

Mineral Dust Aerosols as Ice Forming Nuclei

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Abstract

Mineral dust aerosols are studied as possible enhancers of ice nucleation within clouds. Collection of air samples on filters is subjected to water condensation and subsequent ice nucleation on experimental apparatus. Results show greatly enhanced nucleation from the addition of aerosol particles, though size and composition dependences are not clearly established. Climate implications due to direct and indirect radiative forcings and changes in mineral dust spatial and temporal distributions are not well understood.

Introduction

Soil derived mineral dust is a significant component of natural aerosols. However, little is known of its direct and indirect radiative forcing capabilities. Both the magnitude and sign of mineral dust direct net radiative forcing remain unclear. Although indirect effects such as cloud lifetime and albedo are considered negative for anthropogenically altered aerosols, the current level of understanding is considered very low (IPCC Working Group 1, 2001). Part of the complexity in estimating dust radiative forcing is the fact that sources and sinks are not uniformly distributed and that the residence time of mineral dust in the atmosphere is relatively short from seconds to at most a few weeks. Attempts to model the dust cycle, although promising, only begin to address the complications of emission, sedimentation and wet removal with many over simplified parameterizations (Marticorena and Bergametti, 1995 and 1996). These models do not include mineral surface chemistry, interactions with other aerosols or cloud processing (Sokolik, 1999). Even the radiative forcing effects of simulated dust fields have not been investigated (Mahowald et al., 1999). Even more complication arises from mineral composition variation. The term mineral dust aerosol collectively refers to widely varying mixtures that may include quartz, calcite, gypsum, hematite, and clays such as kaolinite, illite and montmorillonite. The mix of minerals and their shapes and sizes can vary so much that spatial or temporal forcing estimates remain elusive.

One important indirect radiative forcing associated with mineral dust is as ice forming nuclei. Fewer ice nuclei than cloud condensation nuclei exist within the atmosphere and mineral dust particles are often collected from the centers of snowflakes. Kaolinite especially has been identified by electron microscopy with sizes ranging from 0.1 to 4 μm in snowflake centers (Rogers and Yau, 1989). A size requirement of greater than 0.1 μm with a typical mode between 0.5 and 5 μm has been established by several studies (Pruppacher and Klett, 1997). By aerosol standards mineral dust are typically large even considered giant on the order of 1 μm and can be observed under moderate magnification (Twomey, 1977). Clay minerals have been found to be principle ice forming nuclei. Other laboratory experiments lend strong support to the notion that surface soils act as a source of ice forming nuclei (Pruppacher and Klett, 1997 pg 317). In this study, general mineral dust is collected on filters from ground-based sites in Boulder, Colorado to test effects of large mineral dust aerosols on ice nucleation. A cold

stage is used in which condensation followed by freezing is simulated in the laboratory setting to mimic cloud processes.

Methods

Dust was collected on 47 mm Sartorius Filters in Nuclepore Swin-Lok filter holders using an Air Cadet vacuum/pressure station. Two ground-based collection sites were chosen, one at the NCAR Mesa Lab and one at the NCAR Foothills Lab. Approximately 24 liters of air was drawn through each filter holder with a total of 21 samplings. Three of the filter holders held two each Nuclepore polycarbonate filters with a 2 μm over a 0.4 μm pore size filter. As most of the aerosols collected are likely to be invisible even under the most powerful ocular magnification, these Nuclepore filters would help confirm the role of the visible, i.e. large, dust particles in ice nucleation.

Filter samples were viewed under microscope at about 1 μm resolution to obtain a qualitative sense of particle concentration, size distribution and composition. These same filter samples were placed on a cold stage under a fretted Buchner funnel to control humidity at a spectrum of temperatures below -5°C for condensation and ice nucleation. For details of the freezing process and experimental apparatus see Silson (2001 unpublished).

Observations/Results

The Mesa Lab sample were collected on July 29, 2001, a partly cloudy day in the late morning with temperatures around 33°C and relative humidity of 16%. The Foothills Lab samples were collected the next day, which was overcast, about the same temperature and above 30% relative humidity. Both locations had wind activity that aids in the entrainment and transport of mineral dust aerosols. It had not rained for a few days prior to the collection, a process that removes dust from the air.

The microscope revealed particles too small to see with the unaided eye. Although there were a variety of shapes, colors and sizes to these particles, I would classify them under two categories: biogenic and lithogenic. The particles of biologic origin were generally the largest with sizes ranging up to 70 μm on the long axis. They were clear with smooth membranous tube shaped parts and some green coloring. The rock-derived particles were angular in shape and came in pink, orange, red, and black with red rims. Black was a common color especially for particles at the limits of resolution $\sim 1 \mu\text{m}$. Particles were not evenly distributed over the filters and a full count on a 47 mm diameter filter with a $\sim 300 \mu\text{m}$ view was a difficult prospect and probably not very informative anyway.

Ice nucleation experiments were more quantitative with apparent increases in nucleation for sample versus clean filters. For -10°C , filters exhibited 110 and 60 visible ice nuclei for the Mesa Lab and Foothills Lab respectively. The blank filter number for this temperature was 5. Nucleation generally increased in number for decreasing temperature and was significantly greater than the baseline curve established with blank filters (Table 1 and 2).

