Novel Method to Determine the Total Lasting Albedo Effect of Aerosol-Seeded Clouds based on Aerosol Particle Type

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Cloud albedo (reflectivity) is a natural phenomenon that has recently gained much interest because of its potential to initiate rapid global cooling that can reverse anthropogenic warming effects. Cooper et al. (2013) and Crutzen (2006) have proposed multiple methods to artificially seek the skies with aerosol to create clouds and an albedo effect. There has been research on the reflectivity of particles dependent on size by various studies such as Salter et al. (2008), but there has been no definitive research on the effect of cloud duration and the overall albedo of particles over the lifetime of a cloud. This experiment attempts to create a model that simulates a cloud with an aerosol suspension to quantify the overall effects of different common aerosols by measuring the total percentage of light that is reflected before the aerosol deposits for a fixed amount of each solution, aiming to discover trends and deriving formulas based on the results if they are consistent. The model created in this experiment is novel but aims to give realistic values and be scalable to larger cloud volumes. The data collected from three aerosols of interest — a sulfate, carbonaceous, and sea-salt based aerosols — provides evidence that the sea-salt and carbonaceous aerosols have a higher albedo over time than sulfate aerosols and solutions without an aerosol and that this model can be used in a laboratory setting with precise results.

I. INTRODUCTION

Global climate change is perhaps the factor that has the greatest potential to impact the future of the biosphere negatively. With the rate that greenhouse gases (GHGs) are produced and natural systems of recycling carbon dioxide are reduced as forests are cut down, global warming is a significant problem that has steadily grown in the last few decades with the increased consumption of natural gas and oil, as discussed in Wallington et al. (2013). With global warming comes many drastic side effects, many of which are unpredictable and likely will negatively affect ecosystems globally, as Tylianakis (2008) researches. If continued, this will surely cause massive detriment to humankind in general, and this has been the focus of massive focus and research recently.

Some environmentalists suggest that governmental policies should be the solution to the increasing problem. As the government has the authority to regulate industrial activity and business in general, this would seem a possible cause. However, with the great amount of lobbying and the general delay caused by interactions with a bureaucratic giant such as the United States government, other ecologists have opposed this view, deeming it too impractical and gradual to be realized effectively enough to slow or stop global warming.

Social concern over artificial intervention in the environment is another factor to consider when implementing scientific changes to the environment. Any technological solutions to global warming must first overcome societal concerns, such as those considering lasting effects or unintentional side-effects. A solution that will be supported by the common people has to be well-tested to provide just the right degree of global cooling to provide balance without affecting other environmental factors—i.e., negatively affecting the global climate in a different way—and without throwing the Earth into an excessive trend of global cooling or even another ice age.

One interesting solution to the prospect of resolving global climate change is the idea of increasing cloud albedo, or reflective ability, through the use of "stratospheric sulfur injections," as proposed by Crutzen (2005). Crutzen discusses the impact of inserting an aerosol into the atmosphere as CCNs to manually increase cloud density with decreased particle size. The decreased particle size would greatly increase the "Twomey effect" as described in Twomey (1977), in which cloud cover with the same density but smaller particle sizes increases albedo. Crutzen also discusses the better efficiency that this system would have compared to the current political system, in which stabilization of CO_2 would require "a 60–80% reduction in current anthropogenic CO_2 emissions, worldwide they actually increased by 2% from 2001 to 2002 (Marland et al. 2005)" (Crutzen 2005).

Crutzen suggests the use of sulfate aerosols (SO2) into the atmosphere. A significant degree of global cooling is associated with violent volcanic eruptions in which large ejections of sulfate have stayed suspended in the air and diffused globally. For example, the earth cooled on average of about 0.5 ^{o}C globally after the eruption of Mount Pinatubo in 1991 (Crutzen 2005). This half of a degree Celsius may not seem much, but it may offset a considerable amount of the global warming (a temperature increase of 0.85 ^{o}C since 1880 has been attributed to global warming (Stocker et al. 2013)) that has been caused.

However, sulfuric aerosols were not the only item considered for the task. In Leaitch et al. (2010), the use of carbonaceous (carbon-containing) aerosols was tested and received favorable results, with an albedo comparable to that of sulfur. In Cooper et al. (2013), Salter et al. (2008), and Bower et al. (2006), the use of the Marine Cloud Brightening (MCB) model was researched. In these studies, the potential for more practical methods of creating a spray that uses sea salt as the CCN via the deployment of specially outfitted ships. All of these three are tested in this experiment.

