CONF-900790--1

UCRL-101997
PREPRINT

NUMERICAL SIMULATION OF AEROSOL SCAVENGING BY ICE-BEARING CONVECTIVE CLOUDS

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This paper was prepared for submission to
the *AMS* Conference on Cloud Physics
to be held July 23–27, 1990 in S.F., California

April 1990

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1. INTRODUCTION

Precipitation is the most effective mechanism for cleansing the atmosphere of small aerosol particles. Although there are many process paths by which precipitation can ultimately deposit aerosol on the ground, each path begins with the initial capture, or scavenging, of an aerosol particle. There are many different scavenging processes, including Brownian diffusion, thermophoresis, diffusiophoresis, hydrodynamic capture, electrical effects, turbulent attachment, and condensation and deposition nucleation. One of the most effective of these processes, at least in the absence of strong electric fields, is condensation nucleation scavenging (referred to as nucleation scavenging in the remainder of this paper), in which an aerosol particle serves as a cloud condensation nucleus.

Although scavenging is a necessary precursor to aerosol removal by precipitation, scavenging does not guarantee that an aerosol particle will be removed from the atmosphere. For example, the particle will be resuspended if its host cloud droplet evaporates or if the droplet is collected by a raindrop which subsequently evaporates. The removal process becomes further complicated if ice is present in the cloud. The purpose of this research is to study the effects of various ice processes on the net aerosol removal efficiency of convective clouds.

2. SCAVENGING ABOVE LARGE FIRES

In the nuclear winter scenario, smoke generated from many post-nuclear-exchange fires affects the earth's radiation balance, resulting in global cooling, altered circulation patterns, and other disruptions of the earth's atmosphere. The energy release rates from large urban fires may be on the order of 10–100 kw/m^2 over urban areas of tens to hundreds of square kilometers. In many cases the fires would generate strong updrafts and, in most target areas, the relative humidity would be adequate for cumuliform clouds to develop within these updrafts. In these cases, most of the smoke particles would pass through supersaturated cloud regions, thus being subjected to possible nucleation scavenging. Above large fires with very strong updrafts, even insoluble, but wettable, smoke particles could be scavenged by condensation nucleation (Edwards, 1989; Penner and Edwards, 1989). Eventually, smoke-laden cloud droplets would be accreted by raindrops, and some fraction of the smoke would be deposited on the ground in the immediate vicinity of the fires. Of course, the same mechanism operates in natural cumulus clouds to remove natural and anthropogenic aerosol particles. In the case of intense fires, however, the aerosol source is also the heat source for the updraft which, in turn, generates the cloud; thus most of the aerosol particles are exposed to the possibility of nucleation scavenging and rainout very shortly after they are formed. We refer to this removal-at the-source as *prompt removal*. Bradley, et al. (1988) have shown that, if only warm rain processes are considered, approximately 60% of the smoke mass could be promptly removed from the smoke plume above a large mid-latitude city on an unstable summer day by nucleation scavenging and subsequent rainout, and that optical depths due to smoke would be correspondingly reduced over tens of thousands of square kilometers downwind from the fire.

3. THE ROLE OF ICE

In the 1988 study, the smoke plume penetrated the tropopause. Clearly, ice processes would be active at this altitude and greatly complicate the fate of hydrometeor-borne aerosol particles [see Figure 2 of Molenkamp and Bradley, 1990 (this publication)]. In this study we reexamine the prompt removal of smoke above a large urban fire, considering the effects of ice processes.

Although the amount of smoke that is promptly removed from the atmosphere depends upon the effectiveness of various scavenging mechanisms, it is also strongly affected by the specific process paths through which the particles move after their initial capture. Compared to warm cloud processes acting alone, some ice process paths could increase the amount of smoke that is promptly removed while others might actually decrease the net smoke removal efficiency. For example, we might hypothesize that the collection of supercooled smoke-laden cloud droplets by frozen precipitation (riming) would increase the net smoke removal efficiency. On the other hand, the resuspension of smoke particles from evaporating cloud droplets in the glaciated portion of the cloud (due to the Bergeron process) could increase the undesirable climatic impact by injecting smoke at high altitudes, where its atmospheric residence time would be longer than if it had never been scavenged.

