, “oceans with iron nanoparticles”	Journal Article	(Hallstrom, 2008)
2008	“discs, micro-balloons or gratings”, “photophoretic levitation of nano-engineered scatterers”	Presentation	(Keith, Photophoretic Levitation of Stratospheric Aerosols for Efficient Geoengineering, 2008)
2008	Image (Figure 5)	Presentation	(Keith, Climate and Carbon Engineering, 2008)
2009	“engineered particles in mesosphere”, “micro-balloons”	Presentation	(Keith, Geoengineering Research, 2009)
2009	“engineered solid particles”, “aerosols engineered to have characteristics not found in naturally-occurring aerosols”, “particles with radii of ~1000A (or .01µm)”	Report	(Koonin, et al., 2009)
2009	“droplet radius of order 0.1 µm being the optimum for interaction with incoming solar radiation”	Report	(The Royal Society, 2009)

4.2 Societal Issues

Very little is known about the risks of nanotechnology in the environment and geoengineering of the climate individually. Geoengineering itself is cutting edge with many unknown parameters; coupling this with an emerging and powerful field such as nanotechnology may drastically alter the immensity and complexity of a variety of issues. Additionally, benefits can only be surmised without any form of laboratory or small-scale, real-world testing. In performing this UTA, it was most practical and feasible to look at issues and concerns known about one of the two technological domains and then attempt to infer to NanoGeo as a whole.

Though little technical research has been conducted on the structure, assembly, and release of nanoparticles into the Earth's upper atmosphere, many existing issues pertaining to geoengineering in general will be affected by the inclusion of nanotechnology, and vice versa. Environmental, ethical, and moral concerns will be altered in ways, some negligible and others substantial, that should be addressed concurrent to technical advances. Environmental issues and human health concerns are likely to emerge as tantamount since the release of nanotechnology in geoengineering applications will be a global project with exposure to most of the human population.

4.2.1 Economics

A “low-cost backstop” has often been listed as a potential response to climate change, as it has an economic advantage over more traditional responses and can be considered a substitute to emissions reductions (Barrett, 2008). Some have advocated for geoengineering being this potential remedy, as an economically superior option to expensive proposals to reduce GHG emissions and expensive plans to adapt to climate change (Nordhaus, 2008). With the marriage of nanotechnology to geoengineering, it is possible that NanoGeo will become even cheaper as the respective fields develop. Though no cost estimates exist yet, Keith proposes that NanoGeo

particles will have a lower cost and need less frequent replenishment than sulfur aerosol alternatives, resulting in a lower life-cycle cost (Keith, 2008).

It has been estimated that the use of ‘engineered particles’ - often a reference to particles on the nanoscale - could cost just \$1 billion per year in 2100 to compensate for a projected business-as-usual increase in GHG emissions (Barrett, 2008) (Teller, et al., 2002). Even if this turns out to be an overly optimistic estimate, it is likely that NanoGeo would be more than an order of magnitude less expensive than the health benefits alone to the human population of scattering of harmful UV radiation (Barrett, 2008). Other estimates suggest that a geoengineering program, though not specific to NanoGeo, could cost on the order of \$100 billion into perpetuity, which is a favorable comparison to \$1 trillion for mitigation programs (Victor, 2008). If a NanoGeo program’s cost, whatever it may be, is still more than a single country is able or willing to finance, a coalition of world actors could be assembled to further reduce the price while providing the same benefit to that country’s populace (Barrett, 2008).

Another way to look at the cost of a NanoGeo scheme is to calculate its cost of mitigation (COM). This is a gauge where a mitigation method is measured as an equivalent amount of CO₂ removed from the atmosphere. For the stratospheric release of SO₂ the COM is $\ll 1$. Similarly, the tropospheric release of SO₂ has a COM of < 1 (Keith, 2000). Though these comparisons are specific to SO₂ albedo modification and not NanoGeo, they serve as a good proxy as NanoGeo has many system similarities. This indicates that forms of albedo modification - NanoGeo being one - have low costs compared to emissions abatement and are also lower than most other forms of geoengineering, making NanoGeo a potentially financially attractive tool to combat climate change (Keith, 2000).

Many developing countries (China, India, etc.) are investing heavily in nanotechnology research to address some of their most pressing needs, such as economic development and increased quality of life (Salamanca-Buentello, et al., 2005). These countries are also heavily influenced by climate change ramifications like rising sea levels. Governments of these nations may deem the environmental danger posed by climate change to their populations large enough that they will act with newly acquired nanotechnological skills to alter the climate in a way that was not technically or financially possible without nanoparticles. Also, unlike technologies like nuclear weaponry, the resources, know-how, and capital required for developing nanotechnology are comparatively small. Further complications exist in that NanoGeo offers such a low-cost and widely available technology that small, non-state actors could act in self-viewed benevolent manner that ultimately may reward few and punish many, such as varying climate results across the globe (Joy, 2000). Given the many actors pursuing nanotechnology for economic development, regulation of NanoGeo is especially difficult (Lewenstein, 2005). Perhaps of primary concern, it would be difficult to determine who should establish the ideal global temperature. A rogue nation or corporation with relatively modest financial resources could try to control the Earth's thermostat just as the United Nations or any other responsible, governing body could. Even if an international organization possessed the authority and means, diplomatic infighting between nations could be severe regarding the Earth's optimal conditions, especially if certain conditions yield economic benefits to individual parties.

Additionally, even if the effects of geoengineering were detected, great difficulty would exist in determining if nanotechnology was a component, and, if so, who was responsible. There currently is a lack of detection devices for nanoparticles, which would be crucial in determining how nanotechnology was used and by whom (Maynard, 2006). Furthermore, if NanoGeo was

used and believed to be detrimental to a party, it would be exceedingly difficult to show that a *particular* use of NanoGeo resulted in a *particular* detrimental effect, as the ability to show a clear cause-and-effect relationship in a complex climate system is quite unlikely given current knowledge (Davies, 2009). Finally, if a cause-and-effect relationship was determined relating to a harmful effect on one country, other countries may experience benefits of the NanoGeo action. Thus, even parties originally hostile to the idea of NanoGeo may begrudgingly support its use if they receive some climate benefit or are concerned about the sudden climate ramifications of stopping NanoGeo (Victor, 2008).

