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The Occurrence and Effectiveness of Country Breezes by Means of Wind Tunnel and In Situ-Measurements

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1. INTRODUCTION

The country breeze is a thermally induced local wind system. The pressure gradient between a city and its rural environment necessary to create this wind system is based on an imbalance of the energy budget which gains crucial proportions at times of a low overlying wind regime and high radiation.

Country breezes are best described as intermittent slow near-ground flows of air which - in the ideal case - are directed centripetally from all sides towards the city center. The existence of such country breezes has been acknowledged for a long time[1], however, few studies have been conducted to examine either the frequency of occurrence or the parameters determining the depth of intrusion into urban areas.

Based on field experiments and wind tunnel studies, this paper provides answers to many questions in these fields of interest.

2. PROPERTIES OF COUNTRY BREEZES

Concerning the improvement of the bioclimatological situation within a city, country breezes may contribute in two ways: First, the influx of relatively cool air from the rural environment eases the urban heat island and second, downtown air quality is improved as long as pollutants are not previously incorporated into the incoming air.

The intensity and frequency of occurrence of country breezes vary with the time of day and are observed alternately within the UCL (Urban Canopy Layer) and the UBL (Urban Boundary Layer). In the daytime, country breezes which were detached from the ground and located around roof level were verified[2,3], due to the fact that surfaces and air temperatures around roof level are highest in the daytime thus creating unstable atmospheric conditions at that height. Since this "daytime" country breeze does not extend to the bottom of the street canyons it contributes little to ventilation.

However, differences in air temperature between the street canyons and the surrounding rural areas are best developed at night. The radiative loss of heat creates a temperature inversion above rural surfaces at night, whereas the soil heat flux is still warming up the air above urban surfaces. Consequently, a forced exchange of momentum allows for wind velocities measured in cities to be equal or even to exceed those registered in the countryside[4,5,6]. The "nightly" country breeze, therefore, promises the greatest contribution to the betterment of the urban bioclimate. Henceforth, discussion in this paper will be limited to this part of the phenomenon.

Studies on the frequency of occurrence of country breezes confirm their dependence on a thermal imbalance[7,8]. The increment in the frequency of country breeze events by an increasing temperature gradient becomes obvious when correlating the number of hours with country breeze registrations and the difference in temperature between urban and rural sites[9]. In the daytime, differences in air temperatures measured in the UCL and in surrounding rural areas are rather small, thus explaining the minimum of detected ground-level country breeze events (Figure 1). Figure 1 also shows that in the early morning hours (1-6 AM), the formation of country breezes is apparently more frequent than in the late evening hours (8-12 PM). The number of events, for example, registered at 9 PM amounts to only about half of those registered at 5 AM - an observation which leads to the conclusion that not only a difference in temperature but also the built-up of a cold air layer around the city, which reaches its maximum thickness in the early morning hours, might create a surge effect causing an increased flow of air into the neighboring urban settlements.

These measurements prove the existence of country breezes at times of highest thermal discomfort and give reason to expect a significant contribution to the improvement of the urban climate and air quality by this wind system. There is, however, a lack of quantitative data on the dimensions of this phenomenon in time and space, as well as to which extent urban structures hinder this flow of air from penetrating into the city.

3. DISCUSSION OF THE CHARACTERISTICS OF COUNTRY BREEZES

3.1 Methods

This paper presents an analysis of continuously recorded wind data at five stations over a period of 16 months (May 1987-August 1988) in the city of Bochum, Germany. The wind registration devices, installed at a height of four meters, were arranged in a circle around the city center and in supposedly effective ventilation aisles. Data were recorded on an hourly basis. Country breeze conditions were assumed to exist if:

- two paired stations both recorded air flows from the semicircle bisected by the center-to-station line towards the city center
- the difference in the directions of winds entering the semicircle was at least 50 degrees (Figure 2)
- the wind speed at the two stations was below 2 m s^{-1}.

The measuring stations (MS) were further characterized by the following topographical features: MS 1 was located on a slightly elevated open field, MS 2 beside a railway track, MS 3 in an open field, MS 4 and MS 5 in green aisles.

Data from each station was compared with respective data from a station located beyond the city center which lead to a system of following data pairs: MS 1 and MS 3, MS 1 and MS 4, MS 2 and MS 4, MS 2 and MS 5, MS 3 and MS 5.

