Progress in Physical Geography 22,4 (1998) pp. 477–520

Urban effects on precipitation amount

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Abstract: Major reviews of urban effects on local climate, extending from Kratzer in 1937 through to Landsberg in 1981, have dealt primarily with radiation, temperature, wind, and air quality. To a much lesser extent they have examined moisture-related elements including humidity, cloud, precipitation, and storminess. Selecting air temperature to represent the former group and precipitation amount to represent the latter, the author asserts that, because of the intrinsic physical differences between them, there are necessarily important differences in the methods to be used for their proper observation, analysis, presentation, and interpretation pertaining to urban effects. The principal differences are based in the fact that temperature is continuous in both time and space, whereas precipitation is continuous in neither. The author maintains that because of these differences, urban climatologists have had much greater success in specifying and explaining urban effects on temperature than on precipitation amount. Further, he makes the case that, lack of recognition that methods used for the study of urban effects on temperature are too often inappropriate for study of urban effects on precipitation amount, has led to a state of affairs where there remains basic uncertainty about the specification of urban effects on precipitation amount, and even greater uncertainty about their explanation. In making that case, the author includes 1) an historical perspective, 2) a critical evaluation of methods, 3) an overview of the status of urban precipitation climatology, and 4) recommendations concerning future research.

Key words: experimental design; methods in urban rainfall climatology; precipitation; urban climate; urban effects on climate

I Introduction

In the major, extended reviews of urban climatology by Kratzer (1937; 1956) and Landsberg (1956, 1981) air quality, radiation, temperature and wind are given primary attention. Lee (1984) followed a similar pattern, as did Goldreich (1996). Other than the brief review by Diab (1978), this reviewer is aware of none that has dealt primarily with research results pertaining to urban effects on precipitation-related weather elements. Precipitation and temperature-related weather elements are different in important ways, so that research methodologies and related problems of interpretation and presentation associated with studies of the two are likewise necessarily different. It is because this review is of the opinion that, in reviews of urban climatology, these differences have been given insufficient attention this article has been prepared.

Hereinafter, unless otherwise noted explicitly, 'urban effects', 'urban climate' and 'urban climatology' will be understood to mean those aspects pertaining only to humidity, clouds, storms and precipitation. Furthermore, in order to keep the discussion focused, emphasis is on the single element of precipitation amount, as distinguished from, for example, thunderstorm or hailstorm intensity and frequency. For reasons that will be apparent, comparisons are made on occasion between precipitation amount, representing the water-related weather elements, and temperature, representing the others.

This review includes 1) a historical perspective; 2) a critical evaluation of methods; 3) an overview of the status of urban precipitation climatology; and 4) recommendations concerning future research. As it will show, the preponderance of modern work on urban climatology has been carried out and reported in the USA. Reasons for that will be suggested later. The principal method employed in reviewing this work critically is to present and consider several analyses that have been widely accepted as demonstrating the existence – and in some cases even the magnitude – of urban effects; followed by a presentation of counterexamples and counterarguments; and concluding with a summary offered in the spirit of the legal defence method of 'raising reasonable doubt' about what seems to be the conventional wisdom on the subject.

II A historical perspective

Because of each reviewer's own unique experiences, any inclusions and emphases will be in some manner different from what another writer might present. In the case of this article, the author is an American who was formerly associated with the staff of probably the largest research programme ever mounted in urban climatology. Irrespective of whatever bias that may entail, it is a fact that, during the last three decades, the majority of research into urban effects on precipitation has been carried out and reported in the USA. While this review includes mention of research performed elsewhere – especially in crucial matters of analytical methods employed – this historical overview is organized around two clusters of American effort: 1) the so-called La Porte Anomaly, first described by Stout (1962) and then named and characterized more fully by Changnon (1968); and 2) the major, and arguably unique, field observation programme called project METROMEX, centred on St Louis, Missouri, during the period 1971–76.

In a series of reviews commissioned by the World Meteorological Organization (WMO), Oke (1974; 1979; 1983; 1990) published a bibliography on urban climatology that nominally included only items published after 1967. In the last of the series, Oke included (1990: ii) what he called 'a simple indication of the vigour' of urban climatology in the form of counts, by year of publication, of all items from the first 80 years of this century. His bibliography was exhaustive in the sense that he cited essentially every relevant report or publication he could discover at the time. As a background document for this historical overview, these counts appear, summarized by five-year periods, and on a logarithmic scale, in Figure 1a. They are plotted as logarithms of counts so that any variations during the periods with smaller counts will be more apparent, and so that any

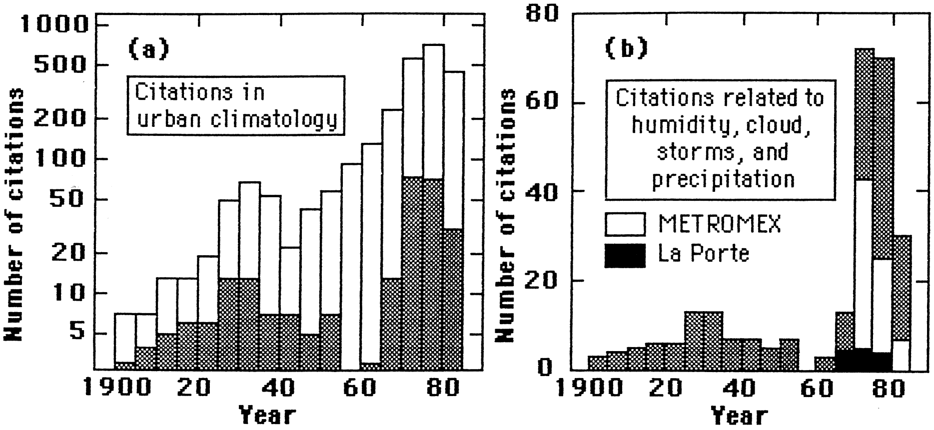

Figure 1 The number of citations in urban climatology – as an index of research activity density during successive five-year periods – from Kratzer (1956) and Oke (1974; 1979; 1983; 1990). (a) On a logarithmic scale, citations representing humidity, cloud and precipitation-related variables are shown shaded, as a component of all citations in urban climatology; (b) on a linear scale, citations about the La Porte Anomaly and about METROMEX are shown as components of all citations shown in shading in (a). See the text for additional comments

'linear' trends might be considered at once to be roughly exponential, as between 1900 and 1935 and again between 1940 and 1980.

As part of his dissertation at Munich University, later brought up to date and translated into English, Father Kratzer (1937; 1956) included a bibliography on urban climatology that was exhaustive in the same sense as Oke's. In it, Kratzer himself assigned each item to one area or another of the subject. His counts on humidity, cloud and precipitation-related variables are shown shaded between 1900 and 1955 in Figure 1a. The present reviewer assigned items from Oke's bibliography in the same manner, and they are shown shaded between 1960 and 1985. He is unaware of any exhaustive bibliography covering the period 1955–65; hence the apparent gap between shaded areas in Figure 1a. This difficulty will not interfere with the general presentation to follow.

All counts appearing as shaded, on a logarithmic scale in Figure 1a, appear on a linear scale in Figure 1b. Counts for items pertaining to the La Porte Anomaly and to Project METROMEX appear within the total counts in Figure 1b.

Kratzer's list of citations representing humidity and precipitation-related variables discloses, between 1900 and 1955, a predominant number in German and a relatively constant overall rate of about 1.3 per year, with the exception of ten 'depression' years just before the second world war when the rate temporarily doubled. Taking Kratzer's list of 82 citations as exhaustive, they constitute about 15% of the 563 citations, on all aspects of urban climatology between 1900 and 1955, that he includes in his second edition. From Oke's list it is estimated that, following that long period of a relatively constant annual number between 1900 and 1955, the number of publications representing humidity and precipitation-related variables increased exponentially at an annual rate of about 14% between 1968 and 1980. To judge by the listings exhibited in Figure 1, citations representing humidity and precipitation-related variables over the full span of 80 years between 1900 and 1985 have continued to constitute between 10 and 15% of all citations in urban climatology.

In Figure 1, the principal features of this historical overview are clearly apparent: 1) the long period until the late 1950s during which the rate of publication of reports representing humidity and precipitation-related variables was low and relatively constant, followed first by 2) an exponential increase in activity until about 1980, and then by 3) a decline to a present-day rate close to that before 1950. Also clearly apparent in Figure 1b are the contributions associated with the La Porte Anomaly and Project METROMEX; the latter representing approximately half of all citations for the decade 1970–80. The point of this discussion, of course, is not the exact numbers of citations nor the estimates of their rates of appearance, but rather to illustrate the sequence of principal features just mentioned, including the relative importance of the two American programmes in their times. The intention, in this historical review, is to trace this sequence by discussing the nature of and the reasons for those features.

It is clear from a careful reading of Kratzer (1937; 1956) that, while including contrary evidence when he encountered it, he tended to accept both the existence of urban effects on precipitation amount and the notion that the effects appeared in the form of enhancement. For the researchers he cited, there was a similar tendency. In that acceptance, Kratzer and others of his time pursued answers to questions about those effects, especially the following:

1) Where did the results of the urban effects appear at the surface: in the city or downwind of it?
2) Under what weather conditions were the effects most apparent?
3) In general, did the magnitude of the effects increase as the regional level of urbanization increased?
4) Was the possibility that the effects were anthropogenic indicated by an inherently human day-of-the-week cycle of daily sums of precipitation amount?
5) Given that the effects were human-made, what were the physical mechanisms producing them?

In pursuit of answers to these questions during the first half of this century, the leading urban climate researchers – especially, but not only, those studying precipitation-related variations – consistently exhibited an uncritical acceptance, as guiding principles for their analyses, of two *non sequiturs*. The first was ‘if the hypothesis is reasonable, and the evidence fits the hypothesis, then the hypothesis is probably correct’. The second was that ‘methods used successfully to establish urban effects on one kind of climatic element can, *ipso facto*, be used successfully to establish such effects on another kind of climatic element’. Acceptance of these two fundamentally flawed principles continues today in research on precipitation-related variables, if much less so for others.

1 European explorations

The conventional wisdom at mid-century concerning urban effects on precipitation amount was based almost entirely on the work of European scientists, and it is well represented in the major synopsis prepared by Father Kratzer (1937). The following are extracted from the translation of his second edition:

> Increased formation of clouds over the city naturally leads to heavier precipitation within the metropolitan area. Generally an increase of precipitation is found within the city (p. 148) (question 1).
>
> More rain falls in east Munich than in the western section ... This higher value for east Munich is especially true in summer ... Particularly during heavy rainfall, the city receives more than the country ... The center of the city shows a larger amount of light rain (p. 150) (questions 1 and 2).
>
> I was able to find ... figures for rapidly-expanding Stockholm and Uppsala for the years 1867–1910 ... Whereas Uppsala shows no significant change in the amount of precipitation in any form, the amount for Stockholm continually increases (p. 148) (question 3).
>
> Ashworth reports on weekly variation [of daily totals during the study period] for the factory-town of Rochdale, showing a minimum of precipitation on Sunday and a maximum on Monday, while a non-industrial town, Stonyhurst, does not show this variation so markedly (p. 153) (question 4).
>
> In order to explain these facts, we must refer to the same causes as we did in the case of city fog and cloud formation. [His list of causes is summarized by the following]:
>
> 1. The enormous amount of condensation nuclei produced by industry, household heating and traffic.
> 2. Ascending air currents produced mechanically by the contours of city blocks and thermally by the relatively warm city (p. 155) (question 5).

While this abbreviated summary omits several second-order aspects considered by Kratzer, it does address each of the five questions posed earlier. Figure 2 shows the data for Stockholm–Uppsala and for Rochdale–Stonyhurst referred to in the summary quotations. It is an example of what has been the case in much of early urban climatology: support for a hypothesis originally developed by means of the mere tabulation and recitation of statistics is often weakened when they are displayed graphically. While Kratzer's words about the statistics may be accurate, their impact as evidence in support of the existence of urban effects on precipitation amount is reduced virtually to the point of extinction when they are presented graphically: the data for Stockholm–Uppsala raise more questions than they answer about the hypothesis of increasing urban effects, while those for Rochdale–Stonyhurst suggest there is really no difference between the stations.

In studies linking urban growth with increasing enhancement of precipitation amounts (question 3), analysts have examined weather records as time series – each for a single urban area in which urbanization is presumed to be increasing, as for Stockholm in Figure 2a. The hypothesis underlying such studies – in which time or urban population is used as a surrogate for the level of urbanization – has customarily been understood without either being stated or questioned. This hypothesis holds that a larger population, or an increasing population, is accompanied by a larger or an increasing local use of energy – both urban and industrial – and that greater use of energy results in greater releases of heat and moisture to the local atmosphere from the urban area. The greater releases, in turn, produce greater magnitudes of urban effects within the city, as suggested in the first quotation by Kratzer above.

2 American explorations

A German national with a 1930 doctorate from the University of Frankfurt, Helmut Landsberg settled in the USA in 1934. After several years in American academia, he moved to national government service, and still later to important work with the WMO. He developed an expertise in urban climatology and, as the senior American expert at the time, he was invited to prepare a review of the subject for a compendial work on

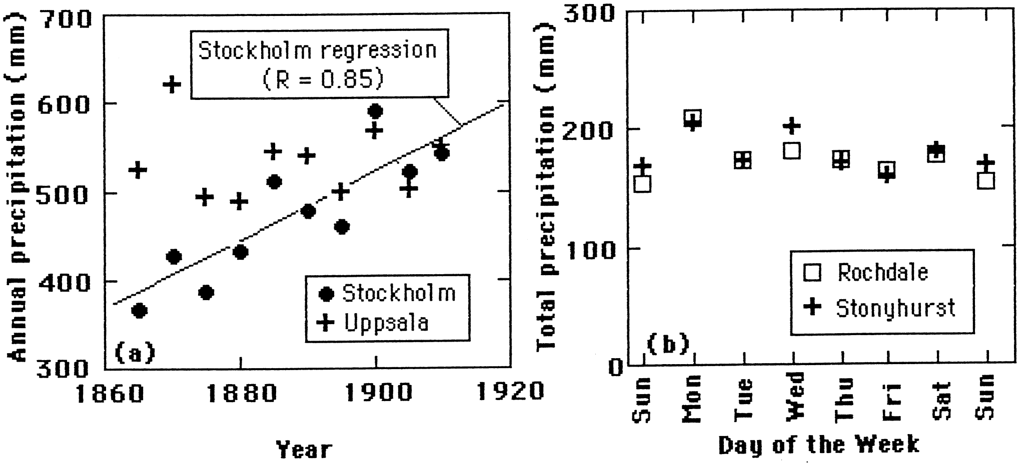

Figure 2(a) Statistics offered by Kratzer to suggest an increasing urban effect on precipitation amount in Stockholm as the city increased in population, as compared with the absence of any increasing effect in smaller, nearby Uppsala. Precipitation amounts are expressed as five-year mean annual totals. (b) Statistics offered by Kratzer to suggest a greater within-week effect in industrial Rochdale as compared with nearby, nonindustrial Stonyhurst. Kratzer does not provide the length of record from which these mean values were obtained

social and physical geography. Drawing on his familiarity with European research (Landsberg, 1956), he cited several British and German investigations to address the five questions listed earlier. Beyond that, to give the article an American content, Landsberg added (1956: 594):

> We have searched the files of United States climatological records to find additional material which might throw further light on the problem. One of the objectives was to obtain data for a locality where topography would inject a minimum of complications. Another was to locate a town which essentially was a point source of population rather than to use cases of vast industrialized regions or metropolitan areas, which complicate the analysis. The best example we could find was Tulsa, Oklahoma, a town which has grown explosively, developing from an Indian trading post into an industrial city in a few decades.