4.2.2 Risk

Taken by itself, geoengineering with sulfur aerosols – presently the most probable material – presents an array of environmental dangers. The eruption of Mount Pinatubo can serve as a proxy for the risks of widespread sulfur aerosol dispersal. After the eruption, large disturbances in the hydrological cycle were observed, with a substantial decrease in rainfall over land and corresponding reductions in runoff and river discharge. A reduction of 2% in stratospheric ozone occurred following the eruption. Rain also became more acidic, evoking memories of dead lakes from acid rain in the Northeastern United States just a few decades ago (Victor, et al., 2009).

Alongside the beneficial cooling effect, many negative effects occur as a result of the dumping of sulfur aerosols into the atmosphere. Models of sulfur aerosol injections for geoengineering purposes predict reductions in Asian and African monsoons, impacting the food supply of billions. Also, more sulfuric acid pumped into the atmosphere likely will act as a catalyst for the chlorine reaction that destroys stratospheric ozone, delaying the ‘recovery’ of the Antarctic ozone layer up to 70 years (The Royal Society, 2009). On a more global level, the sky

will appear whiter as sunlight becomes more diffuse, though sunsets and sunrises are likely to be more colorful (Crutzen, 2006). The difference in appearance of the day and night sky may have unknown effects on humans, animals, and plants. Finally, geoengineering with sulfur aerosols does nothing to reduce concentrations of CO₂ in the atmosphere, which will continue to lead to air quality issues and ocean acidification, amongst others. Sulfates would actually increase the level of acid deposition on Earth as the material passes through the troposphere. Any additional acidification of land and marine ecosystems will – especially in isolated, pristine areas – do additional harm (Robock, 2008).

Nanoparticles as a substitute for sulfur aerosols might circumvent some of the significant side-effects mentioned above. For instance, nanoparticles may be engineered to affect sunlight differently and without undue negative consequences. However, nanoparticles would still primarily reduce radiation, which would decrease the amount of energy available for solar energy and plant growth (Robock, 2008) (Ricke, et al., 2008). A possibility exists that engineered nanoparticles could be designed to avoid the negative impacts of other aerosols on ozone chemistry through longer lifetimes or being lofted out of the lower stratosphere (The Royal Society, 2009). It is important to note that any benefit of engineered nanoparticles over sulfur aerosols is hypothetical at this point, being as no testing has occurred.

As can be expected, the ‘law of unintended consequences’ is referenced as a reason to proceed with extreme caution in geoengineering and nanotechnology alike (Kunzig, 2008) (Lane, 2005). NanoGeo, like many other complex systems, involves the feedback and interaction between many parts. When humans are involved and some degree of error is certain, changes are likely to cascade through the system in ways that are difficult to predict (Joy, 2000). Unintended consequences are important considering that not only does geoengineering have ramifications

that are difficult to imagine, but nanotechnology is also an emerging field with impacts that are often underestimated by a technology's creator (Sarewitz & Woodhouse, 2003). One potential side effect: released nanoparticles in the stratosphere will migrate across the globe, knowing no national or ecological boundaries. Though naturally occurring SO₂ aerosol particles are estimated to have residence times in the atmosphere of only one or two years, engineered particles released high above the Earth in one place are expected to fall on land and in water after longer stratospheric residence times and with a larger global dispersion (Teller, et al., 1997) (Crutzen, 2006) (Keith, 2008). What began as an airborne release now includes unknown environmental effects on air, water, and soil, with unknown effects on ecology and health (Hallstrom, 2008).

This is especially problematic given that little is known about the environmental consequences of nanoparticles on people, animals, and plants in these mediums. In particular, the small scale of nanoparticles drives a relatively larger surface area per mass than chemically identical larger-sized particles. As a consequence, studies have shown nanoparticles to be more biologically active than identical, but larger particles (Oberdorster, et al., 2005). Nanoparticles can remain in the air for a substantial period of time due to their small size and light weight, especially if they are specifically engineered to do so (Teller, et al., 1997) (United Nations Environment Programme, 2007). This feature is likely to increase the chance of inhalation by unknowing persons all across the globe, as NanoGeo particles likely will eventually fall to Earth. When inhaled, nanoparticles are deposited efficiently across respiratory tract regions, evasive of bodily defense mechanisms, and translocated out of the respiratory tract by multiple, less-traditional pathways and mechanisms (Oberdorster, et al., 2005). Nanoparticles in water tend to aggregate and precipitate out over time, which is especially concerning given the lack of data on bioavailability, biodegradation, and biotransformation of water-soluble nanoparticles (United

Nations Environment Programme, 2007). Another unknown fate for fallen nanostructures lies in the soil, as little is known about how nanostructures reside within or chemically bind with it (United Nations Environment Programme, 2007).

It is important to note when discussing NanoGeo that humans and the Earth's biological systems have always been exposed to some types of nanoparticles. Many nanoparticles naturally arise from atmospheric photochemistry and natural combustion like forest fires, resulting in human exposure to millions of nanoparticles per breath around fires. Any combustion process produces vast numbers of nanoparticles naturally; initially only 10 nm in diameter and rapidly coalescing to aggregates of up to 100 nm. The resulting nanoparticulates from air pollution and acute natural sources are well known to cause heart and lung disease at high exposure levels over time (The Royal Society, 2004).

However, inhalation is not the only form of human exposure. Exposure to nanoparticles also occurs from surface contact at the skin barrier and from ingestion of food and drink. Nearly all interactions between the human body and foreign nanoparticles will occur through the lungs, the skin, or the intestinal tract (The Royal Society, 2004). Evidence shows that contact with skin can lead to penetration of the dermis and then translocation to regional lymph nodes (Oberdorster, et al., 2005). When ingested by humans, nanoparticles may see system uptake, though the majority are excreted via feces (Oberdorster, et al., 2005). Little is also known about the possibility of bioaccumulation and ingestion by organisms higher up on the food chain, providing a potential burst of nanoparticle introduction if food from a particularly heavy deposit of nanoparticles is consumed (The Royal Society, 2004).