Table 1 Samples

Mesa Collection 7.29.01				
Temp (°C)	Filter #	Liters Air	Nucleation #	N/L
-5	2	24	0	0
-6	1	24	0	0
-7	3	24	0	0
-8	4	24	0	0
-9	5	24	2	0.083333
-10	6	30	110	3.666667
-11	7	24	95	3.958333
-12	8	24	400	16.66667
Foothills Collection 7.30.01				
Temp (°C)	Filter #	Liters Air	Nucleation #	N/L
-5	1	24	0	0
-6	3	24	0	0
-7	4	24	0	0
-8	5	24	0	0
-9	6	24	51	2.125
-10	7	24	60	2.5
-11	8	24	120	5
-12	9	24	350	14.58333

Table 2 Baseline

Temp (C)	Nucleation #
-5	0
-6	0
-7	0
-8	0
-9	2
-10	5
-11	42
-12	100

In both sample collections, the nucleation number per liter of air (N/L) increased with decreasing temperature. The shapes of these relations are dependent to some extent on the samples collected but the trend is evidence of the ice nucleation enhancement of aerosols, which would not otherwise occur in pure water until very low temperatures were reached.

A few filters were transferred to the microscope after the ice nucleation process was completed. The ice nuclei were so small that they melted before the focus could be achieved but the resultant water droplets did show signs that mineral dust aerosols had acted as sites for ice nucleation. Lithogenic appearing particles were seen inside larger droplets, (>50 μm) but not smaller droplets. Biogenic particles generally adhered to the surface of larger droplets but were also seen within the droplets. I did manage to find one mineral dust particle that did not appear to be within a drop.

The test with the Nuclepore filters had ice deposition in a sheet for the 0.47 μm pore size and the 2 μm pore size at -10°C . Because these filters did not produce distinct ice nuclei, it cannot be ruled out that the pores themselves had some nucleating effect. No conclusions about size dependence for ice nuclei can be established from this test.

Conclusion/Discussion

These results show a clear increase in ice nucleation with the introduction of aerosols. They do not so clearly distinguish the effects between those of biologic origin and those of mineral origin. However, the microscope viewing after ice nucleation does indicate that the mineral dust may have played a more important role as ice nuclei. Biogenic material often consists of both polar and non-polar constituents. It is likely that this explains the surface adhesion of these to drops. This does not rule out the possibility that biogenic material acted as sites for ice nucleation even with a non-polar side.

Because ice-forming nuclei are relatively rare, changes in their concentration or distribution could have important consequences for climate. Feedbacks related to climate change could be either negative or positive. Although dust sources are unevenly

distributed across the Earth, evidence that they have global effects comes from satellite data that can make optical depth images of dust blowing from the Saharan desert to the southeastern United States (Schulz et al., 1998). Evidence for long-range transport of mineral dust has been observed even in Antarctica where snowflakes have been found to contain mineral dust aerosols though no good sources for them exist on the continent (Rogers and Yau, 1989).

Possible effects of mineral dust changes as well as other aerosol changes from anthropogenic sources may be seen in the lifetime of clouds, percentage of clouds and radiative properties of clouds. In the case of mineral dust, a cloud with an increased supply will have many more ice crystals and thus very different optical properties. Cirrus clouds with more ice crystals and thus smaller mean effective sizes reflect more solar radiation and trap more infrared radiation producing stronger cloud-top cooling and cloud-base heating. In most cases, the greenhouse effect outweighs the solar albedo effect except when there are significant numbers of small ice crystals (Rasmussen 1995).

Whether or not mineral dust will increase or decrease in the atmosphere as an effect of global warming remains to be answered. Paleo-data suggests that the dust cycle was 5 to 10 times as strong during the last glacial maximum (LGM) than present (Mahowald et al. 1999). A GCM sensitivity experiment to study and compare cloud responses in LGM and $2\times\text{CO}_2$ conditions found an increased hydrologic cycle for greenhouse warming (Ramstein et al. 1998). This might decrease the sources and residence time of dust in the atmosphere. Cloud responses in warming conditions showed a clear reduction in low level (e.g. stratus) clouds that would cool the climate and an increase in high level (e.g. cirrus) clouds that would warm the climate associated with relative humidity changes. Cloud responses were more perplexing for LGM conditions with increased clouds over high latitudes and decreased cloudiness at low latitudes. Yet this model did not include the possible effects of the increased dust cycle in LGM. If cirrus clouds increase and mineral dust sources decrease due to global warming, then clouds may provide a positive feedback mechanism.

Mineral dust might not be as important in a greenhouse world because of increased precipitation. But the picture is more complicated because human activities also affect mineral dust sources by land use practices such as the plowing of dry fields and over grazing which may lead to desertification. The combination of this and natural variability produced a drought during the 1930's that turned semi-arid land into a prominent dust source (hence the term "Dust Bowl"). Changes in other anthropogenic aerosols such as sulfates complicate the picture even more. Aerosols cannot be perceived as an antidote to increased CO_2 because they have complicated interactions with clouds and sunlight, remain in the atmosphere for only a short time and are not likely to change to the degree at which we are increasing greenhouse gases.

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