An Initial Evaluation of Geoengineering by Al_2O_3 Injection

SESSION C45, Poster TH190A Contact: weisenstein@aer.com

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1. Introduction

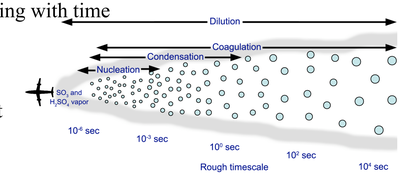
Geoengineering by injection of sulfur into the stratosphere is among the most promising methods of solar radiation management techniques under consideration [Royal Society, 2009]. **However, recent studies** [Heckendorn et al., 2009; Pierce et al., 2010] **indicate that injections of sulfur sufficient to counteract a doubling of CO_2 would have significant adverse consequences, including tropopause heating, stratospheric water vapor increases, and ozone depletion. Alumina (Al_2O_3) particles are more efficient scatterers than sulfate particles and here are investigated for application to geoengineering. However, unlike sulfate, alumina emission has no analog in the natural stratosphere and thus may present unique and unknown risks. We provide an initial evaluation of Al_2O_3 particle evolution in a jet plume, and a sensitivity study of the impact of Al_2O_3 particles on stratospheric ozone. Even assuming that the surface area density of Al_2O_3 is smaller by factors of 5-10 than that generated by sulfate geoengineering, we find that ozone depletion is unacceptably large.**

2. Modeling Approach

Expanding Plume Model for Emission into Aircraft Wake

References: ***Pierce and Adams*** **[2009], Pierce et al. [2010]**

- Needed for emission of condensable gases such as H_2SO_4 or alumina vapor
- Plume radially symmetric, expanding and entraining with time
- TOMAS aerosol microphysics with 43 sections: nucleation, condensation, coagulation
- All sulfur condensed within minutes, only coagulation, expansion, entrainment act after that
- Follow plume for ~2 days until coagulation with background particles becomes important
- Final size distribution depends on emission rate and plume expansion rate only



4. Al_2O_3 Aerosol Properties and Chemistry

- Efficient shortwave scattering: 4 times greater than sulfate per unit volume
- Reduced IR absorption relative to sulfate: less heating of lower stratosphere
- Al_2O_3 could be dispersed behind aircraft by condensation of combusted alumina, as occurs in solid rocket motor plumes
- Measurements show [Karasev et al., 2004] that such particles consist of micron-sized fractal aggregates of nanometer-size primary particles.
- Fractal geometry characterized by R_g (radius of gyration) and fractal dimension f_d, where aggregate mass is proportional to R_g^{fd}
- Measured f_d=1.6 for Al_2O_3 [Karasev et al., 2004], $1.5 < f_d < 1.9$ for soot [Maricq, 2006]
- Plume model of Pierce et al. [2010] modified to perform coagulation of fractal particles, assuming primary particle diameter D_o of 10, 30, or 50 nm and fractal dimension f_d of 1.6, 2.3, or 30. Results of plume model are shown in Figure 3.

- **Heterogeneous reaction on Al_2O_3: $ClONO_2 + HCl \rightarrow Cl_2 + HNO_3$**
  - $\gamma = 0.02$ measured by Molina et al. [1997]
  - Cl_2 rapidly dissociates in sunlight, leading to ozone deletion
- Reaction applied by Danilin et al. [2001] to solid rocket exhaust plumes
  - Calculated 0.0028% global ozone deletion with 1120 tons annual emission
- Fractal particles will have enhanced surface area density relative to spherical sulfate particles, enhancing ozone depletion
- For initial evaluation, we adopt an Al_2O_3 surface area density equivalent to that of 1 MT of SO_2 injected between 30°S-30°N, 20-25 km to represent an equivalent radiative forcing of 5 MT SO_2 injection. Results shown in Figure 4.

5. Snsitivity of Ozone to Al_2O_3 Geoengineering

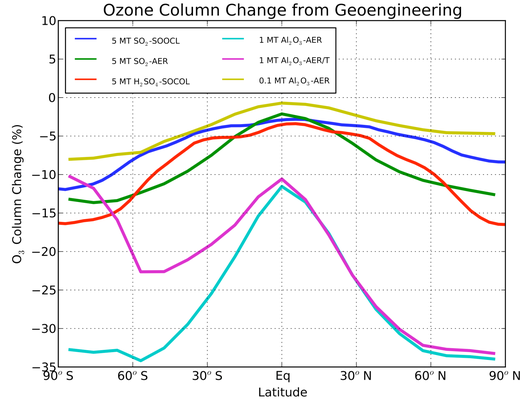
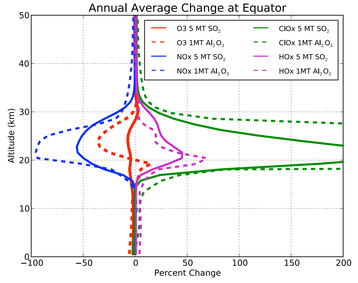
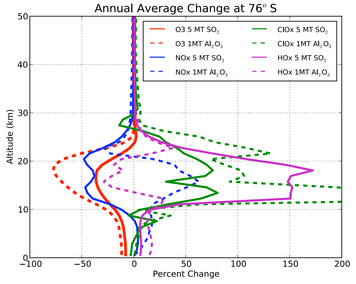


