Effect of Air Pollution on Precipitation along the Front Range of the Rocky Mountains

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Overview: Erica Alston
EAS 8802 Aerosols and Precipitation
Outline

• Introduction
• Data & Methodology
• Results
• Broad Conclusions
Introduction

• Previous studies: Givati and Rosenfeld (2004) found reductions in orographic precipitation of 15-25% in California and Israel
• Previous studies: Rosenfeld (2000) provided evidence of precipitation suppression due to urban pollution in shallow clouds
• Hypothesis: increased pollution over metropolitan areas along the Front Range would lead to suppression of precipitation advected up the terrain (orographic precipitation)
• Specifically, a noted decrease in orographic precipitation downwind (i.e. west) of Denver & Colorado Springs
Data & Methodology

• Location: Front Range of the Rocky Mountains extends meridionally across the central portion of northern Colorado with numerous cities along the eastern slopes;
• Leeward side (downwind side) of the mountain range removed from moisture sources: Pacific Ocean and Gulf of Mexico;
• Semi-arid climate with rainy season April-Sept.
• Focused upon easterly winds carrying low-level moisture and pollution up the terrain

van den Heever & Cotton (2007)
Data & Methodology

- Daily precipitation and wind data from seven stations from the NCDC for 1950-2002.
- Two groups of stations: polluted and pristine (relative to polluted sites) with highly correlation precipitation.
- Within each group compare sites directly downwind (i.e. west) and slightly elevated above urban sites along the Front Range.
- Polluted sites: Denver – Cherry Creek Dam and Morrison; Colorado Springs – Colorado Municipal Airport and Ruxton Park.
- Pristine sites: Greely, Waterdale and Estes Park.

van den Heever & Cotton (2007)
Data & Methodology

- Wind data provided at 1 site: Stapleton International Airport in Denver, CO.
- Data is wind direction at peak wind gust
- Upslope winds = peak winds from the NNE to SSE (20°-160°)
- Upslope winds --> upslope precipitation
- Upslope precipitation summed over entire year

- OEF = orographic enhancement factor
- OEF = Precip @ elevated sites / precip @ lower sites

van den Heever & Cotton (2007)
### Results

<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>$P$ value</th>
<th>Ending/starting ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total precipitation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cherry Creek</td>
<td>Polluted</td>
<td>0.26</td>
<td>1.19</td>
</tr>
<tr>
<td>Morrison</td>
<td>Polluted, elevated</td>
<td>0.88</td>
<td>1.02</td>
</tr>
<tr>
<td>Morrison/Cherry Creek</td>
<td>Polluted</td>
<td>0.10</td>
<td>0.83</td>
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<tr>
<td>Greeley</td>
<td>Pristine</td>
<td>0.01</td>
<td>1.32</td>
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<tr>
<td>Greeley/Waterdale</td>
<td>Pristine, elevated</td>
<td>0.33</td>
<td>1.13</td>
</tr>
<tr>
<td><strong>Upstream precipitation</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cherry Creek</td>
<td>Polluted</td>
<td>0.91</td>
<td>1.02</td>
</tr>
<tr>
<td>Morrison</td>
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<td>0.23</td>
<td>0.78</td>
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<tr>
<td>Morrison/Cherry Creek</td>
<td>Polluted</td>
<td>0.03</td>
<td>0.73</td>
</tr>
<tr>
<td>Colorado Springs</td>
<td>Polluted</td>
<td>0.20</td>
<td>1.34</td>
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<tr>
<td>Ruxton Park</td>
<td>Polluted, elevated</td>
<td>0.56</td>
<td>1.13</td>
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<tr>
<td>Ruxton Park/Colorado Springs</td>
<td></td>
<td>0.03</td>
<td>0.63</td>
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<tr>
<td>Greeley</td>
<td>Pristine</td>
<td>0.13</td>
<td>1.36</td>
</tr>
<tr>
<td>Waterdale</td>
<td>Pristine, elevated</td>
<td>0.99</td>
<td>1.00</td>
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<td>Greeley/Waterdale</td>
<td>Pristine</td>
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<td>0.76</td>
</tr>
<tr>
<td>Greeley</td>
<td>Pristine</td>
<td>0.13</td>
<td>1.36</td>
</tr>
<tr>
<td>Estes Park</td>
<td>Pristine, elevated</td>
<td>0.32</td>
<td>1.25</td>
</tr>
<tr>
<td>Estes Park/Greeley</td>
<td>Pristine</td>
<td>0.31</td>
<td>0.84</td>
</tr>
</tbody>
</table>

