Feasibility of Space-Based Monitoring for Governance of Solar Radiation Management Activities

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Substantive research has begun into proposed schemes to synthetically increase the earth's albedo (reflectivity) as a potential improvised measure to mitigate impacts of global warming if emission reductions are not sufficient or if the climate response is more extreme than anticipated. The authors of this paper do not take a position on whether Solar Radiation Management (SRM) should be used as a strategy to respond to climate change. However, future international agreements regarding development, testing, and implementation of SRM schemes will not be enforceable without effective means of monitoring and verification, especially since the relatively low cost of injecting reflective particles such as sulfur into the upper atmosphere will allow individual nations - perhaps even private corporations or other groups - to experiment on their own. This paper discusses monitoring requirements and the feasibility of space-based remote-sensing systems for detecting and monitoring particle injection into the upper atmosphere. Our preliminary findings suggest that detecting clandestine unilateral small-scale precursor particle-injection with satellite instruments may not be practical. This conclusion suggests that future treaty negotiations will need to consider alternative means of monitoring such activities.

Nomenclature

AC	=	Angstrom Coefficient
AE	=	Angstrom Exponent
AEC	=	Aerosol Extinction Cross-section
AI	=	Aerosol Index
AOT	=	Aerosol Optical Thickness
APS	=	Aerosol Polarimetry Sensor
ASD	=	Aerosol Size Distribution
ASP	=	Aerosol Size Parameter
BC	=	Backscatter Cross-section
PBALH	=	Planetary Boundary & Aerosol Layer Heights
SSA	=	Single Scatter Albedo
CALIOP	=	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	=	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CNES	=	Centre National d'Études Spatiales (French Space Agency)
ENMOD	=	Environmental Modification Convention
EOS	=	Earth Observing System
ESA	=	European Space Agency
GOES	=	Geostationary Operational Environmental Satellite
MODIS	=	Moderate Resolution Imaging Spectroradiometer
mT	=	metric ton
POES	=	Polar Operational Environmental Satellite
SRM	=	Solar Radiation Management
UARS	=	Upper Atmosphere Research Satellite

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I. Background

A common misconception in popular culture is that what is meant by “climate change” or “global warming” is just a natural variation in earth’s weather patterns. However, evidence shows that humans have enjoyed relatively stable temperatures for the last ten thousand years. It is worth noting that during the last ice age (about 20,000 years ago) when sheets of ice covered the Pacific Northwest, average global temperatures were only about 4 degrees Celsius (or about 7 degrees Fahrenheit) cooler than today. During the 20th century the increase in average global temperatures was about 0.6 degrees C, or 1 full degree F. The rate and duration of warming of the 20th century has been much greater than in any of the previous nine centuries, and the current rate of warming is unprecedented in at least 20,000 years.[5] In addition, ice core sample data indicate that the concentration of carbon dioxide in Earth’s atmosphere (currently at about 390 ppm) is higher now than at any time over at least the past 650,000 years.[i] Figure 1 provides a brief overview of the evidence that climates around the world are changing.

Evidence of Global Climate Change:

- increasing average global air and ocean temperatures
- widespread melting of snow and ice
- decreasing average annual Arctic sea ice extent over the last 30 years by:
    - 2.7% per decade in winter
    - 7.4% per decade in summer
- decreasing mountain glaciers and snow cover in both hemispheres
- rising average global sea levels
    - at an average rate of 1.8 mm/year since 1961
- widespread increasing temperatures
    - greatest at higher northern latitudes
    - warming of land regions faster than oceans

Figure 1. Brief Summary of Evidence of Global Climate Change. [ii]

The Environmental and Energy Study Institute reports that, “On February 1st of 2010, the Pentagon presented the current Quadrennial Defense Review to Congress, for the first time including strategic analyses on the effects climate change will have on national security and world conflict. In its review, Pentagon officials stated that, ‘While climate change alone does not cause conflict, it may act as an accelerant of instability or conflict, placing a burden on civilian institutions and militaries around the world.’”[iii]

The objectives of our research project include raising awareness within the National Security Space community regarding the urgency of planning activities in this arena, and assessing the need for potential new space systems to support additional military operations necessitated by global climate change impacts. The focus of this paper is on ways and means of monitoring potential unilateral, possibly clandestine, earth albedo modification (generally referred to as “solar radiation management”) activities.

