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Effectiveness of Using Calcite as an Aerosol to Remediate the Urban Heat Island

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Abstract: The purpose of this study was to develop analytical tools to find the effectiveness of using aerosols to mitigate the urban heat island effect. Specifically, mineral calcite would be placed in a plume over cities to reflect solar radiation. A secondary goal is to compare the relative efficiencies of releasing the particles from tower heights or from aircraft heights. The aim is to reduce daytime temperatures at the surface. The method was to use a one-dimensional model or a single-column model to predict temperatures and weather conditions at all altitudes over a period of one month. The SCAM6 code was altered to incorporate the new capabilities for introduced aerosols. The pre-existing code considered only windblown dust, so the code was enhanced to handle aerosols that were intentionally produced. The key findings are that calcite as an aerosol does affect the weather. The models predict that in humid regions, calcite is less effective because it interacts with water clouds. In arid regions, calcite should be more effective since there are fewer water clouds to interact with. The result is that it is possible to predict reductions in air temperatures if solar insolation can be reduced. It was shown that temperatures can be reduced by 4 °C in arid regions. The conclusions are that calcite aerosol should be effective at mitigating urban heat islands. However, further work is needed related to economic, health, and ecological concerns.

Keywords: urban heat mitigation; arid and humid climates; solar radiation management; single-column model; aerosol reflectivity; solar geoengineering; particulate dispersal; atmospheric modeling; climate engineering

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1. Introduction

Urban heat islands can be mitigated by reducing solar radiation. A modeling method was developed to predict temperature changes. Solar geoengineering and solar radiation management (SRM) are methods to lessen the effects of global climate change by altering the radiative properties of the atmosphere. Some options investigated are to release materials, such as mineral calcite or sulfur, into the stratosphere [1–3]. There are many ethical and legal challenges to SRM on a global scale, including whether it would violate all existing treaties [4]. The author of the current paper has the intention of weather modification at a regional scale for mitigation purposes. Examples of current weather modifications are increasing precipitation or reducing hail or fog by altering cloud properties. The goal of this paper is to provide numerical tools to investigate the creation of plumes of particulates at lower altitudes over cities for cooling purposes. Specifically, this paper will develop modeling tools to predict temperature changes resulting from calcite aerosols at the local level. Synoptic level effects are not considered here.

There are benefits of focusing on local weather modification. First, this solves the ethical issue of whether a country or group of countries has the authority to mitigate climate change globally. This is solved because significant changes would only occur locally. Secondly, a larger number of people can benefit from smaller efforts when the focus is on urban areas. A disadvantage is the opposite of that rationale, as only people in cities will benefit.

To develop the modeling tools, it is necessary to first describe the operational plan. However, it is not within the scope of this paper to show complete engineering plans and cost analyses. Those should be in follow-up papers.

Calcite will be used to mitigate high temperatures due to its exceptional radiant properties [5,6]. Calcite is a common mineral found in limestone. Calcite limestone varies in color, depending on the type of deposit. When it is light in color, it indicates that it is effective at reflecting visible light. Calcite reflection depends on the wavelength. It will reflect in near-infrared light, but it does so less effectively in the longwave band [7], which means that it will have a lesser effect on ground radiation.

The plume of calcite would be generated during daytime hours only so that it reduces solar radiation. The material would need to be continually regenerated at varying rates, depending on the wind speed. A maximum operating speed would be set based on economics. If larger particles are used, they would be controlled by gravity and would go through rapid dry removal. If smaller particles are used, they would more commonly persist until wet removal.

Two mechanisms for the release of particles will be considered in engineering analyses in the future. First, particulates could be released from towers up to 500 m tall. Second, aircraft could release particulates at an altitude of about 2 to 3 km. A low altitude is chosen for aircraft because the process is more efficient at lower altitudes. Factors that affect aircraft distribution efficiency are wind speeds and aircraft energy demands. The common public may refer to this as creating a dust cloud, but the term cloud is more appropriately used for water, ice, or sulfate masses. Likewise, the term dust often implies naturally produced particles. Therefore, the proposed material will be referred to as a calcite plume.

The total mass of calcite required depends on the wind speed and the particle size range. The particle size strongly affects optical properties [5–7]. Dykema investigated calcite in the nanometer range for use in the stratosphere [5]. The mass required is less for smaller particles because there are more reflection surfaces per unit mass for smaller particles. Therefore, smaller particles are preferred for efficiency. Whichever size is picked, the mass will be adjusted to provide the desired level of SRM. Two size ranges will be considered, which are 3 to 5 microns and 10 to 12 microns. The choice of those ranges is based on health concerns.