Another problem with the introduction of aerosols is not only the dynamic nature of the clouds, but also the inconsistencies of the terrain underneath. The same cloud seeded with an aerosol may provide cooling effects on darker colored, more absorptive geography; but over a patch of glistening ice the same cloud may actually produce a warming effect because it absorbs more light and reflects less than the land below it (Bounoua 2002).

Salter et al. (2008) estimates that only £30 million ($39 million) will be required to create the tools to create the ships necessary for his model—in the scale of global economies, this is a very small number. According to the study, changes are estimated to happen relatively quickly, regulating the global environment perhaps even in a decade from when the spray is initiated.

Another environmental concern is the introduction of anthropomorphic aerosols into the atmosphere. Anomalies like the large volcanic eruptions may have temporarily cooled the Earth's atmosphere, but continuous, large-scale introduction of sulfate and similar aerosols may eventually lead to a source of pollution that will result in environmental harm.

These irregularities and dangers of excessive aerosol usage prompt the need for this experiment. This experiment aims to assess the total albedo effect of multiple types of aerosols over time, which takes into account reflectivity and total lasting time. Knowing to what extent the particles will cool over an extended period of time—rather than simply measuring the albedo in one instant as previous studies have done. Salter et al. (2008) states that the conclusions of the study are based on estimates in fields that have not been researched, one of which is "drop life and dispersion," which is the focus of this study. Because aerosols have a multifaceted influence on cloud physics, such as by changing the microphysics, radiative properties, lifetime and extent of clouds, according to Huang et al. (2007), experimentation is preferred over mathematical calculations based on the aerosol properties.

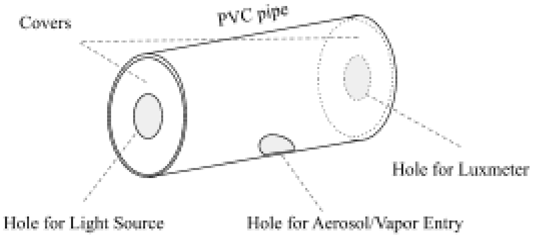
In Cooper et al. (2013), several methods are discussed to create sufficiently small aerosols as CCNs, using the baseline of 0.8μm in diameter, which was the size proposed by Salter et al. (2008), such as commercial nozzle sprayers, toroidal cone sprayer with electrical charging, colliding-jets spraying, ultra-high pressure jet spraying, raleigh-jet spraying through small apertures, electro-spraying from cone-jets with air assist (the same method of spray used in Salter et al. (2008)), and Taylor cone spraying from suspended droplets. However, none of these methods, save the Taylor conejets, were considered practical methods to generate sufficiently small particles. The Taylor conejets are a relatively new method, the study also warns against its usage, citing that no array of the conejets sufficient to create the necessary aerosol spray has ever been created, and that much research is needed in their assembly. Salter et al. (2008) agrees that "the design of an efficient spray generator" is one of the top scientific developments necessary for the MCB to work. As a result, this experiment will use a commercial atomizer that can create particles from equimolar solutions of different aerosols in solution that are approximately 2μm in diameter. While this does not reach the 0.8μm recommended by Salter et al. (2008), Salter mentions that the number of drops matters more to the albedo effect than the mass of the water, and the approximate size should be small enough to generate reasonably-sized, suspendable particles.

II. MATERIALS / METHODS

Device

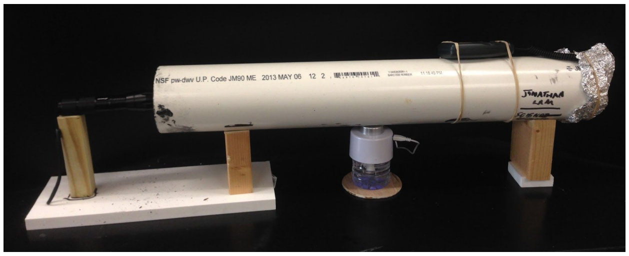
The experimental design was mainly constructed of a large-diameter PVC pipe with holes cut to a snug fit for the devices required. A representation of the design is shown in Figure 1.