It is also important to distinguish between objects which contain nanoscale components within a larger structure and those that exist individually at dimensions of 100 nm or less (The

Royal Society, 2004). For instance, though Keith's self-levitating reflective disk contains components less than 50 nm, the disc as a whole is much larger. The interaction that this disc may have with humans upon contact will differ in many ways compared to nanoparticles a few nanometers in diameter. This is not to say that exposure to nanoparticles within the reflective disc is not important, but simply that there will be different interactions in the environment between a reflective disc of a larger scale and a nanoparticle released into the atmosphere that has all dimensions in the nanoscale. Additionally, it is possible that the disc may break into its constituent nanocomponents over time, through degradation or other unknown processes within the atmosphere. This may be of particular concern regarding carbon nanotubes, which are proposed in some NanoGeo applications as the building blocks of larger mesh structures. If the nanotubes eventually break free individually, human health may be greatly impacted, as nanotubes have often been compared in structure to asbestos, a well-known human hazard (The Royal Society, 2004). A study of exposure to nanoparticles introduced into mice has shown asbestos-like, pathogenic behavior in the mesothelial lining of the chest cavity. Inflammation and lesions in mice suggest a potential inhalation risk to humans (Poland, et al., 2008).

A troubling scenario is the damage that would be caused by any measure of NanoGeo that begins or ends suddenly. In more "conventional" proposals of geoengineering, steady injections of sulfur aerosols would be needed annually to replenish aerosols that have fallen to Earth (Crutzen, 2006). If for reasons of war, civil unrest, or budget crises these measures were suddenly halted, the accumulated CO₂ would warm the planet abruptly (Kunzig, 2008). Several recent models suggest that an increase of 2-4°C over a period of a decade could be entirely plausible (The Royal Society, 2004). This situation would be worse than relatively gradual warming, because people, animals, and plants would have little time to adjust. The use of man-

made nanoengineered particles is likely to have the same risk of abrupt discontinuation. Though the risk may be the same, one large difference is the degree of certainty of success between sulfur aerosols and nanoparticles. As sulfur aerosols have a known ‘Pinatubo effect’ that assists geoengineers in developing and testing models during the occasional explosive volcanic eruption, nanoparticles have no known global-scale natural proxy to compare (Crutzen, 2006). Additionally, nanoparticles and nanostructures are often complex, man-made designs with the possibility of poor design and manufacturing quality. Compared to natural systems that have been refined by nature over millennia, man-made solutions are likely to contain critical flaws and errors which can develop at any time.

4.2.3 Ethics

Quick fixes for climate change – NanoGeo potentially being one - present environmental moral hazards (Victor, et al., 2009). As nations become increasingly aware of such a tool, it is possible that governments will see less imperative for emission reduction policies (Bunzl, 2008). This is perhaps the single largest reason that scientists and research organizations have been extremely reluctant to debate this issue openly. Keith has mentioned in talks that his academic paper addressing nanoscale self-levitating discs has not yet been submitted to a journal due to his own moral hazard concerns (Keith, 2008). Merely the presence and possibility of geoengineering can lead to a reliance on it. Because sulfur aerosols are generally considered the easiest and cheapest option, most apprehension revolves around this action. By incorporating nanotechnology, the moral hazard may be somewhat reduced given the public’s potential uneasiness with nanotechnology. As Keith conjectured, public reaction may be this: “*If the pointy-heads think we need to shoot nano dust into the stratosphere then we should get worried & get serious about cutting emissions*” (Keith, 2009).

NanoGeo presents a risk of misuse or intentional harm as a dual use technology. Unlike nuclear weapons, which require rare raw materials and carefully protected technical information, 21st-century technologies such as nanotechnology are easy to abuse since they are within the grasp of individuals and small groups (Lane, 2005). Knowledge alone enables their use since other factors are relatively easy to acquire and many advances are being developed in commercial enterprises, away from the intense security of military laboratories. In this way, we see perhaps a greater societal threat in knowledge-enabled mass destruction technologies like NanoGeo, than in weapon of mass destruction technologies that are more difficult to acquire and master, like nuclear, biological, and chemical weaponry (Joy, 2000).

Another possibility is that a well-intentioned nation, acting unilaterally to create a more hospitable climate for their people, could inadvertently create negative externalities for many other people of the world (Ricke, et al., 2008). This brings up questions of equity and whether those who have been harmed have the right to seek justice or compensation. This would be a form of distributive justice, relating to uneven harm and benefit. Closely related would be questions of procedural justice and who has the right, moral standing, or ethical guidance to decide when to use NanoGeo, to what extent, and for how long (Bunzl, 2008). Some also question whether the work of one nation, even with the best intentions, violates the ‘good neighbor’ principle often cited in international law and environmental torts (Davies, 2009).

As a remedy to negative effects of NanoGeo, subsequent tools may be employed in an ever worsening chain reaction of technological fixes. Some will view the creation of a ‘technical fix’ to the problem of climate change instead of addressing its source as inherently undesirable (Keith, 2000). This is closely aligned with the ‘unpredictability argument,’ where it is deemed unethical to use NanoGeo because we are experimenting with complex and difficult to

understand systems. Some are likely to view intentional manipulation of the climate as inherently worse than manipulation that occurs as a side effect, such as climate change from anthropogenic carbon emissions (Keith, 2000).

Finally, a ‘slippery slope argument’ may be made: If we open the door to altering the climate as a response to climate change, society will be more likely to accept climate manipulation as an acceptable response to other issues (Keith, 2000). For instance, one could imagine NanoGeo being used to offset occasional yearly temperature and precipitation variations caused by El Nino. Taken to an extreme, the entire globe could be turned into a constantly managed ecosystem, where interventions are used to suppress an ever-widening list of undesirable climate conditions (Victor, 2008).

Table 2 - Summary of NanoGeo Societal Issues

Category	Issue	Description
Economics	Cost	<ul style="list-style-type: none"> • “Low-cost backstop” for a climate emergency • Low Cost of Mitigation (COM) compared to removing CO₂ from atmosphere • Easily accessible to developing countries through existing nanotechnology efforts
	Externalities	<ul style="list-style-type: none"> • Economic costs and benefits not distributed equally amongst those impacted
Risk	Ecological	<ul style="list-style-type: none"> • Altered rainfall patterns • Reduced solar radiation for plant growth and solar power • Continued high marine and atmospheric acidity from unaltered CO₂ concentrations • ‘Law of Unintended Consequences’: Likely other unknown environmental effects • Knowledge of the cause-and-effect relationship in complex climate systems is still maturing • Abrupt discontinuation may pose enormous environmental disruption over a short period of time
	Human Inhalation	<ul style="list-style-type: none"> • Nanoparticles may pose asbestos-like harm in respiratory system
	Human Contact	<ul style="list-style-type: none"> • Nanoparticles may penetrate dermis and translocate throughout the body
	Human Ingestion	<ul style="list-style-type: none"> • Some system uptake by ingestion • Possible excretion from the body through feces
Ethics	Moral Hazard	<ul style="list-style-type: none"> • Existence of climate change “easy fix” may reduce pressure to reduce GHG emissions
	Dual Use	<ul style="list-style-type: none"> • NanoGeo may be used for nefarious purposes instead of global welfare
	Distributive Justice	<ul style="list-style-type: none"> • Uneven harm and benefit distribution of economic and environmental impacts
	Procedural Justice	<ul style="list-style-type: none"> • Who or what has the moral standing in the international community to decide when to use NanoGeo, how, and for how long?
	Technological Fix	<ul style="list-style-type: none"> • A technological solution is often inherently inferior to addressing a root cause