*van den Heever & Cotton (2007)*
• Cherry Creek (upslope) = 142 mm annually, 34% of yearly average
• Morrison = 156 mm, annually, 36% of yearly average
• Site trends are not significant
• Strong statistical evidence that upslope precip @ Morrison decreased relative to upslope precip @ Cherry Creek
  • The OEF ↓ by almost 30%
  • ↓ in upslope OEF is larger and more significant than for total precip ⇒ airflow over urban areas is affecting the precipitation process at the elevated sites

Fig. 4. Same as Fig. 2, but considering only upslope precipitation.
• Greely & Waterdale receive more than a third of yearly precip from upslope events

• Neither has a significant trend in precip

• There is no significant trend in the OEF ⇒ additional support that precipitation suppression occurs west of Denver & Colorado Springs (i.e. polluted areas) because of air pollution
Conclusions

• No statistically significant trends found in the OEF for total precipitation

• Significant trends found in OEF for upslope precipitation for Denver & Colorado Springs sites $\equiv 30\%$ decrease; yet no trends found for pristine sites $\Rightarrow$ hypothesis true

• Results consistent with Givati & Rosenfeld (2004) study that yielded a 15-25% reduction in orographic precipitation

• General conclusion: Urban pollution can decrease precipitation in shallow clouds
Urban Aerosol Impacts on Downwind Convective Storms

Authors: Susan C. van den Heever & William Cotton

www.wunderground.com
Outline

• Introduction
• Model and experiment setup
• High background aerosol concentration results
• Low background aerosol concentration results
• Conclusions
• Broad Conclusions from both articles

van den Heever & Cotton (2007)
Introduction

• METROMEX yielded results of enhanced summer precipitation over St. Louis, MS by 5-25% over background values within 50-75 km downwind of the city
• ↑ thunderstorms associated with ↑ population in cities
• Urban areas enhance lightning activity
• Why? Many hypothesis…

van den Heever & Cotton (2007)
Introduction

1. Greater aerosol concentrations within urban regions act as CCN, giant CCN (GCCN), and ice nuclei (IN)
2. Increased surface roughness of urban areas leads to enhanced surface convergence over and downwind of the urban region
3. The urban canopy diverts thunderstorms around urban regions
4. The urban regions serves as an enhanced source of moisture
5. Sensible and latent heat fluxes within the urban region and thermal pertubations of the boundary layer by the urban heat island (UHI) affect moist and dry convection

van den Heever & Cotton (2007)
Introduction

- GCCN – CCN’s with a radius > 1 µm
- Surface roughness – man-made surfaces have more roughness than natural materials
- Urban heat islands – artificial surfaces have different thermal properties such that they are more capable of storing solar energy and converting it to sensible heat causing air in urban areas to be 2 - 10° warmer than surrounding non-urban areas; most notable on a clear windless night
Introduction

• Hypothesis: to investigate the impacts of urban-enhanced aerosol concentrations on convective storm development and predication over and downwind of St. Louis, MO, ultimately to make a conclusion about which factor is dominant in convective storm development and precipitation
Model and Experiment Setup

- Case study: June 8, 1999
- Environment with weak southwesterly mean tropospheric flow in addition to the warm and moist nature of the surface conditions during METROMEX
- On June 8, 1999, storms in the area came from the southwest and west-southwest.
- Storm activity began in the early afternoon and lasted through the early evening producing locally heavy rain, large hail, and considerable wind damage.
- Huff and Vogel (1978) found that during METROMEX 43% of the storms in the area came from the southwest.
- Same case study as used by Rozoff et al. (2003).

Fig. 1. Composite radar images over St. Louis for (a) 1700, (b) 1800, (c) 1900, (d) 2000, (e) 2100, and (f) 2200 UTC 6 Jun 1999, after Rozoff et al. (2003). The image was adapted with permission of C. Rozoff. Contour intervals are provided every 10 dBZ.
Model and Experiment Setup

<table>
<thead>
<tr>
<th>Model aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
</tr>
</tbody>
</table>

Initialization

- Time step
- Simulation duration
- Microphysics scheme

Convective initiation

- Boundary conditions
- Turbulence scheme

Radiation scheme

- Surface scheme

\[ \text{Hail all activated} \]

**Fig. 2.** The location of grids 1–3 for the simulations described in the text. The field shown is topography (m).

*Modifications by Lilly (1962) and \[ \text{LEAF-2 (Walko et al. 2000)} \] coupled with the TEB model (Masson 2000) for urban regions.*
Model and Experiment Setup

![Diagram of wind vectors and concentration isolines at different times.](image)

