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

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ABSTRACT

Substantive research has begun into proposed schemes to synthetically increase the earth's albedo 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 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, & implementation of SRM schemes will not be enforceable without effective means of monitoring & 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 & the feasibility of space-based remote-sensing systems for detecting & monitoring particle injection (PI) in the upper atmosphere.

Our preliminary findings suggest that detecting clandestine unilateral small-scale precursor PI with satellite instruments may not be practical. This conclusion suggests that future treaty negotiations will need to consider alternative means of monitoring such activities.

Pentagon, Congress, & President Acknowledge Strategic Importance of Climate Change Impacts

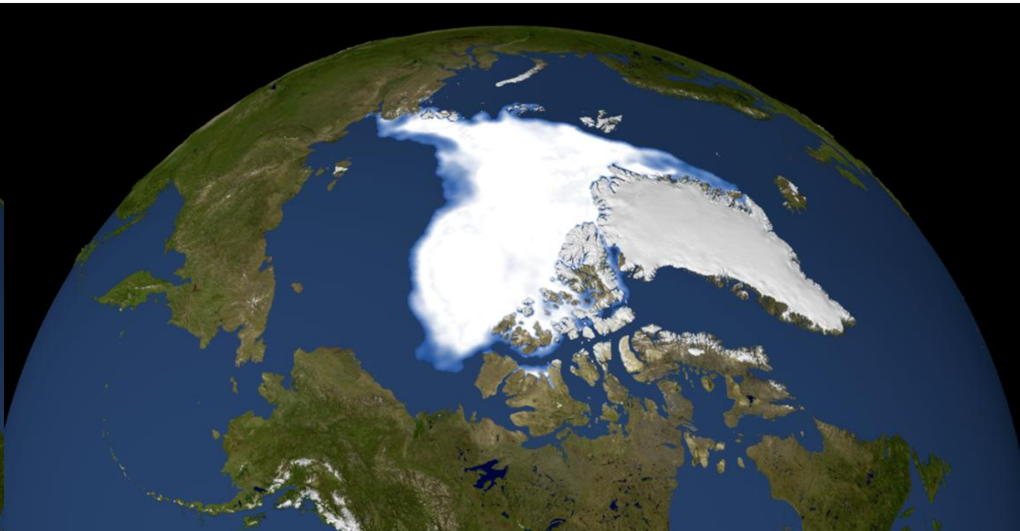
- Congress now requires the Quadrennial Defense Review (QDR) & the National Intelligence Estimate (NIE) to address impacts of Global Warming
- ***2007:*** CNA Think-Tank Study on “National Security & the Threat of Climate Change”
- ***2008:*** National Defense University conducted a wargame simulation of destructive flooding in Bangladesh
- ***2009:*** National Security Presidential Directive requires DoD to:
  “…develop greater capabilities & capacity, as necessary, to protect United States air, land, & sea borders in the Arctic region…
- ***2010*** (QDR): “Pentagon Ranks Global Warming as a Destabilizing Force”

Arctic Ice Melting 3 times faster than predicted by original IPCC models

September 1980

(photos reprinted courtesy of NASA-GSFC)

September 2007



Space-Based Monitoring for Deterrence of Unilateral Solar Radiation Management ("Geoengineering")

- Particle injection (PI) schemes to cool Earth might be conducted <u>unilaterally</u>
    - *Russia has already conducted small scale tests*

- International agreements are being proposed, but will not be enforceable w/o effective means of detection & verification
    - *Especially since the relatively low cost of injecting reflective particles such as sulfur into the upper atmosphere allows individual nations - even private corporations or other groups - to experiment on their own*

- To detect, & hopefully deter, unsanctioned SRM development activities will require monitoring systems that can reliably detect early test phases involving relatively small amounts of particles

- **The authors do not take a position on whether SRM should be used as a strategy to respond to climate—our study looks only at the feasibility of detecting unsanctioned SRM testing and development activities**

Solar Radiation Management

- *Earth's albedo is increasing* due to reflective aerosols from pollution, volcanoes & forest fires
  → *this offsets some of the warming associated w/ increasing GHGs*
- This realization spawned proposed *solar radiation management* (SRM) strategies
  → *e.g., injection of aerosols into the stratosphere*
- 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 CO2*

As promising as this might appear at first glance, there are many potential downsides.