Figure 4. Calculated annual average ozone column changes in percent for several geoengineering cases. Ozone changes calculated by the SOCOL chemistry-climate model are due to changes in aerosol surface area density, changes in stratospheric temperature and circulation, and changes in water vapor and HO_x concentrations. *Heckendorn et al.* [2009] determined that 75% of this ozone loss is due to intensified heterogeneous chemistry caused by the increased aerosol surface area density. Ozone changes calculated by the AER chemistry-transport model are due to changes in aerosol surface area density only. Cases labeled "AER/T" used the temperature field calculated by the SOCOL model which is about 2° colder in the southern polar region. Figures below show changes in annual average O_3, NO_x, ClO_x, and HO_x concentrations at the equator and 76°S.





Global 2-D Sulfate Aerosol Model of AER

References: *Weisenstein et al.* [1997, 2007]

- 40 sectional aerosol size bins, 9.5 degree x 1.2 km spatial resolution
- Microphyscs includes homogeneous nucleation, condensation, coagulation, evaporation, sedimentation
- Sulfur chemistry includes aerosol-gas recycling above 35 km
- Geoengineering input as either SO_2 gas or as particles defined by plume model
- Geoengineering emisssions continuous in time at 30°S-30°N, 20-25 km

Ozone Change Calculations

- *SOCOL 3-D Chemistry-Climate Model* at ETH used for SO_2 and H_2SO_4 geoengineering
  - MA-ECHAM4 dynamics and radiation, combined with MEZON chemistry-transport
  - Ozone changes are due to chemistry, transport, and temperature changes
  - References: Schraner et al. [2008], Heckendorn et al. [2009]
- *AER 2-D Chemistry-Transport Model* used for Al_2O_3 initial evaluation
  - fixed circulation and temperature, full chemistry
  - References: Rinsland et al. [2003], Weisenstein et al. [2004]

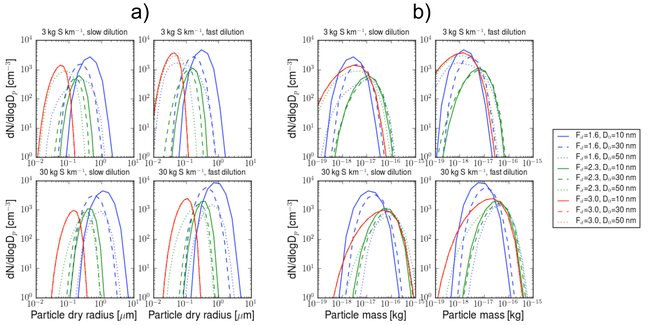


Figure 3. Calculated (a) diameter of gyration and (b) mass distribution of alumina particles 1 day after alumina vapor is sprayed from an aircraft in the stratosphere. The four panels in each figure represent uncertainties in the plume dilution rate and alumina spray rate. The various lines in each panel represent uncertainties in the fractal dimension and the size of the primary alumina particles forming the fractals. The model used for these simulations is the TOMAS microphysics model coupled to an expanding Lagrangian box model [Pierce at al, 2010].

3. Sulfate Geoengineering Results: Burdens, Flux Changes, and Surface Area Density

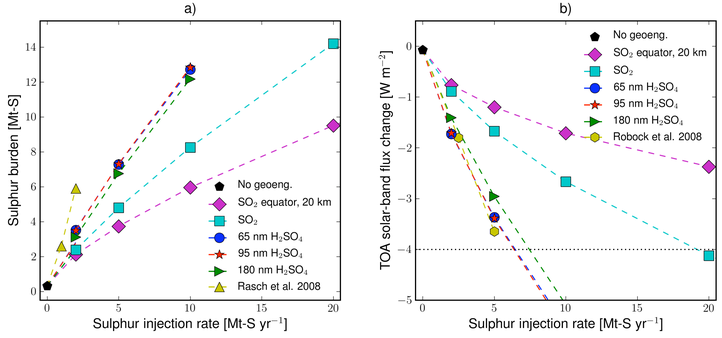


Figure 1. Calculated global annual mean (a) sulfate aerosol burdens, and (b) top-of-atmosphere solar-band flux changes as a function of geoengineering annual emission rate of sulfur, spread from 30°S-30°N, 20-25km. H_2SO_4 emissions are characterized by mode radius after 2 days of plume expansion. SO_2 emission scenarios lead to continuous nucleation and condensation, subsequently growing particles to larger sizes by coagulation and condensation onto ambient particles and yielding fast sedimentation rates and short residence times. Horizontal dashed line in panel (b) represents flux change necessary to counteract a doubling of CO_2.