	Slippery Slope	• Will use of NanoGeo in a controlled manner open the door to perpetual and increasing climate modification?
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4.3 Existing International Law and Governance Structures

To address the societal issues raised, the world community is likely to look to international politics and law to control this emerging technology, as they have done many times before. As NanoGeo is an international environmental issue, international cooperation is required, wherein countries interact with each other under multilateral rules which are previously determined through multilateral negotiation and are monitored by multinational institutions (Frankel, 2005). As many of the world's environmental issues are increasingly being categorized as international externalities, wherein the action of one nation has an undesired effect on another, difficulty in defining property rights to global air and water resources has led to international agreements as a regulatory remedy (Frankel, 2005). Furthermore, no government or international body has developed specific frameworks to regulate nanotechnology (United Nations Environment Programme, 2007).

A recently attempted NanoGeo experiment illustrates the difficulties with international governance. In 2007, Planktos Inc. intended to dump 100 tons of iron nanoparticles over an area of 10,000 km² near the Galapagos Islands in an attempt to spur a plankton bloom – whose limiting nutrient is iron – as an experiment in biological sequestration of CO₂. Of concern to many, experimentation was to proceed with two large unknowns: 1) the effects on permanent ecosystems and 2) the effects nanoparticles distributed in one location would have upon marine biology as they dilute and diffuse in the world's oceans (Hallstrom, 2008). Though the project was scrapped due to intense uproar by the scientific and civil society community, this marked the first potential experimentation of NanoGeo.

In 2008, as a response in part to Planktos Inc's experimental intentions, 5,000 delegates from 191 nations invoked the UN Convention on Biological Diversity, placing a moratorium on projects intended to fight global warming by dumping nutrients into the sea but allowing limited testing near shore. However, the actual document the nations agreed upon refers to the London Convention, which oversees dumping at sea, though not this situation particularly. The UN Convention on the Law of the Sea regulates ocean pollution, but does not distinguish explicitly if chemicals already present in the sea are prohibited; especially if the existing chemicals or elements are to be introduced in a new form such as nanoparticles (Chambers, 2008). The official advice of the London Convention is to postpone ocean fertilization until scientists better understand its impacts (Chambers, 2008).

The new agreement was put to the test in early 2009 when a German-Indian expedition planned to fertilize a 300 km² patch of the Southern Ocean with 6 tons of iron filings to spur algae growth for CO₂ sequestration. Despite well-known concerns by the international community, and high profile opposition by Greenpeace and the German environment ministry, the so-called Lohafex expedition conducted the experiment in March 2009 (Black, 2009). The experiment ultimately proved unsuccessful; the large bloom anticipated ultimately appeared, but was quickly diminished by the "grazing effect," where predators came to the area and harvested the bloom back down to background levels. Though some geoengineers see this as perhaps a last gasp for ocean fertilization, an American company, Climos, has announced plans to perform a similar experiment (Brahic, 2009). As of this report's writing, no international actions have taken place to address the Lohafex experiment's supposed disregard for international consensus. In this instance, an international treaty proved ineffective in preventing an experiment in violation of its rules and underlying principles.

Other previous international policy efforts have addressed a wide variety of societal issues broadly relating to the geoengineering. But voluntary conventions, treaties, and agreements have not been entirely successful. This experience serves to illustrate the need to carefully examine what existing international governance systems may apply to NanoGeo and how or if they can adequately and effectively address the looming experimentation or deployment of NanoGeo in a controlled and internationally sanctioned manner.

Table 3 summarizes key aspects of four international governance mechanisms that have been identified as potentially applying to NanoGeo. These four mechanisms are discussed in greater detail in the following sections.

Table 3 - Potential NanoGeo International Governance Mechanisms

<u>Official Name</u>	The Rio Declaration on Environment and Development	United Nations Framework Convention on Climate Change	The Convention on Long-range Transboundary Air Pollution	The Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques
<u>Known As</u>	The Rio Declaration	UNFCCC	CLRTAP	ENMOD
<u>Intent</u>	“Working towards international agreements which respect the interests of all and protect the integrity of the global environmental and developmental system...” – Preamble	“To achieve... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” – Article II	“The Contracting Parties...are determined to protect man and his environment against air pollution and shall endeavour to limit and, as far as possible, gradually reduce and prevent air pollution including long-range transboundary air pollution.” – Article II	“...Not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to any other State Party.” – Article I
<u>Signed</u>	June 14, 1992 (Rio de Janeiro)	May 9, 1992 (New York)	November 13, 1979 (Geneva)	May 18, 1977 (Geneva)
<u>Entered Into Force</u>	N/A	March 21, 1994	1983	October 5, 1978
<u>Parties</u>	UN Conference on Environment and Development	193 Nations	51 Nations	77 Nations

It is worth noting that three prominent items of international environmental governance pertaining to techniques of geoengineering were not explored in this paper. As stated in the ocean fertilization case, the Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter (London Convention), the Convention on Biological Diversity (CBD), and the United Nations Convention on the Law of the Sea (UNCLOS) are often cited as relevant pertaining to certain examples of current and potential geoengineering. As the London Convention and UNCLOS both pertain to the world's oceans, they were not included in this analysis because the effects of NanoGeo on water systems are likely to be secondary. Three of the explored conventions in this paper pertain directly to air, weather, and climate, which can be primarily affected by stratospheric NanoGeo. Furthermore, the CBD and Rio Declaration both emerged from the 1992 Earth Summit and share many principles. However, the Rio Declaration was solely explored further in this study due to its prevalence in the literature survey and its unique structure as a declaration amongst the other conventions examined.

