Modeling the Effects of Aerosols on Clouds in Coastal Urban Environments

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ABSTRACT
Several studies have found evidence of warm-season rainfall increases over and downwind of cities. This induced precipitation (PCP) has been attributed mostly to induced updraft of warm air masses. Aerosols are abundant in urban environments and it has been hypothesized that they play a key role in the water balance of cities. High concentrations of cloud condensation nuclei (CCN) may induce precipitation in humid urban environments. However precipitation may be reduced due to excess CCNs or by large aerosols. The objective of the present research is to improve our understanding of the role of aerosols in cloud processes of complex coastal urban environments.

KEYWORDS: Aerosols, microphysics, CCN, precipitation, cloud, condensation, and nuclei.

INTRODUCTION
There is increasing evidence that anthropogenic activities can significantly alter precipitation processes. Urbanization is an example of anthropogenic forcing. Recent studies provide evidence that urban environments can modify or induce precipitation under a specific set of conditions. In the past 30 years, several observational and climatological studies have found evidence of warm-season rainfall increases in the order of 9%–17% over and downwind of major urban cities. Urban induced precipitation has been observed in Atlanta, St. Louis, Houston, Cleveland, and other cities. In order to determine how aerosols affect precipitation in complex urban environments such as New York City, it will be necessary to analyze ground and remote sensing data.

Satellite data have been used to show rainfall modifications in Atlanta, Montgomery, and Nashville. Precipitation increases of up to 51% were observed in these locations [1]. Jauregui and Romales presented an analysis of historical records showing that the frequency of intense rain showers has increased in recent decades in correlation with the population growth of Mexico City [2]. Similar results have been observed for moving summer convective storms over Phoenix and Houston, respectively [1]. Weekday precipitation is generally more plentiful than weekend precipitation in St. Louis, Cleveland, and Chicago. This is believed to be due to greater activity during weekdays of industrial pollutants which act as CCN [3].

Aerosols. Aerosols are micron-scale solid particles that are suspended in the air. Some are present from natural processes such as volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray. Burning of fossil fuels and the alteration of natural land cover also generate aerosols. These aerosols made by anthropogenic activities currently account for about 10% of the total amount in our atmosphere [4]. Most are concentrated in the Northern Hemisphere, downwind of industrial sites, slash-and-burn agricultural regions, and overgrazed grasslands. Figures 1 and 2 outline the properties of aerosol-free and polluted clouds.

Figure 1. Properties of a clean cloud.
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I am currently a third year doctoral student at the Graduate Center. My discipline is Mechanical Engineering and my concentration is fluid mechanics and heat transfer. My first research opportunity was during the summer of 2000 at Princeton University. As a participant in the Research Experience for Undergraduates (REU) program, I was able to conduct research on refractory ceramics that are used to line steel furnaces. I ran thermal cycling experiments in order to find the optimal operating conditions for the ceramics. Also as an undergraduate, I researched heat transfer from an elephant’s ear.

Since receiving my B.E. in Mechanical Engineering from City College in 2005, I have worked on many more research projects. My master’s thesis was titled: Shockwave Reflection Off of a Solid Obstruction. After completing that project, I researched shockwave/vortex interaction, vortex dissipation, and electrophoretic deposition in aqueous solutions, a project I did at Lawrence Livermore National Labs in California. Now, I am investigating how aerosols may enhance or reduce precipitation in New York City.

When I’m not engaged in scientific research, I enrich my life by pushing words through a microphone. I make up one half of the music group Upanotch, and enjoy the opportunity to perform our original songs for audiences. The experience helps keep me balanced when the scientific research becomes stressful. In addition to creating music, I draw, write, and play chess.

PROFESSOR JORGE E. GONZÁLEZ-CRUZ teaches and conducts research in energy, sustainability, climate change, climate modeling, and remote sensing. He collaborates with the Cooperative Remote Sensing Science and Technology Center (CREST) and with the Department of Mechanical Engineering. Previously, Dr. González-Cruz served as Professor of Mechanical Engineering and David Packard Scholar at Santa Clara University, and he is a former mechanical engineering department chair at University of Puerto Rico, Mayagüez, where he taught from 1994 to 2003.

Dr. González-Cruz has conducted research about the applications of heat transfer, solar energy, low energy buildings, urban remote sensing and climatology. His work has been sponsored by the Commonwealth of Puerto Rico, the U.S. Department of Energy, the National Science Foundation, the National Aeronautics and Space Agency, the National Oceanic and Atmospheric Agency, the California Energy Commission and several private enterprises.