In that statement, Landsberg revealed a keen awareness of the difficulties involved in establishing and quantifying urban effects on precipitation amount – an awareness not so clearly evident in Kratzer's writings, which were more in the nature of recitation than of analysis. While being quite direct in saying (Landsberg, 1956: 595) that he had already decided that anthropogenic 'nucleation' was a principal cause of urban effects (question 5), he also recognized – as others had apparently not – the potentially confounding factors of topography and of complex, changing patterns of land use. An additional qualifying factor in the search that ended with Tulsa, but which Landsberg did not mention explicitly, was a record of high quality and substantial length.

In his analyses of data from Tulsa, Landsberg employed two means for estimating what precipitation totals would have been at the site of Tulsa if the city were not there. He obtained mean annual values, for 1891–1950, from a network of small towns 'in the region' which he 'assumed to represent Tulsa minus the town effect' (Landsberg, 1956: 594). In addition, he used data, for 1939–52, from the city airport, located 10 km to the north east of the city centre. Figure 3a presents statistics he offered only as tables: the

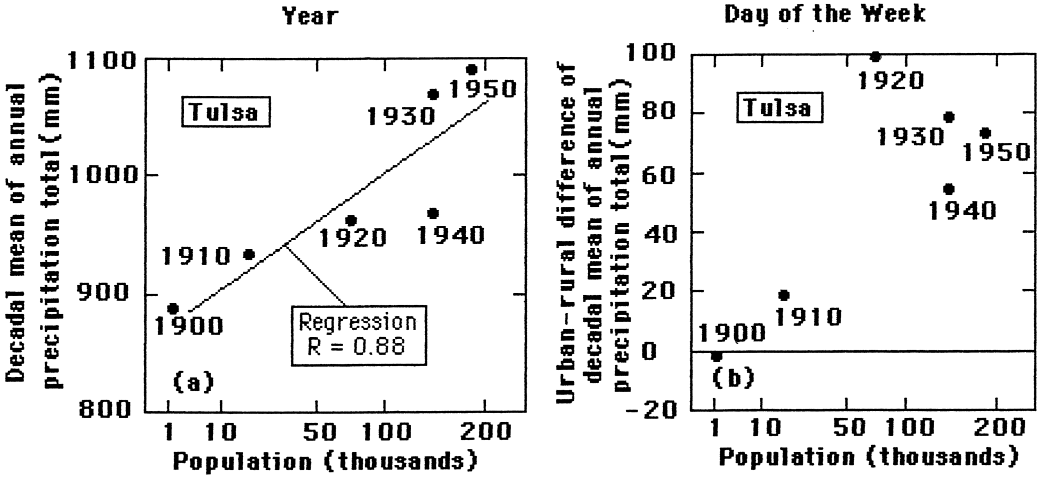

Figure 3(a) Graphical presentation of statistics – offered only as tables by Landsberg – to suggest an increasing urban effect on precipitation amount in Tulsa, Oklahoma, as the city increased in population from 1891 to 1950. (b) For the same six decades, the urban excess of precipitation amount above that for a network of rural stations is systematically related to the population of Tulsa. The number near each data point is the last year of the decade that the point represents. For this presentation, the population is given on a square-root scale. See the text for additional comments

decadal mean annual precipitation totals observed in Tulsa. In Figure 3b are the urban–rural differences in annual means, between the city and the network of towns, for the six decades 1891–1950, which he proposed as an answer to question 3.

With these statistics from the barely industrialized, American midlands, Landsberg reinforced the thinking associated with such results as those for Stockholm in Figure 2a: the lengths of record and the correlation coefficients were similar in the two studies. In Figure 3b, however, the relationship between population size and the magnitude of urban–rural differences is not as suggestive of a causal link as in Figure 3a. Since the urban–rural differences are obtained to reduce the effects of changing regional climate on the estimates of urban effects, this difference between Figures 3a and 3b is disconcerting. As has been suggested by several urban climatologists, the use of the square-root of population can be justified on the basis that, for a hypothetical circular city of uniform population density, the square root of population is proportional to the upwind-to-downwind travel distance (and time) across the city.

Using the shorter period of record at the Tulsa airport to obtain the urban–rural differences in Figure 3b – his second means for estimating the urban effect – Landsberg divided the 168 monthly totals of precipitation into the periods April–September and October–March. For the warmer period, the difference of means was 32.3 mm, and for the colder, 40 mm. Mean precipitation totals being twice as large in the warmer period, these differences expressed as percentages were 4.7 and 11.5, respectively. Landsberg disaggregated these same results by noting that, for the warmer period, the city received a greater total than the airport in 55 months out of 84; and in the colder period, 61 months out of 84. The seasonal difference is probably not significant, but the fact that three of every ten months examined belied the hypothesis of an urban excess is.

Kratzer's summary of mostly European research evidence concerning urban climatology in 1937, and Landsberg's of mostly American evidence two decades later (1956), are in good accord. The discussions in both leave no doubt about the acceptance of both writers of the first *non sequitur*: the hypothesis – in this case that growing industrial cities produce ever-larger enhancements of precipitation amount within their boundaries – is reasonable, and the evidence fits the hypothesis, so it is probably correct. Clearly, the reasonable question as to whether time and population are appropriate surrogates for the unspecified physical state or condition, referred to just above as the 'level of urbanization', remained unaddressed, as it does even today. As to the second *non sequitur* concerned with methods, however, a more seasoned Landsberg (1974: 752) suggested the difficulties inherent in its acceptance for study of precipitation-related urban effects:

> A great deal of attention has been devoted to the urban effects of [*sic*] precipitation. These have been noted for a number of decades but were relatively hard to verify by statistical tests. The reason for this is the very high variability of rain amounts and the poor qualities of the ordinary rain gauge as a sampling device. Decades of observations are usually needed to establish differences at a reasonable level of significance.

The studies described to this point have almost all been of data from single stations or pairs of stations that had been in existence for a long time, and whose location had nothing to do with climatological research. Analyses that were based on networks of observational sites – such as those reported from the work of Haeuser as early as 1911 in Munich (Kratzer, 1956: 150) – were rare; and again they used data from pre-existing stations, located for reasons other than research.

An often-cited, but underappreciated study by Changnon (1962) was part of the American explorations in urban climatology. A young scientist just beginning his career at the Illinois State Water Survey, Changnon had immediate access to both local and statewide rainfall records and to gauges in abundance, as well as the encouragement of his supervisors to innovate. The central result of his study of the small, twin cities of Urbana–Champaign was the 10-year, mean annual isohyetal map in Figure 4. Based on a

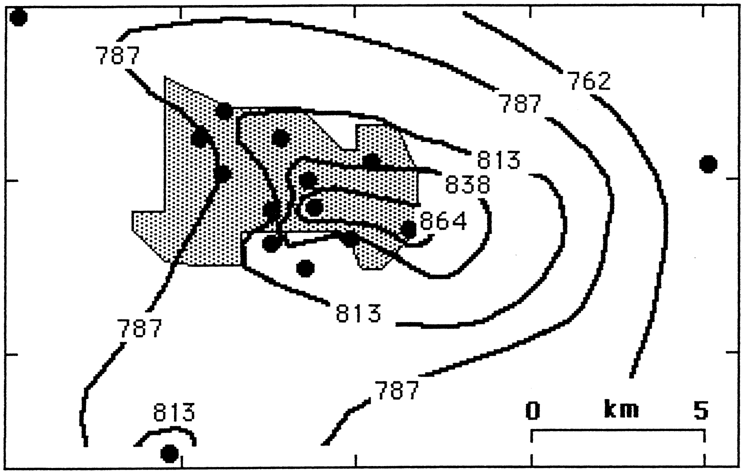

Figure 4 The mean annual precipitation total (mm) for 1950–59 at Urbana–Champaign, Illinois, after Changnon (1962). The original mapping was for totals in inches

special research network of gauges within the city and three outlying gauges within 10 km distance, the map depicts an area of maximization in the eastern portion of the city, with a plume, or a ridge, of contours extending towards the east.

Several aspects of Changnon's map made it significant and influential. For one, it is probably the first of its kind based on records of mean values for periods of a decade or more. Also, supported more by evidence presented in his discussion than by the map itself, it suggests that urban enhancement of precipitation may well appear beyond the urban area rather than just within it, as had previously been the conventional wisdom. Although one may dispute the details of the isohyetal analysis in Figure 4, Changnon's exhaustive discussion of the rainfall records from the network leaves no doubt that, in all seasons, the gauges with the largest catches were consistently in the eastern sections of the urban area.

In the same symposium at which Changnon's results were presented, Glenn Stout – Changnon's colleague at the Illinois State Water Survey – presented another report (Stout, 1962) that – a decade later – opened the way from single-investigator, *ad hoc*, exploratory American efforts to well funded and carefully co-ordinated research programmes. Stout's note presented his analyses of possible causal relationships connecting the estimated annual production of steel in the industrial areas east of Chicago, and the annual precipitation amounts at the small town of La Porte, about 60 km to the east of the industrial areas. He made much of the fact that 'the great increase in annual rainfall after 1933 [at La Porte] coincides with the greater increase in steel production [near Chicago]'. The reference was to an extraordinary increase in the annual precipitation total from about 990 mm to nearly 1450 mm at La Porte, during the 15 years 1930–45, while at nearby stations it fell from 990 mm to about 900 mm through the same period. Discussion in the paper included the following speculation about the reasons for the increase in precipitation amount at La Porte (Stout, 1962: 149): 'either the exposure of the gauge or the pollution from the steel mills has contributed to the anomaly [in the regional isohyetal map].' Stout acknowledged that his analyses – based solely on a gross comparison of time series – were a very preliminary case for the existence of industrial effects on precipitation amount far beyond the industrial areas themselves.

Stout's note about La Porte (1962) was based on exploratory work by the Illinois State Water Survey aimed at preparing more definitive crossboundary isohyetal analyses for the entire state by combining Illinois precipitation data with data from surrounding states; hence the study of Chicago, Illinois, in conjunction with northwestern Indiana, to the east of Chicago. The discovery in the Indiana data of suspiciously large rainfall totals at La Porte, as compared with those at nearby stations, was entirely fortuitous and unexpected, and led directly to a quickening of American research on urban climatology.

3 International recognition

In 1965 the Commission for Climatology of the World Meteorological Organization (WMO) appointed Dr T.J. Chandler of Great Britain as Rapporteur on Urban Climate (Davies, 1970a), thereby institutionalizing the subject in the international research community. Following that, and in response to their perception of an increasing, worldwide interest in 'the interaction of man and his environment' (Davies, 1970b), the WMO and the World Health Organization (WHO) organized and convened a symposium on 'Urban climates and building climatology' at Brussels, 15–25 October 1968. The symposium – convened in a period of relative political stability and increasingly convenient, affordable travel – represented the first formal, international activity providing direct recognition of and impetus to researchers in urban climatology.

Proceedings of the sections on 'Urban climates' and 'Building climatology' at the Brussels symposium of 1968 were published separately in 1970 (WMO, 1970a; 1970b). The former included 34 contributions concerning climatic elements, only four of which were on precipitation-related urban climatology. Two of the four are especially worthy of note. In one, Changnon (1970: 325) presented results from 'studies of four various sized cities in the [American] Mid-west [that] have shown apparent increases in annual precipitation'. In the other, Atkinson (1970: 342) described 'an analysis of the thunderstorms which occurred over London, England, on 21 August 1959'. The two are singled out in the context of this article primarily because they represent distinctly different styles of data analysis, each representing, in turn, a different research strategy.

In Changnon's paper, analysis was based almost exclusively on subjective comparisons of time series of annual sums at individual stations; and of isohyetal mappings of long-term, mean annual precipitation totals in urban-centred regions. This style of analysis has predominated in most subsequent studies of urban effects on precipitation amount reported by American researchers, especially Changnon and his colleagues. Atkinson's paper, on the other hand, was based primarily on analyses of rainfall totals on a region-wide network of gauges, together with careful analyses of contemporaneous mesoscale atmospheric structure and behaviour, during one summer day. His presentations of single-storm isohyets followed a style reported from the work of Haeuser mentioned earlier; but his detailed, mesoscale, synoptic analyses were novel.

The analyses by both Changnon and Atkinson required data from relatively dense networks of gauges. Changnon's, however, was based on temporally aggregated data; while Atkinson's was based on short-term 'case studies', which later would permit temporal aggregation by synoptic weather type. Regarding his methodology of synoptic climatology, Atkinson (1970: 348) said: 'Only by building up detailed case studies . . . will it become possible to say whether or not the urban effect on precipitation is real.' Further consideration is given later to these two research strategies, especially the matter of data aggregation. Despite the clear distinction between the two, both papers included – as might reasonably be expected in preliminary reports – clear-cut examples of acceptance of the *non sequitur* that 'if the hypothesis is reasonable, and the evidence fits the hypothesis, then the hypothesis is probably correct'.

