MESOSCALE METEOROLOGY OF METROPOLITAN REGIONS

Overview of Urban Climate

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ABSTRACT. The broad features of urban climate anomalies are described and explained by combining recent METROMEX data with those from prior studies. The urban heat island is well understood, and urban effects upon cloud nuclei and cloud microstructure are clearly observed and explained in part; but the causes of urban effects upon rainfall remain speculative.

IT IS APPROPRIATE that this conference begin with a session on meteorology. Not only are specific climatic effects associated with cities, but meteorological conditions determine the capacity of the atmosphere to transport, disperse, and scavenge pollutants and thereby influence the location and extent of pollution-related injury to plants and man. Moreover, wind and temperature are factors in the dispersal or ducting of sound pollution.

Urban climate is an old subject; published papers go back over 150 years. It is inevitable, therefore, that some of my material will be old-hat to some of you: to others it will provide an entree into the field. However, most of my remarks will center around Project METROMEX and will represent material that has appeared only in specialized publications and reports.

It was about 1968-69 that several scientists engaged in cloud-seeding research began to discuss the need for study of inadvertent modification of weather around large metropolitan areas. Out of this grew Project METROMEX, involving scientists from the Illinois State Water Survey, the University of Wyoming, the Argonne National Laboratory, and the University of Chicago. We undertook a study of the location and magnitude of anomalous weather fields around St. Louis in an effort to establish cause-and-effect relationships linking those fields to causal agents in the city, and to the extent possible to generalize and extend our findings to larger issues in society. Subsequently, we have been joined by scientists from the Battelle Pacific Northwest Laboratories, the Stanford Research Institute, the Sierra Nevada Corporation, and the NOAA Wave Propagation Laboratory.

The metropolitan St. Louis area was selected for study because it was large enough to have a significant pollution problem, yet small enough to be encompassed by a project of practical size. St. Louis has a long history of public concern over pollution; it was the subject of several prior meteorological studies; it has relatively light commercial air traffic, thus making research flights practical; it was considered to be relatively free of major topographic influences; and it was close enough to Illinois to justify expenditure of substantial amounts of state resources. In addition to support from the State of Illinois, METROMEX is supported by the National Science Foundation, the Energy Research and Development Administration, and the Environmental Protection Agency.

The subsequent choice of St. Louis for the EPA Regional Air Pollution Study (RAPS) has further indicated the appropriateness of St. Louis for such studies and should ultimately enhance the value of both projects. The geographical setting and centers of operations on Project METROMEX are shown in figure 1. Although this project is still in progress, there have been significant findings which, when added to prior data, allow us to determine many of the reasons for urban climate anomalies. Because of space limitations, detailed references to METROMEX publications are not given in this paper. Readers are referred to a recent summary of METROMEX findings and publications *(Principal Investigators of Project METROMEX 1976)*.

For some time it has been known that, in the absence of over-riding topographic influences, cities are warmer than surrounding rural areas. They also have more fog, cloud, and rain, while receiving less sunshine. Cities appear to be drier during summer and more moist