3.2 Results

Country breeze conditions were prevailing during 1186 hours or 10.1% of the total measurement period. They can be accounted for 18.5% of the total period during which the average wind speed measured at the five stations was below 2 m s^{-1}. The analysis of the data also confirmed a diurnal pattern with a higher frequency of country breeze events at night compared to daytime. Furthermore, an annual variation was verified[13]. Country breezes occur about three times more frequently in summer than in winter, a fact likely to be explained by the higher temperature difference between the UCL and its rural environment in summer as compared to winter[10].

The influence of the ventilation aisles (stations 2, 4, and 5), in regard to a stabilization of the distribution of wind direction, is seen in Figure 3. Stations 1 and 3, which were operated on a rather open location, show a comparatively wider distribution. This observation allows for the conclusion that ventilation aisles directed towards the city center enhance the ventilation effect, especially at times of otherwise low flow velocities.

In order to substantiate the air exchange conditions within a city, it is important to know from which directions the country breezes are simultaneously developing. Table 1 provides a general idea on the hourly distribution at the respective station pairs. During certain periods of time, country breeze events were not only observed at one station pair, but also at two pairs (72%), three pairs (20%), four (3%) and five pairs (<1%) (Table 2).

The results presented by the Bochum study verify the value of country breezes to city planning. Many cities could benefit by adequate provisions such as incorporation of ventilation aisles when planning new suburbs.

At this stage, the quantitative determination of the depth of intrusion of country breezes into urban areas remains unanswered.

4. SIMULATION OF COUNTRY BREEZES IN A GRAVITY WIND TUNNEL

Investigations in a wind tunnel offer reliable solutions to questions regarding the depth of intrusion of country breezes into developed areas. This is due to the fact that corresponding wind and immission fields for complex geometrical boundary conditions, which occur in urban areas, can accurately be simulated in a boundary layer wind tunnel. This method is documented in examples about dispersions of automobile exhaust[11,12]. The simulation of nonadiabatic atmospheric boundary layer flows has not yet been fully developed. This publication introduces a method, that demonstrates how a nonneutral local wind problem can be simulated by a physical model and transferred to a real country breeze event. For this reason, a thermal generated gravity wind tunnel has been developed in Bochum.

4.1 Theoretical Aspects

The physical basics of the problem are formulated in the aerodynamical transport equations for mass, momentum and heat as well as, the equation of state for ideal gases. The analogous relation between the natural and the model flow can be described by means of similarity mechanics. Likewise, similarity mechanics defines the laws of how to model the problem. The system invariance of dimensionless transport equations is an essential element of the similarity theory. This means, the transport equations of aerodynamics deliver the same dimensionless solutions for the natural flow processes and similar events in the model if the transport equations are rendered dimensionless themselves.

The basic equations are transformed into the dimensionless form via scale analysis. By scaling the problem, the transport equations can be reduced to their essential terms and the order of magnitude can be objectively estimated. The relevant terms in the system of the transport equations are determined through further omission.

The main groups of scaling are macro, meso and micro scale. Transport processes which appear in the micro scale can be modeled in the wind tunnel. The micro scale is divided into small scale for movements of the order < 100 m and the convective scale for movements > 100 m and < 10 km. A typical local wind system like the country breeze, appears in the lower part of the meso scale and in the micro scale where events in both the small and the convective scale are important.

It is sensible to scale the horizontal occurrences of the local wind system in a convective scale and the vertical occurrences in a small scale. Therefore, the essential characteristic parameters which result from the physical process of the flow have to be known in advance.

After the country breeze has evolved, a cold air layer of thickness d is formed and moves into a region, depending on the difference in air pressure and the roughness of the terrain. With the increasing depth of intrusion, the air layer warms up until it reaches the ambient temperature. In the gravity wind tunnel, it was also observed that the cold air stratifies above the air near the ground and partly avoids the rise of the warm air. Under these conditions, the buoyancy forced convection begins after a few hundred meters.