It is not within the scope of this paper or this journal to consider human health impacts. However, considering that this topic is potentially a very serious issue, it deserves a preliminary discussion here. The selection of particles of 3 to 5 microns and 10 to 12 microns is based on particles smaller than 2.5 microns and 10 microns that make it further into the lungs with varying consequences. To have a preliminary estimate of the health impact, a dispersion model was performed using the method by Turner [8]. When dispersed from aircraft, the worst-case scenario concentration is 0.3 mg/m^3. It cannot be said that the health impacts are not a concern, but these levels are not found to cause lung problems [9]. One reason for choosing calcite is that it has a very low potential for affecting the health of people who breathe it. These assertions require a full investigation later in an appropriate journal. However, it can be said that there is the possibility that health impacts may be tolerable compared to the health consequences of performing no mitigation. Any effect on health from aerosols needs to be weighed against any benefits. Urban heat islands have been shown to increase health consequences, so mitigating heat improves health [10].

Interaction of Aerosols with Clouds

It is well established that aerosols, including dust and mineral particles, interact with the atmosphere. It has been seen that precipitation increases downwind of cities because they are sources of aerosols [11]. Water vapor in clouds usually forms on cloud condensation nuclei (CCN) because water droplets forming only from chains of water molecules are more likely to evaporate than grow. Thus, under most conditions, adding aerosols to the air encourages droplet formation.

All aerosols do not have equal effects on the atmosphere. The size and hygroscopicity of a particle affect its readiness to act as CCN. Calcite initially has a lower hygroscopicity, but through atmospheric aging, over a few hours, it reacts with acids to become hygroscopic [12]. The Kohler equation shows that droplets have an ideal size for rapid growth, so small CCN are ideal for growth. Larger droplets may grow too slowly to be significant, and small droplets may evaporate. CCN over 1 micron are less effective and may produce only large droplets that do not grow quickly [13]. Additionally, chemical reactions with atmospheric water change calcite's optical properties [14].

Hygroscopicity would affect the results in other ways. As water is absorbed on the surface of the aerosol particles, it changes the size and refractive index of the particle. Both changes will make the optical properties less ideal, but the changes will take a long time and will have no significant effect on the result when the plume is over urban areas.

Marine cloud brightening is an example of a proposed mitigation that would use aerosols to change the energy budget. Marine clouds would increase in brightness and cool the sea surface [15]. Placing particles into the air provides more CCN where droplets can form, and that can result in more and smaller droplets being favored, which increases their optical depth.

A second form of interaction with clouds can be significant when large amounts of aerosols are present. The purpose of using calcite in the proposed mitigation is to reduce solar radiation and temperatures at the surface. It will also cause warming in the air column. The evaporation of water at the surface is reduced when solar radiation and temperatures are reduced. Also, the air will be directly warmed by the absorption of light by the aerosols. Aerosols such as black carbon can have a significant effect [16]. Dust in arid regions can have a similar effect [17]. Thermal differences initiate convection, which transports water vapor to the lifted condensation level, but fluxes are reduced with high aerosol loads [18]. Therefore, cloud formation will be reduced by changes in the energy budget.

The two interactions of CCN and flux changes have opposing effects, but they operate at different scales. The result is that low levels of aerosol loading may increase cloud formation, but high levels may decrease it [19]. Therefore, at the target area for mitigation with calcite, reductions are expected. Downwind of a mitigated urban area, the particles will diffuse more widely, so they will likely increase the formation of water clouds.

It will be shown that the proposed mitigation of high temperatures with calcite is more effective in arid regions. All the atmospheric interactions would occur at lower rates there. The mitigation would be performed mostly on cloudless days with very low humidity. Feedback to convective clouds will be modeled for humid regions, but humidity is rarely high in arid regions. Therefore, it is expected that arid regions will have more effective operational parameters.

2. Materials and Methods

A single-column model will be used to numerically model the effects of adding a plume of calcite. The goal of this is to find the surface temperatures during the mitigation effort. The scope of this paper is not to find the synoptic effects but only the regional effects. Global models and three-dimensional models are useful when overturning movement in water clouds needs to be modeled. However, the dispersion of calcite will become more uniform within the planetary boundary layer as the distance from the source increases. Modeling of particulate transport should be much less complicated than for water transport due to water's condensation and evaporation behavior. Therefore, overturning should have a negligible impact on the effect of the calcite.

Two single-column models were evaluated. The first was the OpenIFS program (version 2023-05) at the Centre for Medium-Range Weather Forecasts (ECMWF). However, communication revealed that the program did not account for aerosol interactions with clouds.

The second software was the National Center for Atmospheric Research (NCAR) single-column atmospheric model version 6 (SCAM6), which is based on the community atmospheric model (CAM). The CAM has been used to model the radiative effects of dust [20]. The CAM is limited to modeling the flux of natural dust. It uses a dust emission factor, which produces more dust at higher winds. Winds drive the dust to higher altitudes through the process of inflation. However, in the proposed mitigation, the calcite will be released at a specific altitude at specific times in quantities engineered to produce the desired effect. Therefore, the default methods for handling dust in SCAM6 are insufficient for the needs of this research. The modeling software has about 4000 FORTRAN files, which are open source, so they could be changed to model the material as specified. SCAM6 was selected as the modeling program, but with modifications.

