INDEXED
AP/WP/68.4
SEE ADD.
ENGLISH ONLY

WORLD HEALTH ORGANIZATION

ORGANISATION MONDIALE DE LA SANTÉ

WHO/WMO SYMPOSIUM ON URBAN CLIMATES
AND BUILDING CLIMATOLOGY

Brussels, 15-25 October 1968

The effects of air pollution on urban climates

by

Prof. Dr. Hans-Walter Georgii

University of Frankfurt (Germany)

Growing cities and growing industrial production lead necessarily to an increase of emissions - harmless and hazardous ones - into the atmosphere. The sources are stacks of industrial plants, domestic and community heating and the exhaust gases of automobiles. The gaseous and particulate components emitted into the atmosphere lead to a change of composition and transparency of the air over large parts of the world mainly over the large cities and by this a modification of nearly every element of the climate in these areas is constituted. Investigations started as early as thirty years ago by Linke (1) and Stummer (2) in Frankfurt show clearly the significance of change of climatic elements in cities, mainly of the following components:

1) the intensity of solar radiation
2) the range of visibility
3) the temperature-distribution
4) the relative humidity
5) the local wind-distribution
6) the distribution of precipitation

The growth of the cities leads furthermore to an increasing transformation of the natural country-side into a densely built-up area. This change of the natural topography influences the climatological elements in the city-area, particularly the temperature- and wind-distribution. We must be fully aware of the fact that the urban climate represents a special meso-climatological type of its own standing which is in most cases vastly different from the climatological conditions in the rural surroundings of the cities.

In discussing urban climates we have therefore to distinguish between 1) the modification of the climate by the accumulation of buildings (change of topography) and 2) the modification of the climate by urban air pollution. While earlier literature on this subject, as summarized for instance in Kratzers monography (3) predominantly deals with the influence of the increasing built-up areas, more recent investigations show the increasing influence of atmospheric pollution on urban climates.

Considering the sources of air pollution we see in Fig. 1 and Fig. 2 the increase of automobiles shown as a typical example in the case of the city of Frankfurt (Germany) and the heavy increase of industrial production which outnumbers the linear growth of population.

Urbanisation and industrialization are developments of the same origin, that is why the industrial potential of Europe is growing in conformity with the population density as was outlined recently by Roussel and Stephany (4). While the growth of population is more or less linear, the concentration of the population in cities leads to a progressive increasing population density in certain urban areas. As example may serve the increase and growth of large towns in Germany during the last 150 years.

The growing rate of pollutants emitted into the atmosphere combined with the influence of change of topography leads to an accumulation of trace-substances in the air over cities and frequently to the formation of haze. This haze-dome which builds up over densely populated areas is concentrated or dispersed according to rate of emissions, to the wind profile and the vertical temperature profile.

Aircraft ascents which were made by the author and his collaborators in the area over the industrial region of Mannheim - Ludwigshafen with SO_2 as tracer for pollution show very clearly that the direct influence of locally produced pollutants exceeds to an altitude of about 700 mtrs. above the industrial center. From a number of similar flights, see the example shown in Fig. 3, we could gain the result that the haze and dust-layer caused by pollutants accumulates in a layer rarely thicker than 1000 mtrs. above the ground but generally exceeding 500 mtrs. A second interesting example demonstrates the distribution of SO_2 above a city in 300 mtrs. altitude gained by cross-section flights with an automatic recording SO_2-instrument (see Fig. 4). This figure also shows very clearly that the concentration above urban and industrial areas is by an order of magnitude higher than above rural countryside. I want to stress this point particularly because the modification of the air layer above urban areas is responsible for climatic changes taking place near the ground.

Before going into details of the characteristic properties of urban climate, it is my pleasure and privilege to mention several very valuable investigations on this subject. Screening the scientific journals one finds that a great number of high authorities of our science have been attracted by the special features of urban climatology.

As a curiosity I wish to mention a memorandum by Mr. Franz Xaver Epp to the Bavarian Academy of Science dated 28 March 1787 in which the terrible smell and haze caused by the city of Munich is described and in which quite modern aspects of diffusion and of wash-out of pollutants are touched.

When discussing urban climatology from a more recent and modern point of view it may be appropriate to mention the monography by Kratzer (3), the very valuable studies by Landsberg (5, 6), papers by Emonds (7) and Kalb (8) on the climate of Bonn and Cologne and the very recent work by Chandler (9) on the climate of London, a masterpiece of skilful and careful research on the climatological properties of a large town. Only a short while ago the preprint of a paper by Clarke (10) on the nocturnal urban boundary layer over Cincinnati came to my knowledge which constitutes one of the very few three-dimensional investigations over cities, including vertical temperature soundings obtained by helicopter and pilot-balloon ascents.