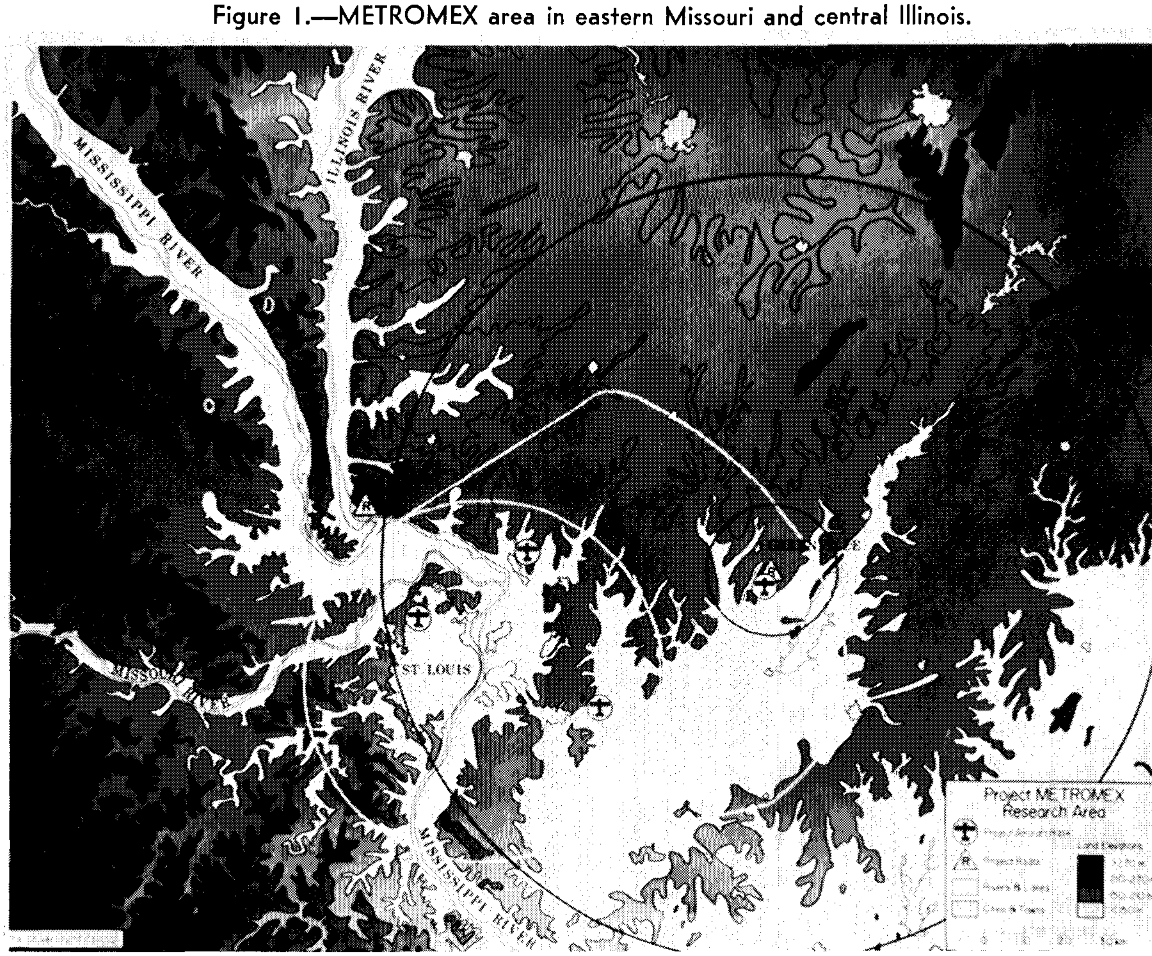


Figure 1.—METROMEX area in eastern Missouri and central Illinois.

during winter than the nearby rural areas. METROMEX has found an excess of thunderstorms and hail downwind of St. Louis.

What can be said about the probable causes of these urban climatic anomalies? Four characteristic differences between urban and rural areas are recognized as potential contributing causes for modifying weather around cities. These four factors are:

1. Contrasting thermal properties of urban-rural surfaces. Most cities abound in rock-like materials whose thermal conductivity and heat capacity are high relative to those of soil and plant materials that dominate the rural scene. These differences have profound effects on urban-rural temperature differences and local convection.
2. Greater aerodynamic roughness of built-up areas. The tall and irregularly spaced buildings of cities represent a much rougher surface, aerodynamically speaking, than do trees and low vegetation. This results in increased mixing (turbulence) and measurable convergence of the low level flow over cities.
3. Smaller amounts of water available for evaporation in cities. In rural areas most of the rainwater remains near the surface and is evaporated or transpired by plants. In cities, much of it is ducted away to non-urban areas for evaporation. The greater use of energy for evaporation results in lower rural temperatures.
4. Anthropogenic heat, gases, and particulates released over cities. Cities release large amounts of heat, gases, and particulates into the air over them. Only recently have we come to recognize the contribution of these to weather effects.

The relative importance of these four factors probably varies with the size and population of a city, its patterns of industry and land use, and with meteorological conditions, both ambient and recent past. We must anticipate that they contribute differently to different weather effects and that their effects combine in different ways depending upon season, time of day, and regional meteorological conditions.

URBAN HEAT ISLAND

One of the longest studied and best understood of the urban weather effects is the *Urban Heat Island.* The characteristics of urban areas invariably result in slight warming of air passing over them during daylight hours and in reduced rates of cooling at night. The result is a shallow pool, or "island" of warm air centered over the city and flowing off as an elevated plume in the downwind direction. (Exceptions are cities under marked topographic influences and in windy, cloudy periods.)

When well developed, the heat island maximizes over the most densely built-up parts of the city and decreases outward to a sharp gradient around the urban boundary. The maximum surface temperature differences between urban and rural areas usually occur at night, in fall or winter months, and during clear skies and light winds of anticyclonic weather conditions.

For those in other disciplines, I should explain that meteorologists use the term "surface" when referring to conditions in air 1 to 10 meters above ground level. The term "skin temperature" is used to denote conditions at the radiating surfaces, as seen by downward pointing radiometers.

Measurements by the Illinois State Water Survey, in METROMEX, show that the heat island at St. Louis is about what one would expect. Under clear to partly cloudly skies, it is best developed at 2000 and 0200 CDT, becomes broader but less intense at 0700 CDT, and is largely obscured by topographic factors at 1100 and 1500 CDT.

The diurnal variation of surface

temperature differs between urban and rural stations. A rural site warms more quickly, from a lower minimum, during the early part of the day, and cools more quickly during the afternoon and evening.

The diurnal pattern of skin temperatures of urban and rural terrain is different from that of air at low levels. Measurements by Dabberdt and Davis *(1974)*, using IR photometers on a low-flying airplane, showed that the maximum difference in skin temperatures at St. Louis occurred early in the afternoon on clear summer days but during night hours on winter days.

The intensities of heat islands increase with size of the city. Oke *(1973)* and Eagleman *(1974)* conclude that it varies with logarithm of population. Ludwig and Dabberdt *(1973)* propose a fourth root relationship. Landsberg *(1974)* shows that careful measurements will reveal local warming around even a few residential buildings.

Cloud cover and regional wind speed are important factors governing the development of heat islands. By altering radiation exchange between the surface and atmosphere, the effect of clouds is to reduce the heat island intensity *(Petersen 1969)*. Wind has the effect of ventilating a city and limiting the differences betwen urban and rural temperatures. Oke and Hannell *(1970)* summarize data on the critical wind speed above which a heat island is not usually detected, and show that the critical wind (U) was related to population (P) through the equation

$$U = 3.4 \log P - 11.6. \qquad [1]$$

In deducing causes for heat islands, it is useful to start by considering the thermal energy balance of the earth's surface, equation 2,

$$SW{\downarrow} + LW{\downarrow} + A = E + P + S + T + LW{\uparrow}. \qquad [2]$$

The energy sources for an area of the earth's surface consist of that portion of the solar radiation, SW↓, and atmospheric radiation, LW↓, which is absorbed by the surface, plus any anthropogenic heat released from terrain objects (A). These energy sources are balanced against the conversion of sensible energy into latent forms through evaporation and transpiration, E, and photosynthesis, P, the flux of sensible heat into the subsurface, S, and by flow of sensible heat into the atmosphere by diffusion, T, and IR radiation, LW↑.