II. Overview of the Problem

Presently the Earth’s albedo (as measured by the percentage of incoming light reflected back to space) is unintentionally being increased by reflective aerosols from pollution, volcanoes and major forest fires: hence, the so-called “solar dimming” or “global dimming” effect, which offsets some of the warming associated with increased greenhouse gases. This realization was the genesis of the proposed solar radiation management (SRM) strategies, such as injection of small reflective particles (aerosols) into the stratosphere. SRM via particle injection as a stop-gap measure to mitigate the impacts of global warming recently received wide public exposure in several mass market books, such as *SuperFreakonomics* by Steven Levitt and Stephen Dubner (2009)[iv], and *Whole Earth*

[5] World Health Organization, http://www.who.int/en/, cited 25 July 2010.

Discipline: An Ecopragmatist Manifesto by Stewart Brand (2009)[v]. It is estimated that increasing the earth's albedo by just 0.5% would roughly halve the heating effect of a doubled level of atmospheric carbon dioxide.[vi]

As promising as this might appear at first glance, there are many potential downsides. The influence of aerosol and clouds on the earth's climate is currently the largest source of uncertainty in climate models and forecasts, and the uncertainties and risks involved in SRM via particle injection are significant. First, SRM does nothing to reduce greenhouse gas concentrations in the atmosphere, and thus does not address problems such as ocean acidification caused by these gases. Also, by design, SRM via particle injection will almost certainly change the concentration of stratospheric aerosol, which is likely to affect El Niño events,[vii] precipitation and temperature-patterns,[viii,ix] and Asian and African summer monsoon patterns.[x]

Pros and Cons of Solar Radiation Management

PROS

- Stabilize global temperatures
- Reduce/reverse sea ice melting
- Reduce/reverse ice sheet melting
- Reduce/reverse sea level rise
- Potentially increase plant productivity
- Potentially increase terrestrial CO2 uptake
- More colorful (red/yellow) sunsets (?)

CONS

- Unknown and unexpected consequences
- Potential for human error
- Continued ocean acidification
- Worsened ozone depletion
- Less sun for solar power
- Environmental impact of implementation:
  - noise, emissions, pollution, debris, etc.
- Rapid warming probable if discontinued
- Cannot stop effects immediately
- White instead of blue skies
- Commercial control issues:
  - regulation, profit, benevolence, etc
- Potential for military use of technology
- Who decides the "correct" temperature?
- Ruins terrestrial optical astronomy
- Ruins much of satellite remote sensing
- Impacts on respiratory health
- Disruption of monsoons
- Changes/reductions in global precipitation
- Full-scale testing is all but required in order to understand how well SRM will or won't work (including the side effects); but full-scale testing will probably have negative side-effects.
- More acid deposition
- Potentially greater tropospheric (heat-absorbing) cirrus cloud formation
- 100's of millions to 10's of billions of $s per year
- Moral hazard: the prospect of it working reduces incentive for mitigation
- Moral authority: do we have the RIGHT to do this?

Source: Adapted from Alan Robock, *"20 reasons why geoengineering may be a bad idea,"* Bulletin of the Atomic Scientists, Vol. 64, No. 2, pp. 14-19, May/June 2008.

Figure 2. Pros and Cons of Solar Radiation Management.[xi]

SRM via particle injection may also disrupt the global hydrological cycle in unforeseen ways or damage the ozone layer. After the Mount Pinatubo volcanic eruption in 1991 spewed 20 million tons of sulfur dioxide into the atmosphere, the ozone layer was temporarily depleted and rainfall decreased, particularly in the tropics.[xii] In addition, plants respond differently to higher CO2 levels (typically with increased growth), so the combination of these factors could alter the balance among species in terrestrial ecosystems. Furthermore, after an extended period, if SRM were abruptly stopped, the climate would be likely to warm rapidly, with potentially severe consequences. Figure 2 summarizes the pros and cons of Solar Radiation Management.