- The influence of *aerosol & clouds* on earth's climate is currently the *largest source of uncertainty in climate models & forecasts*
  - *Meanwhile the uncertainties & risks involved in SRM via particle injection (PI) are also significant.*
- SRM does nothing to reduce atmospheric GHG concentrations, & thus does not address these issues:
  - *ocean acidification*
  - *altered plant growth*
  - *disruption of ecosystems through species imbalance*
- SRM via PI will change the concentration of stratospheric aerosol, very likely impacting:
  - *El Niño events*
  - *precipitation & temperature patterns*
  - *Asian & African summer monsoon patterns*
  - *the global hydrological cycle*
  - *Earth's ozone layer*

Finally, if on-going SRM were abruptly stopped,
the climate would likely warm rapidly, w/ potentially severe consequences.

Pros & Cons of SRM

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 CO_2 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.

International Governance of SRM

- Reaching global consensus on the use of SRM will likely be difficult
  - *in a future climate-challenged world,*
    some countries stand to gain or lose more than others

- For instance, artificial rainmaking increases rainfall in one area at the expense of others
  - *effectively 'stealing' rain*

- No international legal framework specifically applicable to governing SRM activities exists
  - *a single state or a "coalition of the willing" could unilaterally employ SRM*

- A country or other organization may begin experimenting w/ SRM
  - *at the risk of adversely affecting neighboring nations or the planet as a whole*

- Any experimentation w/ SRM should be based on global consensus on:
  - *what strategy to pursue & how activities are to be conducted & monitored*

Particle Injection (PI) Schemes

- Proposed means for lofting particles into the stratosphere:
  - *large-caliber naval guns*
  - *rockets*
  - *balloons*
  - *tethered hoses*
  - *aircraft*
  - *manufactured "nanostructure particles" may use photophoretic lift*

- An altitude of 20 km might be sufficient
  - *particles there would be transported vertically by the equatorial upwelling, & then distributed throughout the stratosphere*
- An altitude of 30 km or more may be required
  - *if greater particle density over the Arctic is necessary to compensate for down-welling in the polar stratosphere*

- Residence time in the stratosphere:
  - *natural particles: only ~ 1 to 2 yrs*
  - *engineered nanostructure particles: possibly up to 10 yrs at higher altitudes*

- Inherently low particle injection efficiency would greatly increase project cost.
  - *Extensive developmental testing will be necessary to maximize the efficiency of PI & minimize the cost of a full-scale injection campaign.*

- The only way to determine actual climate impacts of SRM may be to perform a full-scale test.
  - *For instance, w/ continuous full-scale injection, hydrological cycles will have time to settle into new, stable patterns.*

Novim's 4 Research Questions Provide Context for our Study

1. What monitoring capabilities are required to confidently detect & assess the impacts of stratospheric aerosol intervention?

2. What monitoring capabilities presently exist to meet these requirements, & what new capabilities are needed?

3. When can the new capabilities be developed & deployed?

4. How far in advance do the monitoring capacities need to be operational to provide the necessary calibration & background data?[1]

Our objectives:

- *Perform preliminary investigation of space-based monitoring requirements to detect & track injected particles.*
- *Beside Novim's questions, we are concerned w/ the source & fate of the particles themselves.*

[1]*Climate Engineering Responses to Climate Emergencies,* Novim Report, 2009, archived online at http://arxiv.org/pdf/0907.5140 [cited 25 July 2010].