Before going into details I think I should give a very brief information on the extend of air pollution in the atmospheric air above densely populated areas compared with the composition of the pure atmosphere.

Table 1 shows a comparison of the concentration of trace constituents in a pure and in a polluted atmosphere

trace component	pure atmosphere		polluted atmosphere	
particulate matter	0.01 - 0.02	mg/m^3	0.07 - 0.7	mg/m^3
sulfur dioxide	10^{-3} - 10^{-2}	ppm	0.02 - 2	ppm
carbon dioxide	310 - 330	ppm	350 - 700	ppm
carbon monoxide	<1	ppm	5 - 200	ppm
nitrogenoxides	10^{-3} - 10^{-2}	ppm	10^{-2} - 10^{-1}	ppm
total hydrocarbons	<1	ppm	1 - 20	ppm

Fig. 5 presents some information on the concentration of several gaseous traces in pure atmospheres compared with the polluted atmosphere of the city of Frankfurt/Main. The concentration in Frankfurt during winter was normalized to 1 and the concentrations found at the other locations given as percentages of this value. The absolute values in $\mu g/m^3$ are indicated in the different bars.

Fig. 6 shows the cummulative frequency distribution of concentration of particulate matter in U.S. cities of different size (I, II, III) compared with suburban areas (III a) and the surrounding country-side (IV).

The above mentioned modification of the composition of urban atmospheres leads to a considerable change of the radiation budget in densely populated areas. Taking the "Trübungsfaktor" according to Linke (11) as indicator for the grade of pollution which refers to turbidity by Rayleigh-scattering (a_R), by water-vapour absorption (Wa_w) and extinction of radiation by particulate matter (Sa_s)

$$T = \frac{a_R + Sa_s + Wa_w}{a_R}$$

we could find a value of 1 in a completely pure Rayleigh-atmosphere, higher values are proving a growing amount of trace-substances leading to a reduction of incoming direct and scattered solar radiation in the ground layer of the atmosphere. Measurements of the Linke-turbidity factor carried out in Vienna show an increase from values around 3 in the suburban areas of Vienna to 8 in center of the city. Average values of the turbidity factor according to Linke for Helsinki and Kew indicate the strong effect of the extinction of solar radiation by industrial activity in the case of Kew.

Table 2

	winter	spring	summer	fall	year
Helsinki	2.2	2.9	3.2	2.4	2.7
Kew	4.1	4.9	5.1	4.5	4.6

Besides the increase of turbidity of incoming radiation by atmospheric pollution one also finds a reduction in the duration of bright sunshine in large cities. Chandler (9) reports on a comparison of the length of sunshine at several stations around and in the center of London.

Averages of bright sunshine decrease considerably towards central London as indicated in Table 3.

Table 3 Averages of bright sunshine, London 1921 - 1950

hours per day

	Jan.	July	Year
surrounding country	1.7	6.6	4.3
outer suburbs	1.4	6.5	4.1
inner-high-level suburbs	1.3	6.3	4.0
inner-low-level suburbs	1.3	6.3	4.0
central London	0.8	6.2	3.6

The loss of sunshine in Central London is greatest during the winter months, when atmospheric pollution is heavy due to the high rate of emissions from domestic heating. It is evident that

the change of the radiation budget in large cities effects the temperature distribution compared to that of the country-side and is the cause for some of the specific characteristics of urban climate. It is furthermore evident that the effects of typical urban climate show an optimum under calm sunny weather conditions. We can therefore state that urban climate is a bright-weather-phenomenon producing the greatest difference to the surrounding country-side when the winds are calm and the sky cloudless. With respect to the reduction of incoming solar radiation due to the haze-dome above cities it is generally agreed by different authors (Linke, Berlyand etc.) that the decrease of direct solar radiation amounts to 10 - 20%, the decrease of scattered sky radiation however being less. Several authors emphazise particularly the reduction of the UV-component of solar radiation, a problem which is of special interest to physicians. It may not be wrong to use the term "UV-night" when discussing radiation problems in cities.
In this connection the investigations by Mc Cormick and Ludwig (12) deserve attention. Their paper presents evidence that the atmospheric transmission of the total solar radiation decreases with increasing turbidity. A study of turbidity-measurements made at Washington and Davos suggests a world-wide increase in turbidity over the past several decades. While the increase in Davos may be representative of the world-wide contamination of the atmosphere, part of the Washington increase is probably due to local increase in population and urbanisation. - There is no doubt that the turbidity-network operated in the U.S.A. at 35 stations provides highly valuable information on the total dust content of urban atmospheres and on its fluctuations.