Although all these terms contribute to the formation of heat islands, the most important appear to be energy used for evaporation and transpiration, flux of heat into the subsurface, and anthropogenic heat.

Evaporation is largely responsible for keeping rural temperatures lower on sunny days. Heat stored in urban surfaces during daytime, and returned to the air at night, is responsible for keeping urban areas warm long after radiation cooling dominates the rural scene.

The importance of anthropogenic heat has been debated; however, data compiled by Koenig and Bhumralker *(1974)* show that the urban-heat release in Manhattan exceeds the solar energy absorbed at the surface by a factor of 3.9. Even in an open park-filled city like Washington, D. C., the areal average heat release is equivalent to over 25 percent of the solar insolation.

STRUCTURE OF THE URBAN BOUNDARY LAYER

The heat island and surface roughness of urban areas combine to modify the atmospheric boundary layer from its upwind character. This modification is three-dimensional and varies with time of day and meteorological conditions. Observations of horizontal and vertical winds, temperatures, and water vapor, with sufficient accuracy and detail to delineate the urban boundary layer structure, are difficult to make and as yet inadequate to allow a complete description of it.

METROMEX studies show that the St. Louis heat island is measurable through the depth of the mixing layer. Temperature excesses of 1°K frequently are found as high as 800 m agl. During the summer days we find a mimimum in specific humidity with height-averaged deficits of 1 g kg^{-1} not unusual. These anomalous fields are displaced downward from the urban center by ambient winds. We sometimes find above the heat island a shallow cap of air slightly cooler than rural air at the same levels.

The top of the mixing layer at St. Louis domes up over the city in daytime, and morning rise-rates are faster than over rural areas. The mixing layer frequently undergoes a diurnal cycle as described in following paragraphs. Summer convective clouds appear earlier over the city and usually have higher bases than those over rural areas—up to 300 m in some cases.

Low level airflow at St. Louis is markedly perturbed by the city in light wind conditions. METROMEX data show that a frequent result is airflow convergence up to an average height of 1250 m with values as large as 0.5×10^{-4} sec^{-1} up to levels of 800 m agl. Measurements of atmospheric parameters and urban aerosol particles within and below cloud bases, plus results of tracer experiments, prove that air from the urban boundary layer feeds into and alters the properties of clouds. Measurements also show that clouds and rain are significant removal mechanisms for urban pollutants.

Numerical modelling suggests that the thermal excess at St. Louis is more important than surface roughness in raising the depth of the mixing layer, and under certain conditions, in displacing it downwind.

By combining these METROMEX observations with data from a number of other sources, we can outline the major features of the urban boundary layer during summer and fall convective weather conditions. Although this analysis is pointed particularly toward summer conditions at St. Louis, it should also serve as a point of departure for analyzing the boundary layer over other cities and during other seasons.

Before sunrise over rural areas one usually finds a deep radiation inversion. The inversion may be capped, or even replaced, by an isothermal layer if fog or heavy haze is present *(Pilie et al. 1975)*. Reduced vertical mixing across the inversion tends to decouple the winds from the surface resulting in light winds in the inversion and a sharp wind increase across it. Any shear-driven mixing layer will be quite thin.

Over both urban and rural areas, we may find considerable amounts of haze as a result of upward mixing (somewhere upstream) on previous days. Frequently the haze develops into layers along internal stable levels. The top of the haze may be very sharp, corresponding to a stable layer, and accompanied by a sharp drop in humidity. Other times the haze top will be ill-defined, merely thinning gradually with height.

Frequently, when the haze has a well-defined top, in early morning it will carry a thin stratus cloud layer formed through nocturnal radiational cooling from the haze. Meteorologists frequently call the entire haze layer, the "mixed layer" to differentiate it from the layer of active mixing, the "mixing layer" within it.

Over the city before sunrise, because of the heat island, any surface radiation inversion will be weak, perhaps limited to large air-drainage areas such as along river channels. The absence of a strong low-level inversion allows the wind to remain more tightly coupled to the surface, resulting in a turbulent mixing layer. At sunrise this layer may be 300 to 400 m thick and filled with smoke and haze; it may be capped with a weak elevated inversion. Above the surface mixing layer the haze and any stratus