In conjunction with the Brussels symposium, the WMO produced, and Chandler edited, a bibliography (WMO, 1970c) which, by the nature of its sponsorship, probably represented as wide an international view of the research activity in urban climatology as possible at the time. Chandler's bibliography was – to judge by the title – selective rather than exhaustive. He gave no indication, however, about the criteria used to make the selections. Setting aside entries not directly concerning climatic elements, the bibliography contains 261 pages, of which 37 (14%) referred to precipitation-related urban climatology. By date of publication, Chandler shows the same low annual rate of citations as does Kratzer – two or three per year – between 1920 and 1955 (see Figure 1). Also, he shows the same increase in their number between 1950 and 1965, but not the sharp increase between 1965 and 1970 as does Oke. Other than works from the UK, France, Germany and the USA – which combined account for 78% of the total – the bibliography includes citations from Canada, Czechoslovakia, Finland, Hungary, India, Italy, Japan, Norway, Poland Rumania, the USSR, Sweden and Switzerland. Among the items of the bibliography, most published prior to the late 1960s – when the concerted American effort began – are those by German and British authors.

4 The La Porte Anomaly

Stout's report on La Porte (1962) had drawn scarcely any comment, particularly in the published discussion of the symposium report, where the knowledgeable participants seemed neither curious about nor uncomfortable with Stout's far-reaching speculations. The immensely important, underlying question – left unstated by Stout in his report – was posed explicitly, many years later, by Changnon (1980: 704): 'Can man inadvertently alter precipitation far from a city by [as much as 25%]?' Changnon, in a seminal article published only months before the Brussels symposium (1968), pursued Stout's idea that a combination of effects due to urbanization and industrialization was the principal cause of the unexpected features in the precipitation record at La Porte. He referred to those features as the 'La Porte Anomaly'. In his analyses, he made much greater use than had Stout of isohyetal maps, which thereafter became Changnon's principal method of analysis, first used in his 1962 report on Urbana–Champaign.

In sharp contrast with the case of Stout's report on La Porte (1962), the publication of Changnon's larger article (1968) resulted, during the following few years, in a flood of critical correspondence. Changnon (1980) provided a comprehensive summary of the debates, from which the following items give a sense of the exchanges.

> Those who challenged the reported inadvertent (urban-induced) explanation did so on three general premises: 1) that La Porte records were faulty (observer or site problems); 2) that such increases were not found universally beyond cities; and 3) that the physical proofs of how the alterations occurred were lacking (p. 704).
>
> The next series of controversies ... largely concerned analysis of geophysical data related to rainfall ... Hidore found runoff increases [in the Kankakee River] that seemed related to the La Porte precipitation and gave support to the reality of the anomaly (p. 705).
>
> Harmon and Elton showed a weather-related anomaly in tree rings in the La Porte area ... resulting from a combination of urban effects on rainfall and of lake effects on weather ... Ashby and Fritts concluded that trees in the area showed increasing effects of man-made pollution on growth ... Charton and Harmon turned the unclear tree ring results into a mini-controversy over the question of pollution (toxic) effects on tree growth, but Fritts and Ashby responded that use of tree ring analysis to monitor climatic variations in a polluted area is questionable. In essence, the tree ring investigations neither supported nor refuted the rainfall anomaly at La Porte (p. 705).
>
> None of the studies stemming from the controversies in the 1969–73 period was able to explain adequately the causes nor establish through measurements a systematic physically based explanation for the anomalies at La Porte or elsewhere (p. 705).

Worthy of note, at this point, are the several convenient, time- and space-saving phrases that came into regular use during the debates. 'Downwind increase', 'downwind high', 'precipitation increase' and 'precipitation anomaly', among others, have now become standard terms in the technical shorthand of the field of urban climatology. Because these terms are concise and refer directly to an assumed reality, they are seductively attractive to writers, technical and nontechnical alike. Consider, for example, that 'downwind precipitation increase' is certainly more convenient than 'a local isohyetal maximum of mean values of precipitation in the area that most convective storm cells would ordinarily be expected to traverse after passing over a nearby urban or industrial area'. Use of the terminology in this way, however, seems to imply without supporting evidence that the local isohyetal maximum, now present, was once absent; so that a spatial maximum has been subtly transformed into a temporal increase.

5 From La Porte to METROMEX

Following publication of Changnon's seminal analysis of the La Porte Anomaly (1968) and the convening of the inaugural Brussels symposium in the same year, the geographical centre of research in urban climatology shifted from the UK and Germany to the USA. Evidence of this may be seen in two important events; 1) the planning and commitment of major funding for a multiagency field research programme in Greater St Louis, Missouri; and 2) the mounting of an American equivalent of the Brussels symposium. The conference on 'Urban environment' was convened by the American Meteorological Society at Philadelphia, Pennsylvania, in late 1972. Despite its broad title, it was devoted almost exclusively to problems of air pollution observation, mesoscale diffusion modelling and urban effects on temperature. Of the 44 papers delivered, only three were from outside the USA – two on temperature effects by T.R. Oke of the University of British Columbia – and only four were on precipitation-related urban climatology – all by authors from the Illinois State Water Survey. None the less, with this small beginning, the ideas spawned by the La Porte study were injected into the national mainstream of research on urban climatology and problems of regional air pollution.

The programme at St Louis, which was conceived in 1970 with full field programmes beginning in the summer of 1971 (Changnon *et al.*, 1971), was given the name 'Project METROpolitan Meteorological EXperiment: METROMEX'. There is little doubt that the rapid infusion of funding and effort into both the conference and METROMEX could be traced directly back to the attention to and the controversy surrounding the La Porte Anomaly only a year or two before. It was natural to inquire – immediately after La Porte – whether similar temporal and spatial patterns of precipitation might be discovered in other major urbanized regions. The patterns were considered to be attributable to the effects of air pollution, so it was also natural for funding agencies charged with supporting research, in either intentional precipitation modification or in urban and regional air pollution, to be interested in the same question. Researchers and the agencies joined forces, and the National Science Foundation (NSF) provided funding for a study by the Illinois State Water Survey of existing climatological records. Figure 5 is

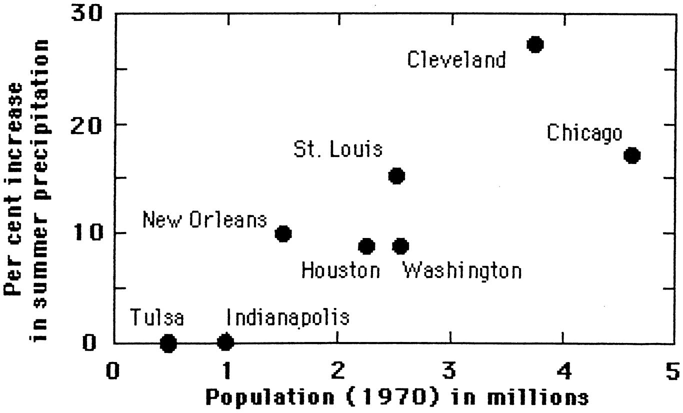

Figure 5 The downwind enhancement of precipitation totals is systematically related to the city population in 1970. The precipitation studies were based on periods of different lengths – from 8 to 20 years between 1949 and 1968 – depending on available records at each city. See the text for additional comments
Source: Data from Changnon, after Landsberg (1981: 202)

representative of the results from that study, known at the time as the 'Eight Cities Study' (Huff and Changnon, 1973).

The Eight Cities Study was innovative in the sense that, while it included analyses of the precipitation climatology of individual cities as had been done previously, it merged these analyses, as in Figure 5. This was a second, new kind of study attempting to link the magnitudes of urban–rural differences to the level of urbanization, in that it combined data from a sample of cities in one time period rather than from one city at different stages of its increase in population, as in the case of Stockholm in Figure 1a and Tulsa in Figure 3. In Figure 5 the dependent variable – the measure of urban effect on precipitation amount – is 'per cent increase in summer precipitation'. Values were obtained from isohyetal analyses of the eight American urban areas named in the figure. The percentage was calculated as [100 × (Maximum within the city/Maximum generally east of the city)], east being assumed 'downwind' for all the cities. The independent variable – the measure of the level of urbanization – is population (this time on a linear scale, as in the original report).

6 Project METROMEX

The findings of the Eight Cities Study received general acceptance and were a central part of the successful effort by a consortium of research units, led by the Illinois State Water Survey, to obtain funding from four government sources for Project METROMEX. Reasons for the selection of Greater St Louis, Missouri, for the intensive study – during the summers of 1971–75 – included: 1) the fact that numerous climatological data were already assembled; 2) its isolation from other large urbanized areas; 3) its relatively uncomplicated geographical setting; and 4) the comparatively uncomplicated matrix of commercial aviation activities that could be interrupted by any airborne probes that would be used. The research modes consisted of both active and passive ground-based sensing, and active airborne sensing (Project METROMEX, 1974). As regards methods and techniques pertaining to studies of precipitation-related processes and outcomes, major contributions of the METROMEX programmes included the following:

1) The deployment of local- and regional-scale networks of continuously recording rain gauges, sufficiently dense as to be essentially equivalent to those of temperature transects, with the resulting reduction in the need for subjective judgement in rendering isopleths.
2) The development of computer-assisted means for translating the records from the continuously recording rain gauges into spatial and temporal aspects of the life histories of individual raincells.
3) Successful use of inert tracer chemicals – released at industrial sources and captured in special rain gauges – to explore the time–distance characteristics of the cloud- and precipitation-modifying urban boundary layer.
4) Mathematical modelling both of cloud physics and dynamics, and of mesoscale windflow.

Less directly related to the subject of this review, but none the less important were the following:

5) Substantial efforts in aerosol characterization and study of plume kinematics, related to ambient weather.

6) Massive partially duplicating efforts to probe and describe the vertical dimension – the morphology and dynamics of the urban boundary layer – by means of several modes of instrumentation, both airborne and ground based.

Conclusions reported by METROMEX scientists on matters related to the subject of this review (Diab, 1978; Braham, 1981; Braham *et al*., 1981) included the following:

7) Local topography plays only a secondary role in the initiation and intensification of precipitation-producing processes.
8) A late afternoon maximum in rainfall amount at the downwind edge of the city is due primarily to decreased thermal stability and horizontal convergence in the lowest air layers caused primarily by thermal and frictional forcing at the urban surface at that time.
9) A generalized sequence shows that on a typical summer day clouds form several hours earlier over the city than over surrounding rural areas; that the cloud bases are higher over the city, but that the distance between cloud bases and the in-cloud level of precipitation formation is much less over the city; so that the cloud column experiencing active precipitation formation is much deeper over the city. That sequence being due in major part to
10) A combination of a moisture deficit and higher mixing depths over the city and the presence of giant cloud condensation nuclei in the urban updrafts; with major results that
11) Urban clouds are more likely than rural clouds to penetrate a mid-level tropospheric arresting level and to merge with other growing cloud systems into more vigorous storm units; thereby producing
12) A local maximum in isohyetal patterns several tens of kilometres east of the city, associated most frequently with moderate to heavy rainfalls from prefrontal storm cells, often embedded in warm-sector squall lines.

For all its magnitude and excellence, METROMEX was a mixed blessing, it represented the successful field testing of dozens of innovations in instrumentation and analysis, and is still the nearest that urban climatologists have been able to come to conducting true field experimentation. This was made possible by such means, for example, as mathematical modelling – to answer hypothetical questions – and a sufficiently large total sample of rain days, over five summers, to permit stratification of case days into synoptic subsamples. On the other hand, the project was logistically so complex and expensive, and produced results of such elaborate and detailed analyses, that climatologists have never undertaken a vigorous critical analysis of its conclusions, accepting them as essentially definitive.

7 The years following METROMEX: a time for consolidation

During the period from 1975 to 1981 – immediately following the METROMEX field programme – important research results of several kinds were published, collectively representing an attempt by climatologists to consolidate observational evidence and a coherent theoretical framework for studying urban effects on precipitation amount. In 1975, Harnack and Landsberg followed Atkinson's strategy in producing the first American example of a detailed examination of 'case studies' of precipitation from individual storm systems moving over an urban area. Rainfall records from a network of stations, again combined with careful analyses of contemporaneous mesoscale atmospheric structure and behaviour, led them to conclusions (Landsberg, 1981: 197) similar to those of Atkinson in his studies around London:

> In these cases of isolated urban showers – when the general synoptic situation did not warrant a rain forecast . . . and changes were generally rated below 20 percent, it could be shown that the $\approx 2^{\circ}$C urban heat island was a trigger factor in the growth of cumulus congestus to cumulonimbus size with ensuing precipitation.

In 1976, Changnon and his two principal collaborators at the Illinois State Water Survey published their considered opinions – based primarily on the by-then huge set of field observations from METROMEX – about the physical processes leading to the kinds of outcomes cited by Harnack and Landsberg. They described their distilled opinions (Changnon *et al*., 1976: 544) as 'a hypothesis':

> The greater frequency of rain initiations over the urban and industrial areas [of Greater St Louis] appear to be tied to three urban-related factors including thermodynamic effects leading to more clouds and greater in-cloud instability, mechanical and thermodynamic effects that produce confluence zones where clouds initiate, and enhancement of the coalescence process due to giant nuclei.

In 1977 Lowry published a purely theoretical study (1977) of the general problem of deducing the existence and magnitude of urban effects from conventional climatological data. As part of the study, Lowry proposed the term 'urban climate' to mean 'the ensemble of values of the various weather elements as they are observed in an urban area'. The development of an urban surface where once the surface was 'rural', or nonurban, usually changes the values of the weather elements there – differently for each large-scale weather situation – from what their preurban values would have been in a given weather situation. These differences themselves form another ensemble of values called the 'urban effects on local climate'. Furthermore, he proposed that, at a larger scale, one may recognize the 'regional climate', and that, within some distance outside the urban area, values of the weather elements at nonurban sites may also be changed by the presence of the nearby urban area. The ensemble of resulting differences from what the preurban values would have been at these nonurban sites, caused by the presence of an urban area, constitutes the 'urban effects on regional climate'.

For good reason, climatologists have adopted the habit of expressing urban effects on most weather elements as contemporaneous differences between those observed within the city and those observed in nearby rural areas. While these urban–rural differences are reasonable first approximations of the urban effects on local climate, and therefore give some insight into that part of the urban climate caused by the urban surface, they are only approximations. It is usually necessary to settle for these urban–rural differences as approximations of the urban effects on local climate, since weather records from preurban times are not available. Nevertheless, within these approximations the urban effects being sought usually cannot be distinguished from those of other influences, including: 1) local topography; 2) local shoreline configurations; 3) temporal changes in the relative frequencies of different synoptic weather types; and 4) the influence of the urban area on nearby rural areas themselves.