There is no question that the visibility in cities is greatly reduced under certain conditions. Accumulation of condensation nuclei produced from many anthropogenous and industrial sources in and in the vicinity of cities lead to a decrease of visibility and often to the formation of fog. Evaluation of the smoke-concentration in London by S.R. Craxford and M.L. Weatherley (13) show clearly the increase of airborne pollutants towards the center of the city during winter months. Closely correlated to this increase of condensation products is an increase in the frequency of fog-occurrence as given by Chandler (9) showing that London as a whole has indeed more fog than the surrounding country. Also the number of days with good visibility is reduced in Central London compared with the suburbs. We want to mention that the frequency of fog-formation in urban environment is higher in spite of the fact that the air-temperature in cities is higher and the relative humidity is lower within the cities compared to the country-side. The explanation for this contradiction must be seen in the mechanism of fog-formation. High concentrations of sulfur dioxide, the formation of sulfuric acid by catalytic oxidation on the surface of particulate matter in a humid environment leads to the formation of small fog-droplets under conditions when in a pure atmosphere fog would not yet form. This has many unpleasant and dangerous consequences with respect to the harmfulness of urban fog, a problem which will be briefly discussed at the end of this paper.

In a recent investigation, Georgii and Hoffmann (14) have determined the correlation between SO_2-accumulation and visibility for the German cities of Gelsenkirchen and Hamburg. The results show that for the weather situation characterized by

1) inversion below 1000 mtrs.
2) ground level wind velocity below 3 m/s

it was found that 80% of all cases of excessive SO_2-concentration (excess of 90% of the cumulative frequency distribution for SO_2) occur at visibilities below 5 kms. and 50% of all cases at visibilities below 2 kms. This again shows the existence of a relation between air pollution and the meteorological element "visibility".

The most striking feature of the urban climate is most certainly the difference of temperature distribution to the rural surroundings of the cities. This so-called "heat-island"-effect, leading also to the city-own wind-field, has been investigated by many authors in a great number of cities. Again, the heat-island-effect is a bright-weather phenomenon, which is particularly effective in calm, clear nights. While the average temperature-difference between city and environment is only 1 to 1.5°C, the difference reaches its maximum during the night and according to our observations during May and June. This is very well demonstrated in Chandlers investigation of the London "heat-island". We find that in some instances the difference of the minimum-temperature can reach 6 to 7°C between suburbs and the center of London.

Measurements of the temperature distribution carried out by Stummer (2) some years ago show clearly the increase in temperature towards the center of the city of Frankfurt/Germany during calm, cloudless nights in spring. The temperature difference amounts in these cases to nearly 4°C (Fig. 7).

Fig. 8 shows the average diurnal trend of temperature measured in 2 mtrs. altitude during "radiation-days" in the center of Frankfurt/Main (Rathenauplatz) in summer and at the boundary of the city close to a large park (Feldbergstraße). While the average maximum temperature during the day shows not much difference between the two stations, there is considerable difference during the night with higher temperature in the center of the town, at the time of the minimum a difference of about 1.5°C is indicated. These findings are in good agreement with the extensive results gained by Chandler who found that the heat-islands of London, Manchester or Washington are strongest before dawn. We can conclude from these results that firstly the consumption of fuel which may supply energy equal to one third of the solar radiation falling on the city and secondly the solar energy stored during the day in the built-up part of the city which is slowly released into the atmosphere during the night are responsible for the urban temperature-pattern. Detailed information on the horizontal distribution of temperature across a city can be gained by temperature traverses as could be shown by Chandler (9) in London or by M. Kalb (8) in Cologne. These traverses project the urban pattern on the thermal structure. Details of the local urban morphology can be recognized very clearly in the temperature distribution. Without going into details of the great number of observations on the heat-island effect in different cities one can state the following causes for the development of the temperature-difference between city and rural surrounding:

1) thermal capacity of buildings
2) decrease of outgoing UR-radiation during the night due to increased amounts of pollution
3) heat contribution from the burning of various fuels