**Fig. 3.** The location of the downwind calculations referred to in the text is shown by the rectangular box. CCN concentration isolines (1300 and 1500 cm$^{-3}$) at 270 m AGL are indicated by the dotted lines, and St. Louis is shown by the shading. The wind vectors at the surface and at ~1600 m AGL are indicated by the thin and thick vectors, respectively. These fields are shown at (left) 1500 and (right) 1900 UTC. The 1-mm accumulated precipitation isoline at 2200 UTC is shown in the right panel by the solid dark lines.

van den Heever & Cotton (2007)
Results - H

• UHI develops for all simulations were the city is included

• UHI intensified around 1600 UTC and by 1800 UTC a heat island of 2° C had formed

• Water mixing ratios over the city are lower than in surrounding rural area

• Wind convergence over and downwind of urban area

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Fig. 4. Time evolution of the RURAL-H – NOCITY-H temperature and water vapor mixing ratio fields at the lowest model level (48 m). Temperature (°C) is shaded, water vapor mixing ratio (g kg⁻¹) is indicated using thick black contours at 1 g kg⁻¹ intervals, and rivers and St. Louis are indicated using thin white lines. Wind vectors for the RURAL-H are also indicated, the scale of which is indicated at the bottom of the figure.
Convection occurs both downwind of St Louis and to the SW of the city. Convection lasts a few hours until base run (RURAL-H). A storm due north of the city develops 15 minutes earlier than in the urbanization test (URBAN-H). Storm location similar to observed storms, but the simulated storms lag the observed storms by 2 hours. Differences highlight the impact that variations in aerosol concentration can have on the dynamics of the storm. Storm evolution and intensity development are similar to that observed at the RA2M. The location of updraft development is similar to that of base run to the city (RURAL-H).
- Greater differences with RURAL–L and URBAN–L when compared to High simulation at 21:15 UTC doesn't occur.

- No storm development NW of city.

- Storm to the north of city splits at 21:15 UTC.

- Storm splitting is influenced by the amount of precip produced and size of raindrops which in turn are affected by urban aerosol concentrations.

- New storm development NW of city around 22:00.

Fig. 11. Same as in Fig. 5, but for the URBAN-L simulation.
Results

- Enhancements in GCCN (GCCN-H) and both GCCN & CCN (URBAN-H) produce more rapid warm-rain process, ↑ 40-50% in comparison to control run (RURAL-H);
- Cloud water forms more rapidly where GCCN concentrations are enhanced; however enhanced CCN (CCN-L) results in slower formation of cloud water.
- After 2045 UTC enhances just GCCN-L and URBAN-L produce more cloud water.
- After 2030 UTC differences between runs is small; with RURAL-H dominating after 2145 UTC.
- Major differences between Fig 8 and 14: (1) ↑ hydrometeor mass for lower concentrations (2) trends in each simulation similar.

Fig. 14. Same as in Fig. 8, but for the lower background aerosol concentration tests.
• Similar trends for both cases where GCN and URBAN initially produce more precipitation, yet trend reverses after 2115 UTC
• Low concentration simulations yield increased downwind precipitation
• Difference between runs high as 30%
• Stronger updrafts between 2000 and 2100 UTC with GCCN-L and URBAN-L; with reversal to CCN-L and RURAL-L becoming dominate afterwards which coincides with the time of storm splitting
• New updrafts develop downwind earlier in the RURAL-L and CCN-L around 2145 UTC
• The downdrafts show a similar patter to the updrafts, where enhanced GCCN-L and URBAN-L develop downdrafts later after 2100 UTC
Conclusions

• While urban enhanced aerosols have numerous effects on the microphysics and dynamics of the downwind convective storms, it is the convergence effects driven by the urban land use characteristics that determine whether convection will actually develop (shown by sensitivity test without the city). Enhancements of GCCNs yield increases in cloud water, rain, updrafts and downdrafts initially than control run. Enhancements of CCNs delayed the formation of cloud water, rain, updrafts and downdrafts, however as time progressed enhanced CCNs and control run produce more cloud water rain and earlier updrafts and downdrafts. Appears that the delay in the updraft and downdraft development in the CCN-L case and the influence of this on storm dynamics and subsequent storm development tend to offset, the adverse effects of suppressed warm-rain processes. Because the lower concentration simulations yielded such significant increases with respect to high concentrations, this implies that areas that are less industrialized or near coastlines will notice a greater effect of downwind urban aerosols.
Broad Conclusions

• Urban aerosols suppress orographic (shallow) cloud precipitation downwind form urban region through primarily the second indirect effect

• Urban aerosols can enhance convective storm precipitation downwind of urban region, yet this effect is more noticeable when background concentrations are lower (e.g. less industrialized area)

van den Heever & Cotton (2007)