Reaching a global consensus on the use of SRM is likely to be difficult, since in a future climate-challenged world, some countries stand to gain or lose more than others. At the local level, for example, artificial rainmaking increases rainfall in one area at the expense of others, effectively ‘stealing’ rain. Currently there is no international legal framework specifically applicable to governing SRM activities, and many commentators have warned that a single state or a “coalition of the willing” could unilaterally employ SRM.[xiii,xiv,xv] One reasonable fear is that a country or other organization may begin experimenting with SRM, even at the risk of adversely affecting neighboring nations or the planet as a whole. Ideally, any experimentation with SRM should be based on a global consensus on what strategy to pursue and how activities are to be conducted and monitored.

In this paper we focus on the most commonly proposed SRM technique which involves lofting particulate-forming sulfur dioxide, aluminum oxide or other types of reflective particles into the stratosphere. We offer no opinion as to whether SRM is feasible or necessary; such questions are the subject of an intense ongoing debate with moral, political and economic dimensions. A recent Novim report outlined a research agenda aimed at reducing the uncertainty surrounding the benefits and risks associated with Shortwave Climate Engineering (stratospheric aerosol injection in particular). The report posed the following questions about monitoring requirements related to measuring the impact of intervention activities on climate:

(1) What monitoring capabilities are required to confidently detect and assess the impacts of stratospheric aerosol intervention?
(2) What monitoring capabilities presently exist to meet these requirements, and what new capabilities are needed?
(3) When can the new capabilities be developed and deployed?
(4) How far in advance do the monitoring capacities need to be operational to provide the necessary calibration and background data?[xvi]

Our main objective in this paper is to perform a preliminary investigation of the space-based monitoring requirements for detecting and tracking the injected particles. In addition to the concerns outlined in the Novim report, we are also concerned with the source and the fate of the particles themselves.

Existing space-based sensors are currently used to measure various characteristics of aerosols, and more advanced sensors have been proposed that might play a role in monitoring future particle injection activities. We undertook the task of determining performance requirements for space-based monitoring systems to detect small-scale SRM development and testing activities, which might be in violation of future treaties restricting unsanctioned development activities.

III. Particle Injection Schemes

Proposed means for lofting particles into the stratosphere include large-caliber naval guns, rockets, balloons, tethered hoses, or aircraft. Manufactured “nanostructure particles” might be able to use photophoretic lift to reach the mesosphere. (Photophoresis is the process whereby small particles suspended in gas or liquid move when illuminated by a sufficiently intense beam of light, typically away from the light source.)

Lofting the particles to an altitude of 20 km might be sufficient; particles at that altitude would be transported vertically by the equatorial upwelling and then distributed throughout the stratosphere. Lofting to 30 km or more may be required if greater particle density over the Arctic is necessary to compensate for downwelling in the polar stratosphere.[xvii] The residence time of natural particles in the stratosphere is only about 1 to 2 years, while engineered nanostructure particles might persist for up to 10 years at higher altitudes.[xviii]

According to Dr. Philip Rasch of the National Center for Atmospheric Research: “Nonlinear (and not fully understood) processes determine the efficiency of forming particles of the proper size.” If, as Dr. Rasch and his colleagues suggest, particle injection efficiency may be inherently quite low, this fact alone would greatly increase the cost of such a project.[xix] Thus, a country or other organization developing particle injection capability will need to conduct extensive developmental testing in order to maximize the efficiency of particle injection and minimize the cost of a full-scale injection campaign.

Even though particle injection development testing could be conducted at small scales, some researchers suggest that the only way to determine actual climate impacts may be to perform a full-scale test. Similarly, extrapolating from single pulses of particles injected from volcanic eruptions may not be a realistic analog for more gradual, continuous injection of particles. For example, with continuous injection, hydrological cycles will have more time to settle into new, stable patterns.[xx,xxi,xxii,xxiii]

IV. Monitoring Requirements

A monitoring system to detect unsanctioned particle injection tests (as part of a broader program of SRM governance) has certain aspects in common with current systems for monitoring arms control agreements, specifically in the area of nuclear weapons testing. Requirements for data access and dissemination, redundant verification means, reliability and operational control issues will need to be considered along with technical sensor requirements. Geo-political constraints and possible funding mechanisms are also important considerations.[6]

Full scale particle-injection SRM would deploy a huge quantity of particles, which would be easy to detect, but by then it would be too late to diplomatically intervene to stop. The ability to detect small scale unilateral tests indicating that a nation or other organization is trying to develop the capability for particle-injection SRM would provide the international community more options for intervening or possibly deterring unilateral unsanctioned activities altogether.