In agreement with Chandler (15) we share the opinion that differences in cloud amounts and fog frequencies are only of secondary importance and of occasional significance. Of great importance in connection with the accumulation and diffusion of pollutants is the thickness of the nocturnal heat island which, of course will vary in dependence of wind speed and lapse rate of temperature. As already mentioned very little detailed information is obtainable with respect to the vertical profile of the temperature-distribution over cities. Chandler assumes a thickness of about 50 to 150 mtrs. which is obviously in good agreement with Clarke's (10) direct measurements in Cincinnati. He reports on a pronounced modification of the vertical temperature structure. The vertical extend of this modification - he call it the "urban boundary layer", increases with downwind distance over the urban area. Depending of the temperature lapse rate Clarke found that the nocturnal boundary layer extends to an altitude of 300 mtrs. or even in some instances 400 mtrs. Clarke's study demonstrates a spatial variation of the temperature profiles within the boundary layer and consequently a spatial variation of the dispersion rate. Above the "heat plume" there exists preferably a stratified layer, the stability of which and the height of which depends mainly of the general weather pattern. Pollutants emitted from tall stacks into the stable layer above the boundary layer will experience little vertical dispersion and probably not reach the ground in the area of the "heat island". It would be very desirable to have more studies like this one carried out in cities with different topographic pattern. - One phenomenon which is closely connected with the reduced nightly minimum temperature in cities and the reduced number of nights with frost was observed by M. Kalb (8) while carrying out a phenological study in the city of Cologne. Miss Kalb made careful observations of the spatial distribution of apple-blossoms in Cologne. Due to higher temperatures in the center of city the number of apple-trees in blossom in relation to its total number increased from the suburbs towards the center of the city. The maximum with 50% of the trees in blossom close to the densely built-up city-area presents a remarkable progress of the development of the plants compared to the surrounding villages where only 10% of the apple-trees were in blossom at the same time. In more distant parts the blossoming period had not started at all. According to the knowledge of the author this study is a quite unique attempt to relate the effect of urban temperature-distribution to the development of vegetation. The "heat-island"-effect is also the main cause for the formation of an own urban circulation-system. But, as it is the case with respect to the temperature difference between city and surrounding country it also applies to the urban wind-system that its features are associated with low wind speed and with stable temperature lapse rate, that means predominantly with anticyclonic weather situations. From earlier measurements of the local wind-distribution in Frankfurt/Main we know that in calm cloudless nights there exists a convergence towards the center of the city reaching a wind-velocity up to 2 - 4 m/s. In accordance with Clarke's findings we can expect a vertical component above the city center and downward motion outside the heat island, thus closing the local circulation system. Naturally, the intensity of this convective cell will depend on the temperature-difference between surrounding area and city. Fig. 9 shows the influx of air near the ground in the city of Frankfurt in calm summer-nights. Besides the temperature difference, the overall wind speed and wind direction of the geostrophic wind is of importance for the formation of the urban circulation-system. As result of the studies in the city of Frankfurt it was found that geostrophic wind speed above 3 - 4 m/s near the ground prevents the formation of an own wind-system in the city. However, wind direction and wind speed are strongly influenced by the change of roughness when the air reaches the city. Nearly all meteorological stations in cities report reduced average wind speed and an increased number of days with calms. Fig. 10 shows an evaluation of the wind-field in Frankfurt/Main during a day with prevailing strong westerly winds. The wind direction is changed within the city and the wind speed is considerably reduced within the built-up area due to the increased roughness. The features of the wind-pattern of that particular day do not reveal an own urban circulation-system, rather a change of wind-velocity and wind direction. It is without doubt that the urban circulation-system is of great consequence for the dispersion and distribution of pollutants produced from sources in the city-area as outlined by M.E. Berlyand (16) in his report at this symposium. When we reduce our observations to the micrometeorological scale very interesting information can be gained on the distribution of pollutants in streets and on its dispersion in dependence of wind velocity and wind direction. Systematic measurements on the concentration of carbon monoxide emitted from automobiles in the city of Frankfurt/Main were performed by H.W. Georgii, E. Busch and E. Weber (17) in different levels above the street. Simultaneously, the wind velocity was measured at street and roof-level. The conclusions to be drawn from this investigation show a significant relation between the ventilation of the streets and wind speed and wind direction. As can be seen in Fig. 11 at wind-velocities below 2 m/s, ventilation is very poor, fresh air entering the space between buildings from above does not reach the street-level, the CO-vertical distribution shows considerable decrease with altitude. It requires a wind speed above 2 m/s (lower part of Fig. 11) for the vortex forming within the street to reach street-level but also then a great difference of the rate of ventilation is observed between the windward-side and the lee-side of the street. This effect produces a horizontal gradient of carbon monoxide across the street. Complete ventilation of the street and dispersion of the pollutants produced from low sources in the street require a wind-velocity of 5 m/s and above. Besides, the accumulation of pollutions in streets depends also on height of buildings and the width of the street. Generally the importance of wind-velocity in cities on the dispersion of pollutants is predominant. Low wind-velocity leads to an accumulation of pollutants in the air of cities as can be seen in Fig. 12 demonstrating the strong increase of CO with decreasing wind speed according to recent measurements in Frankfurt/Main. It should be stressed that new methods and techniques permit the use of tracers - as in this case the carbon monoxide - to study the circulation system in cities and streets and that the application of tracer-techniques will certainly deepen our understanding for small-scale circulation patterns.

