METROMEX: A REVIEW AND SUMMARY

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CHAPTER 1

Introduction

STANLEY A. CHANGNON, JR.

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ABSTRACT

This is a book about how a large metropolitan area in the humid continental climate zone of the central United States affects the summer atmosphere and how these alterations change the weather and influence man. A sizable multi-group field research effort was pursued with a wide variety of instruments over a 6-year period to gather data, and this book assembles and reviews the key findings of METROMEX (Metropolitan Meteorological Experiment).

The findings are organized in a deductive manner, beginning in this chapter with the climatological basis for the choice of St. Louis as the study area for METROMEX. The apparent urban-induced changes in climate at St. Louis are set in the general context of what has been learned elsewhere, largely from analyses of historical data, about how cities influence weather and change the climate. This chapter also describes the research strategy used for METROMEX including the organizational approach, the instrumentation and studies used to address the issue.

This chapter thus sets the background and basis for understanding METROMEX and its findings. The ensuing five chapters treat, in a logical sequence of effects, the findings about surface weather conditions (Chapter 2), the urban boundary layer (Chapter 3), cloud characteristics (Chapter 4), precipitation processes (Chapter 5), and atmospheric chemistry (Chapter 6). Chapter 7 assembles relevant findings into a summary of urban effects on clouds and rainfall. Chapter 8 describes the impacts of the altered precipitation on man and the biosphere. Each chapter is preceded by an abstract that summarizes its major findings.

CHAPTER 2

Surface Weather Conditions

Richard G. Semonin

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ABSTRACT

The detailed precipitation pattern observed during the 1971–75 period revealed similar general features found in long-term records. The summer rainfall increased from west to east across St. Louis, reaching a maximum east and north of the Mississippi River.

The precipitation maximum was located northeast and east of the urban heat island centered on the commercial district of the St. Louis inner city. The heat island was associated with a humidity deficit in the same general area.

Annual precipitation patterns showed a great deal of similarity, particularly the east side location of the maximum. The diurnal distribution of rainfall reflected the diurnal cycle typical of the climatic regime of the area. The shape of the diurnal curve for stations within the area of maximum rainfall was similar to that for those located in the rainfall minimum west of St. Louis. Since the diurnal structure of the rainfall distribution was independent of the rainfall amount, it suggests repeated enhancement of precipitation within storms moving across the urban area.

The surface winds were perturbed as revealed by the unique signature of wind speed cross-sections showing increases then decreases across the city. The same signature appeared in both daytime and nighttime winds indicating that the perturbation was not primarily caused by the heat island which maximized at night.

Severe weather events including heavy rainstorms, hail and wind gusts all showed a maximum in the region of the east side rainfall maximum. Thunder, a frequent precursor of severe weather, also showed a maximum in occurrence and intensity over the city and east of the Mississippi River.

2.1 Climate of the St. Louis area

St. Louis lies midway between the Continental Divide and the Atlantic Ocean and some 500 miles north of the Gulf of Mexico. Its climate is a humid continental type with cold winters, warm summers and frequent short period fluctuations in temperature, humidity, cloudiness and wind direction. The excellent soils and well distributed annual precipitation of 38 inches (97 cm) favor a very high standard of agricultural pro-

CHAPTER 3

Urban Boundary Layer

August H. Auer, Jr.

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ABSTRACT

METROMEX studies documented anomalous summer values of radiation components, temperature, humidity, wind fields and aerosol concentrations in the boundary layer over the urban area. Reflected solar radiation, emitted radiation and net radiation values differed between urban and rural areas, with patterns reflecting land use types. Solar noontime albedo values varied from 15 to 17% for rural land uses, in contrast to 12 to 13% for most urban land uses. The metropolitan area experienced a 4% depletion of net radiation throughout the day, compared to rural areas.

St. Louis had a marked heat island and an identifiable minimum in specific humidity at midday. These effects were most marked at the surface, but often appeared as height-averaged temperature excesses of 1K and moisture deficits of 1 g kg^{-1}, relative to nearby rural areas, extending through the mixing layer to near cloud base. The intensity and three-dimensional extent of the urban thermodynamic properties represented a perturbation that could connect the urban surface to an effect in the overriding mixing layer behavior.

In St. Louis, the mixed layer frequently underwent a diurnal cycle including a morning stable layer with a top close to the surface, a midday convection period with a top typically rising to 2 km, and a late afternoon or evening return to stable conditions. Daytime mixing heights were domed upward over the urban area.

The thermodynamic perturbations varied with existing weather conditions but, in general, were sizable, being as large or larger than the city throughout the mixing layer. In several case studies, the airflow over the metropolitan area was unquestionably perturbed although not in precisely the same manner in all instances. The perturbations occurred in both fair weather and antecedent rain conditions. The exact nature of the perturbations was a function of a number of factors, but in almost all instances, the disturbance was associated with the metropolitan area. Wind field perturbations were most obvious during light wind conditions with changes in wind direction. The amount of perturbation in the wind fields, obtained by subtracting the area mean value, was very similar in both strong and weak winds. Typically, the perturbed airflow extended through a depth of a kilometer, decreasing in magnitude and changing in form with height.