2.1. Modifications to Code

To account for the optical properties of atmospheric calcite, the code was changed to have the necessary values. Some of the optical properties of calcite change are based on mineral content, but the preferred values can be used because those mineral deposits will be selected. A single scattering albedo of 0.94 was chosen [21]. Calcite has an asymmetry parameter of 0.665 [22]. To obtain a half reduction in solar insolation, the Beer–Lambert Law shows that an optical depth of 0.69 is needed.

The CAM model uses 32 pressure levels starting from the top of the atmosphere. The CAM interpolates values between the levels. Level 29 corresponds to the maximum feasible tower height of 500 m above ground. Immediately downwind of the release, the material will be considered to remain mostly at that level. Level 23 corresponds to 3 km, where aircraft may alternately release the material. Since aircraft cause much turbulence, it was assumed that the material would quickly disperse from levels 22 to 24. When the material is divided into levels, it is assumed that the mixing ratio is constant for those levels. Dispersion downwind will be discussed in a following section.

Longwave radiation is filtered at about 20% of the rate as shortwave radiation in calcite [7]. Therefore, optical properties were scaled down for shortwave radiation.

By default, the single-column model version considers relaxation. Relaxation is a smoothing of modeled atmospheric values with expected actual values. Relaxation makes the model perform closer to actual conditions. The expected values that are smoothed include actual values for the solar radiation reaching the surface. Since the goal was to model changes in the amount of radiation reaching the surface, the results would not be accurate if relaxation was used. The goal was not to make accurate weather predictions but to find the net change in conditions due to the mitigation. Therefore, relaxation was turned off. The consequence is that the modeled temperatures would vary from the actual temperatures, but the benefit is that the data for actual temperatures no longer override the calculated results.

It was previously mentioned that several interactions could occur between calcite and vapor. The model will consider the relationship between temperature changes and the convective processes, which will reduce the apparent effectiveness of the mitigation.

Cloud brightening due to increasing the CCN will be neglected due to the extra programming that would be required. These effects would increase the apparent effectiveness of the mitigation, so the results will be lower-bound estimates of the improvement. The interactions will be discussed for each case considered.

The code changes are made in SCAM6 by downloading the programming files that are edited. Those files are placed in a local folder for modifications. Sample modifications are provided in the Supplementary Materials. Aerosol radiant properties are calculated in the file aer_rad_props. The aerosol was added to the altitudes at the amounts mentioned previously. The result of the modeling is that the radiant properties are changed, but no other effects on CCN were considered.

2.2. Cases

SCAM6 provides 15 cases [23]. The only choices that are continental are ARM95, ARM97, and Spartacus. The Atmospheric Radiation Measurement (ARM) of the southern great plains is in northern Oklahoma at a latitude of 36.607 and a longitude of −97.488. The Spartacus site is about 60 km NE of the ARM. No cases were found for arid locations. ARM97 was chosen because there was not much variability in the choices. ARM97 runs 6/18/97 to 7/17/97 starting and ending at 0 UTC.

Heatwaves differ throughout the world. In tropical areas, the temperature often does not vary much from day to day. In humid areas in mid-latitudes, the hottest days often correspond to humid air masses. During those hot days, there are often periods of cloudiness. In arid regions in mid-latitudes, heatwaves are commonly stalled high-pressure systems. A weak jet stream allows for an omega block to form, which prevents the regular progression of fronts from west to east. When this occurs, atmospheric conditions tend to persist for several days, and heat domes strengthen. Sinking air dries as it warms, so it typically remains cloudless during that time.

Since calcite mitigation has a lower interaction with clouds in arid regions, it is chosen as the targeted area. Yet, there are no arid cases available, so ARM97 will be used to model the effects in humid areas. Then, new cases will be created from it to approximate dry conditions.

2.3. Modifications of the Input Data for Arid Conditions

It was mentioned previously that no cases for the single-column model were available for arid regions, but that is expected to be the ideal location for mitigation. To find the effect of mitigating in those regions, the ARM97 input data were edited to simulate conditions of low humidity. This only applies to cases labeled “Arid”.

Each case provided with SCAM6 has one main file of atmospheric data in NetCDF format. Those data cover actual conditions at the point of observation. Within the file for ARM97, the input values associated with water such as precipitation, relative humidity and mixing ratio, cloud liquid, surface evaporation, and horizontal and vertical advection of water were all changed. Values were matched to Las Vegas, NV on 24 May 2023. On that day, there was no precipitation, temperatures rose to 34 °C at ground level, winds varied from still conditions to 50 kph, and the relative humidity never exceeded 20%. Full data are provided in the Supplementary Materials. NetCDF files vary in content and format based on the data available, but SCAM6 requires a specific data set and format. When the pressure levels required were different than the source files, values were calculated at the needed pressure levels. When no data from Las Vegas were provided for necessary items, such as the water mixing ratio, the relative humidity was used to calculate them.

