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Sub-micrometer salt aerosol production intended for marine cloud brightening

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ABSTRACT

This paper is largely concerned with research focused on, but not restricted to, aspects of Marine Cloud Brightening (MCB), one of several geo-engineering ideas for reducing the amount of sunlight arriving at the Earth's surface, thereby compensating for global warming resulting from fossil-fuel burning. Predominant attention is given to the development of techniques for generating sprays of sub-micrometer salt particles that can enter marine stratocumulus clouds and increase their albedo, thus producing a cooling. Generation of sub-micrometer salt particles by spraying salt solutions at supercritical conditions is described, along with a description of the apparatus used. Log-normal particle size distributions having median diameters of 32 to 286 nm, with GSDs (Geometric Standard Deviations) around 2, were generated by two variations on the technique.

1. Introduction

Marine Cloud Brightening (MCB) is one of several Solar Radiation Management (SRM) ideas designed to produce a global cooling to roughly balance the warming resulting from fossil-fuel burning.

A significant number of papers (e.g., Latham, 1990, 2002; Bower et al., 2006; Salter et al., 2008; Latham et al., 2008, 2012a,b; Rasch et al., 2009; Jones et al., 2009, 2011; Korhonen et al., 2010; Bala et al., 2010) have been published on MCB, which is based on the idea that the albedo of maritime stratocumulus clouds, and possibly their longevity, can be substantially enhanced (Twomey, 1977; Albrecht, 1989) by seeding the clouds with salt or seawater aerosol particles, which are activated as Cloud Condensation Nuclei (CCN), so as to increase the cloud droplet number concentration, *N*. Seawater aerosol or salt particles would be produced at or near the ocean surface beneath selected clouds and turbulence would cause a high fraction of them to rise into the clouds and become activated to cloud droplets. GCM (General Circulation Model) computations indicate that this geo-engineering technique could produce a cloud albedo enhancement and negative forcing sufficient to maintain the Earth's average surface temperature and polar sea-ice coverage at approximately current values, at least up to the CO_2-doubling point.

One concern that has rightfully been raised regarding deployment of any of the SRM geo-engineering techniques that is capable of creating significant global negative forcing, is that if the technology breaks down, or has to be terminated because it produces unresolvable negative consequences, a major global-scale warming will rapidly be produced. It would therefore be sensible, if SRM deployment is ever deemed to be necessary, to have at least two such techniques acting in concert, so that (hopefully) the remaining technique(s) could be ratcheted up in order to eliminate the possibility of sudden temperature rise. Computations indicate that both the stratospheric sulfur seeding geo-engineering technique

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(Crutzen, 2006) and MCB–if they are found to function as predicted in GCM modeling studies–could maintain the global average surface temperature at roughly current values until at least the CO_2-doubling point, which may not be reached for several decades. So the two techniques acting in parallel could perhaps buy sufficient time for a clean form of energy to take over, globally, from fossil-fuel burning. An additional possible advantage of having the two techniques deployed at the same time is that fine-tuning (using the sub-global flexibility associated with MCB) should be possible for a significant time.

In our view MCB, and any other SRM technique, should never be deployed unless its usage is approved and deemed to be necessary by a yet-to-be-formed fully international panel representing all countries. It would be vital for a comprehensive examination of all techniques under consideration to be conducted and to accept only those that would not create unacceptable consequences that could not be fully resolved in advance of deployment.

There exist several unresolved questions regarding MCB. For example: (1) GCM modeling assumes a more simplistic picture of these clouds than is warranted, and more complex models need to be developed; (2) It is vital to determine whether undesirable consequences of MCB seeding exist. If they do, and if they cannot be eliminated, then work on this idea should be abandoned; (3) there still exist some technical problems that need to be definitively resolved, particularly in relation to the development of a spray device for producing, in copious quantities, sea-salt or sea-water aerosol particles.

We present herein 1) a discussion of the theory behind a novel technique, 2) a description of an experimental apparatus based on that theory, and 3) results of experiments using the apparatus for the production of salt aerosol of the size-range and particle flux required for effective utilization of MCB, should that ever be warranted. The technique could also be of significant value in aerosol studies, both in the laboratory and in the field.