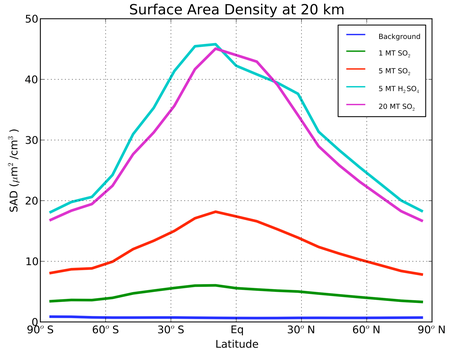


Figure 2. Calculated annual average sulfate aerosol surface area density at 20 km due to geoengineering emissions of SO_2 or of H_2SO_4 with particle mode radius of 95 nm. Emissions of 1, 5, or 20 MT/yr occur continuously in time between 30°S and 30°N and at 20-25 km. H_2SO_4 emissions into an aircraft plume produce much smaller particles than injection of SO_2, hence the greater surface area for equivalent emission rate. The radiative forcing due to a doubling of CO_2 can be approximately offset by either 7 MT/yr of H_2SO_4 emissions or 20 MT/yr of SO_2 emissions. For our sensitivity studies of ozone change due to Al_2O_3 geoengineering, we employ the surface area density of 1 MT/yr of SO_2 emissions.

6. Conclusions

- **Geoengineering is at best a partial solution** to climate change, with many unintended adverse impacts
- **Geoengineering by SO_2 injection** is very inefficient due to particle growth and sedimentation rates
- **Geoengineering by H_2SO_4 injection** into an aircraft wake can better control particle size and make -4 W/m² shortwave flux change achievable
- **Geoengineering by Al_2O_3 injection** appears to produce unacceptably high ozone loss, while ozone loss by SO_2 and H_2SO_4 geoenginerring is also substantial
- **Impacts not explored** here include regional changes in surface temperature and precipitation patterns. Ocean acidification would not be ameliorated by stratospheric aerosol geoengineering.
- Adverse effects of geoengineering should be compared with the climate change resulting from **insufficient CO_2 reductions**
- **Geoengineering research** can lead to better understanding of climate change, human impacts, and volcano-climate interactions

References:

Danilin, M. Y., et al. (2001) global stratospheric effects of the alumina emission sby solid-fueled rocket motors, *J. Geophys. Res., 106,* 12,727-12,738.

Heckendorn, P. et al. (2009) Impact of geoengineering aerosols on stratospheric temperature and ozone, *Environ. Res. Lett.*, 4, 045108.

Karasev, V. V., et al. (2004) Formation of charged aggregates of Al_2O_3 nanoparticles by combustion of aluminum droplets in air, *Combustion and Flame, 138*, 40-54.

Maricq, M. M. (2007) Coagulation dynamics of fractal-like soot aggregates, *Aerosol Science, 38*, 141-156.

Molina, M. J., et al. (1997) The reaction of ClONO2 with HCl on aluminum oxide, *Geophys. Res. Lett., 24*, 1619-1622.

Pierce and Adams (2009) A computationally efficient aerosol nucleation/condensation method: Pseudo-steady-state sulfur acid, *Aerosol Sci. Technol., 42*, 216-226.

Pierce et al. (2010) Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft, *Geophys. Res. Lett., 37*, L18805.

Rinsland, C. P., et al. (2003), Post-Mount Pinatubo eruption ground-based infrared stratospheric column measurements of HNO_3, NO, and NO_2 and their comparison with model calculations, *J. Geophys. Res.*, **108**, 4437, doi:10.1029/2002JD002965.

Royal Society (2009) Geoengineering the climate: Science, governance, and uncertainty, *RS Policy Document 10/09*, The Royal Society, London.

Schraner et al. (2008) Technical Note: Chemistry-climate model SOCOL: version 2.0 with improved transport and chemistry/ microphysics schemes, *Atmos. Chem. Phys., 8*, 5957-5974.

Weisenstein, D. K., et al. (1997), A two-dimensional model of sulfur species and aerosols, *J. Geophys. Res., 102* (11D), 13,019–13,035.

Weisenstein, D. K., et al. (2004), Separating chemistry and transport effects in 2-D models, *J. Geophys. Res.*, 109, D18310, doi: 10.1029/2004JD004744.

Weisenstein, D. K., et al. (2007) Global 2-D intercomparison of sectional and modal aerosol modules, *Atmos. Chem. Phys., 7*, 2339-2355.