4.3.1 The Rio Declaration

The Rio Declaration on Environment and Development (The Rio Declaration) was produced at the 1992 UN Conference on Environment and Development, known as the Earth Summit, and consisted of 27 stated principles intended to guide future sustainable development around the world. The Declaration reaffirmed the Declaration of the United Nations Conference on the Human Environment, which was adopted at a conference in Stockholm in 1972, and sought to build upon that prior agreement. As a primary goal, the declaring nations agreed to work “towards international agreements which respect the interests of all and protect the integrity of the global environment and developmental system” (The Rio Declaration, 1992).

Very little is said within the Declaration about economic issues, other than stating that nations shall cooperate in an open international economic system and recognizing that economic disparities exist between the developed and developing world. However, states are encouraged to develop systems within their own boundaries to develop domestic law to address liability and promote compensation regarding environmental damage and pollution (The Rio Declaration, 1992).

Risk and ethics are addressed much more fully than economic costs. Principle 15 of the document declares that, “In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation” (The Rio Declaration, 1992). It is clear from this that the authors envisioned a situation such as climate change where absolute scientific certainty could never be attained. Given that circumstance, nations must act to use appropriate means to counter environmental damage (Davies, 2009). This clearly supports the ideas of conservation, pollution reduction, and mitigation, but also seems to lend some support to geoengineering (Davies, 2009). The authors may not have considered a situation where there exists even greater uncertainty in the scientific consensus regarding measures to stop environmental degradation. Some are likely to read the Rio Declaration as supportive of geoengineering, while others are just as likely to believe the opposite. Taken to the next level, the incorporation of nanotechnology applies even greater uncertainty to that which already exists for geoengineering. Given the largely unknown environmental effects of nanoparticles, even more severe threats of serious or irreversible damage from climate change would be required to legitimize breaking the precautionary principle.

The Rio Declaration also addresses ethical issues of concern for transboundary issues related to the ‘good neighbor principle.’ States shall work in the spirit of global partnership to protect the world’s ecosystems, avoid unilateral action addressing environmental issues outside their jurisdiction, seek consensus when taking international environmental action, and notify other states prior to actions which may have significant transboundary environmental effects (The Rio Declaration, 1992). Applied to NanoGeo action, the Rio Declaration then indicates that any action should seek international consensus and be undertaken by a global partnership. However, if a state were to act alone, it would be the responsibility of that party to give prior and timely notice to the world community and avoid at all costs negative environmental effects.

The Rio Declaration does not explicitly mention ‘nanotechnology’ or ‘geoengineering’, making relevancy to NanoGeo questionable. However, NanoGeo by principle is a global action with transboundary actions and effects. Also, if the particle used in a NanoGeo scheme were classified as an air pollutant, the Declaration would have bearing on spread and distribution. It can be argued that the Declaration has little effectiveness given worsening global environmental conditions, climate change as a very prominent example. This problem may be closely tied to the lack of real enforcement mechanisms within the Declaration. Parties “shall cooperate in good faith and in a spirit of partnership in the fulfillment of the principles embodied” in the Declaration, leaving no substantive punishment for parties which may break or ignore the principles (The Rio Declaration, 1992).

4.3.2 UNFCCC

The United Nations Framework Convention on Climate Change (UNFCCC) was created as an “overall framework for intergovernmental efforts to tackle the challenge posed by climate change.” The Convention set the beginning framework for countries to: 1) gather and share

information on GHG emissions, 2) launch national strategies for addressing GHG emissions and their expected impacts, and 3) cooperate in preparation for adaptation. The Convention entered into force on March 21, 1994 after the fiftieth nation ratified it. To date, 193 countries including the United States have ratified the agreement (UNFCCC Website, 2010).

Closely related to the UNFCCC is the Kyoto Protocol which entered into force on February 16, 2005. To date, the Protocol has been ratified by 184 nations; the United States was a signatory of the Protocol in 1998 but has not ratified the agreement. Binding GHG emission reduction targets are set for 37 industrialized countries and the European community. The primary distinction between the two agreements is that the Protocol *commits* industrialized countries to stabilize and reduce GHG emissions, whereas the UNFCCC *encourages* them to do so voluntarily and sets the process for more binding protocols (Kyoto Protocol Website, 2010).

The UNFCCC mentions economic issues in its text. It explicitly recognizes that “various actions to address climate change can be justified economically in their own right,” which appears to address low-cost backstop techniques like NanoGeo. Article 3 also advances the concept that “policies and measures to deal with climate change should be cost-effective so as to achieve global benefits at the lowest possible cost,” leaving the possibility that NanoGeo may be just such a measure (UNFCCC, 1992). Like the Rio Declaration, the UNFCCC also recognizes economic disparities between developed and developing countries, laying out the importance of burden sharing amongst developing nations and the goal of developed nations assisting developing nations with financial resources, such technology transfer and grants. Some have argued that geoengineering options might transform the greenhouse gas issue from a complicated regulatory regime to that of a simple international cost-sharing problem within the UNFCCC or a derivative protocol (Keith, 2000).

The Convention is principally written in an attempt to combat anthropogenic climate change. To address this global risk, it invokes the responsibility of nations to prevent transboundary harm from their own activities. The precautionary principle is also invoked so that lack of scientific certainty does not deter action. Ethically, generational equity is to be considered in the protection of the climate for future generations (UNFCCC, 1992).

Like the Rio Declaration, ‘nanotechnology’ and ‘geoengineering’ are not explicitly mentioned in the text of the document. However, some argue that subsequent protocols to Kyoto or closely related Intergovernmental Panel on Climate Change (IPCC) assessment reports should look at geoengineering options and incorporate them into mainstream mitigation discussions (Victor, et al., 2009). Article 7 endorses the evaluation of measures that enhance the removal of GHG gases from the atmosphere, which would apply to some forms of geoengineering, such as ocean sequestration, but not NanoGeo specifically. As previously mentioned, the UNFCCC provides a means for international agreements on measures to reduce emissions, but it does not explicitly address measures taken to mitigate effects, such as NanoGeo (Davies, 2009).

While the UNFCCC prompted many nations to adopt the Kyoto Protocol, targets within the Protocol have not been met by many nations and talks on a subsequent protocol have been disappointing (Svoboda, 2008). The Convention was in part hampered by its lack of effective enforcement. A Convention of the Parties was created as the supreme body of the document, but this is largely an administrative entity. Article 14 lays out the process for the settlement of disputes between parties through negotiation or other peaceful means. A party can submit a dispute to the United Nations International Court of Justice, participate in an arbitration process outlined, or request the creation of an arbitration commission. In the case of an arbitration commission, a judgment rendered must be considered in good faith by all parties (UNFCCC,

1992). Though an enforcement process is outlined in the document, the UNFCCC is a noncommittal agreement without specific targets or quantifiable goals, making it difficult to bind parties to either action or inaction.