Precursor tests with natural particles like sulfur or aluminum oxide may be conducted for the purposes of designing and optimizing the methods for dispensing (guns, rockets, balloons, hoses, aircraft, etc.) and for studying particle clumping and dispersion and persistence characteristics. (Unlike nuclear tests, which can be conducted underground, such tests would need to be deployed in the stratosphere in order to be relevant.)

Even if SRM experiments and development tests are conducted on a small scale with minimal risk, detecting such experiments will be important in order to enforce international control and oversight since early experiments would be precursors to larger experiments, which could be dangerous and/or politically disruptive. For sanctioned tests, which are announced and coordinated in advance, ground and aircraft-based sensors will be sufficient for monitoring; however, such tests could afford a prime opportunity for testing and calibrating space-based sensors.

As a worst case, experimenters might deliberately try to avoid detection, either by timing injections to avoid satellite coverage, or by other means such as using weather patterns or another type of particle to mask particle signatures. Small amounts of self-levitating engineered nanostructures of the type described by Keith might be very difficult to detect, but the high-tech manufacturing process would probably be difficult to conduct clandestinely, and some particles would eventually rain out and be detected from ground samples.

The challenge with trying to determine the requirements of a monitoring system is that a wide range of unknowns exist. They include:

- type of material released (precursor gases or metallic particles?)
- particle size
- amount released
- release altitude
- release/dispersal mechanism and area over which this is done (initial density)

In addition, the physical process of dispersion itself in the stratosphere is highly variable. As an example of this variability and uncertainty, estimates of eddy diffusivity in the stratosphere values in the literature can vary by more than an order of magnitude.[xxiv]

To better understand the requirements for particle injection monitoring, a notional particle injection release scenario is considered:

A small clandestine test might involve the delivery and release of 1 to 10 metric tons (mT) of precursor gases or man-made particles via a fighter sized aircraft or other means. Releases of much smaller levels are also possible, as it is expected that these tests would consist of a series of missions, building up in size and complexity. It is also expected that these experiments would be accompanied by close support observational aircraft. To detect this type of an unannounced test (which could be conducted anywhere in the globe), there would have to be full time, near

[6] Alan Robock's Congressional testimony on Geoengineering, 13 December 2009.

continuous monitoring to detect anomalous aerosols or particles in the stratosphere. The aerosol cloud would not be expected to stay around together more than a few hours at detectable levels (the detectable level will vary greatly depending on background and sensor technique used) before dispersing. The maximum size of the aerosol cloud at those levels might be on the order of a few kilometers. The high wind speeds and shear prevalent in the stratosphere mean that the aerosol cloud may get transported hundreds of kilometers downwind while getting 'shredded' in filaments. As a rough quantitative example, 1 mT of sulfur released over an initial volume of 10^7 m^3 is estimated to have a mean particle density of 1000 particles/cm^3 in about an hour and 100 particles/cm^3 in 10 hours. This calculation assumes horizontal eddy diffusivity value of 100 m^2/s and vertical eddy diffusivity value of 0.1 m^2/s. These concentration values of course will change greatly depending on the parameter values and the modeling technique assumed, and will be refined in a follow up paper.

As the test sizes get bigger, the detection and monitoring problem becomes easier, and the planned co-operative tests greatly reduce the temporal and spatial coverage requirements, so requirements for those missions are subsumed by the small clandestine mission requirements.

V. Detection of Particulate Injection from Space

Although we focus on the need for monitoring for small, clandestine tests, there are 3 mission areas for space monitoring related to SRMs of which the above mentioned monitoring for treaty violation is just one. A second mission is to follow the fate of the particles after the release to improve understanding of the dispersion processes. A third mission is to understand the climatic impact of these tests which requires longer term environmental observation. The latter two missions would need to be performed either in support of an open and coordinated experiment or a clandestine one. The functional requirement for the first two missions are similar, as they involve the capability to sense the presence, location, density, type and size distribution of particles in the stratosphere. The third mission requirements are broader in that they are looking for direct and indirect impact on the environment as a whole, although many of the same sensors and space platforms will be capable of performing all of the missions. For the purposes of this paper, we will include the consideration of the first and second mission requirements described above.