Figure 1. Diagram of experimental design



The experimental design was constructed, with two wooden circular covers with diameter 10.2cm cut to fit snugly inside the 11.4cm diameter, 70.0cm length PVC pipe on the ends, and 5.0cm and 5.5cm diameter holes were cut in the centers of these covers: one for the light source and for the luxmeter, respectively. The light source used was a Prosvet XMl-T6 tactical flashlight, the luxmeter was a HongYan LX1010BS 100000 Lux Digital Luxmeter Light Meter, and the humidifier was an ultrasonic Water Bottle Humidifier from WinnerBin. Another 1.0cm diameter hole was cut through the bottom of the PVC pipe in order to allow the entry of the atomized aerosol solution. A stand for the apparatus was constructed to keep the pipe from rolling and to provide proper elevation for the aerosol generator to fit underneath. The cover with the light source was permanently secured with glue to prevent any light from entering. The cover for the luxmeter was removable to allow for cleaning and be covered with a layer of aluminum foil to prevent ambient light from entering. The hole for the aerosol entry had a wax paper lining that could be secured to the nozzle tightly with a rubber band. A photograph of the apparatus is displayed in Figure 2.

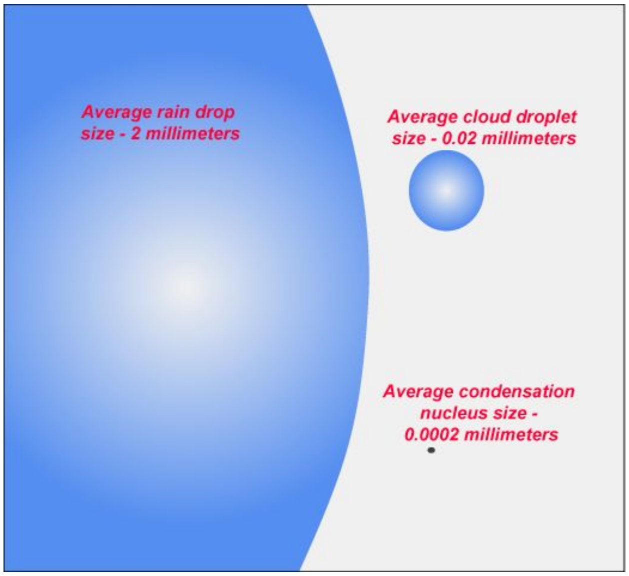
Figure 2. Photograph of experimental design



Solution Preparation

The solutions were prepared for the aerosol suspensions. Since true, dry aerosol particles could not be generated by accessible tools, a mist containing an appropriate ratio of aerosol to water was created. The appropriate ratio of diameters of a cloud droplet size and the condensation nucleus size are 0.02mm:0.0002mm, or a ratio of 100:1 (Atkins), and are represented visually in Figure 3.

Figure 3. Visual comparison of raindrop, cloud droplet and CCN sizes



(Image source: http://apollo.lsc.vsc.edu/classes/met130/notes/chapter5/ccn.html)

The ratio of the radii are equal, according to the following calculation:

$$r_{droplet} : r_{CCN} = \tfrac{1}{2}(100) : \tfrac{1}{2}(1) = 100 : 1$$

The volumes are different by a factor of 100^3.

$$V_{droplet} : V_{CCN} = \tfrac{4}{3}\pi(100)^3 : \tfrac{4}{3}\pi(1)^3 = 1000000 : 1$$

By using the known density values of water and the aerosols, the molarity of H_2SO_4 and the masses of the dry aerosols per liter of solution were calculated. For this experiment, a sulfuric acid (H_2SO_4) stock solution, sea salt (NaCl), and a carbon powder (C) served as the base of the aerosol solutions.

Per every 1.00L of solution, droplet concentration is $\frac{1}{1000000}$ of that volume, which is $1.00 \times 10^{-6} L$.