The modifications to the input data have limitations. One limitation is that the case file is 1 of 126 NetCDF input files that the program uses. About 15 are used for other cases exclusively. Some of the other files provide data for items such as topography, emissions, stratospheric ozone levels, and sea surface temperatures. Another limitation of the modified data is related to the same issue, which is that the main data set only goes to a pressure level of 11,500 Pa. All atmospheric data above 11,500 Pa are found by the program from global data in the other NetCDF files. This limits the applicability of the results because only the bottom levels of the model represent the intended properties. Therefore, this analysis of arid conditions does not represent Las Vegas, but it represents if the low altitude atmospheric conditions at the ARM were trending towards it. It represents dry air masses going over the site.

3. Results

It is necessary to have three cases analyzed. Only the ARM97 site was used since it was the most like the expected conditions. The first case is where no calcite is released. The second and third cases represent differing heights for the release of the calcite. Each three were performed for humid and arid conditions.

Three cases of humid conditions are shown here. First was the standard ARM97 case, modified for no relaxation and no set value of solar incidence at the surface (OK-base). Second was the same modified for the dispersal of calcite from towers (OK-L29). Third was the same but with dispersal from aircraft (OK-L22-24). All cases assumed that calcite would only be released during the daytime.

SCAM6 produces a NetCDF file for the results at each model altitude for 20 min intervals. The data can be exported from a NetCDF file using Panoply. The data are plotted in Excel.

Air temperatures in the lowest level are shown in Figure 1 for the base case and low-altitude mitigation plotted hourly. The model begins with day zero as the start time.

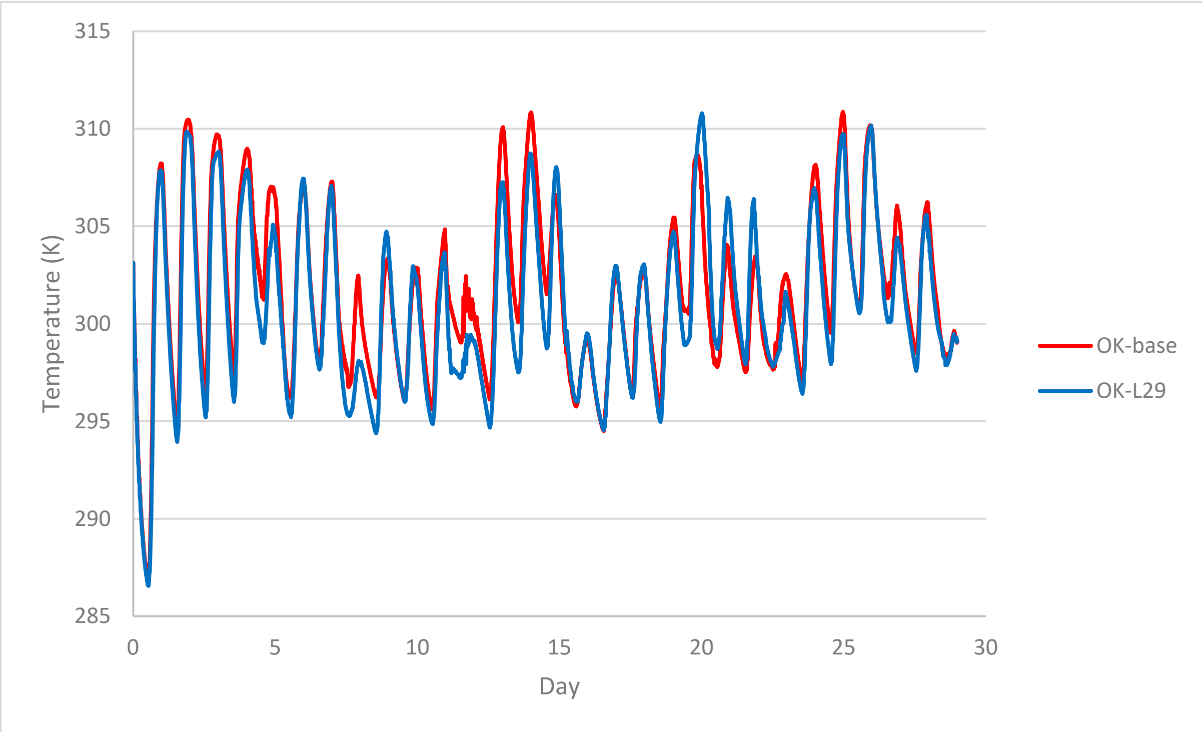

Figure 1. Temperatures (°K) in the base and mitigated case at the 992 hPa level. Daytime maximums are more commonly reduced than increased.

The mitigated case is generally cooler, but day 20 shows that the mitigated case may be warmer. Compared to the base case, the average temperature drops by 0.73 and 0.98 °K for OK-L29 and OK-L22-24, respectively. The average temperature is found with the following Excel command: average. Since there is not much difference between OK-L29 and OK-L22-24, only one is shown in Figure 1. The temperatures are shown in Celsius in Table 1 with the FSDS, which is the solar radiation reaching the surface.