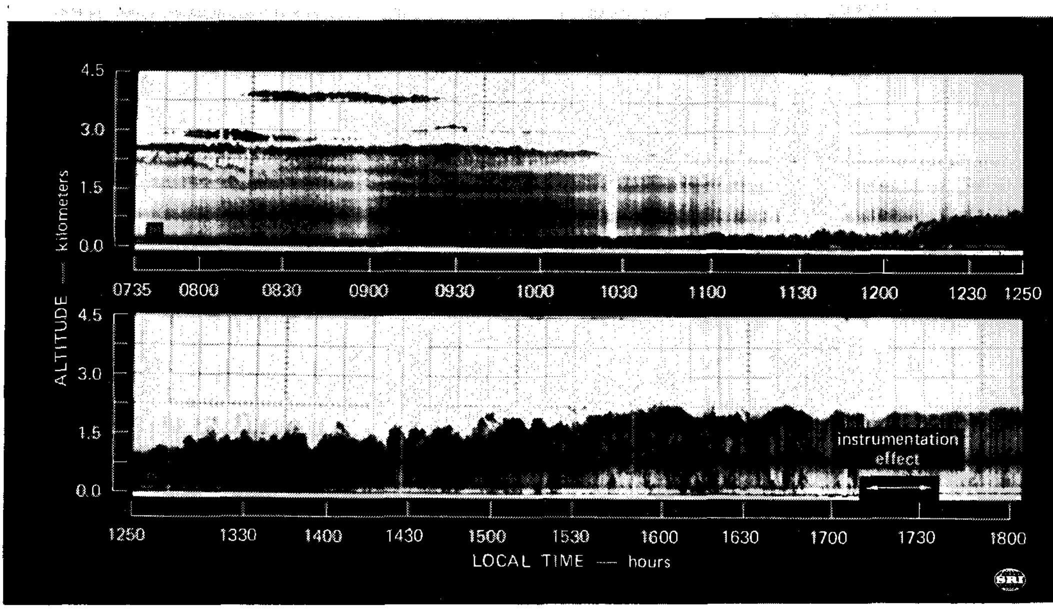


Figure 2.—Height-time cross section of the aerosol structure over St. Louis on 13 August 1971 as observed by Russell *et al.* (*1974*).

cloud will be very similar to that over the rural areas.

After sunrise, both in urban and rural areas, any stratus present and the haze particles, will adsorb solar and IR surface radiation and begin to evaporate, improving visibility in the haze levels. These processes at St. Louis are seen clearly in time-height cross sections obtained by our colleagues from Stanford Research Institute with their Lidar (fig. 2, *Russell et al. 1974*).

In rural areas, the surface temperatures will rise rather quickly because the surface inversion limits the depth of initial heating. Dew may be present, in which case the initial temperature rise is delayed by diversion of energy into its evaporation. This in turn will provide additional vapor and tend to cause low-level visibility to decrease, or fog to thicken, for a brief interval in the manner discussed by Pilie *et al. (1975)*.

Within the city after sunrise, skin temperatures begin their climb almost immediately, aided by reduced amounts of dew. This results in a superadiabatic surface layer and initiates thermal convection. Uninhibited by a strong surface inversion, these "thermals" begin to thicken the mixing layer by enfolding air from above it, diluting the smoke and haze that has accumulated during the night. Because of the greater depth of air involved, the surface temperature will rise less rapidly than in the rural areas. As the mixing layer deepens and larger and larger thermals are involved, the top takes on a hummocky character seen so nicely in the Lidar data.

We are assisted in visualizing these dry thermal plumes through the work of Hall *et al. (1975)*, who used three covolume scanning acoustical sounders to study dry thermals near Boulder, Colorado. Their data show that individual thermals tended to rise nearly vertically and advect with the wind. They were more sharply defined on the upwind edge and less so on the downwind. (Perhaps due to mixing with the environment?) When the mixing layer was unstable to depths of 300 to 500 m, thermal updrafts were 2 mps and more over a broad mid-height range. Between the thermals were downdrafts with speeds of about one-half that of the updrafts. From double theodolite pilotballoon data at St. Louis, Ackerman *(1974)*, found similar values for dry vertical currents in the urban boundary layer. This "boiling" of the lower atmosphere is made visible on the Lidar by the presence of large quantities of aerosol particles (note fig. 2, 1130 to 1530 CDT).

After burnoff of the radiation inversion, the rural mixing layer develops in a similar manner but at a slower rate. According to Lidar data at St. Louis, the rural buildup lags that over the city by about 2 hours.

For several hours near mid-day, both urban and rural areas may have superadiabatic surface layers, above which the lapse rate is nearly adiabatic to the top of the mixing layer. In some instances, these superadiabatic layers are surprisingly deep. Using data from an instrumented TV tower in suburban Philadelphia, Davis and Newstein *(1968)* showed superadiabatic layers over 270 m deep on several days of pollution episodes in November 1966 and January 1967; presumably they are even deeper in summer.

On clear days the loss of energy by radiation and diffusion begins to exceed the incoming radiation by mid- to late afternoon, and surface temperatures start to decline. Typically, urban areas lag the rural by an hour or so in the onset of evening cooling. As surface temperatures decline, the source of energy for dry thermals is cut off and vertical mixing decreases.

On days when moisture conditions in the lower part of the boundary layer are adequate, clouds form at the tops of the strongest thermal plumes. When the mixing layer is limited by a strong stable layer, these clouds appear to sit in the top of the mixing layer with only their tops protruding above it (fig. 2). Under more favorable conditions, bulging cumuli may rise through the mixing layer to some elevated stable layer where their growth is arrested. Here they evaporate, leaving the pollutant materials they had ingested through the base as an elevated haze layer.

On days with very large cumulus clouds, the vertical structure of the boundary layer deviates from the orderly progression described above. For now the air motions induced by the cloud, (inflow into updrafts and outflow from downdrafts), begin to dominate the local wind field; evaporation of rain may destroy the heat island. In addition, cloud-shadowed and rain-cooled surfaces are less effective in feeding thermals.

The cool temperatures and high visibility of air that had descended in the downdraft and spread over the surface as a cool air dome are in marked contrast to the hot, hazy conditions before the storm.

In terms of air pollution, a major impact of large convective storms over urban areas is their ability to suck up very large volumes of surface-polluted air, scavenge many of the pollutants for deposition in the rain, and exhaust the remainder at heights up to the tropopause. Large convective storms over urban areas probably contribute appreciably to the Junge sulfate layer in the lower stratosphere.