Based on this analysis, then Lowry addressed the general problem of separating the 'signal' of urban effects – both within the city and in nearby areas, and themselves related to the natural variability of the processes within and between rain days –

from the ‘noise’ due to the other influences just noted. Lowry’s conclusions amounted to these:

1) The familiar urban–rural differences, as estimates of urban effects, do not isolate them from landscape effects and secular changes in the relative proportions of synoptic types. And since
2) Isolating urban effects requires ‘controls’, consisting of preurban observations in each of several synoptic weather types,
3) The solution requires a) a system for synoptic stratification; b) records from both before and after urbanization; and c) station-by-station differences, before and after urbanization, stratified by weather type.

A system for synoptic stratification is usually not an insurmountable requirement, but obtaining records from both before and after urbanization is at best difficult. Landsberg (1981: 10) ventured that Lowry’s ‘framework . . . is idealized and in practice may well be very difficult to realize’ while Oke (1995: 109) suggested that even the best of existing analyses ‘would not meet all the stringent requirements set by Lowry to evaluate unequivocally the urban effect’. They are, of course, both correct. Their statements are reflections of the fact that evaluating urban effects on precipitation amount is so difficult and still has not, up to now, been satisfactorily accomplished.

Difficult or not, two studies based on analyses before and after urbanization were published during the years immediately following METROMEX. In the first, Lowry and Próbald (1978) worked with seasonally and synoptically stratified, daily rainfall data from periods before and after the construction – all within less than two years, in a previously agricultural area – of a major Hungarian steel works and the urbanized areas for housing and servicing the workforce in the new town of Dunaujváros. Any effects they might have found, therefore, would be a mixture of urban and industrial. In the second study, Landsberg (1979) reported on weather observations before and after the first seven years of the planned residential community of Columbia, Maryland, near Washington, DC. Knowing of the plans for the town, Landsberg and his colleagues initiated a programme of observations several years before construction began, also in a previously agricultural area. Any effects they might have found, therefore, would be purely urban.

Lowry and Próbald plotted mean seasonal isohyetal maps, with data merged across synoptic types. Those maps included several areas of rainfall maxima; but, as evidence for the presence of urban effects, they were inconclusive for the following reasons. There were areas of maximum ‘downwind’ of Dunaujváros, but 1) they could as easily have been perceived of being ‘downwind’ of Budapest, the large city north of Dunaujváros; and 2) one of these maxima appeared in the preindustrial period. For comparing annual precipitation totals within seasons and synoptic types, Lowry and Próbald used a standard *t*-test of the ensembles of values before and after construction of the urban–industrial complex. There were several large and positive *t*-statistics (enhancement), but 1) they were not spatially coherent, and 2) some stations showed enhancement in one season and suppression in another. While Lowry and Próbald deemed these results somewhere between inconclusive and negative, it was clear they were not positive in support of the existence of rainfall effects due to the urban and industrial development of Dunaujváros.

In his single, brief and passing mention of precipitation at Columbia, Landsberg (1979: 78) said: ‘At the present stage of growth [seven years and a population near 20 thousand] there was no discernible influence on precipitation and none can be anticipated for the next decade.' In 1980, Changnon published results of a study of the precipitation climatology of the La Porte region in the years 1964–73, following the time period examined in his seminal article of 1968. In addition to giving summaries of the evidence leading to the La Porte Anomaly debates and to the content of the debates themselves (see earlier), the article included evidence and discussion leading Changnon (1980: 702) to the following conclusions:

> A variety of recent studies . . . show that the anomaly in the La Porte area began to shift locale in the 1950s [about 25 km to the west-southwest] and then disappeared in the 1960s. Taken in totality, it seems likely that the anomalous precipitation at La Porte was due to urban influences on the atmosphere, but the anomaly either ended or shifted into Lake Michigan (where it cannot now be detected) as the general circulation pattern changed.

He reached these conclusions with the aid of the same tools of analysis used in the 1968 article: regional isohyetal maps and time series of summer season precipitation totals at individual stations.

Landsberg's final effort to summarize definitively the state of urban climatology, prior to his death in 1985, resulted in a timely book (1981). In the introduction to his Chapter 8 on urban precipitation (Landsberg, 1981: 177), he revealed again the targeted scepticism he had displayed in the disaggregation of monthly data from Tulsa, Oklahoma (see earlier):

> The temperature and wind fields of urban areas are fairly well understood and well documented by observations. Physical models are available to support the empirical facts. In contrast, the urban moisture field is controversial in many respects. Among the only partially answered questions [is]: Do metropolitan areas change precipitation patterns – and in which direction? . . . Even the well-designed METROMEX project yielded only limited answers.

Also in 1981, the principal scientists associated with Project METROMEX published their final report (Changnon, 1981). Chapters 5 and 7 summarize their conclusions regarding urban effects on clouds and rain (Braham, 1981; Braham *et al*., 1981), several of which are summarized earlier in this article. In addition to those, this review considers another result from METROMEX as being of particular importance: rudimentary testing of hypotheses became possible with the development by Schickedanz of computer-assisted methods for the identification, quantification and tracking, through their lifetimes, of individual raincells (Braham, 1981: 96). As will be considered presently, this system of analysis permitted separation of individual, local rain events originating in clouds likely to have been affected by the St Louis urban area from events in clouds not likely to have been so affected.

8 Since 1981

In the years since publication of the METROMEX final report (Changnon, 1981), the vigour of research in urban precipitation climatology has subsided substantially, as the centre of attention has shifted to the study of cities in tropical and subtropical regions (Oke, 1986; Jauregui, 1993). In support of this observation, consider the following. In 1996, the section on inadvertent weather modification at the American Meteorological Society's 'Conference on planned and inadvertent weather modification' (AMS, 1995: 1963) included only five papers, none of which pertained to urban effects on precipitation amount. A computer-assisted search of the literature for the last decade produced only three papers concerned primarily with urban effects on precipitation amount: at Pittsburgh, Pennsylvania (Rosenberger and Suckling, 1989), Moscow (Stulov, 1993) and Mexico City (Jauregui and Romales, 1996). The methods used in these three papers will be considered in the next section. Finally, these three contributions contained references to 10 other reports on urban precipitation climatology that were not listed in Oke's bibliography to 1988 (1990), five of them in Russian: an annual international average almost identical to that prior to 1955.

III Methods: a critical evaluation

Prior to the end of the 1960s, research results in urban precipitation climatology were scattered, fragmentary and based mostly on pre-existing data gathered for purposes other than that of studying urban climates and effects. By the end of the decade, urban climatologists were certain that they had established the existence of urban effects on climate, but they realized that the effects were due to a set of factors and processes more complex than had been supposed at the outset. They suspected, furthermore, that the nature of urban effects on temperature and on precipitation amount would prove to be different in important ways, and that the methods used to study them would probably have to be quite different as well.

Early studies consisted almost exclusively of analyses of routinely gathered climatic data and accompanying speculation about the causes of whatever urban effects they suggested. Experimentation and the explicit testing of hypotheses were not yet part of the effort. This pattern is, of course, the hallmark of a new science coming of age, as is the premature attempt to generalize. Despite Landsberg's clearly stated cautions against such attempts, because the true effects of cities are unique (1962: 5), he nevertheless included a table (Landsberg, 1962: 3) that clearly constituted generalization. Furthermore, even today that table is usually the only item reported *in toto* from his several early reviews.

Before undertaking a critical evaluation of research methods in urban climatology, a scientific overview is useful. In the process of urbanizing and industrializing large regions, Humanity and Nature are in effect conducting a confounded experiment, which, by the nature of the system, can, in very few instances, be subjected to the straightforward paradigm of the scientific method. It is a certainty that the processes of urbanization and industrialization cause changes in weather and climate. But one cannot undertake a controlled experiment with and without the city present; nor can one replicate an observation, because no two cities and no two weather sequences are exactly alike. Likewise, one cannot put a city and its surroundings in a controlled experimental chamber, as could be done with a plant or an animal. The dilemma is common in geophysical science; an investigator may be able to demonstrate the presence of an effect; but isolating, quantifying and explaining it without resort to controlled experiments is a daunting endeavour, and in some cases is simply impossible.

1 Problems inherent in analysis of precipitation-related variables

Earlier (sections II, 2 and II, 7 above) Landsberg was quoted in recognition of the methodological difficulty of establishing the existence of precipitation-related urban effects. Atkinson (1970: 343) translated Landsberg's recognition into a matter of physical differences between those effects and effects on other climatic elements:

> Within the field of urban climatology the modifications due to airflow, radiation exchange, temperature and pollution are comparatively easy to recognize and to measure: consequently most of the recent work on these facets of urban climatology has been concerned with unravelling the details of the spatial and temporal variations of the urban effect rather than simply to establish its reality. This is not the case in studies of urban rainfall. In contrast to analyses of near-surface atmospheric phenomena, much of the literature on urban precipitation is primarily concerned with establishing whether or not the urban area has any effect at all on precipitation distribution.

Atkinson's words represent a responsible statement of what was earlier referred to here as the second *non sequitur*: that methods used successfully to establish urban effects on one kind of climatic element can, *ipso facto*, be used successfully to establish such effects on another kind of climatic element. It will be argued that his words still hold true now, nearly three decades later.

For purposes of this discussion, the two primary differences between rainfall-related climatic elements and others, as represented by temperature and precipitation, are the facts that 1) temperature is continuous in both time and space, while precipitation is continuous in neither; and 2) the physics of heat and heat transfer is better understood than cloud physics and the physics of precipitating cloud systems. These differences in continuity, of course, lead in turn to differences in the methods and requirements for the measurement and sampling of the two types of climatic element. Temperature can be sampled in a variety of ways: by maximum and minimum thermometers in fixed networks; by continuously recording instruments in fixed networks; by traverses of mobile instruments; and by instantaneous, thermal remote sensing. An investigator can be confident about his or her mapping of a temperature field between fixed sampling sites, provided they each have a standard exposure. In contrast, precipitation occurrence, rate and amount can be sampled with confidence only by instruments in networks consisting entirely of fixed sites – 'with confidence' mainly because continuous sampling by means of weather radar is usually neither precise nor accurate, and is prohibitively expensive.

Because of these differences between temperature and precipitation, for example, ordinary isohyetal maps are different from ordinary isothermal maps in two very important ways. First, they are maps of a time integral of a spatially and temporally discontinuous variable; whereas, isothermal maps present values – in some cases mean values – of a spatially and temporally continuous variable. Secondly, because an observation network for precipitation amount consists of a discrete set of sites, and because precipitation networks have usually been effectively much less dense than those for fixed temperature stations in combination with mobile temperature surveys, construction of ordinary isohyets has almost invariably required more subjective judgement than that of isotherms. The term 'ordinary' isohyets is used here in contrast with those of instantaneous rainfall rates produced in the 'raincell' method of analysis, to be considered later.

2 Methods, presentations and interpretations

There are many examples in which basic analytical methods that were useful in studying the urban thermoclimate were subsequently applied uncritically in the study of urban hydroclimate: two-point differences, time series, mappings and correlation analysis – both graphical and statistical. These and other methods will be examined critically – each in turn – by the presentation of well-known examples put forward as evidence in favour of various conclusions, followed by counterexamples that tend to cast doubt on the conclusions drawn from the analyses.

a Two-point differences: Before isohyetal mapping became commonplace in the 1970s, climatologists chose, from among a few pre-existing fixed stations in an urbanized area, pairs of stations that – based primarily on their geographical locations – could reasonably represent an urban–rural difference, using two-point differences and ratios of rainfall amount as measures of urban effects. As shown in Kratzer's summary, investigators published many two-station statistics that seemed to support their hypotheses – especially about the location of greatest amounts within the city – and remarked scarcely at all about the evidence they presented that was contrary.

Without knowledge of the form of the actual precipitation fields, researchers could not be aware of the precipitation amounts of the few existing fixed stations relative to amounts elsewhere in the fields. The same was true, of course, of temperature studies. In the case of temperature, however, the many two-point studies of urban–rural differences were followed by development and elaboration of the notion of the generalized Urban Heat Island (e.g., Oke, 1982: 3), with its 'summit' – the point of maximum urban effect – which permitted the characterization of a city with a single value: the temperature difference between the summit and the city's rural surroundings. This form of two-point difference, of course, is usually not between pre-existing fixed stations, but it has turned out to be physically meaningful. The temptation was strong to search for analogous precipitation fields – Urban Rain Islands, so to speak (e.g., Jauregui and Romales, 1996) – but this led to no such basis for generalization and characterization. In fact, doubts arose as to whether the 'summit' of the precipitation field – if, indeed, there were one – lay within or beyond the city, constantly or intermittently, and under what weather conditions. Thus, as noted in the introduction, two-point, urban–rural differences – especially when they are not based on mapping of the underlying field – are at best reasonable first approximations of the urban effects on local climate, and they usually provide little physical insight as to the causes of urban effects.

In a generalization of the numerous isohyetal mappings published in the 1970s for mid-latitude urban areas and based on moderately dense networks of gauges, Lowry and Lowry (1998) have published an idealized isohyetal map, in the same sense that Oke's map (1982: 3) represents an idealized temperature field. They characterize their map as follows:

1) Contours suggesting fluid flow over a fixed obstacle – sometimes referred to as the 'rock in the stream' analogy.
2) A spatial patchiness characteristic of most fine-scale isohyetal maps, perhaps resulting from the generally cell-like nature of passing rainstorms.
3) A tongue-like ridge of larger values on the 'downwind' side of the urban centre, in this case to the east reflecting a generally westerly flow.

Early two-station temperature statistics and early isothermal maps both showed that the city is consistently warmer than its environs, and most early two-station studies of precipitation amount indicated that more falls within the city. It is no wonder that climatologists who made the first urban isohyetal maps fully expected to find the largest values of precipitation amount consistently within the city. Based on their map, Lowry and Lowry note that it is not difficult to understand why so many of the early two-point studies, carried out in ignorance of yet-to-be-published isohyetal patterns, fostered that expectation.

> Most places within the urban area receive a precipitation total greater than that received at most places outside the urban area. Thus, most two-point, urban–rural comparisons of stations with locations chosen quasi-randomly – as would be the case for pre-existing weather stations – will yield a result suggesting that urban effects appear consistently as an enhancement of precipitation amount within the city. The evidence that precipitation is greatest within the city and the evidence emerging later that the urban effect may be greatest downwind of the city are therefore not in conflict.