H_2SO_4:

$$1.00 \times 10^{-6} L \times \frac{184g\ H_2SO_4}{L\ H_2SO_4} \times \frac{mol\ H_2SO_4}{98.08g\ H_2SO_4} = 1.88 \times 10^{-6} M$$

$$\text{NaCl: } 1.00 \times 10^{-6} L \times \frac{216g\ NaCl}{L\ NaCl} = 2.16 \times 10^{-4} gL^{-1}$$

$$\text{C: } 1.00 \times 10^{-6} L \times \frac{225g\ C}{L\ C} = 2.25 \times 10^{-4} gL^{-1}$$

The solutions were prepared using the standard experimental procedure of dilution. For the sulfuric acid, use the equation $M_1 V_1 = M_2 V_2$ to prepare a $1.88 \times 10^{-6} M$ solution from the stock solution. For the dry solutions the respective masses of solution were placed in a volumetric flask and the flask was filled up with water to the 1L mark. However, because the average cumulus cloud density is is approximately $0.5g\ m^{-3}$ (Perlman) and approximating the suspension density to be equal to that of water ($1g \times cm^{-1}$), the total volume of the aerosol suspension should be:

$$1L\ cloud \times \frac{m^3}{1000L} \times \frac{0.5g\ suspension}{m^3\ cloud} \times \frac{cm^3\ suspension}{g\ suspension} \times \frac{L}{1000cm^3} = 5 \times 10^{-7} L\ suspension$$

Therefore, $5 \times 10^{-7} L$ of each aerosol suspension were created to simulate the conditions of a cumulus cloud per liter of cloud (volume of container). Multiply this number by the volume of the apparatus. The volume of the apparatus was calculated using the formula for the volume of a cylinder:

$$V_{container} = \pi r^2 h$$

The solutions were thoroughly mixed.

Data Collection

For the control value, or the total flashlight luminosity, the flashlight was shone directly into the apparatus without aerosol and its brightness was recorded in luxes under "Total flashlight brightness." This is the total amount of light reaching the light sensor, and would be analogous to the sun shining on the Earth without any aerosol suspension (cloud) to reflect light back into space.

Beginning with the sulfate solution, all of the prepared solution was placed into the aerosol generator the spray generator was turned on on. When all of the solution was atomized atomized, a timer was started, the light source was turned on, and the brightness of the reflected light was immediately measured. This number was subtracted from the total flashlight brightness to get the reflected brightness of light. The difference was divided by the total flashlight brightness to get the albedo value. A formula is shown below.

$$a = \frac{b_{total} - b_{measured}}{b_{total}}$$

(such that $b_{measured}$ is the measured brightness in luxes for the experimental trial, b_{total} is the total flashlight brightness, and a is the albedo.)

This process of measuring the reflected light at regular ten-second intervals was repeated until the reflected light has become negligible (within 10% of the control), and results were measured in the sulfate table under the respective elapsed time.

The procedure of measuring the reflected light was repeated with two more identical sulfate samples for trials 2 and 3 for sulfate.

The top panel was removed and the inside of the apparatus rinsed out with water and a wet cloth, before being dried with water. This was performed under a fume hood and carefully to avoid coming in contact with sulfuric acid.

The procedure of measuring the reflected light for the sulfate solution and the cleaning of the container were repeated with the sea salt and carbon aerosol solutions.

A scatter plot of time versus albedo (ratio of reflected light versus total flashlight brightness) was graphed for each material, and an exponential best-fit equation was calculated. Although the results followed a trend that seemed to evidence the data, the data points between trials were prone to large random error (i.e., due to equipment problems). With better equipment, this model and the data collected with this model can be improved upon by other scientists to collect data in a laboratory rather than in the stratosphere, which may be damaging to the environment.

III. RESULTS

CHARTS

Table 1. Raw Control data (H_2O only)

Time since beginning (s)	Measured Albedo		
	Trial 1	**Trial 2**	**Trial 3**
0	0.9502	0.9552	0.9577
10	0.9005	0.8408	0.8942
20	0.8408	0.7861	0.8148
30	0.7960	0.6915	0.7302
40	0.7413	0.6020	0.6296
50	0.6965	0.5323	0.5397
60	0.6418	0.5025	0.4762
70	0.5920	0.4627	0.3704
80	0.5572	0.4279	0.3810
90	0.5174	0.4030	0.3175
100	0.4776	0.3731	0.3228
110	0.4627	0.3682	0.3069
120	0.4428	0.3483	0.2804
130	0.4080	0.3284	0.2381
140	0.3831	0.3184	0.2222
150	0.3632	0.2985	0.2116
160	0.3483	0.2935	0.2063
170	0.3184	0.2886	0.1905
180	0.3035	0.2886	0.1799
190	0.2836	0.2836	0.1693
200	0.2687	0.2836	0.1640
210	0.2587	0.2786	0.1587
220	0.2488	0.2786	0.1534
230	0.2388	0.2736	0.1534
240	0.2338	0.2687	0.1481
250	0.2289	0.2687	0.1481
260	0.2239	0.2687	0.1429
270	0.2239	0.2687	0.1429
280	0.2239	0.2687	0.1376
290	0.2189	0.2687	0.1376
300	0.2189	0.2687	0.1376