Before leaving the subject of urban boundary layers, let's consider the results of numerical models of flow over heated islands. Estoque and Bhumralker *(1969)* show that for wind and stability conditions typical of summer at St. Louis, enhanced vertical mixing resulting from the heat island and surface roughness will bring down the higher momentum winds aloft, causing a gradual acceleration of the horizontal winds and slight subsidence over the heated surface. This study also shows that the main convective updraft will be displaced to the downwind edge of the island, very suggestive of the downwind thermal plumes observed by Clarke *(1969)* at Cincinnati. If the models can be applied to conditions over urban areas, subsidence could help explain the moisture deficits observed over St. Louis. Moreover, the downwind displacement of the convection field fits with observed rain excesses on the downwind side of the city.

URBAN EFFECTS UPON CLOUDS AND HAZE

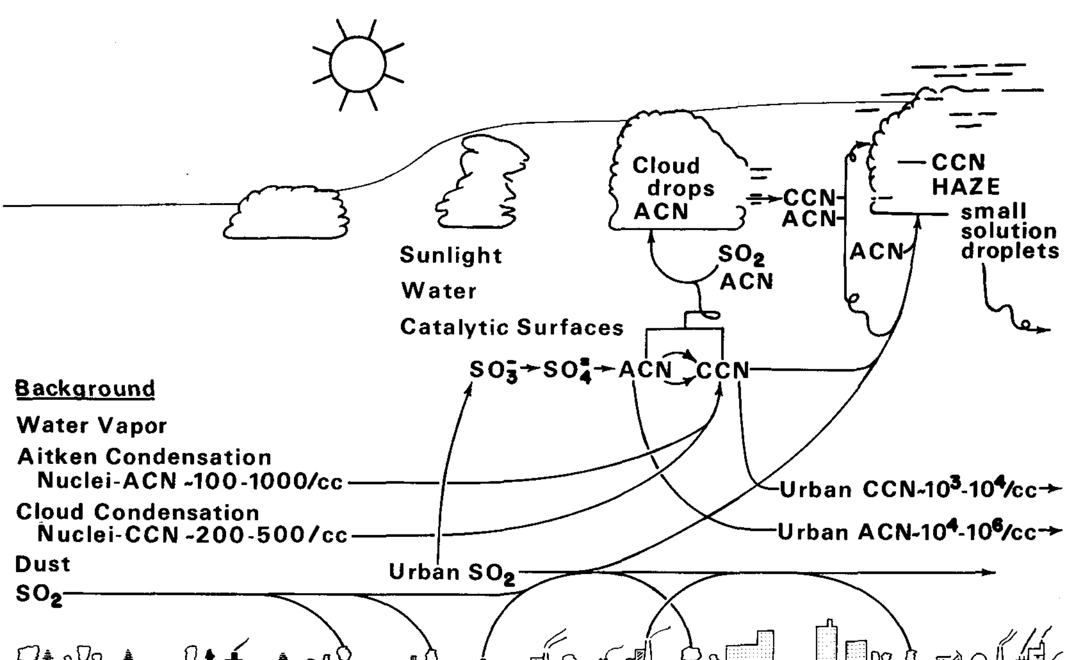
Cities such as St. Louis have a marked effect upon the sizes and concentrations of drops in clouds that ingest the urban air. This effect results from the large numbers of cloud condensation nuclei, CCN, that form within the urban plume. The processes whereby this takes place are outlined in figure 3.

In the pristine atmosphere, far removed from man-made influences, CCN are thought to be submicron particles of ammonium sulfate and sea salt. The sulfate appears to come from biologically derived sulfur gases such as H_2S. In urban atmospheres large quantities of SO_2 are released from fossil fuel combustion and by certain industrial and mining-smelting activities. Much of this sulfur dioxide quickly mixes to the surface where it is absorbed by plants in the first few hours downwind (at least in summer). METROMEX studies give a half-residence time of 4.5 hours for SO_2 released from St. Louis in summer.

Some small fraction of the SO_2 undergoes gas-to-particle conversions to give small particles of sulfuric acid and sulfates. Chemists still are studying the various reactions involved in this process, but there seems to be general agreement that the transformation is most rapid in the presence of sunlight, water, and trace catalytic surfaces. Sulfur dioxide is not the only gas that undergoes conversions to particles. Oxides of nitrogen from automobile exhaust, and other urban effluents, may undergo similar transformations.

Particles formed by gas-to-particle conversions quickly reach sizes of 5 x 10^{-6} cm and are called Aitken particles or Aitken condensation nuclei (ACN) since they are measured in de-

Figure 3.—Schematic outline of processes responsible for the production of urban nuclei and urban aerosols.