The reader will note that, in these considerations of two-point differences, cities 'enhance' the precipitation-producing process, with scarcely a mention that, under some circumstances, even suppression may be the outcome.

b Time series: As noted in the historical perspective, analysts have sought to link urban growth with increasing enhancement of precipitation amounts by examining weather records as time series, as for Stockholm in Figure 2a. It was noted also that the hypothesis underlying such studies – in which time, and later urban population, is used as a surrogate for the level of urbanization – has customarily been understood without being stated.

Table 1 exhibits the same result of linear correlation analysis, regarding precipitation amounts at Tulsa, as shown in Figure 3a: for the six decades between 1891 and 1950, the square root of Tulsa's population at the end of a decade is highly correlated with the decadal mean of the annual precipitation in the city. Likewise, the date – during the seven decades ending in 1900 to 1950, and then in 1980 – is highly correlated with both the decadal mean of the annual precipitation in the city and the square root of Tulsa's population. For these time periods, the three variables are intercorrelated, and the underlying hypothesis seems to be validated.

Before one accepts such results as evidence of an increasing role for 'urbanization', it must be recognized that such a long-term time trend could also result as much from such factors as changes in the relative frequencies of regional synoptic weather types as from changes in urbanization. This kind of dependence becomes apparent in the case of the precipitation amounts from Tulsa when one adds an eighth decade – ending in 1970 – which was exceptionally dry. For the eight decades $(\text{population})^{1/2}$ now increases linearly with a coefficient of correlation of $r = 0.99$ rather than 0.98, but the trend for the decadal mean of the annual precipitation becomes less evident, with r decreasing from 0.91 to 0.59.

A more sophisticated example of the analysis of time trends in support of an increasing role for 'urbanization' appears in Figure 6. The diagram is well known as being offered in support of the notion of increasing urban effects on 'downwind' precipitation totals – relative to centre city totals – in the St Louis region (e.g., Changnon *et al.*, 1971: 960; Huff and Changnon, 1972a: 831). Rather than depicting a time series for an urban precipitation total or an urban–rural difference, it shows five-year running means of the ratio

[(Downwind summer precipitation total)/(Centre-city summer precipitation total)]

at St Louis, referred to hereafter as the St Louis Rural/Urban Ratio (STL RUR). Huff and Changnon (1972a: 829) asserted its support for the notion as follows: 'If urban-induced,

Table 1 Variables and coefficients of linear correlation referred to in the discussion of time series studies of urban effects

Independent variable	Dependent variable	Period of record	Coefficient of linear correlation (R)
Tulsa, Oklahoma			
(City population)$^{1/2}$ (see Figure 3a)	Decadal mean annual precipitation	See note (a)	+0.88
Date (decade-ending year)	Decadal mean annual precipitation	See note (b)	+0.91
Date (decade-ending year)	(City population)$^{1/2}$	See note (b)	+0.98
Date (decade-ending year)	Decadal mean annual precipitation	See note (c)	+0.59
Date (decade-ending year)	(City population)$^{1/2}$	See note (c)	+0.99
St Louis, Missouri, and Chicago, Illinois			
St Louis Rural/Urban Ratio (STL RUR)	Chicago Rural/Urban Ratio (CHI RUR)	1941–64	−0.54
Summer days, smoke/haze, St Louis	Summer days, smoke/haze, Chicago	1950–64	−0.80
Summer days, smoke/haze, St Louis	Summer days, smoke/haze, Chicago	1965–80	+0.94
Summer days, smoke/haze, St Louis	St Louis Rural/Urban Ratio (STL RUR)	1950–64	−0.76

Notes:
(a) Six decades ending in 1900 to 1950.
(b) Seven decades ending in 1900 to 1950, and 1980.
(c) Eight decades ending in 1900 to 1950, 1970 and 1980.

this observed trend would be expected with gradual expansion of the urban–industrial complex; if topographically related, the trend should not occur.' In addition to wondering about such questions as when the trend began, and why at that particular time; and whether the trend would continue after 1964, and if so, why; one has to

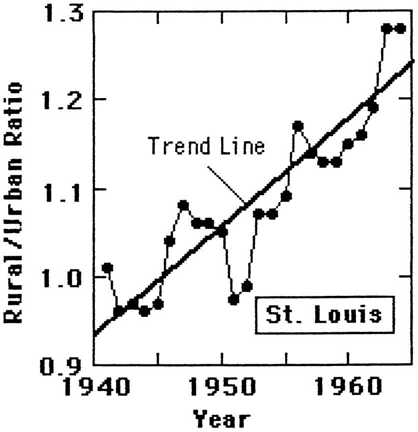

Figure 6 The five-year running mean of the ratio of downwind, rural summer precipitation total to that in central St Louis, Missouri, increased systematically during the period 1941–64

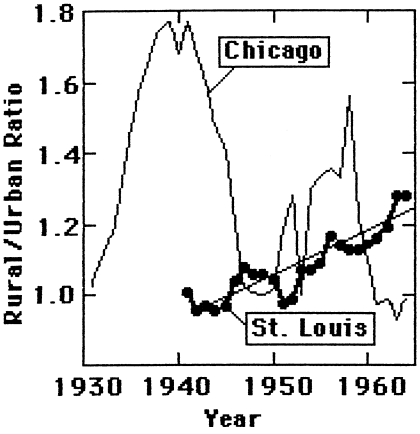

Figure 7 The STL RUR from Figure 6 is plotted against the same ratio for Chicago, Illinois

wonder if a changing regional climate might explain much of the trend in Figure 6. Pursuing answers to these questions has led this reviewer to an interesting pair of comparisons between climates in the St Louis area and in the area of Chicago, Illinois – 400 kilometres to the north-northeast – during the period 1950–80, the first half of which is represented in Figure 6. The first comparison is based on data representing precipitation-related variables; and the second, apparently corroborative comparison is based on data representing weather during periods without major storm events.

In Figure 7, the STL RUR is displayed together with the same kind of ratio for Chicago (Huff and Changnon, 1972b; 50), referred to hereafter as the Chicago Rural/Urban Ratio (CHI RUR). This juxtaposition makes clear not only that the variability in such a measure as an RUR can be much greater than that observed at St Louis during the period 1941–64 but also that periods of major negative trends can occur in urbanized areas in which neither population nor industrialization are decreasing. Of particular interest is the fact that there is a negative correlation between the STL RUR and the CHI RUR during the 25 years they overlap (see Table 1).

Data scaled from the illustrations of Vinzani and Lamb (1985) form the basis for the second comparison. They present the three-year running means of the annual number of summer days during which either smoke or haze had limited visibility to six miles or less at St Louis's Lambert Field and at Chicago's Midway Airport, during the period 1950–80. During the first half of that period – which is included in Figure 6 – the two measures of visibility are significantly negatively correlated (see Table 1). During the second half of that period – an extension of the period in Figure 6 – the two measures, for the same two regions, are significantly positively correlated (see Table 1).

The two comparisons involving St Louis and Chicago suggest to this reviewer that there was a major, region-wide change in climate – whatever its form – occurring in the American midwest within only a few years about 1965, a conclusion consonant with those of others (e.g., Clark, 1979; Changnon, 1980) that the anomaly in the La Porte area disappeared in the 1960s. Furthermore, the two comparisons are a basis for suspecting – although they certainly do not constitute proof – that the trend in Figure 6 does not provide convincing evidence for an increase in the magnitude of an urban effect on downwind precipitation amounts caused by urbanization at St Louis.

Table 2 Value of the trend slope (mm/year) from the time series in Figure 2 of Jauregui and Romales (1996). In all cases the trend variable is the wet season rainfall total (mm)

Period	City	Airport	City minus airport
1941–85	+5.8	+0.7	+5.1
1941–64	+5.6	–	+5.9
1965–85	−0.5	–	−1.3
1941–62	+4.0	–	+5.2
1967–85	−4.5	–	−2.8

Following on the suggestion of a region-wide change in climate occurring within a few years about 1965 leads to still another interesting result. Jauregui and Romales (1996) employed the basic method of time trend analysis, with annual wet-season precipitation totals (May–October) at Mexico City as their primary evidence for an urban effect, increasing over the 45-year period 1941–85 'as the city grew'. They exhibited trends for a city station and an 'upwind' station at the airport. Over the full period of record the time trends showed, as in the first line of Table 2, that totals at the city station increased at a rate slightly greater than eight times those at the airport. As a corollary, the urban–rural (i.e., upwind–downwind) difference increased at a rate slightly less than that for the city station.

Following the inference arrived at just above – that changes in the North American climate occurred within only a few years about 1965 – leads to the remaining results presented in Table 2. Dividing the full record into two periods – the first ending in 1964 – the increases in both the urban totals and those of the urban–rural difference cease about 1964, reversing to slightly negative trends thereafter. Similarly, if one removes the years 1963–66 as 'a period of transition' in the climatic change, the increases in both the urban totals and those of the urban–rural difference cease during 1963–66, reversing to significantly negative trends thereafter. The point of this analysis is not that it constitutes proof of a major climatic change about 1965, but that such a proposition would yield an acceptable counter argument to the one offered by Jauregui and Romales – based on the time series analysis – that urbanization increased quasi-linearly and that rainfall in the city responded to that increase.

c *Mapping:* By far the most-used analytical method in urban rainfall climatology, isohyetal mappings are usually based on time integrals of the rainfall rate, which is spatially and temporally discontinuous. The integrals can be for any time interval; which is to say, for any level of temporal data aggregation. In principle, the mappings can be based on observational networks of any density. In addition, these ordinary isohyetal mappings can be constructed either manually by a skilled analyst or automatically by an appropriate computer algorithm. Subjectivity is more of a problem for manual analyses than for one by a computer; and the sparser the network, the greater is that problem.

In general, the maps are geometrically least complex when the period of integration is long and the network density is low, regardless of the method of analysis. In the direction of shorter time periods, Atkinson (1970) examined a network with rainfall rates integrated over 24 hours, while Harnack and Landsberg's analyses (1975) were for periods of only about one hour. The extreme case of a short period of integration –

two- and five-minute rainfall rates – and a dense network is represented by the 'raincell' approach pioneered by Schickedanz 1974) just before his untimely death. In order of decreasing subjectivity and increasing expense would be 1) manual analyses, 2) computer-assisted analyses and 3) raincell analyses, which, to be at all valid, require a dense network of continuously recording gauges and a complex, computer-assisted data-handling routine.

Figure 8 is adopted from an analysis, on a moderately dense network, of the two-decade means of the rural/urban rainfall ratio at St Louis (Changnon *et al*., 1971: 960). The ratio, it should be noted, is self-normalizing with respect to the precipitation amount observed in the city centre, and independent of the system of physical units used to quantify precipitation. Changnon and his colleagues make clear that they ascribe the largest values of the ratio, in the darkest-shaded area in Figure 8, primarily to a downwind urban effect. They regarded the bluff line – located in the same area of the map and described just below – as, at most, only a secondary factor. Unlike the data aggregation for the STL RUR in Figure 6, the data here are two-decade means rather than five-year running means; but the two are connected by the fact that the 'urban' stations in the STL RUR are the same base stations used to calculate ratios in Figure 8, and the 'rural' station in the STL RUR is in the southern end of the dark-shaded area in Figure 8.

Figure 9 has been constructed in an attempt to demonstrate the importance of subjectivity in determining the conclusions one draws from isohyetal mappings. It is one of many possible reanalyses based on the same network and values of the ratio as those in Figure 8, with the locations of major waterways added. It would be as easy to argue, based on Figure 9, that the largest values of the ratio are due primarily to the west- and south-facing bluff lines – following the eastern and northern banks of the river system – as it would be to accept Changnon's assertion that they are due primarily to urban effects. The bluffs, lying along the eastern edge of the flood plain of the Mississippi River, are about 60 m high, and mark a sharp boundary between one set of land surface characteristics to the west, and another to the east. To the west – towards the river – the surface is a mixture of open fields and pavement; whereas, just to the east it is mainly forested. These areas are not only at different elevations but they also have different albedos, roughness and summertime vapour flux. It is certainly possible that this combination of factors might have triggered an enhancement of precipitation amounts near the bluffs even before urban development took place in the St Louis area. The very fact that this review includes such a detailed consideration of the local landscape around St Louis is a direct result of the fact that this region is virtually the only one in the world studied in sufficient detail to permit a substantive assessment of possible explanations for the location of the maximization of precipitation amount.

In addition to the matter of the bluffs, one might argue as well, based on Figure 9, that the gap in the area of large values is due to suppression of rainfall by the urban area. An additional, more subtle argument could be made, based on Figure 9, that areas of small values of the ratio – lying upwind of and parallel to the bluffs – are due to the fact that cloud systems take in water vapour as they pass over those wetlands, and later release rainwater after an appropriate processing time and forced lifting by the bluffs.