Monitoring System Requirements

- A monitoring system to detect unsanctioned PI tests has aspects in common w/ systems for monitoring arms control agreements. Requirements for data access & dissemination, redundant verification means, reliability, & operational control issues need to be considered alongside technical sensor requirements.
- Full scale SRM via PI would deploy an easily detectable quantity of particles, but by that stage it would be too late to diplomatically intervene. The ability to detect small scale tests indicating that some entity is trying to develop the capability for SRM via PI would provide the int'l community more options for intervening, or possibly deterring unilateral unsanctioned activities altogether.
- Precursor tests w/ natural particles (e.g. sulfur or aluminum oxide) may be conducted for the purposes of designing & optimizing the methods for dispensing, as well as for studying particle clumping, dispersion, & persistence characteristics.
- For sanctioned tests (announced & coordinated in advance), ground & aircraft-based sensors will be sufficient for monitoring; however, such tests could provide a prime opportunity for testing & calibrating space-based sensors.
- As a worst case, experimenters might try to avoid detection, by timing injections to avoid satellite coverage, or by using weather patterns or another type of particle to mask identification. Small amounts of self-levitating engineered nanostructures might be very difficult to detect, but the high-tech mfg process would be difficult to hide, & some particles would rain out & be detected from ground samples.
- The biggest challenge w/ trying to determine the requirements of a monitoring system is the wide range of unknowns, such as:
  - *type of material released (precursor gases or metallic particles?)*
  - *particle size*
  - *amount released*
  - *release altitude*
  - *release/dispersal mechanism & area over which this is done (initial density)*
- In addition, the physical process of dispersion in the stratosphere is highly variable.
  - *For instance, estimates of eddy diffusivity in the stratosphere can vary by more than an order of magnitude.*

A Notional Particle Injection Test Scenario

- A small clandestine test might involve the delivery & 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 smaller levels are also possible, as these tests would likely consist of a series of missions, growing in size & complexity.

- These experiments would likely be accompanied by close support observational aircraft.

- Detecting small, unannounced tests anywhere on the globe would require nearly continuous monitoring to recognize anomalous aerosols or particles in the stratosphere.

- The resulting aerosol cloud would not be expected to last more than a few hours at detectable levels before dispersing.

- The maximum size of the aerosol cloud at those levels might be on the order of a few km.

- High wind speeds & shear prevalent in the stratosphere mean that the aerosol cloud may get transported hundreds of km 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 & 100 particles/cm^3 in 10 hours, assuming horizontal eddy diffusivity value of 100 m^2/s & vertical eddy diffusivity value of 0.1 m^2/s.

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

Detection of Particulate Injection from Space

- We envision 3 potential space monitoring missions:
  - *Missions 1 & 2 both involve the functional capability to sense the presence, location, density, type & size distribution of particles in the stratosphere:*
    - 1st mission: treaty compliance monitoring for small, clandestine tests
    - 2nd mission: follow particles after release to improve understanding of the dispersion processes
  - *Mission 3 involves longer term environmental monitoring to understand the climatic impact of these tests*
    - many of the same sensors & space platforms will be capable of performing all of the missions.

- At this time we are mainly concerned w/ type 1 & 2 missions,
  - *& w/ discovering the 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 & growth rates*
  - *observe particle dispersion characteristics*
  - *observe particle vertical spreading & motion*
  - *observe evolving particle size distribution & location*
  - *observe particle attitude (for certain types of particle schema)*
  - *measure albedo levels*
  - *support associated model validation & analysis*

Space-Based Sensor Requirements

- These test objectives will require sensors able to quantify aerosol optical depth (AOD) or extinction coefficients in the stratosphere as a function of wavelength.
  - *From these measurements, estimates of particle # density & size distribution can be derived.*
  - *Spectral data will also be used to discern particle material type.*
  - *Specialized algorithms will have to be developed to differentiate particle shapes, particle attitudes, & material types.*
  - *Since there is quite a bit of uncertainty around deriving these attributes from the directly observed radiance & backscatter measurements, significant research will be needed in order 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.
  - *Ability to accurately determine the altitude of an aerosol layer would be critical but not sufficient for determining its origin.*
  - *Depending upon the latitude, jet aircraft do fly above the tropopause.*
  - *At higher latitudes, it may be difficult to distinguish normal jet contrails & cirrus clouds from a PI scheme.*

- Another challenge is that b/c observed instantaneous AOD 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 injection tests.

- The required sensor revisit rate, spatial resolution & measurement accuracy required for accurate geolocation all depend upon the dispersal rate & other characteristics of the aerosol tests, esp during the first minutes to hours of injection.

- Other critical parameters to monitor (in addition to ambient conditions) are particle size distribution & spatial distribution as the plume spreads out.