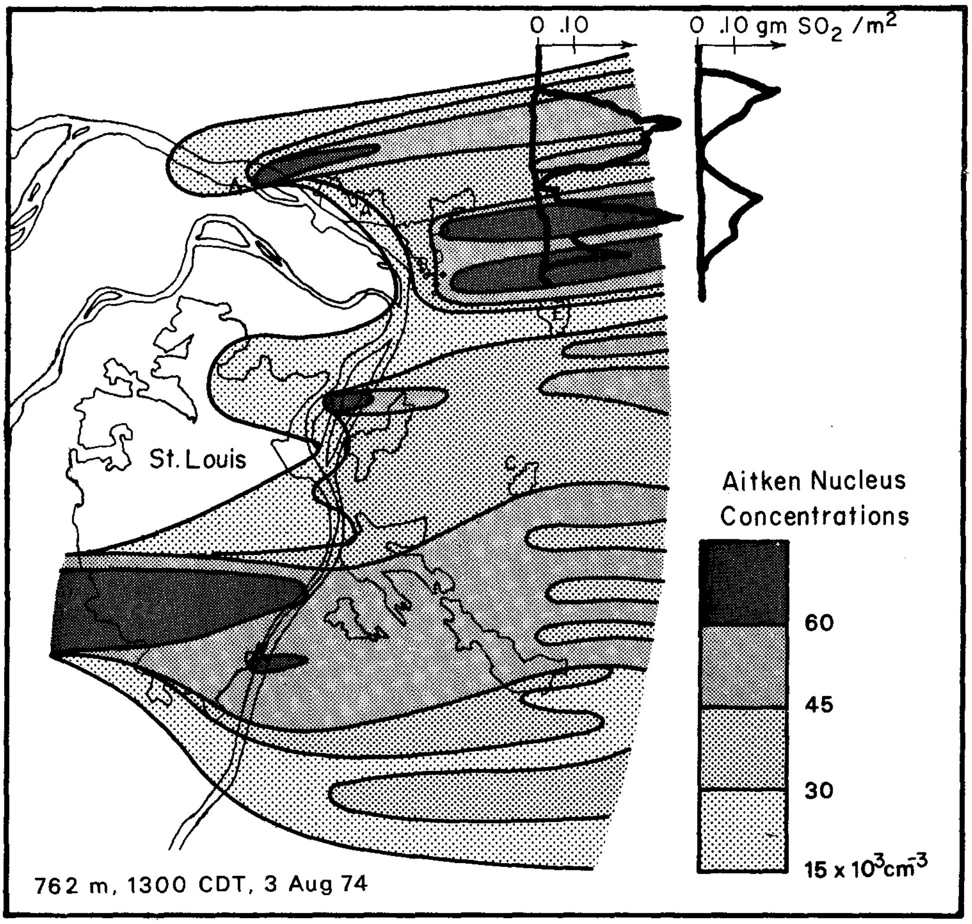


Figure 4.—Aitken nuclei plumes in the urban boundary layer over St. Louis on 3 August 1974, with superimposed plumes of SO_2 as measured by Vaughan *et al.* (*1975*). The plumes in the upper right show the SO_2 overburden (gm/m^2) above two north-south highways.

vices that cause them to nucleate droplets through supersaturations of several fold.

The concentrations of ACN in clean oceanic air, or over land well above the influences of man's activities, usually are a few hundred cm^{-3}. In the rural boundary layer upwind of St. Louis, summer concentrations are of order 10^3 cm^{-3}. In the urban plume typical values are $10^4 - 10^5$ cm^{-3}. Estimated source strengths of industrial areas are about 1-3 x 10^6 cm^{-2} sec^{-1}.

Aitken particles are too small to directly affect clouds, but they serve as excellent tracers of the urban plume. Using data from our instrumented airplane, we have prepared maps showing ACN plumes for selected clear-sky situations. One such is shown in figure 4. These maps show several Aitken particle plumes arising from industrial areas and large power stations, the large SO_2 emitters in data compiled by EPA. Presumably highway traffic also is a contributor to urban ACN, but our data in St. Louis do not readily resolve such disperse sources. While we were obtaining these data, other scientists were measuring the vertically integrated SO_2 along two highways over which the airplane was flying (*Vaughan et al. 1975*). Their results are also shown in the upper right quadrant of figure 4. It is clear that the ACN plumes coincide exactly with total SO_2 plumes.

Maps such as these show that the urban plume is a composite of plumes from a number of intense point sources superimposed upon a background from the city. Our data show that in the neutrally buoyant boundary layer, the ACN plumes quickly mix vertically through the depth of the mixing layer and spread horizontally about 10 degrees.

Once formed, Aitken particles continue to grow by further adsorption and oxidation of SO_2, and by coagulation among themselves. New ones keep forming and others are destroyed by coagulation and by interception by haze and cloud particles. The latter process is relatively slow since our measurements inside urban clouds show ACN concentrations exceeding nearby clear air values several fold, at least up to 3 km above cloud base.

The larger the size of a submicron soluble particle, the lower the supersaturation required for it to nucleate and begin growth into a cloud drop. The supersaturation in the bases of many clouds is approximately 0.5 percent (R.H. = 100.5 percent). Particles capable of nucleating in this range of supersaturation are called cloud condensation nuclei (CCN).

Our measurements at St. Louis show that the city is a source for CCN, in both winter and summer, with source strengths of about 10^4 cm^{-2} sec^{-1}. This is equivalent to a volume source of about 0.1 particle sec^{-1} cm^{-3} of urban plume.

One of the key issues as to whether urban CCN can be small sulfate particles concerns the reaction rates of SO_2 conversion into SO_4. Measurements of sulfates in rain over and immediately downwind of St. Louis account for 10 to 20 percent of the SO_2 emission, according to METROMEX measurements. If one assumes that all urban CCN are pure sulfate formed from SO_2, the amount required is substantially less than that observed. Thus it appears that conversion of SO_2 can account for urban CCN, at least in St. Louis.

Ingestion of anthropogenic CCN into the bases of urban clouds results in drop concentrations up to twice that of nearby rural clouds. The sizes of urban cloud drops are correspondingly smaller and the spectra more peaked. A typical example of urban and rural cloud drop spectra is given in figure 5. These observations are in accord with theories relating drop spectra to CCN and updraft speeds *(Mordy 1959, Warner 1969, Fitzgerald 1972)*.

HAZE FORMATION

The mechanism of urban CCN production and nucleation in urban clouds appears to be closely related to one of the most serious of all air-pollution problems—viz., the formation of haze and low visibility during periods of stagnant anticyclonic circulation. During such periods, we find that the minimum visiblity is in the upper part of the mixing layer where there is a scattered to broken layer of shallow cumulus clouds. These clouds evaporate without raining. Between the clouds, and below their bases, are haze particles with modal sizes of several microns, and concentrations of order 1 cm^{-3} of particles up to 15 microns diameter. To be stable at the slight subsaturations involved, these haze particles are most likely small solution drops.