With the thickness of the layer d, the temperature difference $(\Delta T)_0$ on the ground and the velocity of the cold air U, a Froude number, as a decisive similarity number, can be derived from the momentum flux equation.

$$Fr = \frac{\overline{U}}{[g \cdot d \, (\Delta T)_0 \, / \, T_\infty]^{1/2}} \qquad \text{Equation 1}$$

In proof of the depth of intrusion and the determination of the thickness of the streaming country breeze in the gravity wind tunnel by means of a tracer gas, the transmission number, as an additional dimensionless number, is derived from the mass transport equation.

$$f^* = 10^9 \, \frac{C \cdot U \cdot d \cdot b}{\dot{Q}} \qquad \text{Equation 2}$$

The Froude number (Equation 1) describes the ratio of the inertial force to the buoyancy or to the gravitational force, respectively. The scale analysis has demonstrated the buoyancy as the dominant term. For the country breeze in nature to be similar to the flow in the wind tunnel, the Froude number in nature and in the prototype have to be identical.

The transmission number includes the validity of mass conservation in nature and in the model. It must have the same value in both systems.

4.2 Natural Conditions

To answer the questions if and to what extent cold air from a cold air region, separated from the urban area by a river, penetrates into that area, in situ measurements have been carried out in the city of Duisburg, Germany. Figure 4 depicts the investigation area. The in situ measurements included temperature profile measurements and SF_6-tracer measurements. For the tracer measurements on the night of August 3, 1990, a continuous tracer flow was released into the atmosphere for about 4 hours from an open field on the Rhine River bank. The tracer was followed by measuring devices on the opposite side, in order to ascertain the transmission direction, the duration, and the velocity of the air movements. During the night of measurement, the temperature profile measurements resulted in maximum temperature differences of 6 K between the cold air producing area on the left side of the Rhine and the urban area, located on the right side of the Rhine.

A flow with a velocity of 0.34 m/s appeared to be directed to the housing area. The thickness of the flow layer was scaled identically to the one measured in the wind tunnel lacking a vertical probing during the measurement night. According to Equation 1, a Froude number of 0.17 results in these conditions.

4.3 Methods of Wind Tunnel Analysis

The experimental conditions, necessary for the simulation of the country breeze, are derived from the requirement that the Froude number in the model and in nature have to be identical. The investigation area was, therefore, modeled in the scale 1 : 800. The housing area itself was modeled particularyly in aluminium since the surface had to take temperatures up to 700 K. The surface was heated differently in destinct sections in order to carry out a scaled simulation of the temperature differences within the housing area. To simulate the cold air production, the replicated open field area on the left side of the Rhine was cooled down to nearly 80 K using liquid nitrogen. The housing area, the highway, and the densely wooded area located on the left side of the Rhine which contributed minor to the cold air production in nature were not directly cooled. The temperatures in these areas reached approximately 270 K. Altogether an area of about 4 km in length and 1.4 km in width, was modeled.

Figure 4 shows the investigation area which is divided into a matrix from A 1 to N 45. A frame with 100 m squares results. The letters denote the coordinates from south to north and the numbers from west to east. The west-east-axis is parallel to the wind tunnel axis.

After adjusting the temperature differences, a gravity induced flow is actuated, essentially directed from west to east. This flow can be modified by varying the temperature differences. In order to reach the Froude number given by nature, a surface temperature of 80 K on the cooled side and about 630 K at the warmest point are required. For these conditions, horizontal and vertical temperature profiles are measured and tracer measurements are carried out to estimate the flow velocity and the depth of intrusion of the country breeze in the modeled housing area on the right side of the river. The temperatures were measured in nine altitude sections including the surface by thermo couples at the points marked by circles in Figure 4. For the tracer experiments in the wind tunnel in the area of the open field, a point source with a tracer containing propane was modeled. This area corresponds to the area in nature which cools down the most, reaching the lowest termperature during the night. From this place, tracer pulses with different pulse durations were injected. At the points in the housing area marked by the crosses in Figure 4, tracer signals are measured with a high frequency flame ionization detector (FID) in three different altitude sections. The concentration measurements have a temporal resolution of 3 ms which is approximately 2.5 s in the natural scale. On the basis of the concentration measurements, the depth of intrusion of the country breeze into the housing area and the thickness of the cold air layer can be estimated. With two FID located in succession, the velocity of the cold air flow can be derived from the distance between the two probes and the transit time difference.