The purpose of most of these tests would be to better understand the mechanics of effectiveness of the particles in bringing about change in albedo. Specifically, the following experimental objectives are assumed:

- demonstrate the particle or precursor gas delivery mechanism
- observe aerosol formation and growth rates
- observe particle dispersion characteristics
- observe particle vertical spreading and motion
- observe evolving particle size distribution and location
- observe particle attitude (for certain types of particle schema)
- measure albedo levels
- support associated model validation and analysis

From a space sensor requirements point of view, these translate to the ability to quantify aerosol optical depth or extinction coefficients in the stratosphere as a function of wavelength, from which estimates of particle number density and size distribution can be derived. Spectral information will also be used to discern particle material type. Specialized algorithms will have to be developed (most likely from ground-based reference test data) to differentiate particle shapes, particle attitudes, and material types. Since there is currently quite a bit of uncertainty around the retrieval process for these derived parameters from the directly observed radiance and backscatter measurements, a significant research program would have to be in place (to substantiate the baseline science and engineering, and to establish confidence in the retrieval methodologies) for the functional system to produce actionable results.

Detection of an aerosol cloud in the stratosphere (not related to a major volcanic eruption) would be a good indication of human intervention. With the exception of volcanic aerosols, and some noctolucent and polar stratospheric clouds associated with specific polar regions and seasons, natural clouds generally do not extend into the stratosphere. Thus the ability to accurately determine the altitude of an aerosol layer would be critical, but not sufficient for determining its origin. For example, depending upon the latitude, jet aircraft do fly above the tropopause. So especially at higher latitudes, it may be difficult to distinguish normal jet contrails and cirrus clouds from a particle injection scheme. Another challenge is that because observed instantaneous aerosol optical depth values can change by a factor of two or more from day to day, only very large spikes in sensor measurements would flag man-made particle injections.

The required sensor revisit rate, spatial resolution and measurement accuracy required for accurate geolocation all depend upon the dispersal rate and other characteristics of the aerosol tests, especially during the first minutes to hours of injection. Other critical parameters to monitor (in addition to ambient conditions) are particle size distribution and spatial distribution as the plume spreads out.

The types of space-based sensors that would be most effective in detecting intentionally injected aerosols are passive multispectral imagers, both reflective and emissive, and active laser-based sensors or lidars. These two types of sensors have complementary advantages and deficiencies and would need to be used in combination in order to be most effective.

For sensors with nadir viewing geometry, such as NASA's MODIS, the combination of background clutter and relatively short column depths makes it difficult to detect and characterize aerosol concentrations with low optical depths (i.e., less than or equal to 0.1 – 0.3). Even thin high cirrus clouds, consisting of rather large ice crystals, are difficult to detect or measure with these instruments.

Solar occultation sensors (which view the earth's atmosphere tangentially against the backdrop of the sun as it sets or rises) are significantly more sensitive to small aerosol concentrations as a result of very long viewing path lengths. However, viewing is limited to times and regions correlating to occultation events, resulting in spotty coverage for any given orbital pass. In addition, horizontal resolution and geolocation capabilities are poor due to the sensing geometry.

Active lidar sensors, such as the Cloud-Aerosol Lidar with Orthogonal Polarization instrument (CALIOP), on board NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) spacecraft, can detect aerosol layers with higher sensitivity than the nadir looking passive sensors, and provide accurate aerosol heights and horizontal positions. In particular, the low background density in the stratosphere (< 10 particles/cm^3 at 20km[xxv]) means that even fairly diffuse particles can be detected with lidars.

One of the challenges in detecting injection tests lies in distinguishing intentionally injected particles from naturally occurring particles. There may be some spectral, polarization or geometrical behavior peculiarities that would allow for their differentiation. For instance, non-spherical particles tend to depolarize the scattered photons from a polarized light source. Thus, if the scattered signals are resolved polarimetrically, lidar sensors can provide some information regarding the shape of the aerosols present.