We believe that these particles form by repeated cycling of Aitken particles, SO_2, and CCN through the short-lived clouds (fig. 3). With each nucleation and growth into a droplet, the CCN grow larger. The end product is a large number of large solution particles. Easter and Hobbs *(1974)* discuss the chemistry of this process when operating in shallow wave clouds.

Once created, these solution drops can survive vertical mixing through the depth of the mixed layer and advection over great distances from the SO_2

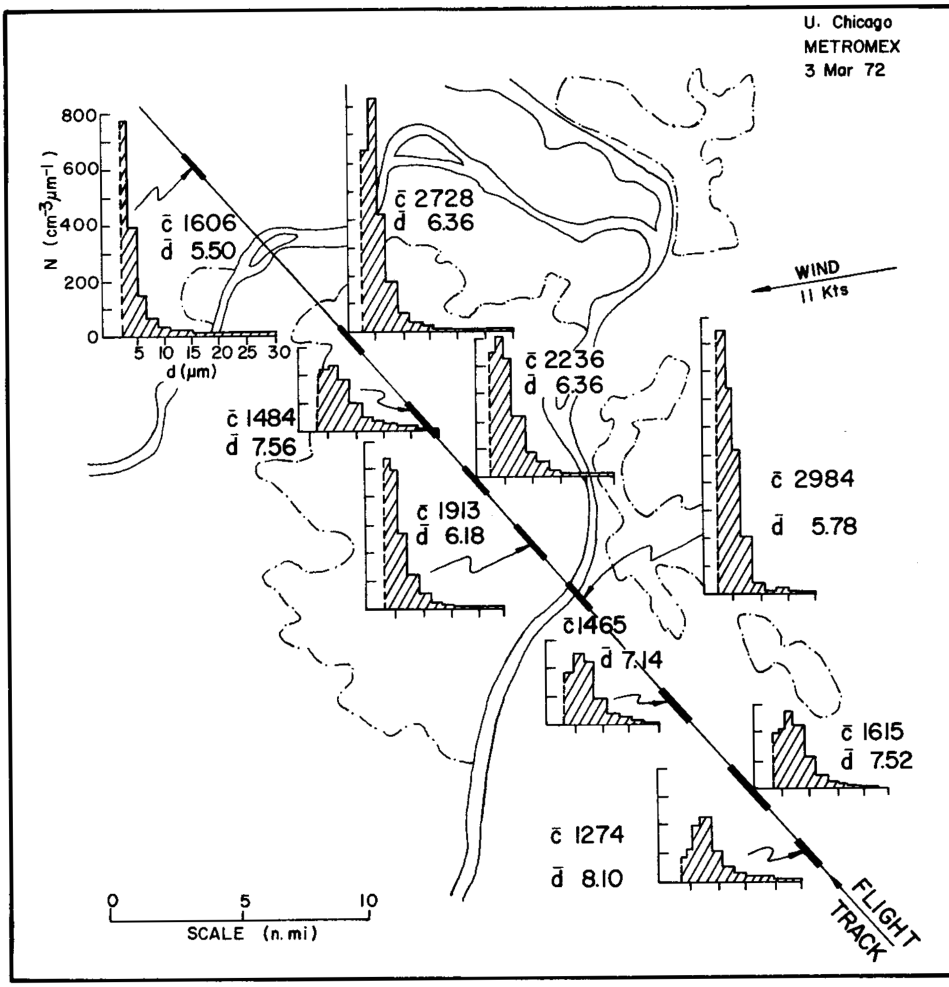


Figure 5.—An example of the effect of urban-CCN on size spectra of drops in clouds. Note the great difference between rural spectra (southeast end of the track) and those downwind of industrial areas and large power stations.

sources. In a sense these drops constitute a disperse cloud which in severe pollution episodes may become thick enough to obscure the sun.

URBAN EFFECTS UPON PRECIPITATION

The meteorology of urban effects upon precipitation is poorly understood compared with that of the urban heat island and the changes in cloud microstructure and visibility resulting from the growth of urban CCN. The issues are at least an order of magnitude more complex, involving interacting cloud dynamical and cloud microphysical processes, both of which are poorly understood and dependent upon conditions of the atmosphere below and around the clouds.

Urban rainfall effects have been studied in two ways: by statistical analysis of precipitation elements observed around cities and by studying the urban-rural difference of cloud dynamical and cloud physics parameters known *a priori* as related to natural precipitation.

Viewed by one who has not been involved in the statistical treatment of observed rain around cities, this approach seems to be troubled by questions of the accuracy and representativeness of historical data and by the difficulty in separating urban effects from local topographic effects. It is well established that low hills (100 to 200 m) can produce local precipitation anomalies comparable to that attributed to urban effects (e.g., *Jones et al. 1974, Bergeron 1968*). Every city is uniquely integrated into its local topography, and there is no statistical device that will unambiguously separate natural topographic effects from those due to man's alteration of the topography by buildings, parking lots, etc. Weekend vs. weekday partitioning of the data and stratifying by wind direction can help reduce, but not eliminate, this problem.

The belief that there is more rain in or near cities than would have occurred at the same location had the city not been built seems to rest mainly upon two facts: (1) local excesses have been observed at a number of (though not all) cities located in a variety of topographic situations; and (2) studies of historical data have shown increasing rain anomalies at some cities as they have grown and become industrialized.