A suggestion of the difficulties created by subjective analyses of subjectively drawn isohyetal maps is the fact that, using this method through the years, Changnon and his colleagues – while originating the notion of in-cloud processing time to account for downwind maxima – have produced a series of maps in which, for a sample of urban areas, the 'downwind distances' to the maxima ranged from a few kilometres at

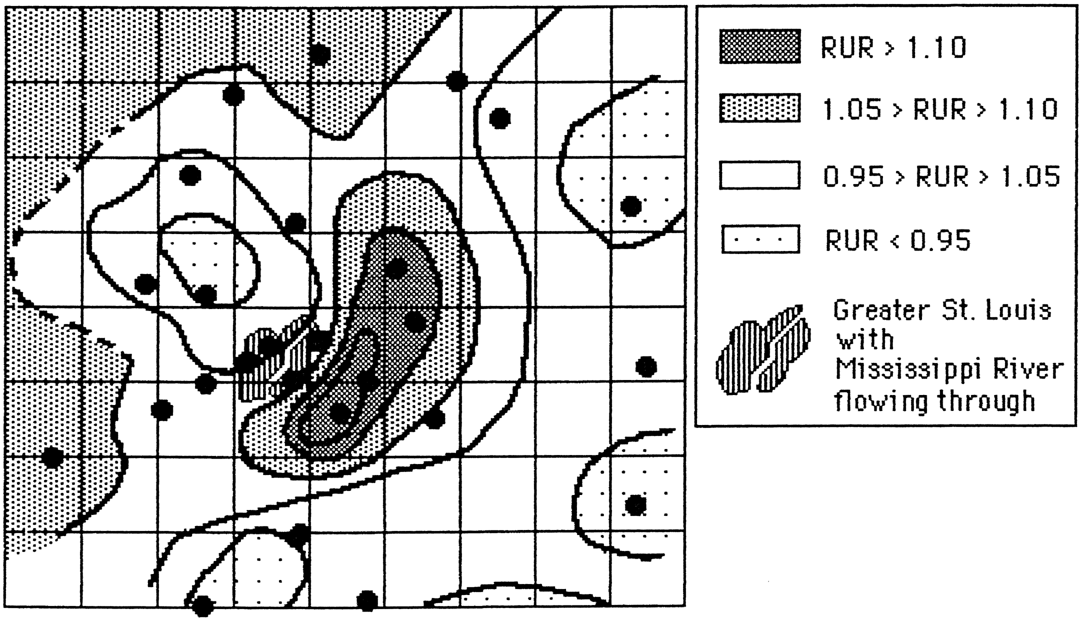

Figure 8 The average Rural/Urban Ratios (RUR) of summer rainfall in the St Louis area, 1949–68, with locations of recording stations shown

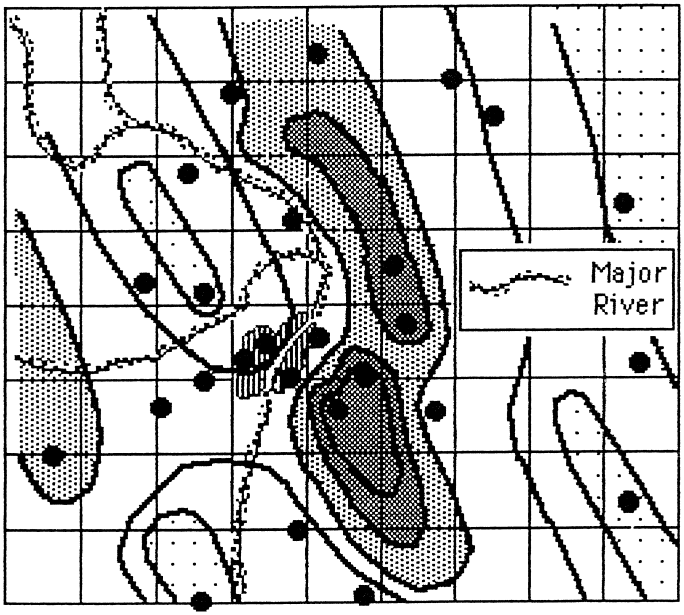

Figure 9 One possible subjective reanalysis of the data mapped in Figure 8, with locations of major waterways added

Urbana–Champaign to the roughly 60 kilometres at La Porte, Indiana. Distances estimated at other cities studied were between these two values. Assuming that the isohyetal analyses at these various cities detected real urban effects on precipitation amount, any explanatory model involving processing time would have to account for this range of distances.

As a final note concerning the use of mapping techniques, Huff and Changnon (1972a: 830) have employed isohyetal analyses both by skilled analysts and by computer techniques in an effort to 'separate the components of the downwind high resulting from urban-induced rainfall and that resulting from natural climatic variations' east of St Louis. In both, no data were plotted at stations in the preassigned 'effect areas'. Then the analysis proceeded without those data, isohyets being constructed so that 'pattern configurations and rainfall gradients established in the surrounding area were taken into consideration'. The estimated urban effects were then obtained by subtracting, for stations in the effect areas, the values obtained in those analyses from the recorded values at the stations. This effort is certainly an admirable attempt to separate confounded effects; but, by its nature, its goal is to quantify effects whose existence and even location are presumed already to have been established. The appropriateness of that presumption – especially for the St Louis area – is discussed later in the summary section of this review.

d Graphical correlation analysis: The term 'graphical correlation analysis' refers in this review to the method of presenting ostensibly independent and dependent variables in a graphical form, leaving the significance of the result to the presenter, or the viewer, to interpret. An example of this method is the presentation from the Eight Cites Study in Figure 5. There are at least two reasons for discounting this presentation as evidence for urban effects being proportional to the level of urbanization. First, values of the dependent variable – the ordinate – are based on subjective interpretations of subjectively analysed isohyetal fields. Secondly, values of the independent variable may include information about not only the level of urbanization but also about the regional landscape. Examination of the regions surrounding each of the eight cities discloses that, for example, Tulsa and Indianapolis, while being the smallest of the eight, are also situated in the least complex landscapes – with no significant topographic variation and no major waterways (Changnon *et al.*, 1976: 544) – so that the size of the population, as used here, is itself confounded and does not represent what it purports to represent in the correlation analysis.

In another well-known example, Changnon (1979: 403) and Braham (1981: 85) exhibited, in graphical form, the data presented in Table 3. The tabulation is of the rainfall total, in a wind-orientated quadrant, during 15 summer months relative to the total in the upwind quadrant centred on St Louis, Missouri (see the note in Table 3). Notice that these ratios are self-normalizing with respect to the precipitation amount observed in the upwind quadrant, and independent of the system of physical units used to quantify precipitation. Braham (1981: 85) comments that 'It is important to note that in every partition the downwind quadrant rainfall is greater than that in the upwind quadrant.' That is, while all numbers in the first column are equal to one, all numbers in the second column are larger than one. Changnon and Braham left no doubt that they accepted this statement as evidence for an urban enhancement of precipitation amounts downwind of the city of St Louis, regardless of the presumed direction of storm movement. Note in passing that this exercise is based on an acceptance of the notion that urban 'enhancement' appears downwind of, rather than anywhere within, the city; and elsewhere, Braham (1979: 373), alone of senior METROMEX scientists, seems to allow for the possibility that urban effects can take the form of 'suppression'.

Table 3 Precipitation totals from 302 rain events, relative to the totals in the upwind quadrant,[a] during June, July and August of five summers (1971–75) classified into four quadrants, surrounding central St Louis, Missouri

Regional wind from	Upwind quadrant	Downwind quadrant	Quadrant left of wind	Quadrant right of wind
South east	1.000	1.106	0.882	1.066
South west	1.000	1.372	1.000	1.166
North east	1.000	1.121	0.940	1.232
North west	1.000	1.452	1.161	1.032

Note:
(a) The quadrant boundaries in all cases were east–west and north–south, centred on the city. Each rain event was classified according to the low-level regional windflow direction during the three hours preceding onset of the event.
Source: After Changnon, 1979; Braham, 1981.

In Table 3, the fact that, in the case of prestorm winds from the northeast quadrant, the downwind total is not the largest of the four is scarcely a substantial reason for doubt about Changnon and Braham's conclusion, cited just above. The following examination of these results, however, may be more substantial. With only three of the 12 values in quadrants other than upwind being $\leqslant 1.0$ and treating those 12 values as a random sample from a larger population, one can estimate that the probability of having all the numbers in the second column larger than 1.0 is 0.67 (see the Appendix). With two samples of every three meeting Braham's criterion of 'success' by chance alone, it is hardly a firm basis for contending that one has detected urban enhancement.

e *Physical and mathematical modelling:* These methods probably come as close to actual experimentation as one can in urban climatology. In his successful pursuit of the physical explanation for the Urban Heat Island, Oke (1981) merged field observations of nocturnal cooling rates from several urban areas with others made experimentally using physical-scale models of urban blocks and canyons. The urban-centred system of processing forming clouds and producing rainfall, however, is scarcely amenable to such physical modelling; but mathematical models have been used to seek insight – with what success cannot be known for certain – into the role of landscape features in those processes.

Probably the best-known and most systematically employed mathematical models in precipitation-related urban climatology have been of mesoscale processes (Vukovich *et al.*, 1976; Hjelmfelt, 1982). Their major shortcoming, in the present context (Cotton and Pielke, 1995: 82), is that they 'could not [because of limited computer capacity] simultaneously simulate both the mesoscale responses to the physiography and urban heat island, and the response of deep precipitating convection to those forcings'. Overlooking that shortcoming and the fact (Goldreich, 1996: 344) that the models 'disregard some important parameters, like stability and windspeed shear', the modellers consistently conclude (Braham, 1981: 108) that 'thermal forcing is the main cause of urban effects, while topographic features play a secondary role by interacting with, and causing an enhancement or suppression of, the thermally driven heat island circulation depending on wind direction'. While the results of these studies have produced additional understanding about urban and topographical effects on the changing morphology of the urban boundary layer, especially in situations without precipitating clouds present, they appear not to have contributed substantially to the separation of these effects in explaining the location and timing of rainfall occurrence.

f Hybrid methods: Researchers seldom use only one method of analysis and presentation, and the examples of individual methods presented above have in fact been extracted from longer publications for purposes of discussion. In two recent short contributions, several methods used in equal amount must be considered together in order to appreciate the conclusions presented. The term 'hybrid methods' is used here for those cases.

Rosenberger and Suckling (1989) published results based on such a combination of analytical methods. They examined 30 years of climatic records, from 26 stations, 'to determine whether an area of enhanced precipitation exists downwind of the Pittsburgh, Pennsylvania, urban area' (Rosenberger and Suckling, 1989: 76). Their study network extended about 30 km on either side of a 210 km-long axis, from about 60 km to the west-southwest to about 150 km to the east-northeast of central Pittsburgh. Rather than ignoring or discounting elevational differences within the study area, as has been done in so many studies through the years, they considered them directly. Three other commendable features of their article are the facts that 1) precipitation amounts are treated as point variables, with no isohyets appearing in the report; 2) precipitation amounts are expressed as normalized, network-wide, rankings for a single study period, such as July; and 3) the authors include, for each station, its latitude, longitude and elevation. Two shortcomings are the facts that 1) stations in large sectors to the north and south of the axis are omitted, a decision based on the assumed primary storm track; and 2) the data are aggregated into one period, with no information about possible changes through the course of the 30 years. Their methods of analysis included graphical correlation (as defined earlier) and multivariate statistical testing of the null hypothesis. Rather than presenting a description of each of the results reported by Rosenberger and Suckling, the following summary consists only of comments and a discussion of their Table 5 based on an analysis, prepared for the present review, of their data.

In a manner similar to that of Rosenberger and Suckling, an 'effect' area with 12 stations was designated, extending about 90 km 'downwind' to the east-northeast of central Pittsburgh; and the 14 remaining stations were assigned to a 'no-effect' area, including 11 stations 'upwind' to the west–southwest and three stations far 'downwind' to the east-northeast. Table 4 demonstrates that – as is often the case in such studies –

Table 4 Independent and dependent variables in least-squares linear intercorrelations among three variables related to location and precipitation amounts in the area of Pittsburgh, Pennsylvania

Model	Elevation	Distance downwind from central Pittsburgh	Normalized precipitation amount	Coefficient of linear correlation
1	Independent	–	Dependent	+0.81
2	–	Independent	Dependent	+0.82
3	Independent	Independent	Dependent	+0.84

Source: After Rosenberger and Suckling, 1989.

Table 5 Normalized rankings, for the years 1958–87, of mean July–August precipitation totals at stations in 'Effect' and in 'No-effect' areas in the Pittsburgh, Pennsylvania, region, classified by elevation zone

Elevation zone (m)	200–250	250–300	300–400	>400
Precipitation ranking in decreasing order[a]	Effect	Effect	Effect	Effect
	No-effect	No-effect	Effect	No-effect
	No-effect		Effect	Effect
	Effect		Effect	No-effect
	Effect		No-effect	No-effect
	Effect		No-effect	
	Effect		No-effect	
	No-effect		No-effect	
	No-effect		No-effect	
	No-effect			

Note:
(a) Rankings within an elevation zone are arrayed from the largest at the top to the smallest at the bottom. There is significance in a ranking's position within a column, but no significance to any two rankings being in the same row.
Source: After Rosenberger and Suckling, 1989.

location, elevation and precipitation amount are confounded in the effect area downwind of Pittsburgh.

In Table 5, stations are listed in decreasing order of their precipitation ranking, from top to bottom within a column. The table shows that for a given elevation, there is a clear tendency for station totals to be greater in the effect area than in the no-effect area. The correlation is by no means strong, but the analysis addresses the matter of elevation differences directly.

Stulov (1993) reports that, based on monthly precipitation totals from 25 summers, averaged for five urban stations and for 13 regional (rural stations within 150 km of Moscow, the monthly urban–rural difference – using the *t*-statistic – is significantly greater than zero. On average in summer, that is, there is an urban excess of precipitation amount. Using radar tracking of storm cells on individual days, however, he notes that (Stulov, 1993: 37):

1) when a 'potentially unstable moist air mass flows onto the city and cumulonimbus clouds … begin to form intensively directly over the city, … precipitation falls in the lee of the city and behind it'. That is, the city initiates the formation of the cells. He notes, also that
2) when 'a [pre-existing] core of convective precipitation moves across the city, an increase in precipitation is associated with the amplification of convective processes (sometimes the core slows its movement). This … most often occurs when cold fronts move across the urban area'. Finally
3) a 'third variant is typical of relatively fast moving cold fronts and occlusions. In a number of cases, the movement of the [pre-existing] cores of intensive precipitation slowed down over the city, which in itself should lead to increased total precipitation over the area'.

To this reviewer, those three observations amount to saying that the location of the maximum – the 'summit' of the isohyetal mapping for an individual storm or storms of the same type – depends mainly on the synoptic situation. It would follow, then, that the location of the maximum, averaged or totalled over a period of time depends very much – because of changing probabilities of occurrence of the different synoptic types – on which period of time. It would follow, in turn, that debating whether the 'summit' is generally within or beyond the city, in the long run and for cities in general, is comparatively uninstructive. Stulov's combination of static and dynamic methodology is commendable for its simplicity, but it leaves open the question – to be considered later – of the effects of data aggregation on research conclusions.

3 Flawed methodology: a summary

Through nearly a century of research into urban effects on precipitation amount, the general trend in methodology might be characterized as 'more but not better'. More cities have been studied; longer periods of record have been analysed; more variables representing potential effects have been considered; more sophisticated types of instrumentation have been deployed; and network densities have increased. Still, in all, the battery of analytical methods used has remained both stagnant and flawed. This trend is exemplified in the study by Jauregui and Romales (1996), cited above, of Mexico City. Fully 60 years after Kratzer's study of Stockholm, 40 years after Landsberg's study of Tulsa and 20 years after METROMEX, they employed differential time series analysis, without either questioning the use of time as an appropriate surrogate for 'the level of urbanization' or considering other possible explanations for the trends they observed.