The main disadvantages of using lidar sensors are a small field-of-view and requirement for relatively high-power lasers. For example, CALIOP's footprint on the ground is only 100m wide, resulting in a 16-day revisit time, far too long for a single spacecraft to accomplish the monitoring mission considered in this paper.

Currently there is interest from NASA and others in increasing significantly the footprint of an orbiting lidar sensor. This will likely mean an increase in laser power, allowing the beam to be either spread out or split into multiple spots while maintaining sufficient power density for high sensitivity. While high power solid-state and fiber lasers have been demonstrated on the ground, considerable development will be required to qualify any of these approaches to meet the challenging requirements for use in space.

The mission to detect particulate injection will require both passive and active sensors. For example, a suite of sensors consisting of visible and thermal multispectral imagers; a long-wave (5-12 micron) hyperspectral imager for chemical resolution and detection; a passive solar occultation spectrograph; and a multi-wavelength, polarization sensitive, wide swath (~10 km x 0.5 km) lidar system might be typical.

Detection of a particle injection test would require extensive analysis of the temporally and spatially co-located passive multispectral sensor data and lidar data. However, even with very advanced spacecraft-based sensor systems, detection of the small tests would be difficult given the background noise and infrequent revisit rate of a single spacecraft. A large constellation of spacecraft would reduce the revisit time, but the huge cost of such a system weighed against the risk-benefit analysis of quickly detecting a small particle injection test is likely to be a non-viable proposition. Due to the high level of uncertainty and the lack of background reference data set, it is likely that the detection, identification and monitoring function for actionable treaty purposes will need to be shared and cross checked by several assets.

Our preliminary analysis suggests that detecting tests of particle injection schemes from space will be quite challenging, especially for unannounced small-scale, localized injections of particles with short term observables.

Figure 3 (below) lists various spacecraft hosting sensors capable of monitoring global aerosol properties.

VI. Conclusion

International governance of potential SRM activities needs to be established soon, to deter unilateral experimentation with particle injection. The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) Treaty, the Convention on Biological Diversity, the United Nations Framework Convention on Climate Change, the Montreal Protocol on Substances that Deplete the Ozone Layer, and the Long-Range Transboundary Air Pollution Convention and others[xxvi] may serve as models for a governance framework and a binding international treaty that prohibits unilateral and potentially dangerous application of SRM.[xxvii,xxviii]

To detect and hopefully deter unsanctioned SRM development activities will require monitoring systems that can reliably detect early test phases involving relatively small amounts of particles. Our preliminary finding is that reliable detection of small clandestine tests from space will be very challenging. This preliminary finding has important implications in future treaty negotiations, which may need to consider alternative methods of monitoring such activities. As with nuclear test monitoring, detecting clandestine particle-injection experiments and development activities will require a combination of techniques and involving extensive ground, space and other means. However, given the strong need for improved understanding of the role of aerosols in the stratosphere, as well as for applications such as the monitoring of volcano dust for airline safety, the impetus may exist for the development of a multifunction system of space-based sensors.

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Spacecraft	Sponsor Orgn	Purpose	Instrument	Sensor Type
POES	NOAA	stratospheric aerosols	AVHRR	Advanced Very High Resolution Radiometer
CALIPSO	NASA-CNES	stratospheric aerosols	CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CloudSat	NASA	stratospheric aerosols	CPR	Cloud Profiling Radar
Earthprobe	NASA	tropospheric aerosols; volcanic SO2; AI	TOMS	Total Ozone Mapping Spectrometer (UV)
EnviSat	ESA	SO2, tropospheric & stratospheric trace gases	SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
EOS-Aqua	NASA	atmospheric, land & ocean imaging; stratospheric aerosols	MODIS	Moderate resolution Imaging Spectroradiometer
EOS-Aqua	NASA	atmospheric temperature, moisture, trace gases; SO2	AIRS	Atmospheric InfraRed Sounder (spectrometer)
EOS-Aura	NASA	AOT; SSA; SO2; O3	OMI (Ozone Monitoring Instrument)	hyperspectral UV-Visible spectrometer
EOS-Terra	NASA	atmospheric, land & ocean imaging; stratospheric aerosols	MODIS	Moderate resolution Imaging Spectroradiometer
EOS-Terra	NASA	atmosphere; volcanology; AOT; AE; SSA; ASD;ASP	MISR	Multi-angle Imaging SpectroRadiometer
GLORY	NASA	distinguish natural from man-made aerosols in atmosphere	APS	Aerosol Polarimetry Sensor
GOES	NOAA/NASA	weather & atmosphere; stratospheric aerosols	VISSR	Visible Infrared Spin Scan Radiometer
ICESat	NASA	PBALH; AOT; AEC; BC	GLAS	Geoscience Laser Altimeter System
Meteosat Second Generation (MSG)	ESA	SO2; ice	SEVIRI	Spin Enhanced Visible and InfraRed (rapid-scan, multispectral) Imager
Odin	Sweden/CSA	NO2; aerosols	OSIRIS (Optical Spectrograph & InfraRed Imaging System)	IR limb scanner
SeaStar	NASA	AOT; AC	SeaWiFS	Sea-viewing Wide FOV Sensor
UARS	NASA	atmospheric concentration profiles of various chemicals such as HCl and SO2	MLS	Microwave (Atmospheric) Limb Sounder