Although the perturbations in the horizontal and vertical wind fields were directly related to cloud development, it appeared likely that the perturbations impacted was more by modifying the storm history, particularly in view of the fact that the precipitation anomalies were associated primarily with the heavier rain storms. Thus, the role of urban-induced modifications in airflow within the context of urban modification of the precipitation processes was more discernible in individual case studies.

CHAPTER 4

Cloud Characteristics

RICHARD G. SEMONIN

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ABSTRACT

Studies of convective clouds revealed marked influences on their characteristics and distributions. Surface cameras and satellite photographs showed first clouds of the day in the St. Louis area initiated most frequently over the center of the metropolitan area and over the intensely industrialized area of Alton-Wood River. These areas were also cloudier in the later afternoon. The cloud base heights of cumulus over the St. Louis commercial district and adjacent downwind area were higher than comparable rural clouds.

Aircraft measurements of many summer clouds showed that the median updraft speed was 2.5 m s^{-1} and the most frequent updraft location was on the right front flank of the storm. The measurements of Aitken nuclei inside and outside of cumulus with bases extending into the mixing layer showed the direct ingestion of surface source material into convective clouds. The average downwind increase of the cloud condensation nuclei (CCN) concentration was 94% measured at 1% supersaturation in a thermal diffusion counter. Measurements of the cloud droplet size distribution in small cumulus and stratus clouds showed narrower distributions of sizes with greater number concentrations in downwind clouds compared with upwind clouds.

All of the observations of CCN and cloud microstructure obtained by the various investigators supported the concept that the urban effect on cumulus clouds is to shift the droplet size spectrum toward smaller median droplet diameters, and, with a lesser degree of confidence, the observations suggest an increase in the number of larger droplet sizes. The measured and calculated liquid water content (LWC) in the urban-effected clouds beyond St. Louis consistently showed increases associated with such clouds.

4.1 Introduction

The Illinois Water Survey operated two all-sky cameras and one directional camera to photograph clouds in the research area during various periods of the project. These cameras were located in St. Louis and near Alton to provide statistical data on the time and relative location of cloud initiation in these two areas, as well as documented histories of convective storms as they traversed the area. In addition, GOES (Geostationary Operational Environmental Satellite) data were available for 1975 permitting analysis of cloud frequencies for fixed hours during the day.

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CHAPTER 5

Urban Precipitation Processes

ROSCOE R. BRAHAM, JR.

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ABSTRACT

Precipitation processes in convective clouds in and around St. Louis were studied by radar, numerical modeling and surface rainfall data.

Statistically significant differences were found between radar first echoes which developed over the urban and non-urban areas. Urban first echoes occurred with over twice the frequency (area normalized) and had lower bases and tops. The area of maximum first-echo frequencies was centered over downtown St. Louis and extended north and northeast along the Mississippi River. Modeling studies showed that the urban clouds which gave rise to the first echoes must have had lower cloud-base updraft speeds; a finding which is compatible with measurements showing that the daytime urban boundary layer was drier than that of nearby rural areas. Based upon studies of echoes which could be followed through their lifetimes, it is concluded that urban convective clouds, on average, reach greater maximum heights, last longer, and are more likely to merge with other clouds.

The frequency distribution of heights of the tallest echo in the non-urban area, at each half-hour, was found to be bimodal with peak frequencies near 6 and 12 km and a frequency minimum near 9 km. In contrast, urban echoes gave a unimodal distribution with higher-than-rural frequencies at all levels from 5 to 13 km. Evidently, many urban clouds were able to penetrate a mid-level tropospheric arresting level, which often limited the growth of non-urban clouds.

Simulations with boundary layer numerical models and comparisons of rainfall amounts received over different areas were used to estimate possible effects of local topography. These studies led to the conclusion that topography probably does play a role, but definitely is not the major cause, in determining St. Louis area rainfall patterns.

The possibility that urban clouds may be envigorated through glaciation, and thereby be able to penetrate the atmospheric condition which frequently restricted rural clouds to 6 km top heights ($\sim -10°C$) was examined. Measurements appear to rule out the possibility that St. Louis was a strong source for ice-forming nuclei. However, measured cloud microphysical characteristics give rise to the possibility of increased glaciation through the Hallett-Mossop ice mechanism.

It is concluded that the rainfall maximum which was observed to occur over the downwind edge of St. Louis, during late afternoon hours, resulted primarily from modification of boundary layer dynamics from surface thermal and frictional forcing. Even though the urban heat island normally had its minimum value during these hours, the decreased stability of the lowest air layers, associated with afternoon heating, allows even a small heat anomaly to have a considerable effect on boundary layer motions.