Types of Space-Based Sensors

- The most effective sensors for detecting particle injection aerosols are:
  - *passive multispectral imagers, both reflective & emissive*
  - *active laser-based sensors or lidars*
  - *these two sensor types have complementary advantages & deficiencies*
  - *need to be used in combination in order to be most effective*
- Sensors w/ nadir viewing geometry, such as NASA's MODIS:
  - *combination of background clutter & relatively short column depths makes it difficult to detect & characterize aerosol concentrations w/ low optical depths (i.e., less than or equal to 0.1 – 0.3)*
- Solar occultation sensors are much more sensitive to small aerosol concentrations as a result of very long viewing path lengths.
  - *But viewing is limited to times & regions correlating to occultation events, giving spotty coverage for any given orbital pass.*
  - *Also, horizontal resolution & geolocation capabilities are poor due to the sensing geometry*
- Active lidar sensors, such as CALIOP on board NASA's CALIPSO spacecraft
  - *can detect aerosol layers w/ higher sensitivity than the nadir looking passive sensors*
  - *provide accurate aerosol heights & horizontal positions*
  - *low background density in the stratosphere means that even fairly diffuse particles can be detected w/ lidars*
- One challenge in detecting PI 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 differentiation*
  - *For instance, non-spherical particles tend to depolarize the scattered photons from a polarized light source*
  - *So if scattered signals are resolved polarimetrically, lidar sensors can provide data re the shape of the aerosols present*
- The main disadvantages of using lidar sensors:
  - *small field-of-view*
  - *requirement for relatively high-power lasers*
  - *e.g., CALIOP's footprint on the ground is only 100m wide, resulting in a 16-day revisit time*
    - *far too long for a single s/c to accomplish this monitoring mission*
- Interest from NASA & others in increasing the footprint of an orbiting lidar sensor
  - *considerable development will be required to meet the challenging requirements for use in space*
- The mission to detect PI will require a suite of both passive & active sensors. For example:
  - *visible & thermal multispectral imagers;*
  - *a long-wave (5-12 micron) hyperspectral imager for chemical resolution & detection;*
  - *a passive solar occultation spectrograph;*
  - *a multi-wavelength, polarization sensitive, wide swath (~10 km x 0.5 km) lidar system*

Atmospheric Monitoring Spacecraft w/ Aerosol Sensors

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

Notional Mission Requirements for Detection or Support of Particle Injection SRM at a Range of Scales

	MISSION TYPES				
	Detect unannounced Test (Small)	Detect unannounced Test (Big)	Support planned Localized Test	Support Planned Subscale Test	Support Operational System
Scale	small (1-10 mT)	med (10mT~100mT)	med (10mT~100mT)	large (100mT~1000mT)	Large (10^6 mT)
Deployment	Single	Single	Single	Single to Several	Massive
Observation needs	Full time continuous global monitoring Detect anomalous aerosol levels	Full time continuous global monitoring Detect and type aerosol	target region over few days Detect, particle size and distribution	Detect aerosol properties and albedo also long term effects and other side effects (ozone, etc)	Full time global monitoring aerosol properties and albedo
Revisit time	hours	~day	hours	~day	days
Coverage	full globe	full globe	local region	full globe	full globe
Mission duration	continuous	continuous	series of days	continuous	continuous
Detection levels	10 particle/cm^3	100 particles/cm^3	10 particles/cm^3	100 particles/cm^3	10 particles/cm^3
Minimum resolution	1 km	10 km	1 km	10 km	10 km
Assessment	Response timeline requires dedicated system (existing systems with resolution cannot provide full coverage)	Probably a satellite similar to one of the current systems could do it	Probably a satellite similar to one of the current systems could do it	Probably would mobilize existing assets, plus launch many new ones, especially to detect unintended consequences	Probably would mobilize existing assets, plus launch many new ones, especially to detect unintended consequences

Findings

- Detection of a particle injection test would require extensive analysis of the temporally & spatially co-located passive multispectral sensor data & lidar data.

- However, even with very advanced spacecraft-based sensor systems, detection of the small tests would be difficult given the background noise & 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 PI test is likely to be a non-viable proposition.

- Due to the high level of uncertainty & the lack of background reference data set, it is likely that the detection, identification & monitoring function for actionable treaty purposes will need to be shared & cross checked by several assets.

Conclusions

- International governance of potential SRM activities needs to be established soon, to deter unilateral experimentation w/ 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, & the Long-Range Transboundary Air Pollution Convention & others may serve as models for a governance framework & a binding int'l treaty that prohibits unilateral & potentially dangerous application of SRM.

- To detect & 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 w/ nuclear test monitoring, detecting clandestine particle-injection experiments & development activities will require a combination of techniques & involving extensive ground, space & 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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