2. Theory

2.1. Particle size

In simplified terms, in order for seawater aerosol particles to function as CCN and convert into cloud droplets, they must contain a minimum salt mass, which is a function of the supersaturation observed in the cloud, as calculated by the Köhler equation. The average supersaturation in marine stratocumulus clouds is a matter of discussion and various observations, but is estimated to be on the order of 0.5% (Hudson, 2009).

Based on this simplified consideration, one would estimate the minimum salt mass to be on the order of 7×10^{-20} kg (as sodium chloride). Using a seawater density of 1.02 and a salt concentration of 3.5% (mostly sodium chloride), one calculates a minimum initial spray droplet diameter of approximately 160 nm. Using the density of sodium chloride (2165 kg/m^3) the minimum salt mass corresponds to a dry salt sphere approximately 40 nm in diameter.

In practice, the injected aerosol will be competing with a variety of background aerosols including those from air pollution and natural sources, and it is found that suitable nuclei should have minimum diameters ranging from 40 to 100 nm (dry basis), depending on ambient conditions. These correspond to initial spray droplet diameters of 160 to 400 nm.

The practical implementation of CCN production at the suggested scale of 10^{17}/s per source (Salter et al., 2008) has yet to be realized. The required droplet size and number is well beyond the reach of any conventional spraying technology. Additionally, it is thought that the size distribution should be relatively narrow in order to reduce the range of fall-speeds and thus the efficiency of coalescence, leading to longer cloud lifetimes.

The most straightforward way to produce small droplets in a relatively narrow size distribution would be to make use of the Rayleigh jet formation with acoustic-controlled breakup (Rayleigh, 1878), where liquid jets are formed by forcing liquid through small orifices. Such methods require very little energy, and can produce almost mono-disperse droplets if the jets are stimulated at the right frequency, provided coalescence can be avoided (Neukermans, 1973). In such a process one finds that the diameter of the droplets formed is approximately 1.89 times the diameter of the orifice. For example, using holes of 0.4 μm in diameter one might produce droplets on the order of 0.8 μm in diameter (a bit smaller if the jets contract upon exiting the orifice), the size proposed by Salter et al. (2008). Such small holes are relatively easy to fabricate with modern etching techniques. However, the technical challenge lies not as much in fabricating such holes, as in keeping them open during operation. Our efforts in keeping 0.5-μm holes open over extended periods were unsuccessful, even using continuous polish-filtering of the liquid. The amount of liquid sprayed to produce 10^{17}/s nuclei through 0.4-μm holes would be on the order of 30 L/s. Spraying this amount of liquid from a single source is bound to give rise to substantial evaporative cooling of the surrounding air, which could impede the rise of the nuclei into the clouds.

We have looked at alternative droplet formation methods which, while requiring more energy, suffer less from evaporative cooling. Since the volume of the liquid to be sprayed increases with the cube of the droplet diameter one can reduce local evaporative cooling by producing the smallest useable droplet. We have described these efforts in a previous publication (Cooper et al., 2013). The most promising method is probably the formation of Taylor cone jets from seawater, which fortuitously produces relatively narrow size distributions of salt particles with median distribution diameters of 60–85 nm. However, in order to produce 10^{17}/s particles this method would require the formation of at least 10^8 Taylor cones. The creation of a spraying structure with such a number of emitters is an undertaking that is obviously not trivial. We describe here an alternative method, which while requiring substantially more energy, and producing wider distributions, is perhaps easier to implement for research purposes.

The formation of small droplets is impeded by the surface tension of the liquid, as surface energy needs to be provided when the increased surface area of small droplets is created. Intuitively, it can be seen that low fluid surface tension is desired if the liquid is to be dispersed very finely. In more quantitative terms, for the injection and dispersion of liquids, the following relationships are observed (Abraham, 2009):

$$SMD = C\frac{\sigma_l {\mu_l}^{1/m} {\rho_l}^{1/n}}{{V_l}^2 \rho_g} \tag{1}$$