The fundamental pattern for research into urban effects on precipitation amount has continued to be one primarily of numerical description, accompanied by speculation as to causation of such effects as analysts believed they had discerned. Description and speculation are certainly valid ways to begin an effort to establish the existence of effects, but by themselves they can seldom be used effectively in systematically testing, modifying and retesting hypotheses. It is that systematic testing – the heart of the scientific method – that has, with few exceptions, never been undertaken. Broadly speaking, the result of the pattern followed up to the present has been that the 'believer' has found ample evidence for urban enhancement, especially in isohyetal maps; whereas, the sceptic has maintained that the assertion of urban enhancement cannot really be tested without some knowledge of what would have happened in a particular storm event at that place under the same weather conditions before the city was there.

Contributing to the widened gap between the believer and the sceptic has been the use – as noted earlier – of several convenient, time- and space-saving phrases, including 'downwind increase', 'downwind high', 'precipitation increase' and 'precipitation anomaly'. Further widening the gap is the fact that there has never been – especially in modern research – a straightforward use of two-tailed testing, analyses having instead been based exclusively, and unapologetically, on the presumption of enhancement to the exclusion of suppression. In this section, open to the scrutiny of more qualified statisticians, an attempt is made to examine briefly each of several aspects of the scientific method, and then several other matters, as they pertain to research into urban effects on precipitation amount. Results of this examination are considered again in the last section in which recommendations are made for future research.

a Experimental control: A central feature of the scientific method is the experimental design, centred on the establishment of a 'control' against which to test a null hypothesis. In the case of research on a particular urbanized area, the ideal control is the preurban system in that area. Landsberg's study of Tulsa (1956: 594) came about as close as one could to that ideal, with the population being less than 1000 when the record began. The method fell short, however, because he aggregated data across weather types, going so far as to analyse decadal mean annual totals. The result, as has been discussed above, was a study vulnerable to the contentions that Landsberg used no physical measure of the vague notion of 'level of urbanization', and that Tulsa's time trends doubtless reflected secular climatic changes confounded with increasing urban effects.

Landsberg's study of the first seven years at Columbia, Maryland (1979), met the criterion of using preurban data for an area; but the length of record was too short, and he made no effort to make comparisons within weather types. The various studies of weekend rainfall amounts versus weekday amounts are a form of control, but such studies have consistently aggregated data across weather types. Finally, Braham (1979) has commented critically on the practice of the *ex post facto* delineation of a 'control'. In particular, he considered the designation – based in large measure on prior knowledge of rainfall patterns, and for purposes of stratifying data – of 16 subareas within Greater St Louis, one of which was taken to be a 'no-effect' area.

b Sample size: The matter of sample size leads directly to the question of definition of the experimental unit, and to the problems arising from different levels of data aggregation, some of which are clearly inappropriate for the system being sampled. Braham (1979: 371) wonders 'how long a record [of precipitation amounts] is needed to eliminate sampling uncertainties' and he suggests that the five summers of METROMEX is too short. The aggregations of data that he considers are of several types: for example, 1) individual monthly totals; 2) monthly means for five summers; and 3) totals for all days – a day is itself a level of aggregation – within a 'storm intensity group'. Without belabouring the point, one can argue that, for three examples, the 302 rain events in Table 3; the 15 summer months in which they occurred; or the individual summer rain days in the long record at Tulsa (Landsberg, 1956) could be treated – albeit with a greater investment of analytical resources – as independent tests of Braham's criterion: more rainfall downwind than upwind. Schickedanz (1974: 892) makes clear the extent of such an investment of resources involved when one takes an individual 'surface raincell' as the experimental unit.

c Replication: When the same designed experiment is repeated, such as in several urbanized areas, each would be a replication. The same hypothesis is tested in each replication by whatever experimental design has been selected. In the present context, however, conducting 'the same experiment' would imply such particulars as 1) the same experimental unit, for example, a rain day or a rain event; 2) the same synoptic weather setup; 3) the same definitions of 'upwind' and 'downwind' including quadrant size dimensions, orientation and gauge density; and 4) similar sample sizes across replications.

Discussing the theoretical details of such an experimental design is beyond the scope of this review; but it is appropriate to note that, while one may be tempted to say simply that no two cities and no two weather sequences are alike, that should not be a deterrent to using replication in precipitation-related urban climatological research. One might be tempted to view the investigation of isohyetal patterns for St Louis (e.g., Braham, 1981) and for the Detroit–Windsor area, on the Michigan–Ontario border (Sanderson and Gorski, 1978), as two replications of the same experiment. For reasons already discussed, however, subjective judgements about patterns subjectively constructed are scarcely a proper experimental design. The search for evidence of urban effects on precipitation amount has not included – very likely for reasons of funding – purposefully undertaken experimental replications in the sense described here.

d Stratification: The sorting of sample data into strata for purposes of statistical analysis is a powerful tool for reducing sample variances, thereby strengthening inferences then obtained from tests of hypotheses. Stratification in urban rainfall climatology is employed often – if not always to good effect – and in some instances it is not employed when it ought to be. Several stratification schemes familiar to any casual reader of the literature include 1) synoptic weather type (e.g., Braham, 1980: 79); 2) prestorm wind direction (e.g., Braham, 1980: 84); 3) network-wide daily rainfall intensity (e.g., Braham, 1979: 374); and 4) regional 'wetness' of individual summers (e.g., Huff and Changnon, 1972a: 833). While these schemes are certainly valid, they have scarcely ever been used for the purpose of reducing sample variances, since they were not then followed by appropriate statistical testing of an hypothesis.

What would seem to be a productive form of stratification has not yet, to the knowledge of this author, been employed: experimental units (e.g., individual days of the same synoptic type, or with the same rainfall intensity, both within the same season) stratified according to whether they occurred when an area was just beginning to urbanize or when the area was fully urbanized.

e Randomization: Research on planned weather modification – 'cloud seeding' – came to rely on experimental designs in which one of each of a substantial number of pairs of rain events was selected randomly to be 'treated'. Subsequently, a standard *t*-statistic was employed to test the null hypothesis that the mean values of a chosen measure of precipitation amount were the same in both 'treated' and 'untreated' samples. The temptation has been strong to follow this idea in considering urban effects on individual 'surface raincells', those passing over or being initiated in urban areas being considered as 'treated'. Schickedanz (1974: 892) went to some pains to explain why this is futile in the case of inadvertent, as opposed to planned, modification:

> The chief problem in evaluating inadvertent rainfall changes is that the treatment (urban) effect is not assigned at random to the experimental unit. Even if randomization is disregarded, there is the difficulty that the treatment effect is uncontrollable, or else the factors which control [it] are unknown or the degree to which they are present is unknown.

A principal reason for including randomization in the design is that it is assumed in the *t*-test model to be present – a fact that becomes very important when the difference between treatment means is small. Schickedanz (1974: 892) went on to say:

> Since the lack of randomization is unavoidable ... the approach will [have to] be that of 'data analysis'. In this approach, the final proof and acceptance of inadvertent modification ... does not rest entirely upon statistical evidence and results from tests of hypothesis. The test statistic [is to] be treated as an informative summary statistic and is to be clearly distinguished from the concept of the test statistic as a strict accept–reject rule. Thus, the flexibility of attack and the willingness to study things as they are, rather than as they, hopefully, should be, are stressed.

It seems to this author that application of that outlook – especially to data other than surface rainfalls (e.g., Huff and Changnon, 1972a: 825) – is regrettable, and gives too much room for one to settle on conclusions as being valid because 'comparative analyses

... indicated' they are (Huff and Changnon, 1973: 1225); because one map 'is very similar' to another (Braham, 1979: 375); because an examination 'indicated close agreement between the major features of ... spatial distributions' (Huff and Vogel, 1979: 375); or because one '[feels] there is substantial evidence for believing' that they are (Braham, 1979: 375).

f Aggregation of data: Another matter beyond those dealing with aspects of the scientific method and the testing of hypotheses is worthy of consideration. The aggregation of data is an important, but usually overlooked, aspect of the kinds of analyses being considered here. As a single example, if the data for Stockholm, in Figure 2a, are aggregated from five-year period into decades, the coefficient of linear correlation increases from 0.85 to 0.95. One wonders, if the data for Stockholm had been disaggregated to annual or summer season values, and those for Tulsa to daily values (Landsberg, 1956), whether support for the unstated hypothesis would have been so compelling.

Other than suggesting that readers of research reports on urban rainfall climatology take note of the degrees of aggregation present in the articles they read, and without dwelling at undue length on the matter, the following small study will illustrate the problem more pointedly. Interested in data aggregation into five-year running means in the study leading to the result in Figure 6, but without access to the data set producing that result, this author formed his own data set from Lambert International Airport, representing an urban St Louis station; and a pair of rural, downwind stations with slightly overlapping records – Southern Illinois University at Edwardsville and Scott Air Force Base – located near Centerville, Illinois, the rural station in the STL RUR of Figure 7. Using monthly precipitation total as the unit of analysis, the Rural–Urban Ratio was calculated for each of the 117 months of 39 summers (June, July and August) beginning in 1948. Figure 10 displays the frequency distributions of these calculated ratios for 117 months and 39 summers. In the figure, 11 monthly totals with RUR values exceeding 2.1 were merged at a value of 2.2 for the ratio.

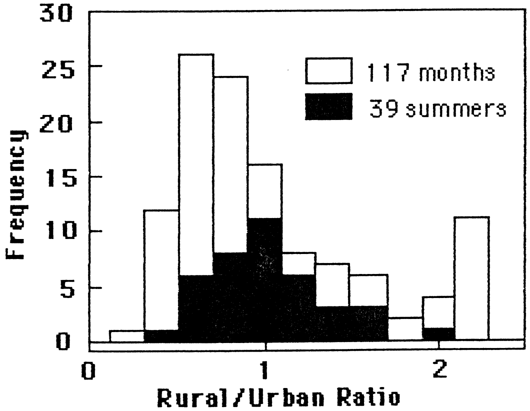

Figure 10 Frequency distributions of the Rural/Urban Ratio for two locations in Greater St Louis, Missouri, for June, July and August of each of 39 consecutive summers beginning in 1948

When disaggregating summers into months, one could expect a transfer of units towards extreme values, as has occurred in Figure 10. It would not in general be expected, however, that disaggregation should transfer so many values near 1.0 to values well below 1.0, approximately the mean value for both distributions and the mode for the monthly values. At issue here is not the fact that, for these stations, the mean value is not larger than 1.0, as one might expect in view of Figure 7. Rather, it is the marked shift in frequencies to values less than 1.0. As in the cases of Stockholm and Tulsa, just cited, one realizes that the level and kind of data aggregation could have a major effect on the conclusions to be drawn from the data.

IV Status

Urban climatologists are now confident of their understanding about both the urban effects on local thermoclimate and the physical processes leading to those effects. In contrast, they have been unable to fashion coherent analyses of the evidence, supported by the results of designed experiments, about urban effects on precipitation. As a yardstick against which to measure progress during the last three decades, consider the part of Atkinson's summary of the 1968 Brussels symposium that refers to rainfall (1970: 375):

> The problem is as much to prove the influence of towns as to explain it. Lecturers [in the symposium] have, to my mind, demonstrated the influence to be both possible and real, in spite of the utmost difficulty of the wider problem of separating the urban effect from the situation that would exist if the city were not there. This can only be done by a combination of both theory and field evidence coupled with the use of advanced techniques of statistical analysis.

To judge by recent articles, Atkinson's words apply as well now as they did then.

International efforts in urban climatology during the past decade or so have, with continuing encouragement from the professional staff of the WMO, centred on tropical and subtropical regions (e.g., WMO, 1993a; 1993b; 1994). These efforts have coalesced around an organizational structure with recognizably METROMEX-like characteristics; TRopical Urban Climate Experiment – TRUCE (WMO, 1997). Not only has the emphasis shifted markedly to matters of architecture, impacts of natural disasters, and human health and comfort; but also, research in urban rainfall climatology has virtually disappeared from the menu. Two items from these WMO reports are cited as indicative of the international status of research in urban rainfall climatology. First, an extended abstract by Khairullin (WMO, 1993a: 14), as it relates to rainstorm climatology, reads like Landsberg's 1962 summary: 'Cities can considerably influence thunderstorms and hail activity, particularly as regards the extreme characteristics. The number of days with thunderstorm in cities in the European territory of Russia is greater by 7–10%, and that with hail by 10–15% than in surrounding areas.'

Elsewhere, a section title in the working plan for TRUCE seems to indicate considerably less certainty for tropical regions: 'Urban effects on precipitation amount: increase or decrease?' (WMO, 1997: 4). This reviewer has been unable to discern any indication that today's scientists, operating in the area of urban precipitation climatology, have moved beyond employing any but the most basic and flawed methods considered in the previous section.

1 The current institutional perspective

In the USA, what may be characterized as the official, or institutional, view of the status of precipitation-related urban climatology can be found in the policy statement of the American Meteorological Society on 'Planned and inadvertent weather modification' (AMS, 1992), which is current as of this writing. The following are extracted from the statement:

> The effects of inadvertent weather modification are becoming better understood. Cities and industrial complexes affect local weather conditions and alter precipitation (p. 331).
>
> Urban effects on ... precipitation have been well documented (p. 332).
>
> Major cities with populations in excess of 1 or 2 million, and located in continental climates, influence warm-season clouds and increase precipitation by 10–20%, with a lesser effect on precipitation in cold season. Recent studies of urban areas in tropical regions have confirmed that significant modification of weather conditions also occurs in this climatic zone leading to cloud and precipitation increases (p. 336).
>
> The extent of impacts produced by inadvertent weather modification requires improved definition. Further atmospheric studies are needed of cities of varying types and in different physical settings to better understand and predict local and regional-scale weather influences from ever-growing urbanization. More complete understanding and documentation of the physical processes involved in ... inadvertent weather modification is needed (p. 336).

2 The current professional perspective

Three quotations are offered as representative of opinions being published in recent years by American urban climatologists. One finds the following in Landsberg's last summary (1981: 186), accepted by many as definitive:

> Of all meteorological elements in the urban environment, precipitation still confronts us with the most puzzles ... Precipitation amounts are extremely dependent on elevation and many urban areas have considerable height differences. The presence of water bodies that may stabilize air masses in summer and furnish moisture in winter has a great influence on the occurrence and amounts of precipitation. Yet ... there is much evidence for increases of precipitation in urban areas in comparison with rural environments near cities but not under their disturbing influences. There are a number of factors that make an increase of precipitation by urban areas plausible. But these intermingle and their effects have not yet been disentangled.