Table 1. Temperatures and solar radiation.

Case	Ave. Temp (°C)	Ave. FSDS (W/m^2)
OK-base	28.5	397
OK-L29	27.8	339
OK-L22-24	27.6	344
Arid-base	35.1	401
Arid-L29	33.0	378
Arid-L22-24	30.5	365

Figure 2 compares the downwelling solar flux at the surface by the hour for the base and OK-L29 cases. There is a reduction of 14.8 and 15.4% for OK-L29 and OK-L22-24, respectively, compared to OK-base. This is about one-third of the goal of a 50% reduction in solar insolation at the surface. One explanation for this lower effectiveness is that convection was much reduced, so cloud formation was reduced. Convective cloud cover was reduced by 2.6 and 7.2% for OK-L29 and OK-L22-24, respectively, so the benefit of these clouds for cooling was lost. Additionally, the protection provided by the calcite is much less effective because the water clouds already reflected some of the solar radiation.

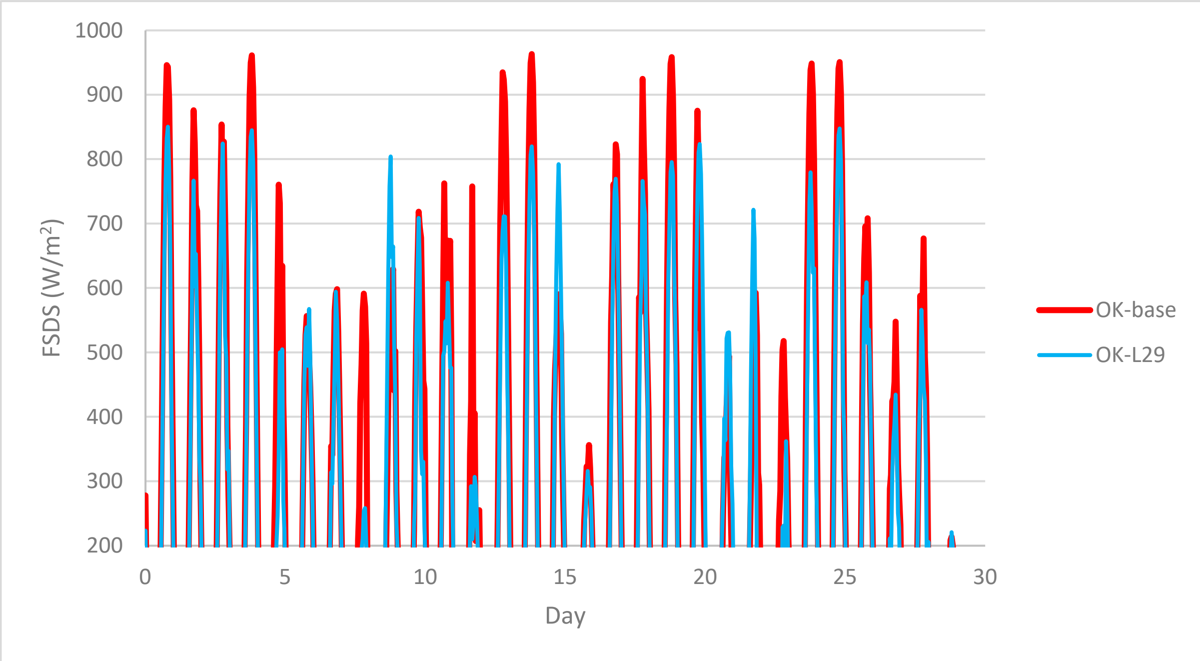

Figure 2. Downwelling solar flux at the surface (W/m^2) in the base and mitigated cases. Peak solar flux is more likely to be reduced than increased.

The model was run for all 29 days, but the weather conditions may not call for running a heat mitigation system for all of those days. Action times will be selectively chosen based on the need and the expected benefit. Figure 1 shows that dramatic improvements in temperatures can sometimes be achieved under ideal conditions. Therefore, the results discussed in this section are not the best-case scenario.

The effects of horizontal advection are considered in these results. If a plume of calcite is placed over a city, hot air will be blown from outside the city into the city. As air travels the distance from the edge towards the center of the city, it will cool. Horizontal advection is accounted for in the model, so the temperatures are considered to be averages under the mitigated area.

It was mentioned that calcite needs to go through atmospheric aging for a few hours to become more hygroscopic. Also, it was mentioned that for the particle size that was chosen, it will grow very slowly into droplets. Considering that on most days the wind will remove the particles within the first few hours, aging and droplet growth will be smaller than further downwind, which one rationale for neglecting this beneficial interaction causing cloud brightening over the city. If large particles are used, they would settle quickly without ever interacting.