4.4 Results of Modeling the Country Breeze

The initial information is taken from the progress of the temperature profiles. Figure 5 represents instantaneous temperature profiles for two lateral sections as measured in the wind tunnel and are used to analyse some structures of the flow. In a height between 25 and 35 mm, a mixed layer of nearly 10 mm is formed. The lower cold air layer is limited by the mixed layer. Temperature profiles can be calculated to profiles in the natural scale by the equivalent:

$$\left[\frac{T_W - T}{T_W - T_\infty}\right]_{\text{Model}} = \left[\frac{\Theta_W - \Theta}{\Theta_W - \Theta_\infty}\right]_{\text{Nature}} \qquad \text{Equation 3}$$

Figure 6 shows examples of temperature profiles in a steady state flow at lateral sections G and J. This represents a mean of the flow for the duration of a cold air bubble (in general several bubbles). The originally stable stratification labilizes with increasing depth of intrusion. The depth of intrusion of the cold air can be accurately determined by means of presenting the transmission profiles (see Equation 2) as a function of the distance from the Rhine bank. For cross section G, Figure 7 documents that the distance does not exceed 800 m. In reality, the modeled country breeze does not penetrate at any point further than 1100 m from the bank on the right side of the Rhine into the suburb. Therefore, the breeze is not relevant for ventilation of the Duisburg city center, which lies about 4.5 km from the Rhine River bank. The depth of intrusion was even smaller, as stated in tracer measurements in nature. This can easily be explained by transferring the flow velocity initiated in the gravity wind tunnel to nature. At first the flow velocity in the model has to be determined by measuring the transit time of the tracer pulses. Furthermore, the thickness of the country breeze layer can be derived from the altitude profiles of the model tracer measurements (see Figure 8) and is 20 m on the average in the natural scale. With these quantities measured in the model, Equation 1 yields a Froude number of approximately 0.85, which corresponds to a flow velocity of 1.7 m/s in the natural scale. This velocity could probably be reached in reality if a stationary cold air flow would evolve as it did in the model experiment, i. e., if an ideal cold air reservoir was present. The depth of intrusion proven in the wind tunnel with a flow velocity of 1.7 m/s, therefore, could only be reached if the open field on left side of the Rhine represents an ideal cold air reservoir.

The investigation indicates the possibility of simulating country breezes in a gravity wind tunnel. The simulation of short-term nonstationary country breezes will be one of the next phases of development which allows for less conservative statements. During the next stage of development, the size of the area of measurement will be enlarged to investigation regions up to 4 km lateral to the main flow direction to permit the simulation of larger scale lateral drifts in the future.

5. CONCLUSIONS

Since country breezes were not only prevailing during 10% of the total measuring period but also during 18% of the time with low overlying winds in the UCL, their importance for city planing in Bochum was corroborated. A thermally induced convergent influx of air into urban areas was displayed for 10% of the time at one pair of stations and for 7% at two pairs of stations, respectively. Unless there are ventilation aisles, the studies on the depth of intrusion by wind tunnel and in-situ measurements in the city of Duisburg revealed that country breezes do not have a striking extension into urban structures and, therefore, do not contribute significantly to either air quality in the UCL or the reduction of the urban heat island.

Based on the results introduced in this paper and[6], Table 3 provides an overview of the major types of urban ventilation aisles and parameters which exert influence on the development of the country breeze.

NOMENCLATURE

$\overline{U}$	flow velocity of cold air towards the developed area [m/s]
T_∞	temperature in a great distance from the ground [K]
Θ	potential temperature [K]
Θ_∞	potential temperature in a great distance from the ground [K]
$(\Delta T)_0$	temperature difference on the ground between an open field and an urban area [K]
g	gravitational acceleration = 9.81 m/s^2
d	thickness of a cold air layer flowing towards an urban area [m]
C	local tracer concentration [$\mu g/m^3$]
b	lateral width of a cold air layer [m]
$\dot{Q}$	source strength of a tracer [kg/s]
Fr	Froude number

f^*	transmission function
w	reference value on the floor

6. REFERENCES

1 A. Carpenter, London fog inquiry 1901-1902, London, 1903.

2 J.H. Shreffler, "Detection of centripetal heat island circulations from tower data in St. Louis," Bound. Lay. Met. 15, 1978, pp 229-242.