Concluding we may state that the city as multifold source of pollutants and as obstacle to dispersion and transport of pollutants from the source increases the danger of an accumulation of hazardous and noxious components. Unfortunately, little information is available on the effect of urban climate on man. Apart from cases of smog disasters which have been widely dealt with in the literature - we have to mention in this context the 1952 smog episode in London and the 1962 smog episode which lasted for several days over large parts of Western and Central Europe - there seems to be general agreement that the increased concentration of pollutants in city air constitutes a hazard to respiratory diseases. In this connection the work by J. Lawther (18) on the urban factor on bronchitis and lung cancer deserves special mentioning. While eye-irridation is a common attribute of the photochemical smog in Los Angeles nevertheless, Los Angeles air pollution has so far not been reported to have shown any direct adverse effects on human health. In many countries and in many cities all over the world, simultaneous investigations of air pollutants and epidemiological studies are forthcoming which will supply an increasing amount of information. We hope that one consequence of these studies will be that in spite of the rapidly growing population in our cities the level of air pollution will not only be kept from rising but gradually reduced to our all benefit.

REFERENCES

(1) Linke, F. — Das Klima der Großstadt in: Biologie der Großstadt, Verlag Th. Steinkopff, Leipzig 1940, p. 75-90

(2) Stummer, G. — Klimatische Untersuchungen in Frankfurt/M. und seinen Vororten in: Ber. Met. Geophys. Inst. U. Frankfurt, Nr. 5, 1939

(3) Kratzer, A. — Das Stadtklima Verlag F. Vieweg & Sohn, Braunschweig 1956

(4) Stephany, H. and Roussel, A. A. — World Review on air pollution: Europe Proc. Internat. Clean Air Congress London 1966, p. 25

(5) Landsberg, H. — Air Pollution and Urban Climate in: Biometeorology II, Pergamon Press, 1966, p. 648

(6) Landsberg, H. — The climate of towns in: W.L. Thomas: Man's Role in changing the face of the earth University of Chicago Press 1956, p. 584

(7) Emonds, H. — Das Bonner Stadtklima Arbeiten zur Rheinischen Landeskunde, Bonn, Heft 7, 1954

(8) Kalb, M. — Einige Beiträge zum Stadtklima von Köln, Met. Rdsch. 15, 1962, P. 92

(9) Chandler, T.J. — The climate of London Hutchinson & Co, London 1965

(10) Clarke, J.F. — The nocturnal boundary layer over Cincinnati, Ohio Manuscript 1968

(11) Linke, F. — Die Sonnenstrahlung und ihre Schwächung in der Atmosphäre Handbuch der Geophys. 8, 1942, p. 239

(12) Mc Cormick, R.A. and Ludwig, J.H. — Climate Modification by Atmospheric Aerosols Science 156, 1967, p. 1358

(13) Craxford, S.R. and Weatherley, M.L. — Air Pollution and town planning Nat. Soc. for Clean Air, Oct. 1964

(14) Georgii, H.W. and Hoffmann, L. — Beurteilung von SO_2-Anreicherungen in Abhängigkeit von meteorologischen Einflußgrößen Staub 26, 1966, p. 511

(15) Chandler, T.J. — Night-time temperatures in relation to Leicester's urban form Met. Mag. 96, 1967, p. 244

(16) Berlyand, M.E. — Meteorological factors in the dispersion of air pollutants in town conditions Manuscript, WHO Symposium on urban climates, Brussels 1968

(17) Georgii, H.W., Busch, E. and Weber, E. — Untersuchung über die zeitliche und räumliche Verteilung der Immissionskonzentration des Kohlenmonoxid in Frankfurt/Main Ber. Inst. f. Met. u. Geophys. Univ. Frankfurt Nr. 11, 1967

(18) Lawther, P.J. — Air Pollution, Bronchitis and Lung Cancer Postgrad. Md. 42, 1966, p. 703