Table 2. Raw H_2SO_4 data

Time since beginning (s)	Measured Albedo		
	Trial 1	**Trial 2**	**Trial 3**

0	0.9956	1.000	0.8636
10	0.9476	0.9950	0.8068
20	0.8952	0.9300	0.7273
30	0.8472	0.8750	0.6648
40	0.8035	0.8300	0.5795
50	0.7817	0.7850	0.5000
60	0.7598	0.7500	0.4659
70	0.7424	0.7300	0.4545
80	0.7031	0.7000	0.4375
90	0.6681	0.6900	0.4318
100	0.6419	0.6400	0.4318
110	0.6288	0.6000	0.4148
120	0.6070	0.5800	0.4091
130	0.6070	0.5700	0.4148
140	0.6114	0.5500	0.4091
150	0.5983	0.5450	0.4091
160	0.5895	0.5300	0.4034
170	0.5852	0.5250	0.4034
180	0.5764	0.5200	0.4034
190	0.5677	0.5100	0.4034
200	0.5633	0.5050	0.4034
210	0.5590	0.5000	0.4034
220	0.5546	0.4950	0.4034
230	0.5502	0.4850	0.4034
240	0.5415	0.4800	0.4034
250	0.5371	0.4750	0.4034
260	0.5328	0.4750	0.4034
270	0.5328	0.4700	0.4034
280	0.5328	0.4700	0.4034
290	0.5328	0.4700	0.4034
300	0.5328	0.4700	0.4034

Table 3. Raw NaCl data

Time since	Measured Albedo

beginning (s)	Trial 1	Trial 2	Trial 3
0	1.0000	1.0000	1.0000
10	0.9820	0.9674	0.9918
20	0.9660	0.9139	0.9801
30	0.9427	0.8665	0.9622
40	0.9187	0.8190	0.9128
50	0.8880	0.7685	0.9087
60	0.8547	0.7151	0.8764
70	0.8187	0.6677	0.8372
80	0.7873	0.6202	0.7967
90	0.7500	0.5816	0.7740
100	0.7200	0.5519	0.7493
110	0.6940	0.5193	0.7253
120	0.6740	0.4985	0.6992
130	0.6487	0.5045	0.6820
140	0.6313	0.4955	0.6696
150	0.6273	0.4866	0.6573
160	0.6167	0.4748	0.6484
170	0.6000	0.4748	0.6442
180	0.5887	0.4629	0.6291
190	0.5627	0.4629	0.6326
200	0.5720	0.4718	0.6209
210	0.5647	0.4718	0.6223
220	0.5560	0.4570	0.6174
230	0.5587	0.4510	0.6264
240	0.5533	0.4421	0.6154
250	0.5353	0.4362	0.6044
260	0.5400	0.4451	0.6085
270	0.5253	0.4421	0.6071
280	0.5273	0.4362	0.6016
290	0.5233	0.4451	0.5934
300	0.5213	0.4273	0.5824