LEGEND:
AC: Angstrom Coefficient; AE: Angstrom Exponent; AEC: Aerosol Extinction Cross-section; AI: Aerosol Index; AOT: Aerosol Optical Thickness; ASD: Aerosol Size Distribution; ASP: Aerosol Size Parameter; BC: Backscatter Cross-section; PBALH: Planetary Boundary & Aerosol Layer Heights; SSA: Single Scatter Albedo

Figure 3. Atmospheric Monitoring Spacecraft with Aerosol Sensors. [7, xxix]

References

[i] "New evidence extends greenhouse gas record from ice cores by 50 percent, adding 210,000 years," American Association for the Advancement of Science, 24 November 2005, URL: http://www.eurekalert.org/pub_releases/2005-11/aaft-nee111805.php [cited 25 July 2010].

[7] NASA, NOAA, & ESA websites (http://www.nasa.gov, http://www.noaa.gov, http://www.esa.int), cited 25 July 2010.

[ii] *Summary for Policymakers of the Synthesis Report of the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report*, IPCC Plenary XXVII, 1-23, Valencia, Spain, 2007.

[iii] “Pentagon Ranks Global Warming as a Destabilizing Force,” *Climate Change News*, Environmental and Energy Study Institute, 8 February 2010, URL: http://www.eesi.org/ccn_020810#7 [cited 25 July 2010].

[iv] Levitt, S., and Dubner, S., *SuperFreakonomics*, Harper Collins, New York, 2009.

[v] Brand, S., *Whole Earth Discipline: An Ecopragmatist Manifesto*, Viking Penguin, New York, 2009.

[vi] Crutzen, P.J., "Albedo Enhancement by Stratospheric Sulfur Injections: A contribution to resolve a policy dilemma?" *Climatic Change*, Vol. 77, 2006, pp. 211-219.

[vii] Adams, J.B., Mann, M.E., and Ammann, C.M., “Proxy evidence for an El Niño-like response to volcanic forcing,” *Nature*, Vol. 426, 20 Nov. 2003, pp. 274-278.

[viii] Rasch, P.J., Tilmes, S., Robock, A., Oman, L., and Stenchikov, G.L., “An overview of geoengineering of climate using stratospheric sulphate aerosols,” *Phil. Trans. Royal Soc. A.*, Vol. 366, pp. 4007-4037, 2008.

[ix] Trenberth, K.E., and Dai, A., “Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering,” *Geophysical Research Letters*, Vol. 34, 5 pp., 2007.

[x] Robock, A., Oman, L., and Stenchikov, G.L., “Regional Climate Responses to Geoengineering with Tropical and Arctic SO2 Injections,” *Journal of Geophysical Research*, Vol. 113, 15 pp., May 2008.

[xi] Robock, A., “20 reasons why geoengineering may be a bad idea,” *Bulletin of the Atomic Scientists*, Vol. 64, No. 2, pp. 14-19, May/June 2008.