4.3.3 CLRTAP

The Convention on Long-range Transboundary Air Pollution (CLRTAP) is the first legally binding international agreement to deal with air pollution on an inter-nation basis. It entered into force in 1983 after the twenty-fourth state ratified it. The beginnings of CLRTAP date back to the 1960s when it was demonstrated that sulfur emissions in continental Europe were related to Scandinavian lake acidification. Between 1972 and 1977 several scientific studies confirmed conclusively that air pollutants could travel thousands of miles before depositing on land or in water. Additionally, these studies concluded the primary causation of acidification in Scandinavian lakes was from particular polluting regions. Because of these studies and the start of international cooperation on this issue at the 1972 United Nations Conference on the Human Environment in Stockholm, high level meetings at the ministerial level were held in 1979 in Geneva. The resulting Convention was signed by 34 governments and the European Community and has since been amended by eight specific protocols that add additional air pollutants and binding agreements. The Convention now has been ratified by 51 nations, including the United States in 1981 (CLRTAP Website, 2010).

The Convention makes little mention of economic costs associated with transboundary air pollution. In Article 7, Section A, the Parties agree to cooperate in research and development of reduction strategies for air pollutants including economic feasibility. As stated in Article 8, Section D, the Parties are also responsible for exchanging information pertaining to projected costs of emissions controls at the national level (CLRTAP, 1979).

Risk is given slightly more attention with the acknowledgement of parties to limit, gradually reduce, and prevent as much as possible detrimental environmental effects to other nations resulting from transboundary air pollution (The Royal Society, 2009). These environmental impacts will be studied further through research on the effects of major air pollutants on “human health and the environment, including agriculture, forestry, materials, aquatic and other natural ecosystems...,” as stated in Article 7, Section D (CLRTAP, 1979). In Article 9, Section H, the Parties also agree to emphasize the need to monitor chemical components in water, air, and vegetation, and further monitoring programs regarding the effects on health and the environment.

Very few additional ethical principles other than risk-based principles are explicitly outlined in the Convention. The Preamble recognizes the Declaration of the United Nations Conference on the Human Environment, which lays forth a set of ethical principles. More specifically, Principle 21 of the Declaration is acknowledged, which states that states have a sovereign right to their own resources, but also a responsibility to ensure that their actions do not affect harm upon their neighbors (CLRTAP, 1979).

The Convention has a potentially high level of relevancy to NanoGeo. In particular, NanoGeo as a global project would cross national boundaries, which violates the central tenet of the Convention (Davies, 2009). NanoGeo may be less likely to be in violation of the Convention than sulfur aerosol methods of geoengineering as engineered particles are not explicitly mentioned in the Convention; sulfur compounds are often explicitly referred to as pollutants within the language of the Convention and are the historical impetus for the agreement (CLRTAP, 1979). A case could be made for the distribution of nanoparticles in the stratosphere being “air pollution” as defined by the Convention and thus under the jurisdiction of an existing

protocol or a new protocol tailored specifically to NanoGeo. According to Article 1, “air pollution” is defined as “the introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment” (CLRTAP, 1979). Furthermore, “long-range transboundary air pollution” is defined as “air pollution whose physical origin is situated wholly or in part within the area under the national jurisdiction of one State and which has adverse effects in the area under the jurisdiction of another State...” (CLRTAP, 1979). By these definitions, NanoGeo from one state is likely to fall under the purview of the Convention, as NanoGeo is likely to have detrimental effects upon different populations and ecosystems as previously mentioned, and is likely a global action not contained within a single nation’s borders.

The effectiveness of the Convention can be called into question since it has only been ratified by a small portion of the world community, 51 nations. As it was originally intended to address a regional issue in Europe, many nations are not covered by the Convention’s obligations. The Convention has been effective in bringing attention to transboundary environmental issues, such as air pollution, but emissions of many varieties of air pollutants continue to be a problem around the world. Language within the Convention does not clearly lay out repercussions for parties found to be in violation of the agreement, other than agreement to seek a solution through negotiation.

Similar to the UNFCCC, CLRTAP spawned eight protocols that are binding and more enforceable, but they may not have the broad reach to potentially include NanoGeo as they are specific to particular specified air pollutants or classifications (CLRTAP Website, 2010). However, working groups that are responsible for the organization and oversight of particular

protocols may see fit to include NanoGeo within a pre-defined classification and thus seek enforcement over any breach.

4.3.4 The ENMOD Convention

The Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques (ENMOD) entered into force on October 5, 1978 after the twentieth state ratified the Convention. The ENMOD Convention was largely a response to the efforts of the US and Soviet Union during the Cold War to use weather and climate as tools of warfare. The United States and the Soviet Union held bilateral talks and sought to forge an agreement so that neither superpower would be likely to attempt weather modification for military purposes. The two country's delegations to talks in 1976 agreed to a draft text, which was then forwarded to the United Nations General Assembly for consideration. In the fall of 1976, the General Assembly debated and subsequently adopted the resolution, thus sending it to nations for ratification. The Convention entered into force for the United States on January 17, 1980 upon the Senate's unanimous consent and the president's signature (State Department ENMOD Website, 2010).

ENMOD is perhaps the most referenced treaty pertaining to geoengineering – and NanoGeo by extension – in literature (Victor, et al., 2009) (Keith, 2000) (Davies, 2009) (Ricke, et al., 2008) (Svoboda, 2008) (Kintisch, 2009) (Davis, 2009).

Little mention is made of economic considerations in the body of the treaty. In Article V, Section 5 it is stated that parties to the convention are to provide assistance to another state if the Security Council decides that the state has been or may be harmed due to treaty violations. (ENMOD, 1977) Although this does not explicitly state financial assistance, it seems reasonable to presume this would be appropriate. ENMOD also makes little mention of ethical principles or

concerns. The Understanding Related to Article III states that the Convention does not deal with questions pertaining to whether or not peaceful weather modification techniques are in accordance with generally recognized principles and rules of international law (ENMOD, 1977). This illustrates that peaceful actions of NanoGeo may or may not violate ethical principles expressed elsewhere like in the Rio Convention; regardless, this treaty does not delve into that area.