Table 4. Raw Carbon data

Time since beginning (s)	Measured Albedo		
	Trial 1	Trial 2	Trial 3

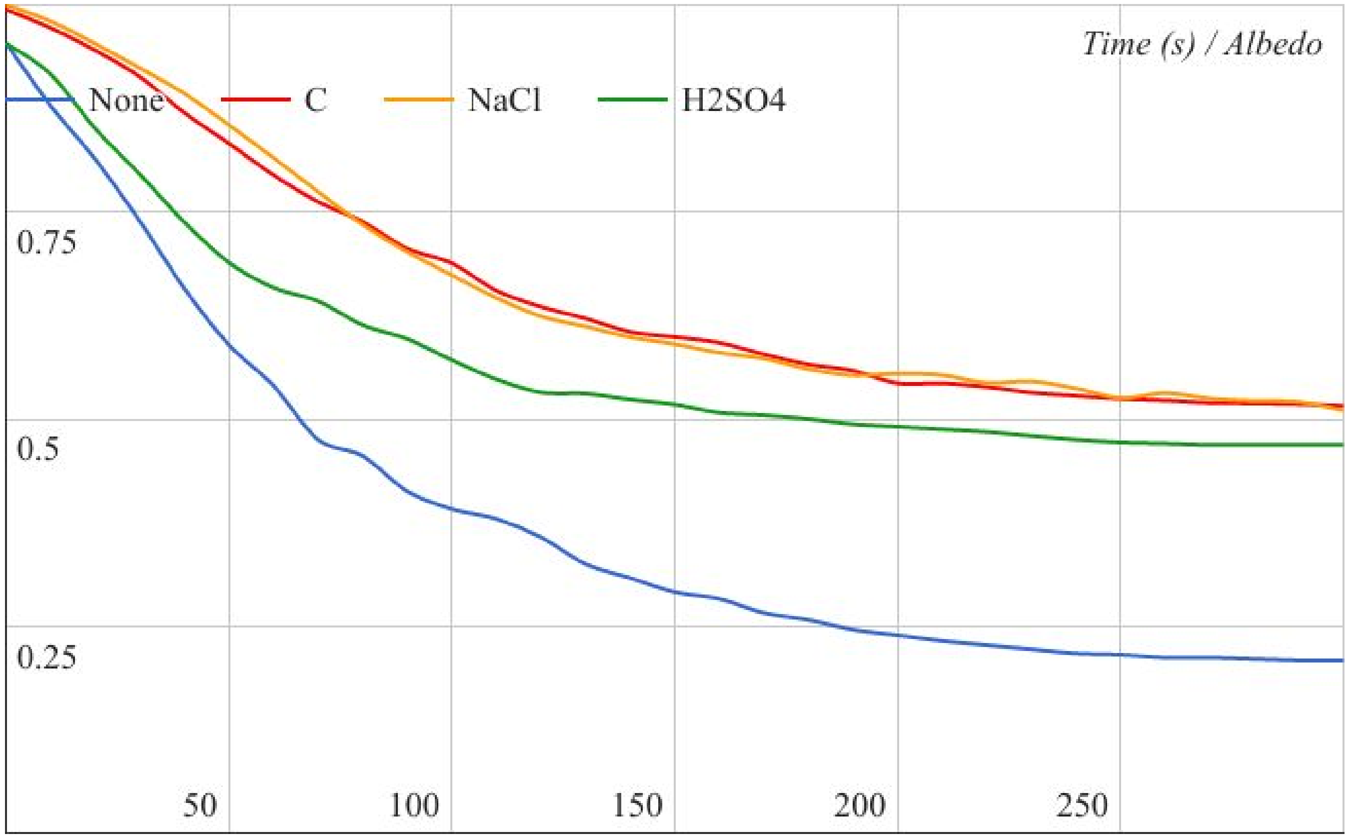
0	0.9829	1.0000	1.0000
10	0.9593	0.9878	0.9698
20	0.9309	0.9675	0.9372
30	0.8984	0.9418	0.9000
40	0.8512	0.9188	0.8395
50	0.8122	0.8863	0.8000
60	0.7683	0.8620	0.7535
70	0.7317	0.8390	0.7163
80	0.7041	0.8268	0.6837
90	0.6821	0.7889	0.6465
100	0.6593	0.7794	0.6256
110	0.6350	0.7348	0.5953
120	0.6171	0.7172	0.5721
130	0.6081	0.7118	0.5442
140	0.5927	0.6928	0.5302
150	0.6065	0.6766	0.5140
160	0.6049	0.6712	0.5000
170	0.5943	0.6563	0.4837
180	0.5772	0.6482	0.4721
190	0.5683	0.6414	0.4651
200	0.5553	0.6252	0.4488
210	0.5553	0.6252	0.4488
220	0.5504	0.6211	0.4442
230	0.5447	0.6157	0.4349
240	0.5463	0.6076	0.4302
250	0.5431	0.6022	0.4279
260	0.5407	0.6008	0.4256
270	0.5358	0.5995	0.4233
280	0.5366	0.5995	0.4209
290	0.5382	0.5968	0.4186
300	0.5374	0.5940	0.4163