3.1. Downwind Cases

If large particles are used, they would settle before traveling far downwind, so there are no cases to model for that scenario. If small calcite particles are used, they may persist in the air for a long time. Although a city would only be mitigated during the day, calcite may persist through day and night downwind. Calcite is less effective at blocking longwave radiation, but it has a significant effect. Therefore, it was necessary to perform cases downwind to determine the effect there.

In the downwind models, the calcite is considered to persist equally during the day and night. The material would normally disperse in a widening plume. The calcite was spread into a model with a few levels (OK-L25-31-24hr and OK-L22-24-24hr) and is not intended to be a complete model of downwind conditions. New cases would have to be created for the local atmospheric conditions downwind. These cases represent if the calcite were to persist just beyond the city for a long time.

The interaction of particles with clouds downwind would occur more than over the target area. The calcite would have had time to age, and droplets could have had time to grow. This causes cloud brightening, which is a beneficial effect, so neglecting it would give lower-bound results. The purpose of the analysis downwind is to confirm that conditions have not worsened, not to have exact temperature predictions.

The results were that the calcite was still beneficial for net cooling in all cases. However, the cooling was reduced. In general, some nights did not cool as much because of the effect of calcite in the infrared range. The same is true for cases yet to be presented, which satisfies the goal of this analysis. Accurate estimation of any benefits further downwind will involve performing a dispersion analysis and creating new SCAM6 cases.

3.2. Results for Arid Regions

The new cases had the same numbering as the previous cases. Arid-base, Arid-L29, and Arid-L22-24 were labels for the arid air mass. The resulting air temperatures are shown in Figure 3.

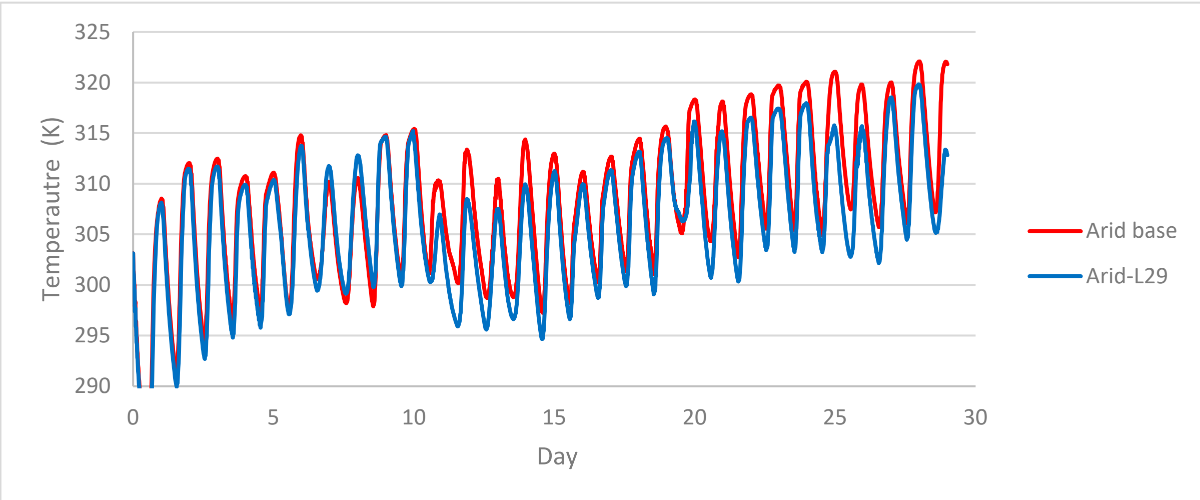

Figure 3. Temperatures (°K) in the base and mitigated case for arid conditions at 992 hPa. Temperatures show an increasing trend. The mitigated case has significantly lower temperatures.

Figure 3 shows that the air temperatures in the arid case dramatically increase during the model run. This is expected since there is less cloud cover. The diurnal range had dramatically increased. This is also likely due to lesser cloud cover since the cool days shown in Figure 1 had clouds and precipitation. Therefore, this case successfully approaches arid conditions.

The downwelling solar flux at the surface was reduced by 18.1 and 20.9% for Arid-L29 and Arid-L22-24, respectively, compared to the base. This is a substantially greater reduction than in the original cases but is less than the goal. There were no low convective clouds formed in any of the arid cases. However, high clouds were still present since higher atmospheric conditions are largely determined by the model using other input files. Despite the vertical distance between the calcite plumes and high clouds, there must have been some interaction because the total cloud cover varies between each model case. To measure the change in clouds, the portion of time was found where the cloud fraction exceeded 60%. Comparing the cloudiness between the humid and arid base cases showed that the cloud fraction only decreased by 8% overall.

The temperatures in Figure 3 have an upward trend. Logically, the ground temperature needs time to adjust to new atmospheric conditions. The CAM manual lists optional output parameters but lists no options for ground or soil temperatures.

After about 10 days, the mitigation has a dramatic effect on the temperatures, which may be due to varying atmospheric conditions each day. Another explanation is that soil temperatures build over time. Soil temperatures buffer air temperature changes. In Figure 1, for humid conditions, there does not appear to be any buildup of benefit. After each set of days where there are differences between OK-base and OK-L29, there is a set of days where the temperatures are not significantly different from each other. However, Figure 3 suggests that the benefit of mitigation may be magnified with time.