3 J.H. Shreffler, "Heat island convergence in St. Louis during calm periods," J. of Appl. Met. 18, 1979, pp 1512-1520.

4 T.J. Chandler, The climate of London, Hutchinson, London, 1965.

5 R.D. Bornstein, "Observation of the urban heat island effect in New York City," J. of Appl. Met. 7, 1968, pp 575-582.

6 W. Beckröge, "Dreidimensionaler Aufbau der städtischen Wärmeinsel am Beispiel der Stadt Dortmund," Materialien zur Raumordnung, Band XLI, 1990.

7 D. Klaus, W. Lauer, E. Jauregui, "Schadstoffbelastung und Klima in Mexiko Stadt," Abhandlungen der mathematischen naturwissenschaftlichen Klasse 5, Akademie der Wissenschaften und Literatur, XXX., 1989.

8 P. Stock, W. Beckröge, O. Kiese, W. Kuttler, H. Lüftner, Klimaanalyse Stadt Dortmund, Planungshefte Ruhrgebiet P0 18, Kommunalverband Ruhrgebiet, Essen, 1986.

9 W. Kuttler, "Planungsrelevante Stadtklimatologie," Mitteilungen der Deutschen Meteorologischen Gesellschaft 4, 1988, pp 23-28.

10 W. Kuttler, "Spatial and temporal structures of the urban climate - a survey", Environmental meteorology, L. Grefen und J. Löbel, Eds., Kluwer, Amsterdam, 1988, pp 305-333.

11 E. Romberg, "Wind tunnel studies on the effect of traffic, pollution protecting hedges and structures on the diffusion of exhaust gases on roads," in Proceedings of the 1988 International Road and Traffic Conference on Roads and Traffic 2000, Vol. 5, Road and Transportation Research Association, Berlin 1988, pp 53-58.

12 E. Romberg, H.-J. Niemann, Windkanaluntersuchungen über die Ausbreitung von Abgasen an Hochleistungsstraßen, Abgasimmissionsbelastungen durch den Kfz-Verkehr", Fachgespräch am 24. Februar 1987 im Umweltbundesamt, Texte Umweltbundesamt, Berlin, 1988, pp 137-177.

13 A.-B. Barlag, W. Kuttler, "The significance of country breezes for urban planning," Energy and buildings, 15-16, 1991, pp 291-297.

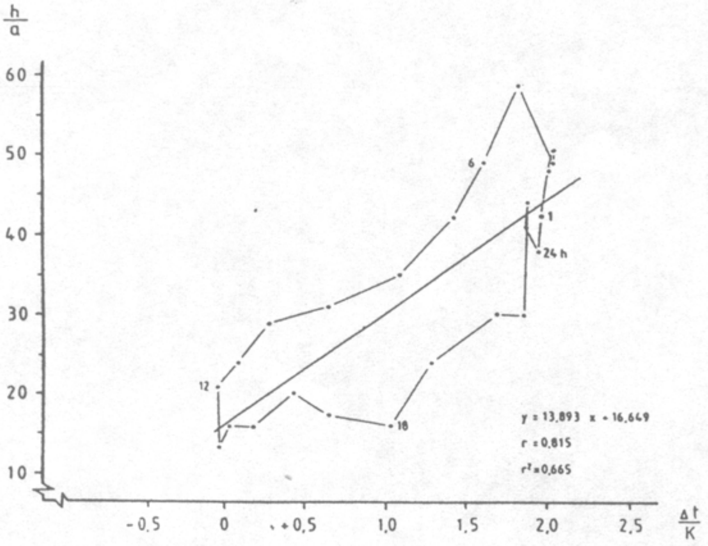

FIGURE 1. Dependence of country breeze hours on the heat island intensity in the city of Dortmund (measuring period from January to December, 1985)[9].

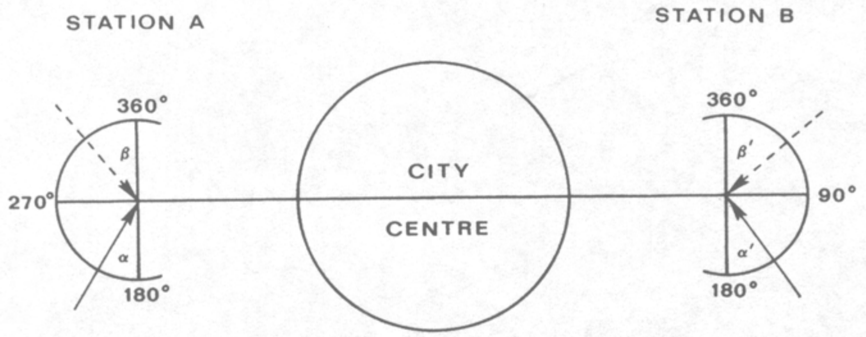

FIGURE 2. Illustration of the minimum requirements for depicting a country breeze: The angles α, α' and ß, ß' representing the wind direction at stations A and B (pair of stations) toward the city (semicircle) ~~may not~~ exceed 50°.