The cause of a secondary rainfall maximum, which was found in the Alton-Edwardsville, Illinois, area around midnight, was not established.

5.1 Introduction

In this chapter we bring together the findings of a wide variety of METROMEX studies relating to urban effects upon precipitation. We begin by examining the patterns of surface rainfall as a function of time of day, synoptic weather conditions, and various combinations of surface wind directions and storm motion directions. This is followed in order by studies of precipitation initiation as revealed by radar, comparative studies of the complete life histories of urban and rural echoes, and a study of properties of individual areas of rain (raincells). Next we summarize an urban-rural comparison of the tallest radar echoes present at various times of the day, and discuss various possible physiographic influences on rainfall at St. Louis. This chapter closes with a discussion of mechanisms postulated to account for observed urban precipitation effects.

5.2 Diurnal rainfall variations

Huff (1977) may have been the first to point out that two basically different storm types are suggested by the diurnal variations of rainfall in the St. Louis area. Fig. 1 shows rainfall amounts, expressed as overlapping three-hour averages, for the raingage network as a whole and for several areas within it. In most areas

CHAPTER 6

Atmospheric Chemistry and Source-Receptor Relationships

JEREMY M. HALES

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ABSTRACT

The chemical and physical attributes of pollutants and potential weather-modification agents in and around the St. Louis/METROMEX region were carefully studied. Both airborne and precipitation-borne pollutants were examined with special emphasis on the transformation and natural-removal processes, which occurred as these materials drifted downwind of the metropolitan area. Precipitation scavenging of airborne pollutants was of particular interest owing to its intrinsic relationship with many potential weather modification processes.

A definite urban plume of Aitken condensation nuclei was emitted by the St. Louis area. The general urban plume is a composite of individual sources, and often was characterized by concentrations of several tens of thousands of nuclei per cubic centimeter. The urban plume tended to approach regional concentrations after 4–5 h of downwind travel, an effect which obstensibly was caused primarily by a combination of coagulation and dilution mechanisms. The St. Louis area was also a general source of CCN during all seasons of the year. In contrast, the city seemed to act as a sink or "deactivator" for ice-formation nuclei, at least during winter months. Importantly, aerosol particles in the accumulation mode tended to increase in concentration immediately downwind of the urban complex, and with subsequent decreases after about 3 hours of travel time.

Importantly, sulfur dioxide emitted from the metropolitan area on clear days was removed by a combination of dry deposition and chemical conversion. Chemical reaction rates within the urban plume were typically of the order of 10% per hour. Thunderstorms were effective scavengers of St. Louis-emitted SO_x and NO_x, and a definite urban deposition pattern occurred immediately down-storm of the metropolitan area. Free-hydrogen ion deposition patterns showed no easily discernible evidence of the city's presence, however. Convective storms were also effective scavengers of particulate tracer materials released into clouds. Tracer deposition patterns resulting from these tests testify to the complexity of flow patterns in convective-storm systems.

CHAPTER 7

Summary of Urban Effects on Clouds and Rain

R. R. BRAHAM, JR., R. G. SEMONIN, A. H. AUER,
S. A. CHANGNON, JR., and J. M. HALES

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ABSTRACT

METROMEX observations relating to urban weather modification are summarized and examined against background knowledge and theory.

The diurnal variations of the urban heat island, low-level moisture over the urban area, boundary-layer wind field and air stability combine to produce low-level convergence and vertical air motions over and downwind of the city during daylight hours.

Observations show that, during the forenoon hours, the urban area experiences earlier cloud buildup and enhanced frequencies of radar first echoes due to the rapid deepening of the boundary layer. During the period from about 1500 to 2100 CDT there was a rainfall maximum centered over the eastern metropolitan area and adjacent rural areas. This rainfall maximum, with an area-average amount ~25% above background, is attributed directly to urban enhancement. It apparently comes from urban-induced invigoration of convective clouds which would naturally have been restricted to top heights less than about 6 km. Associated with these storms was an area of increased frequency of thunderstorms and hail over St. Louis, and to the east.

A secondary rainfall maximum occurring between 2100 and 0300 CDT was found north and northeast of St. Louis, in the Edwardsville-Alton area. Evidence about these storms is incomplete. The mechanism by which, and the extent to which these nocturnal storms were modified by the city, were not determined.

Possible mechanisms of urban-weather modification are discussed. These include possible effects of anthropogenic nuclei, physiography and lower urban θ_e, as well as boundary-layer convection, and enhanced cloud glaciation. Enhanced boundary layer convection, perhaps with help from enhanced cloud glaciation, are believed to be the major urban weather mechanisms operating at St. Louis.

CHAPTER 8

Impacts of Urban Modified Precipitation Conditions

STANLEY A. CHANGNON, JR.

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