ENMOD does little to identify particular risks attributable to weather modification, but it does identify the potential for these in broad principles. Within the preamble, the Parties to the Convention recognize that scientific and technical advances may open up new possibilities of weather modification (ENMOD, 1977). One such advance is NanoGeo, as this paper explores. Also within the preamble, the Declaration of the United Nations Conference on the Human Environment is recalled, a document that deals with environmental risks and concerns. Additionally, the preamble recognizes that hostile weather modification “could have effects extremely harmful to human welfare” (ENMOD, 1977). The Understanding Relating to Article II recognizes phenomenon that could be related to environmental modification, such as the “upset in the ecological balance of a region”, but nothing is said about what these particular risks or ramifications may be (ENMOD, 1977).

ENMOD is a highly relevant document to NanoGeo, because it appears to recognize the presence of peaceful weather modification techniques and their potential benefits to society. The preamble states that the parties to the Convention recognize that peaceful environmental modification techniques “could improve the interrelationship of man and nature and contribute to the preservation and improvement of the environment for the benefit of present and future generations” (ENMOD, 1977). Though this language is likely recognition of small-scale cloud

seeding activities that modify weather, it leaves open the door to many other methods. To address exactly what is meant by “environmental modification techniques,” Article II provides a definition which includes deliberate modification of the atmosphere’s dynamics, composition, and structure, which applies to the basic functioning of NanoGeo (ENMOD, 1977). Article III explicitly states that this Convention “shall not hinder the use of environmental modification techniques for peaceful purposes...,” which would apparently give the legal go ahead for NanoGeo, or at least not prevent it (ENMOD, 1977). Furthermore, the Understanding Relating to Article I provides definitions for the terms “widespread,” “long-lasting,” and “severe,” in which environmental modification is defined as encompassing an area at least several hundred square kilometers, lasting at least a season, and involving serious or significant disruption to natural resources (ENMOD, 1977). This wording is comparable to Keith’s definition that “geoengineering is defined as intentional large-scale manipulation of the environment” (Keith, 2000). Other authors, including those of the IPCC95 report, also conclude that these definitions in conjunction with ENMOD may set relevant precedent to covering geoengineering (Davis, 2009) (Keith, 2000). It should be noted, however, that ‘geoengineering’ is never explicitly referenced by name in the document (Davies, 2009). And lastly, the Understanding Relating to Article II recognizes that changes in climate patterns are an example of phenomenon that could be caused by environmental modification techniques, which is exactly what NanoGeo attempts to accomplish (ENMOD, 1977).

ENMOD was effective because most nations agreed that Agent Orange should not be used due to its potential harm to the environment. In response to environmental modification efforts by the US and Soviet Union mentioned previously and further suggestions by some scientists that nuclear explosions could create an advantageous field of warfare, the international

community came together to roundly condemn these practices (Robock, 2008). However, it is possible that the treaty itself was not effective, but that the idea of weather modification lost traction because of a string of experimental failures (Victor, et al., 2009). Some argue that the treaty itself is weak and ineffective, regardless of whether weather modification for war could work (Ricke, et al., 2008).

The Convention has yet to be tested, making it difficult to determine exactly how enforcement action would be taken. Article V, Section 3 states that any party which feels that the Convention has been violated may lodge a complaint with the UN Security Council as a sanction (ENMOD, 1977) (Ricke, et al., 2008). Article IV also states that each party to the Convention should take measures it deems necessary to prohibit and prevent any violations of the Convention under its jurisdiction (ENMOD, 1977). This seems to imply that states must take responsibility for breaches of the Convention within their borders, which may include individuals. This Article partially addresses the concern that NanoGeo might be undertaken by an individual that has the will and means, but who is not held to a specific international agreement prohibiting their actions. The state would arguably be responsible for that individual's actions. Others disagree with this assessment, believing that the Convention does not explicitly enough cover individual actors to address this possibility (Svoboda, 2008).

4.3.5 Summary

Table 4 provides a comprehensive summary of the criteria applied to each of the four identified international governance mechanisms. Based upon the preceding discussions, a judgment was made by this author on how well each mechanism applied to each criterion. Each mechanism was judged to have High (H), Medium (M), or Low (L) applicability to the six criteria identified pertaining to the unique characteristics and circumstances of NanoGeo.

Table 4 - Criteria Assessment of International Governance Mechanisms

		The Rio Declaration	UNFCCC	CLRTAP	ENMOD
Criteria	<i>Economics</i>	L	L	L	L
	<i>Risk</i>	H	L	M	M
	<i>Ethics</i>	H	L	L	L
	<i>Relevancy</i>	M	M	H	H
	<i>Effectiveness</i>	L	M	M	M
	<i>Enforcement</i>	L	M	L	M

Note: H=High, M=Medium, L=Low

4.4 Discussion

It is important to note that this UTA is the work of one individual and involved judgment calls of a non-technical expert on a variety of hard to define and anticipatory concerns. A next step would be for a team of international and respected stakeholders to talk about the six criteria – and others which may be identified – and discuss if existing international governance mechanisms apply to NanoGeo. This could set in motion a more serious discussion about the very real possibility of NanoGeo being deployed in the future, or at a minimum tested on a smaller scale, and the need for and appropriateness of international governance regimes.

Several trends emerge from Table 4 that are noteworthy. All four international governance mechanisms contain few provisions for the application of economic concerns for NanoGeo. This means that the economic concerns with NanoGeo, such as its low cost and potential for different economic impacts upon developed and developing countries upon deployment, are unlikely to be adequately addressed. UNFCCC, CLRTAP, and ENMOD contain few references to ethical concerns in general, though the Rio Declaration is a notable exception in this instance. Additionally, there is a less than desirable degree of enforcement contained within each of the four agreements. Part of this concern relates to the fact that enforcement of breaches by parties of treaties usually takes a considerable amount of time, through many different mechanisms as discussed. In the instance of the use of NanoGeo by a nation, it could take a considerable amount of time for a complaint to work its way through the many different levels of dispute resolution. By the time a resolution, if any, could be enforced, NanoGeo may have been occurring for quite some time, years perhaps, and the world may be apprehensive of suddenly stopping this action for fear of unexpected effects.