Professor González holds three patents in solar energy equipment and aerosol detection. In 1997, he received a prestigious career award from the National Science Foundation, and in 1999, he received the Outstanding Mechanical Engineering Faculty Award at the University of Puerto Rico, Mayagüez. He received his PhD in Mechanical Engineering from the Georgia Institute of Technology.
Aerosols in the atmosphere have direct and indirect effects on the Earth’s climate. The direct effect is related to their optical properties. Aerosols scatter and/or absorb solar and terrestrial radiation. The level of scattering and absorption depends on their physical and chemical characteristics. As a result, aerosols act to modify the Earth’s radiation budget and thus influence the warming/cooling of the planet. The quantity and the chemical composition of aerosols also influence water budgets, as they are the main source of rain droplets. Hygroscopic particles are aerosols with chemical affinity to water, and they act as nuclei for rain water droplet formation via condensation. Thus, as hygroscopic aerosol concentration increases within a cloud, the amount of water available for condensation is spread over many more particles, resulting in smaller water droplets. Due to their size, these small droplets have a lower probability of becoming precipitable water. Thus, changing aerosols in the atmosphere can change the frequency of cloud occurrence, cloud thickness, and rainfall amounts. In situ and remote sensors can quantify aerosols within the cloud column but not determine their composition.

**Microphysics.** Microphysical processes are cloud processes (condensation, evaporation, etc.) which take place on the scale of the individual aerosol or precipitation particle, rather than the scale of the visual cloud. These processes include collision, coalescence, droplet break-up, and droplet growth. This work aims at understanding the microphysical processes of aerosols typically found in complex urban environments.

**Background in aerosol effects on PCP.** Cloud microphysical processes are affected by changes in the aerosol concentration as well as aerosol composition. High aerosol concentrations yield more cloud water but less rainwater in the atmosphere. Aerosols mainly influence clouds and precipitation when they increase the number of small cloud droplets. High particle concentration suppresses the growth of existing cloud droplets by diffusion. That’s because there will be more particles competing for the available water vapor. This can also affect collision and coalescence since the droplet radius necessary for these processes to occur cannot be realized. Observations of polluted areas over Thailand and Indonesia showed smoke clouds that did not precipitate at all [5]. These clouds contained a low concentration of small droplets. Similar results were found in continental clouds of smoke-filled areas in the Amazon [6].

**HYPOTHESIS**

Based on analysis of background information, it is hypothesized that aerosols may enhance (as well as decrease) precipitation in urban environments. Aerosols and cloud microphysics contribute to precipitation in urban environments without added convection.

The aim of this research is to demonstrate this hypothesis for complex urban environments. We will investigate cloud microphysics by analyzing weather and particle size distribution data from ground and satellite observations and by modeling the atmospheric microphysical processes at the meso-scale. This paper emphasizes the modeling component.

**MODELING**

Mathematical models are used to enhance our understanding of physical processes and represent experimental scenarios. Mathematical modeling of cloud microphysics will allow determining the optimum conditions for the particles to grow. The model may also allow ingesting real in situ data (such as particle size distribution and composition obtained...
from satellite and ground observations) into the model in order to analyze causes and effects in an efficient manner. Atmospheric mesoscale models such as the Colorado State University Regional Atmospheric Modeling System (RAMS) contain a cloud microphysics component that can be used to simulate precipitation in coastal urban environments. We describe in this paper these modeling capabilities and further improvements.

Figure 3 shows how CCN size distribution may vary during clear skies (blue line), and cloudy skies (red and green lines) for a coastal urban environment. The data were based on measurements in northern coast of Puerto Rico using six channel handheld radiometers [7] and converted into particle size distributions. The data were first reported by Comarazamy et al. (2006) and will be used for analysis here.

Figure 4 shows results from a PCP simulation using the data from Figure 3. The simulation was conducted using the algorithm proposed by Saleeby and Cotton [8] for microphysics of clouds as implemented in RAMS. The figure depicts PCP in polluted (right) and non-polluted air (left). It can be observed that the total PCP in polluted air is less than a third of that in clear air.

The work of Saleeby and Cotton [8] provides a detailed description of the initial stages of particle growth. A user defined particle distribution function whose resulting growth can be traced over time can be implemented using such approach when combined with the work presented by Rogers and Yau [9] for particle growth by condensation. The resulting droplet growth equation from conservation of mass for a single droplet or radius $r_t$ is given by Equation (1) below which enables determining growth of a CCN particle into a cloud droplet.

$$ r_t \times \frac{d r_t}{d t} = \left[ S_t - 1 - \frac{a}{r_t} - \frac{b}{r_t^2} \right] F_{kt} + F_{dt} $$