Table 5. Average Albedo vs. time trend lines

Aerosol	**Equation of Best Fit Line**	**Correlation Coefficient**
None (control)	$y = 0.794(0.987)^x + 0.188$	$r = -0.875$ $r^2 = 0.766$
H_2SO_4	$y = 0.514(0.985)^x + 0.464$	$r = -0.846$ $r^2 = 0.715$
NaCl	$y = 0.569(0.990)^x + 0.480$	$r = -0.909$ $r^2 = 0.827$
C	$y = 0.558(0.990)^x + 0.473$	$r = -0.922$ $r^2 = 0.851$

CHARTS

Chart 1. Average albedo vs. time for different aerosols



IV. DISCUSSION

The data shows consistent data that models a smooth curve for every albedo. An exponential equation (in the form $y = ab^x + c$ to model each curve is shown to have a high correlation coefficient ($|r| > 0.8$ in for each model in Table 5), thus evidencing the precision of this model. While this does not give evidence toward the accuracy of the model— with no comparable data of these albedos in a similar environment available— it supports the idea that this experiment can be utilized to provide reliable data for researchers with adjustments and better equipment to match existing data.

The data evidences that sea-salt and carbonaceous aerosols (see Tables 3 and 4, respectively) perform better in terms of overall albedo than the control (no aerosol) and sulfate aerosols (see Tables 1 and 2, respectively). This can be visually seen in Chart 1, in which the NaCl and C average albedos for each time interval are noticeably higher than the control and H_2SO_4 albedos at the same intervals. The data for the C and NaCl aerosols are very similar for all time intervals. The rate of decline of the H_2SO_4 interval is very similar to that of the NaCl and C aerosols, as can be seen by their similar common ratios in their equations ($b \approx 0.5$ for all three graphs) (Table 5). However, it has a lower beginning and final albedo. The control has a much lower initial and final value than all of the solutions with an aerosol.

Some factors that may have affected the validity of the data are the integrity of the batteries in the flashlight, the amount of solution atomized, and the temperature of the system. There was a slight difference between the flashlight's initial brightness and its brightness after every trial; this effect was noticeable after several trials, when the brightness of the flashlight became significantly lower. Such a decrease in brightness would cause a calculated decrease in transmittance, which would thus raise the calculated albedo fraction. While this effect was mitigated by measuring the brightness of the flashlight before every trial to have a more recent "initial" flashlight value, the decrease in flashlight brightness *during* the trial may still have been significant, and should be measured at the end of the trial and taken into consideration in the measurements.

Another factor that may have been inexact in this experiment was the amount of aerosol emitted by the humidifier. Because the humidifier was not a scientific instrument and meant for commercial, household usage, the volume and droplet sizes of the aerosol was approximated. Because the calculated aerosol volume to match the density of a cloud is very small, the droplet density may have been too great and increased the measured reflectivity and calculated albedo.

Another potential source of error was that there was an assumption that all of the light energy would have been either transmitted or reflected. However, much as the case with real clouds, some of the light energy may instead be scattered to the side (not directly reflected back nor transmitted linearly toward the photometer) or converted to kinetic (thermal) energy stored in the cloud. Because there was a slight but noticeable temperature increase in some of the trials, especially the trials involving the carbon aerosol, the calculated albedo might have been higher than the actual albedo. This makes sense because carbon (in the form of black carbon, or soot) is known to be a pollutant and a cause of global warming, absorbing much heat rather than reflecting much light. Thus the temperature of the air inside the apparatus must be something to be taken into consideration as well, with a thermometer to measure the temperature change and appropriate calculations to measure the total energy exchange to take into consideration into the transmittance and albedo calculations.

V. CONCLUSIONS

The high correlation coefficients provide evidence for the precision of this model. Assuming this experimental method was accurate as well as precise, and if all of the light was either reflected or measured by the luxmeter, the NaCl and C aerosols produced a much higher albedo than the control and the H_2SO_4 in terms of albedo maintained throughout the experiment, which directly refutes the hypothesis that the H_2SO_4 would reflect the most light (have the highest albedo) and the C would reflect the least.

Future experimentation would scale the data to the real-world proportions of clouds, which would be the next step in actually utilizing this data in the world. Also, it would likely take into account the thermal effects of the gas with a thermometer to exclude aerosols that would have more a greenhouse gas effect on the atmosphere than a radiative cooling effect through cloud albedo.

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ABBREVIATIONS

CCN, cloud condensation nucleus.
MCB, marine cloud brightening.

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