Immediately following that, Landsberg goes on to say that the principal three among these factors are 1) the Urban Heat Island, which produces the updrafts necessary for sustained precipitation; 2) the obstacles of the rough urban surface that retard horizontal motion in the urban boundary layer, which in turn causes pre-existing precipitation cells to linger over the city; and 3) the presence of pollutant aerosols. Noting that the aerosols may either promote or inhibit precipitation, depending on their size and physical properties, he says that (1981: 187) 'the evidence is mounting that the pollution effect on urban precipitation is secondary to the aero- and thermodynamic impacts'. Regarding the natural variability of rainfall, Landsberg concludes with two telling comments: first (p. 187), 'the passage of a single tropical storm can affect the relevant sample statistics for a long time'; and (p. 188) 'none of the [urban–rural] differences is larger than the standard deviation of annual precipitation. Thus, statistically they cannot be very significant.'

The following are extracted from a far-reaching summary by Changnon (1992):

> The scientific community has accepted the causes and reality of man's accidental modification of clouds and precipitation at the local, urban, and regional scales. Extensive long-term research, coupled with statistical and visual evidence, have provided undeniable evidence of change (p. 622).

> METROMEX established the causes of urban-induced cloud changes, the reality and magnitude of warm-season rainfall increases, and the types of increases in storm activity such as more thunderstorms, lightning, hail, and damaging surface winds (p. 624).

Finally, Cotton and Pielke (1995: 73) have little to say about urban effects on temperature, but they add an important fourth element to Landsberg's list of three causal factors for urban effects on precipitation: the injection of moisture from industrial sources (1995: 73). They indicate that they 'draw heavily on [the findings of Project METROMEX] to discuss the potential mechanisms causing urban-induced changes in weather and climate'. Elsewhere in their summary they say (1995: 73):

> There is considerable evidence which suggests that major urban areas are causing changes in surface rainfall [*sic*], [and other storm-related weather elements] . . . St Louis exhibits a major summertime precipitation anomaly relative to the surrounding rural area . . . The clouds producing those changes are deep convective clouds and thunderstorms . . . The rainfall observations also indicated a maximum around midnight . . . located northeast of the city . . . The storms responsible for the nocturnal maxima were well organized storms such as squall line thunderstorms that swept across the urban area and moved across the affected region.

After giving this clear indication that urban effects on precipitation amount have not only been identified but also explained, Cotton and Pielke go on to say (1995: 81):

> One may ask: is it really necessary to identify the actual mechanisms responsible for an urban precipitation anomaly? Can't we be satisfied that the rainfall analysis [from St Louis] shows a strong rainfall anomaly downwind of the urban area? *The answer is clearly no*! [The emphasis is theirs]. For one thing we cannot be sure that the statistical analysis of the rainfall records did not produce an urban 'signal' purely by chance . . . Could local physiographic features . . . be the primary causal factors in creating a rainfall anomaly? [Mesoscale mathematical models of St Louis] revealed that there may be important interactions between the local topography and the downwind thermal plume of the urban heat island. It was concluded by the METROMEX team that these effects were small, at least in the afternoon hours. They could not dismiss the possibility that physiographic effects could have contributed to the nighttime maximums, however.

Taken together, these quotations summarize what is proposed here as the currently accepted status of understanding about urban effects on precipitation. They contain all the relevant elements (in no particular order of importance):

1) A list of plausible causal factors and mechanisms.
2) A mixture of certainty and uncertainty; for example, the unhesitating association of urban and industrial effects on precipitation amount with deep convection, together with doubt about where and when one should expect to find the evidence of those effects.
3) Lingering doubt that urban and industrial effects can be 'disentangled' (Landsberg's term) from the effects of topography and open water sources.
4) Heavy dependence for 'evidence' on inherently subjective analyses from a single field study – METROMEX.

V Summary and recommendations

1 The central conundrum – factors producing the Edwardsville High

In the opinion of this writer, the geographical foci of essentially the entire subject of urban effects on precipitation amount are Edwardsville, Illinois – at the northeastern edge of the METROMEX research area – and the farmland surrounding Panther Creek, Illinois, 250 km to the north. The former is the namesake for the 'Edwardsville High' where local maxima of rainfall amounts, and especially of large daily totals, appear so frequently in isohyetal mappings of that most-studied of all urbanized regions (e.g., Braham *et al.*, 1981). The latter was the location of an early study of isohyetal patterns deploying a reasonable dense gauge network, and extending for a full decade (Changnon, 1962: 62).

The observational heart of the entire subject lies in the fact that the Edwardsville High lies both where time and distance might well result in enhanced totals from urban-affected rain systems that had passed over central St Louis some 30 km to the west-southwest and where the bluff line east of St Louis – described in some detail in the discussion of Figure 8 – forms a right-angle 'funnel', which by itself could result in enhanced totals (e.g., Braham, 1981: 107). This dual nature of the Edwardsville High represents an inescapable confounding of two possible causal factors, each of which by itself could conceivably account for the local maxima.

With unending consistency, both METROMEX scientists and external reviewers have maintained that the bluff line is a 'relatively minor terrain feature' (Braham, 1981: 105) whose physiographic effect constitutes, at best, a secondary forcing in the processes of enhancement (e.g., Braham, 1981: 108; Cotton and Pielke, 1995: 82). Lost in the efforts to reinforce that notion is the evidence from Panther Creek that without physiographic forcing, and by virtue alone of the cellular nature of summer storms in that region, local isohyetal maxima will appear with no city nearby. The Panther Creek study is never mentioned in those efforts, but another such relevant study is mentioned once (Braham, 1981: 106):

> The hills to the southwestern part of the [METROMEX] raingage network are essentially similar to the Shawnee Hills in extreme southern Illinois [about 190 km southeast of St Louis] which are known [Jones *et al.*, 1974] to cause a local precipitation maximum of $\approx 15\%$ more rainfall than nearby flat rural land.

Thus, evidence unrelated to METROMEX and St Louis, which has never appeared in the refereed literature but which was published by METROMEX scientists, would, in the opinion of this reviewer, lend support to the counterargument that the combination of the cellular nature of summer storms, and terrain of the characteristics found in the general St Louis area, could account for the Edwardsville High irrespective of the presence and level of urbanization and industrialization of Greater St Louis. The point being made here is not that the counterargument is necessarily correct; it is instead that St Louis is largely irrelevant, an argument that is supportable with evidence as broadly appropriate – for all its absence from published discussions – as that being used to argue that thermal forcing due to St Louis is the primary factor producing the Edwardsville High.

The point about the Edwardsville High is a corollary of the most fundamental point in this review: the claim is not that urban effects on precipitation-related processes and outcomes do not exist, but rather that the effects – which almost certainly do exist, but which are inextricably confounded with other factors – have not yet been demonstrated and described, let alone quantified, in a manner compatible with sound scientific methods. The difficulty to be overcome by future research in urban climatology lies primarily in the fact that the results of METROMEX have been neither systematically and critically analysed and reviewed – using counterargumentation in the best and healthiest sense of the protocols of the scientific method – nor have they been replicated in any other urban area.

2 Why urban rainfall research is being neglected

The starting point for laying out a new research effort is an acceptance of the facts that 1) METROMEX was, as noted above in the historical review, logistically so complex and expensive, and produced such elaborate and detailed results, that climatologists have been inclined ever since to consider its conclusions as definitive; and 2) high cost – especially for staff and complex electronics – is probably the main reason research in urban rainfall climatology has languished in the last two decades.

3 A checklist for future urban rainfall research

Consider now some suggestions regarding research that might profitably be undertaken. Some of the suggested studies would be expensive to carry out; others not. Likewise, some studies would require access to existing databases not heretofore available; so that a specific initial recommendation is that qualified investigators be offered direct access to all existing data. Proceeding from here, it is contended that the new research should have *at least* the following characteristics:

1) Designed experiments – especially including legitimate controls and, where appropriate, stratification schemes – in which explicitly stated hypotheses are tested by means of standard statistical methods.
2) Replication of the experiments in several urban areas.
3) Use of spatially small, and temporally short, experimental units reflecting the discontinuous nature of the precipitation systems being sampled; which would also be favoured by
4) Disaggregation of standard climatic data, whenever they are used, partly to achieve larger sample sizes and partly to avoid merging effects between dissimilar synoptic weather systems.

4 Controls for the use of rainfall maps

Beginning with suggestions for relatively inexpensive studies, one can accept that the temptations to use map analysis are several, but that the analyses should be subjected to several considerations and restrictions. There should be 1) a commonly agreed-upon computer program used to carry out any isoplethic analyses free of human subjective judgement. Then, too, 2) there should be at least a minimal gauge density for a network, and probably an agreed-upon maximum density as well. The density for recording precipitation gauges in METROMEX was about 25 km^2 per gauge (Schickedanz, 1974: 891). Finally, 3) a threshold value of an agreed-upon numerical index of geometrical correlation should be invoked when one contends that two maps are, for example, 'similar' or 'in agreement as to their major features'. A corollary of the third point is that it might prove useful, especially in analysing replications of isohyetal analyses among several cities, to develop and employ a numerical index of geometrical complexity. That notion first arose long ago in the mind of this author upon reading Changnon's words (1962: 63) comparing the isohyetal maps of Champaign–Urbana and Panther Creek:

> [Superimposed] on the average annual pattern of precipitation of [the Panther Creek map] are two rectangles, each the size of the Champaign–Urbana area. These rectangles have been placed in two portions of the rural pattern where variations were comparable with those exhibited in the urban network. This indicated that the annual urban pattern could be entirely the result of natural causes.

If one were to insist on using interpretations based on subjective, visual inspection of mapped, standard climatic data, then one could employ an alternative mode in which observed or averaged values were treated as point data; plotting, for example, different-sized disks at station locations rather than numbers surrounded by isohyets.

Using some form of objective, isoplethic mapping technique; and building on Changnon's notion (1980: 702) that 'the [La Porte] anomaly either ended or shifted into Lake Michigan', one could develop still another mode of analysis by constructing, preferably for each of several urban areas, a set of maps, each depicting the precipitation field for some relatively short time period – say, a day or a week – and then photographing and projecting the set, in actual time sequence, as a 'motion picture'. That notion is based on a vivid recollection of seeing, as a graduate student, a complete set of historical weather maps of North America projected in this manner. The great natural patchiness of the precipitation field would surely be clear to the viewer; but any quasi-permanent or systematically developing map elements would emerge as well, being then available for further analysis.

5 Synoptic stratification and preurban analysis

The last suggestion for a set of relatively inexpensive studies incorporates comments made earlier – in the third example of the section on sample size – regarding the use of small experimental units, stratified subsamples and replication. Based on an existing lengthy record of standard, climatic data – Tulsa in the example above – the study would employ small experimental units – for example, individual days – stratified first by synoptic type, or rainfall intensity, both within the same season; and further stratified according to the time period they were observed relative to the full span of urban development for the area in question. The null hypothesis of 'no effect' could be tested using two or more temporal classes. In the case of two classes, for example, subsamples would represent the years when the area was just beginning to urbanize and when the area was fully urbanized. The testing could then be replicated with comparable data from other urban areas.

6 Raincells as the experimental unit – design for a replicable, effect–no effect experiment

Moving finally to a suggestion for a relatively expensive study, this reviewer would envisage an experimental design based on what this reviewer believes is the key to unlocking the door to the establishment and the quantification of urban effects on rainfall amount. The key is the use of individual raincells as the experimental unit of analysis – the idea advocated by Atkinson in 1970, made technically possible through the work of Schickedanz shortly thereafter, and set aside because of his early, untimely death.

The experiment would be based on a series of observations of rainfall rate obtained with twin networks of recording rain gauges of density similar to that deployed in METROMEX. In replication at each city, one of the networks is deployed with an appropriate layout on the ground 'downwind' – let us say to the east – of an urban area; while the other is deployed 50 km or so in a 'crosswind' direction – to the north or the south of the city, and with the same layout – in an area devoid of urban development. As nearly as possible, the rural area would be a physiographic surrogate for the urban area prior to urbanization. Then, using weather radar as a monitoring tool, pairs of raincells would be identified in the passing stream of storm entities, one passing over each of the twin networks. The observational networks would be 'turned on' – that is, the rain gauge records would be analysed – only for those time periods when these pairs of raincells passed over the networks. Using the computer-assisted mapping techniques, and the physical measures of raincell morphology and development, pioneered by Schickedanz (1974), one would gradually develop a data set for that city-environs system that could be tested statistically against the null hypothesis of 'no effect' with the whole experiment being replicated at other cities.

The reviewer trusts the reader will understand that the list of recommendations, which is not exhaustive, is intended only to be indicative of directions to be followed, offered in the spirit of the legal method of 'raising reasonable doubt'. He trusts further that the reader will find the relationship between these suggested studies and the list of four characteristics offered earlier in this section to be clearly apparent; and that the reader will consider the suggested studies to be improvements over studies done in the past.

Appendix

The probability of 0.67 proposed with respect to the data in Table 3 was calculated in the following way. If the 12 values in quadrants other than upwind consist of $n_1 = 3$ being $\leqslant 0.1$, and $n_2 = 9$ being > 1.0, the number of permutations of the 12 are $(12!/3!\,9!) = 220$. There are three ways to fail to meet Braham's criterion:

1) Having an n_1 in exactly one downwind quadrant. This can happen in each of four ways for each of the three $n_1 = 12$ ways.
2) Having an n_1 in exactly two downwind quadrants. The number of possible pair sequences is the number of permutations of three things taken two at a time $= [3!/(3-2)!] = 6$; and the number ways to place those six pairs in downwind quadrants is the number of combinations of four things taken two at a time $= [4!/2!\,(4-2)!] = 6$; so the required number is $6 \times 6 = 36$ ways.
3) Having an n_1 in exactly three downwind quadrants. The number of possible ways to achieve this form of failure is the number of permutations of four things taken three at a time $= [4!/(4-3)!] = 24$ ways.

Thus, the number of ways to fail to meet Braham's criterion is $(12 + 36 + 24) = 72$; the number of ways to succeed in meeting Braham's criterion is $(220 - 72)$; and the probability of success is $(220 - 72)/220 = 0.67$.

Acknowledgements

The assistance of Dr Sara Pryor in carrying out the literature search referred to at the end of section II is acknowledged with thanks, as are the editorial reviews of the draft manuscript by my sons, Porter and Samuel. I am especially grateful for the encouragement and a constructive review by Professor T.R. Oke, who early on said to the writer 'You've convinced me it hasn't been done correctly. Now tell me what methods are correct.'

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