In order to examine the effects of the various ice process paths on net aerosol removal, this experiment considers only cases in which the initial capture of the smoke particle is due to condensation nucleation. By performing a series of sensitivity studies, we examine the relative impacts of specific processes that transfer nucleation-scavenged smoke particles between liquid and solid hydrometeors and that resuspend dry smoke particles when hydrometeors evaporate or sublimate.

4. THE OCTET SIMULATION SYSTEM

The OCTET Simulation System is designed to model convective and stratiform clouds, mesoscale storm systems, smoke plumes, and mesoscale circulations. OCTET is so named because it consists of a hierarchy of eight numerical models. Each of these models is based on a three-dimensional, nonhydrostatic, compressible dynamic framework (similar to that of Klemp and Wilhelmson, 1978) with wave-permeable lateral boundaries and with a turbulence parameterization based on a time- and space-dependent turbulent energy equation. The model hierarchy progresses from a model with water vapor but no condensation, to a model with warm cloud microphysics, to a model with warm and cold cloud microphysics, to a (planned) model with warm and cold cloud microphysics and electrification physics. Each of these four models has a counterpart model that includes aerosol physics (and aerosol-hydrometeor interactions for the three cloud models). The various OCTET models are generated from a single master source code, using preprocessing directives and conditional compilation. Model options include two different warm cloud parameterizations, Lagrangian tracer/samplers, interfaces with the LLNL CAMP detailed microphysical model (Edwards, 1989), and time-variable fire geometry (for smoke plumes). Diagnostic tools include aerosol and water mass budgets, a three-dimensional interactive graphical analysis post-processor, and a three-dimensional visualization post-processor.

The OCTET model used for this study has prognostic equations for the three velocity components (u,v, and w), the pressure perturbation, the potential temperature perturbation, the mixing ratios of water vapor, cloud water, rainwater, ice crystals, snow, and graupel/hail, and the mixing ratios of dry aerosol, aerosol in cloud droplets, aerosol in raindrops, aerosol in ice crystals, aerosol in snowflakes, and aerosol in graupel/hail.

5. MODEL VALIDATION

The same (although fortunate) lack of observational data that necessitates the use of numerical models for studying post-nuclear-exchange fires also hinders model validation. We can, nevertheless, validate many of the basic features of our models by comparing simulation results with observations of relatively small fires. In order to check the dynamics and the warm cloud microphysics parameterization, we used OCTET and CAMP to simulate the smoke plume and cloud above a prescribed burn of diseased forest land that was conducted in Hardiman Township, Ontario, Canada, in August, 1987 (see Bradley, et al., 1990a and 1990b). The model was initialized using data provided by ground-based, radiosonde, and instrumented aircraft (provided by the University of Washington) observations, and fire characteristics derived from pre- and post-burn fuel inventories (provided by the Canadian Forestry Service). The model output was compared with ground-based plume observations and with measurements of aerosol and cloud properties taken by the instrumented aircraft.

The validation study confirmed the accuracy of OCTET's dynamic framework and warm cloud parameterization and also the use of tabulated output from the CAMP model to parameterize the condensation nucleation process in OCTET. The graphic images of the simulated smoke plume were strikingly similar to photographs of the actual plume, and the calculated size distribution and concentration of smoke-laden cloud droplets were in good agreement with aircraft observations. Chuang, et al. [1990 (this publication)] have extended our research on the Hardiman Township fire to consider the effects of entrainment on nucleation scavenging.

6. DISCUSSION

At the time of this writing, simulations were underway using the cold cloud and aerosol physics parameterizations discussed in Molenkamp and Bradley (1990). The latest results will be presented at the conference.

7. ACKNOWLEDGEMENTS

We wish to express our gratitude to Conrad Wilgus for his programming assistance with the OCTET Simulation System. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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