It is also worth mentioning that all four mechanisms are moderately or highly relevant to NanoGeo. This is primarily the result of UTA methodology used. The mechanisms identified were determined based in part on their prevalence in literature relating to geoengineering. The primary criterion used by most literature and media in identifying potential regulatory mechanisms is relevancy, so we expect to find substantial relevancy here as well. However, if a random sampling had been conducted of all international treaties and declarations, we would obviously expect many mechanisms with little – and mostly no – relevancy to NanoGeo.

From the analysis, it appears that CLRTAP and ENMOD are better suited to address the NanoGeo criteria than the others. Though both make little mention of ethical and economic concerns, they were judged highly relevant to NanoGeo. If a mechanism bears little relevancy to an issue, it is much less meaningful how it addresses other issues such as cost impacts and enforceability. Relevancy could be seen as a gatekeeper criterion in this instance; if a treaty or declaration is not relevant to NanoGeo, the judging of other criteria is largely futile and need not occur. This is also an acknowledgement that not all criterion are weighted equally against each other in this qualitative analysis.

In the particular case of NanoGeo, though ENMOD is highly relevant, it does little to regulate the actual peaceful deployment of such a technology (Kintisch, 2009). By acknowledging the potential benefits of weather and climate modification and making no statement on what would qualify as reasonable or appropriate measures, the Convention does little to contain or regulate peaceful uses. A potential solution would be to modify the ENMOD Convention to cover the prospect of NanoGeo and other peaceful geoengineering methods. Though the Convention does contain provisions for amendments, it seems a poor fit to use an international agreement intended to prohibit a malicious activity as a means to permit a peaceful

one. Some believe that geoengineering as a field is too potentially important to “become the victim of legacy law – of accidentally relevant rules not suited to this new context” (Davies, 2009). Additionally, outright prohibitions on NanoGeo, whether in the context of a modified or new treaty, are likely to be dismissed by the international community, as too little is known about NanoGeo in this emerging field and there is potential need for it in case of a climate emergency (Davies, 2009).

As a fundamentally different international agreement than ENMOD, CLRTAP seeks to regulate, not prohibit, transnational air pollution. In this context, CLRTAP could potentially allow a limited amount of testing and research into NanoGeo if the nanoparticles released were to be classified as “air pollution.” A treaty modification would not be required to encompass NanoGeo, since mechanisms are already set forth to adopt protocols which address the release of certain classifications of pollutants and emissions (CLRTAP Website, 2010). However, any new protocol would be required to be ratified separately by States to the larger Convention. A benefit to seeking regulation from CLRTAP is that a framework for an agreement is already constructed. In this way, the piece-meal approach of CLRTAP, with a Convention and subsequent protocols, may be beneficial in that it could allow NanoGeo research and related issues to mature in pace with regulation.

It may also be possible for NanoGeo to be collectively regulated, through a combination of directive from both ENMOD and CLRTAP. ENMOD would potentially prohibit any nefarious use of NanoGeo, thereby addressing dual-use concerns. Concurrently, CLRTAP would potentially regulate and guide NanoGeo experimentation, if any, by a specific protocol created for just such a novel concept. Looking to CLRTAP for regulation is an acknowledgement of the potentially dangerous side effects of NanoGeo and their distribution between the potential users,

beneficiaries, and victims. In this way, synergy is created between the two international agreements to potentially provide for a responsible and peaceful way forward for a still maturing field.

Instead of treaties in this early stage of technological development in NanoGeo, a possible path forward is a limited international research program. With a controlled way forward, norms are likely to develop among researchers and sponsoring organizations which will dictate responsible development and testing of NanoGeo and other geoengineering forms. Norms are considered “soft” international law, unlike “hard” international law represented by treaties. Though norms and treaties can appear at opposite ends of a law spectrum, effective forms of international governance often contain significant overlap between the two (Davies, 2009). This controlled research and development approach is advocated as a balance between skepticism of NanoGeo’s potential concerns and the very real possibility that it might be desperately needed to stave off climate catastrophe. A “red team” of skeptics would continue to address important NanoGeo questions, while a “blue team” pursues what NanoGeo or geoengineering approaches may work if we need to act quickly (Homer-Dixon & Keith, 2008).

The literature search in UTA for NanoGeo yielded many different proposals for limited, but robust, research into geoengineering. Though many authors concede the very real and important societal concerns may emerge with any form of geoengineering, there appeared to be a broad consensus that an outright ban in whatever form is simply impractical, unenforceable, and, most import of all, potentially disastrous if an unimaginable climate emergency occurs and we are left with no recourse. Some authors have advocated for Russia, the US, China, and Brazil taking leading roles in research due to their size, economic and political clout, resources, and unique climate change issues (Victor, 2008). Some argue for a US-centric research approach

with varying amounts of international cooperation (Robock, 2008). Others advocate for a more centralized international entity, such as the International Council of Science, to be overseen by leading academies, given a substantial budget, and operated with transparency and peer review to be the world's research authority on geoengineering issues (Victor, et al., 2009). To oversee the spectrum of international research, the IPCC or a new, similar organization could synthesize findings. A new protocol under the UNFCCC could then be created based upon the assessment of this synthesizing organization (Barrett, 2008).

There is a lack of strong literature in the form of skeptics pertaining to NanoGeo. As research and experimentation into nanoparticles aerosols has yet to occur, and the field of geoengineering itself is only beginning to enter the mainstream lexicon, it is perhaps not surprising that there is little sign of alarmist reaction. During this paper's exploration of NanoGeo literature, no substantive mention of detrimental effects particularly pertaining to nanotechnology and geoengineering was ever discovered. In this sense, very little outrage has been found, though it may be reasonable to expect if experimentation were to begin. As evidenced by the international condemnation of the Lohafex and Planktos experiments, the chorus of naysayers will likely grow stronger in time as more information pertaining to specific experimentation of NanoGeo is developed and released.

It is quite likely that the world will begin more serious conversation about the promises and perils of using geoengineering in the near future to combat the growing threat of climate change. Additionally, the continued maturation of nanotechnology presents those who wish to combat climate change through geoengineering another set of tools and techniques that may enhance their abilities. With both concepts in relative adolescence, many potentially unknown threats and benefits loom, magnified all the more by their mutual existence. Scientific research is

just beginning to technically explore the marriage of these two powerful forces, while little is being done to address the potential environmental affects and the related international governance and ethical issues. This paper has evaluated the societal concerns and potential of four international governance regimes to address them. It is a starting point to what needs to be a larger and more inclusive international societal effort to anticipate and prepare for NanoGeo.

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