METROMEX has been involved in statistical analyses of rain data, but it also has been deeply involved in measuring physical variables associated with rain at St. Louis in an effort to understand the physics of urban rainfall. According to studies from the Illinois State Water Survey, the largest urban effects at St. Louis are associated with squall lines and squall zones, conditions favorable for natural development of large clouds and moderate to heavy rain. Thus we are faced with the task of working with large clouds whose mere size and complexity make direct observations difficult.

A number of hypotheses have been advanced for physical mechanisms whereby cities might induce local rain excesses. These tend to divide into two groups: those stressing dynamical effects arising from the heat island and surface roughness, and those involving microphysical effects associated with urban derived nuclei, aerosol particles, etc. In either case, one assumes that the urban effect operates by altering natural precipitation mechanisms in some manner.

There are two mechanisms of natural precipitation *(Byers 1965)*. The first recognized and best known is one involving ice particles growing by vapor diffusion in a supercooled cloud; i.e., a cloud of liquid droplets which have cooled below 0°C without freezing. Ice particles are initiated by ice-forming nuclei (IFN). In general, IFN are not the same particles as CCN.

Although data are conflicting, so far it appears that St. Louis is not a significant source of IFN. In fact, it may act to poison natural IFN, especially in the winter months.

The second mechanism of natural rain formation involves collision and coalescence between cloud drops. Many collisions are required because a single rain drop has the mass of about one million cloud drops. Initiation of this mechanism is favored by a broad spectrum of cloud drops such that drops larger than about 40 microns diameter can overtake and coalesce with smaller ones. This mechanism does not require ice particles and can operate equally effectively in clouds either warmer or colder than freezing.

It has been known for some time that coalescence is the dominant mechanism for initial development of rain in cumulus clouds in the Midwest in summer.

Theory says that the narrow drop spectra in urban clouds should delay initiation of the coalescence mechanism. But in fact, the RHI radar shows that coalescence is speeded up, not delayed, in summer clouds over St. Louis. It appears that these clouds also develop a few very large cloud drops, too large to relate to the CCN spectra as usually measured. These drops appear as a "large drop tail" on spectra measured in clouds downwind of the city. We presume that these large drops are associated with particulate pollution from the city.

When developing precipitation in a cloud becomes intense enough to be detected by radar we have what is called a radar "First Echo" (FE). In the St. Louis study we find that FE's are warmer than 0°C, hence are coalescence induced. Also, on average, urban FE are slightly lower and warmer than those of rural areas.

The Greenville 3-cm radar shows that the frequency of formation of FE is not uniform over the radar area, with a region of maximum occurring over and downwind of St. Louis.

At the time cumulus clouds produce 3-cm FE's, they have tops barely reaching the freezing level. Unless these clouds continue to grow, the rain they produce will be rather modest.

Let's turn to some of the Illinois State Water Survey measurements of summer rain at St. Louis. They show that the rain pattern for the first three summers of METROMEX was a north-south ridge of rain excesses about 10 miles east of the Mississippi River, and a trough of low rain amounts across the western suburbs. The greatest rain totals were around Edwardsville, Illinois, about 18 miles northeast of the famous St. Louis riverfront Arch. The average rain amount in the ridge is about 1.36 that of the trough.

Over 60 percent of the rain in the Edwardsville area occurred in storms depositing an inch or more. In addition, Edwardsville had substantially more thunderstorms and hail than were observed west of the Mississippi River. Obviously the rain excess at Edwardsville came from clouds much larger than those producing FE's.

When rain periods were stratified by pre-storm wind direction, the downwind quadrant had the larger amounts of rain.

The fraction of each station's total rain that fell during the hours of strongest convection, 1500-1800 CDT, shows a strong maximum centered directly over the city.

Time and space does not permit enumerating the many other observations about clouds and rain which are available on METROMEX. These may be obtained from the Project Principal Investigators.

The most thoroughly developed hypothesis, thus far, to explain the excess in summer rain east of St. Louis, is that of Boatman and Auer *(1974)*. Measurements made by the University of Wyoming group showed that some thunderstorms moving into the city picked up drier and warmer urban air (lower θ_e), which caused the updraft to weaken. University of Chicago radar showed decreases in the heights of the echo tops shortly thereafter. Boatman and Auer argue that the decreasing strength of the updrafts would accelerate the release of suspended precipitation.

This hypothesis is logical and fits observations. It may indeed account for some of the rain excesses over the city. However, it is hard to see how it relates to the observation of increased thunderstorms and hail east of the city since these storms would presumably be declining in intensity as they cross the city.

A second hypothesis that seems reasonable but is less well investigated says that the low-level instability associated with the heat island, plus any action of the city to focus and localize the release of regional instability, might be sufficient to allow the development of large clouds in marginal situations. For example, it has been observed that radar echoes near St. Louis have a bimodal top-height distribution. Large numbers of echoes have tops around the freezing level as a result of mid-level stability on convective days. If the additional buoyancy at cloud base permits some of these clouds to penetrate the stable layer and reach glaciation levels of −10 to −20°C, the heat of glaciation may then provide significantly additional growth, and more rain. It may also be that glaciation is accelerated in urban clouds through microphysical processes associated with urban derived nuclei; however, this possibility has not been demonstrated.

At this time, and stressing again that Project METROMEX is still in progress, it seems to me most likely that any urban effects upon rainfall are associated with cloud dynamical effects associated with the heat island and surface roughness. Cloud microphysical effects, so obviously important in altering cloud-base microstructure and in the development of haze, are probably of less importance in explaining rain anomalies unless there are feedback processes that we have not yet explored.

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