[xii] "Mt. Pinatubo's cloud shades global climate," *Science News*, Science Service Inc., 1992, URL: http://www.thefreelibrary.com/Mt.+Pinatubo's+cloud+shades+global+climate.-a012467057 [cited 25 July 2010].

[xiii] Barrett, S., “The Incredible Economics of Geoengineering,” *Environ Resource Econ*, Vol. 39, pp. 45–54, 2008.

[xiv] Victor, D.G., “On the regulation of geoengineering,” *Oxford Review of Economic Policy*, Vol. 24, Issue 2, pp. 322–336, 2008.

[xv] *Climate Change: Preliminary Observations on Geoengineering, Science, Federal Efforts, and Governance Issues*, GAO Report, GAO-10-546T, March 18, 2010.

[xvi] Blackstock, J.J., Battisti, D.S., Caldeira, K., Eardley, D.M., Katz, J.I., Keith, D.W., Patrinos, A.A.N., Schrag, D.P., Socolow, R.H., and Koonin, S.E., *Climate Engineering Responses to Climate Emergencies*, Novim Report, 2009, archived online at http://arxiv.org/pdf/0907.5140 [cited 25 July 2010].

[xvii] Keith, D., "Photophoretic levitation of aerosols for geoengineering," *Geophysical Research Abstracts*, Vol. 10, EGU2008-A-11400, 2008.

[xviii] Hoffman, R., “Controlling the global weather,” *Bulletin of the American Metrological Society*, Vol. 83, No. 2, pp. 241-248, February 2002.

[xix] Rasch, P.J., Tilmes, S., Robock, A., Oman, L., and Stenchikov, G.L., “An overview of geoengineering of climate using stratospheric sulphate aerosols,” *Phil. Trans. Royal Soc. A.*, Vol. 366, pp. 4007-4037, 2008.

[xx] Soden, B.J., Wetherald, R.T., Stenchikov, G.L., and Robock, A., "Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor," *Science*, Vol. 296, No. 5568, pp. 727-730, April 2002.

[xxi] Matthews, H.D., and Caldeira, K., “Transient climate-carbon simulations of planetary geoengineering,” *Proceedings of the National Academy of Sciences (PNAS)*, Vol. 104, No. 24, pp. 9949-9954, 2007.

[xxii] Crutzen, P., “Albedo Enhancement By Stratospheric Sulfur Injections: A Contribution To Resolve A Policy Dilemma?” *Climatic Change*, Vol. 77, No. 3-4, pp. 211–219, August 2006.

[xxiii] Teller, E., Wood, L., and Hyde, R., "Global Warming and Ice Ages: Prospects for physics based modulation of global change," Lawrence Livermore National Laboratory, Report UCRL-JC-128715, Livermore, CA, Aug 15, 1997.

[xxiv] Legras, B., Joseph, B., and LeFevre, F., “Vertical diffusivity in the lower stratosphere from Lagrangian back-trajectory reconstruction from ozone profiles,” *J. Geophysical Research*, Vol. 108, Issue D18, pp. ACL 1-1, 2003.

[xxv] McLinden, C. A., McConnell, J.C., McElroy, C.T., and Griffioen, E., “Observations of stratospheric aerosol using CPFM polarized limb radiances,” *J. Atmos. Sci.*, Vol. 56, pp. 233–240, 1999.

[xxvi] Virgoe, J., “International Governance of a possible geoengineering intervention to combat climate change,” *Climatic Change*, Vol. 95, No. 1-2, pp. 103-119, July 2009.

[xxvii] “Geoengineering’s Governance Vacuum: Unilateralism and the Future of the Planet,” Report prepared by ETC Group for the U.S. National Academies Workshop: *Geoengineering Options to Respond to Climate Change: Steps to Establish a Research Agenda,* Washington, D.C., June 15-16, 2009.

[xxviii] Cheney, G., *They Never Knew: The Victims of Nuclear Testing*, Impact Books, Danbury, CT, 1996.

[xxix] Belsma, L., “Satellite Data for the Air Quality Forecaster,” *U.S. EPA’s 2004 National Air Quality Conference: Your Forecast to Breathe By*, Baltimore, MD, 2004 [online archive],
URL: http://www.epa.gov/airnow/2004conference/monday/satellitedata.pdf [cited 3 August 2010].