Compared to the arid base case, the average temperature drops 2.06 and 4.57 K for Arid-L29 and Arid-L22-24, respectively. The efficiency of the mitigation might be improved by targeting ideal atmospheric conditions. There is no need to mitigate on cloudy days, but it may be necessary to mitigate on all sunny days to achieve the maximum benefit.

The interaction of aerosols with clouds was discussed in the previous cases. It was acceptable to neglect the interaction because it would have been beneficial. In the case of arid regions, the interaction is even less likely in the target area. Figure 4 shows the cloud location and the distribution of particles. The particle distributions were found using the method by Turner [8] if it would disperse for 50 km downwind. According to a Gaussian distribution, only 0.1% of the particles would go above the line specified as three sigmas, and 2.2% would go above two sigmas. In the figure, we see that the clouds are above that level. Therefore, most of the material will stay away from most of the clouds over the city. Yet, further downwind, the material would spread more vertically.

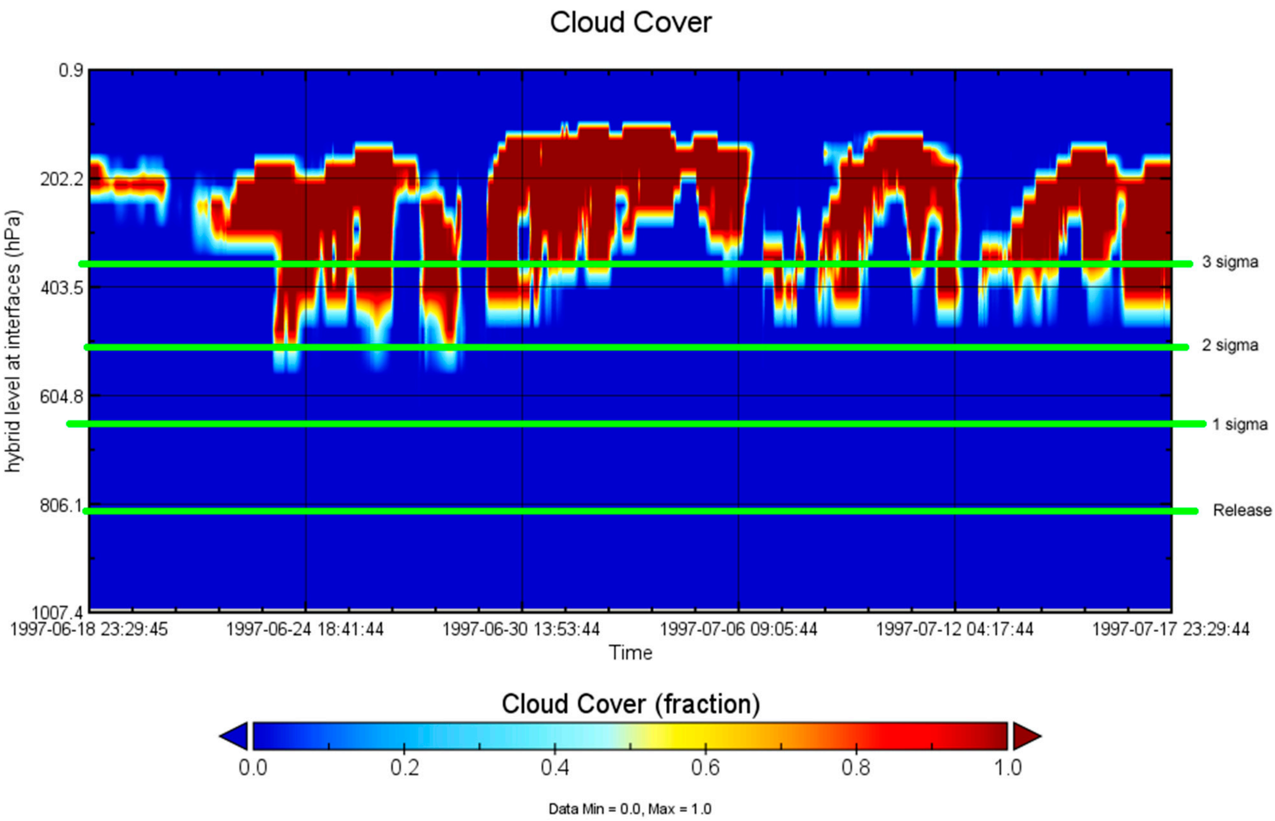

Figure 4. Dispersion of particles compared with cloud location. Clouds are very common in the model, even when conditions are modified to be more arid. The calcite is released far below the clouds, so little of it will reach the cloud level within the target area for mitigation.