Where $F_{dt}$ and $F_{kt}$ are the concentration and thermal diffusional terms, respectively, or,

$$ F_{dt} = \frac{\rho_i \times R_v \times T_t}{D \times E_{st}} $$

$$ F_{kt} = \left[ - \frac{L}{R_v \times E_{st} \times T_t} - 1 \right] \times \left[ \frac{L \times \rho_i}{K \times E_{st} \times T_t} \right] $$

Additionally, $S_t$ is the atmospheric supersaturation level, or the amount of water vapor above saturation conditions. Other relevant variables are:

- $D_t =$ mass transfer coefficient
- $K =$ coefficient of thermal conductivity (J/m-s-K)
- $L =$ latent heat of water (J/kg)
- $T_t =$ particle temperature (K)
- $R_v =$ water vapor gas constant
- $\rho_i =$ water density (kg/m$^3$)
- $a, b =$ droplet size correction factors.

When studying droplet populations, it is necessary to estimate the impact in the water balance of the resulting cloud. This can be estimated by analyzing the rate of change of the saturated water vapor, given by the following equation:

$$ \frac{d s}{d t} = \left[ \frac{1}{T_t} \times \frac{\varepsilon \times L \times g}{R \times T_t} - \frac{g}{R} \right] \frac{d z}{d t} - \rho_i \times \left[ \frac{R \times T_t}{\varepsilon \times E_{st}} + \frac{\varepsilon \times L^2}{p \times T_t \times c_p} \right] \frac{d X}{d t} $$

Where:

- $\varepsilon =$ gas constant ratio
- $g =$ gravitational acceleration (m/s$^2$)
- $R =$ ideal gas constant (J/mol-K)
- $\frac{d z}{d t} =$ updraft velocity (m/s)
- $\frac{d X}{d t} =$ rate of change of the mixing ratio (J/mol-K)
- $c_p =$ constant pressure specific heat (J/kg-K)
Based on observations, the number of particles of a particular radius that exist in the droplet population is typically assumed to follow an exponential distribution

\[
N(r) = \frac{N_t}{r_t \times \sqrt{2\pi} \times \ln \sigma \exp \left\{ -\frac{\left[ \ln \left( \frac{r}{r_t} \right) \right]^2}{2 \times (\ln \sigma)^2} \right\}
\]

(5)

where:
- \(N_t\) = total number of CCN particles
- \(r\) = distribution of median radius (m)
- \(\sigma\) = distribution breadth parameter

The previous set of equations can be used to determine initial particle growth within a cloud to describe condensation growth. The solution of these equations requires numerical integration due to their non-linear nature.

RESULTS
Figure 5 shows an initial particle size distribution for a typical CCN population found in coastal environments, following actual data presented in Figure 3. A numerical code was written in Matlab\textsuperscript{TM} to solve the droplet growth equations described above using a Runge-Kutta 4th Order numerical integration. Ambient conditions were assumed as follows. Temperature was 273°C, and atmospheric pressure was 100kPa, with a constant updraft. Results of our analysis are presented in Figure 6 and compared with Saleeby and Cotton's modified method to make it suitable for growth of a single droplet (Fig. 7). For the same initial particle sizes, ranging from 0.1 to 1 micron, the droplet radius vs. time plots are quite similar for both approaches. The main difference occurs at a time of 10 seconds. This is likely due to the addition of parameters in the Saleeby and Cotton for mass diffusivity, and consideration of hydroscopic properties of the particles. In both cases, the particles quickly grow beyond the critical Aitkens radius, which enables further stable growth and eventually rain formation.

DISCUSSION
The results of Figures 6 and 7 provide insightful confidence for predicting droplet growth mostly by condensation under uniform ambient conditions. Comparison of two different approaches shows similar results. The growth is asymptotic to a single mean value of close to 2.5µm that exceeds the critical Aitkens diameter for further growth by collision and coalescence [9]. This implies that aerosols smaller than this diameter will grow by condensation inhibiting precipitation if in larger amounts, or evolving into rain droplets. Aerosols larger than this size will not contribute to the water balance within a cloud.

CONCLUSION / FUTURE WORK
Observations show that aerosols may reduce and or enhance precipitation in cities. Aerosol particle distribution can change from day to day, exhibiting different profiles on clear and cloudy days. Creating a numerical microphysics model that enables alteration of the particle size distribution function...
is of paramount importance. The next step in this research is to couple the new microphysics model with an atmospheric mesoscale model to improve our understanding of the role of aerosols in complex urban environments.

ACKNOWLEDGMENTS
The authors acknowledge the financial and motivational contributions of NASA, under the COSI Program, and of the NOAA CREST Center.

REFERENCES

Solar Panels in Morning Light: Increased levels of atmospheric particles reflect the sun's rays away from Earth, causing a decrease in captured energy by solar panels.

Computer Science sophomore Alexandru Eva used the PovRay scripting language to generate this image of solar panels.