4. Discussion

Other methods of solar radiation management usually focus on global temperature changes rather than local ones. An exception is marine cloud brightening (MCB) because when it is performed wherever, an effect can occur, and the resulting effect is local. By injecting salt into supersaturated marine clouds, MCB could result in local reductions in the solar radiation of up to 8 W/m^2 [24]. Small-scale experiments with MCB have achieved about 1 W/m^2 [25]. These values are much lower than the benefits from calcite that are in Table 1, where the change was shown to be in the range of about 40 to 60 W/m^2.

Methods to inject aerosols into the stratosphere are not intended for mitigation of the heat island effect; they intend to reduce the average global temperatures. Therefore, the goal is for a lower change. Stratospheric aerosol injection with sulfur could have an effect of 3.71 W/m^2 [26]. Mitigation with calcite has stronger effects.

It is clear from the new results here with calcite mitigation that arid regions will have better results than humid regions. The atmospheric conditions above the ARM were changed in the arid cases, but mimicking arid conditions was only marginally successful. It was previously mentioned that the cloud fraction was only reduced by 8% between the OK-base and Arid-base cases. There is seldom cloud cover above Las Vegas, so much more benefit could be achieved in actual arid regions.

It is assumed that the conditions in an arid region can be roughly approximated by extrapolation from known cases. Only two sets of cases are available, the OK-set and the Arid-set.

Cloud cover may be used as an extrapolation variable. It was discussed previously that much of the efficiency loss compared to ideal conditions is due to several interactions with clouds. Although low convective clouds were eliminated using dry air at low levels, many clouds still exist at higher levels.

Cloud cover in SCAM6 is fractional by hour and by level, so summing would produce apparent coverage values greater than one. Another definition was needed. For the purposes of this paper, cloud cover is defined as when the summed cloud fraction exceeds 60% at a time. Using this, the SCAM6 modeler predicts cloud cover of 81.3% and 75.6% for all times for the OK-base and Arid-base, respectively.

The downwelling solar flux at the surface is the primary metric for evaluating the efficiency of the mitigation. With calcite at the optical depth chosen, solar radiation reaching the surface could be reduced by up to half, which was defined as operating at 100% efficiency.

A linear extrapolation of solar flux by cloud cover shows that the ideal conditions would be reached before reaching zero cloud cover. Based on this, it is expected that the system would filter half of the solar radiation when the cloud cover is reduced by 40%. Extrapolating between other cases, such as OK-L29, with Arid-L29 gives the same results within 7%.

The results can be generalized to other regions. Relative humidity varies from region to region. A first-order approximation of the results can be found by linear interpolation.

Non-linear processes will likely make the actual results vary from the linear extrapolation. However, it can be said that the trend suggests a very good chance that the system could be highly effective in arid regions.

Mitigating urban heat islands is challenging. On a global scale, it would have only a small effect on temperatures [26]. One challenge is public involvement because changes need to be made neighborhood by neighborhood [27]. The proposal provides an alternative.

5. Conclusions

Calcite reflects shortwave radiation more efficiently than longwave radiation, so as an aerosol, it is very effective at cooling the ground surface. Plumes of calcite can reduce temperatures in cities.

Trends from model cases show that calcite plumes might be 30% as effective in humid regions as in arid regions. In humid regions, calcite interacts in many ways with water clouds. When solar flux is reduced, convective cloud formation is reduced, and that makes the mitigation less effective. However, in arid regions, which often have no clouds, mitigation with calcite particles could be very effective.

Placing calcite in the atmosphere in any region will reduce solar radiation. The amount of reduction may be lower in humid areas. Regardless of the actual temperature improvements, the reduction in solar radiation will have other direct benefits. First, comfort levels will improve. Second, solar heat gain (SHG) in climate-controlled spaces will reduce, and so air conditioning expenses will be saved. SHG is an identical term to downwelling solar radiation.

If small particles of calcite are used, they may be dispersed downwind for a long time. A disadvantage of that is that calcite blocks nighttime ground radiation. The cases showed that if the material persisted for the whole day at a similar location downwind, it would still have a net beneficial effect.

The results are limited by the small number of cases that were considered. It was not possible to precisely model atmospheric conditions in arid regions, which are the locations that could benefit the most from mitigation with calcite as an aerosol. However, as the air becomes dryer, the trend in the data is progressing towards ideal conditions for using calcite.

The research proposes mitigation methods. Experimental trials could be the next step to validate the results.

Several economic, health, ecological, and social issues should be considered in future research. The benefits of releasing calcite were similar for tower and aircraft heights, but those would have different costs and implementation concerns. Those issues are outside the scope of this paper.

Excessive heat is a concern for the health of urban residents. Local protection from extreme heat can improve health and the future economic viability of large cities. A large number of people live in cities, so there are many people that may potentially benefit from this sort of mitigation.

Supplementary Materials: The following supporting information can be downloaded at https://doi.org/10.17632/n5xkn59j7h.1 and by contacting the author. Data include instructions to modify SCAM6, code, input data, output data, and analysis of the output and numerical models.

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