must

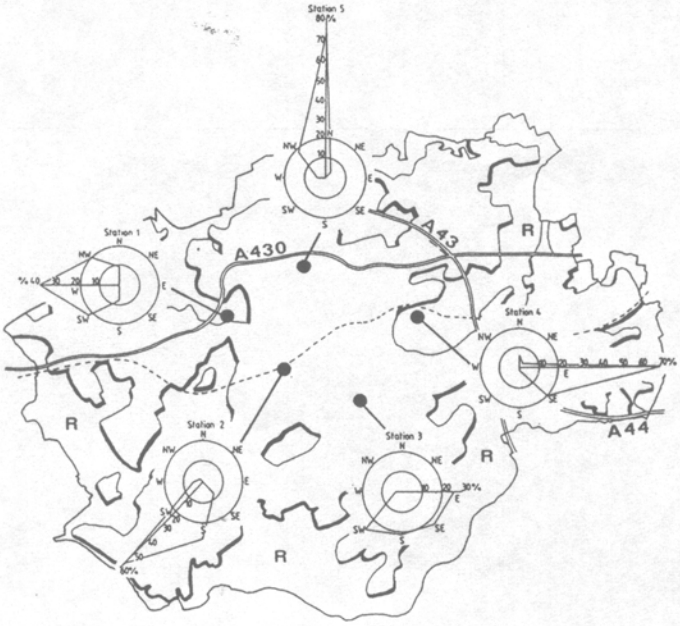

FIGURE 3. Country breeze distribution in the city of Bochum (measuring period from May 1987 to August 1988)[13].

TABLE 1. Total number of country breeze hours (measuring period from May 1987 to August 1988)[13].

Station pair	Country breeze hours (h)	Part of total time (%)
Total	1186	10.1
1/4	200	1.7
2/4	451	3.8
3/5	325	2.8
2/5	394	3.4
1/3	194	1.7

TABLE 2. Simultaneous registration of country breezes at several station pairs (measuring period from May 1987 to August 1988)[13].

Number of stations pairs	Country breeze hours (h)	Part of total time (%)
At least 1	1186	100
At least 2	766	72
At least 3	234	20
At least 4	39	3
5	8	>1

TABLE 3. Aisles for country breezes and their applicability to fresh air transport.

1. MAIN TRAFFIC ROUTES

- low z_0-values
- in the daytime strong warming up
  - unstable lapse rate near the ground
  - increasing frictional resistance
- at night relatively warm
  - neutral/unstable lapse rate near the ground
  - increasing frictional resistance
- exhausts by motor vehicles (depending on the volume of traffic high in the daytime and relatively low at night)
- preload by surrounding domestic fuel emissions

Valuation: Restricted utilization; necessity to analyse the air quality particularly within the street canyons. Improvements of air quality by traffic routes are not expected.

2. RAILWAY TRACKS

- low z_0-values
- in the daytime warming up
  - unstable lapse rate near the ground
  - increasing frictional resistance
- at night cooling down of the ballast surface
  - neutral/stable lapse rate near the ground
  - small frictional resistance
- unless there are no diesel engines running there are no emissions to be expected

Valuation: Utilization only recommended in case of no diesel engine running. Significant improvements of air quality are not expected.

3. GREEN AISLES/PUBLIC PARKS

- z_0-value depends on the nature of the vegetation (height, density, etc.)
- in the daytime hardly warming up
  - stabilization of the air layers near the ground
  - reduced frictional resistance (dep. on the nature of the vegetation)
- at night cooling down
  - stabilization of the air layers near the ground
- development of small scale circulations possible
- no release of emissions
- filtering aerosols and gases

Valuation: Utilization recommended. An improvement of air quality is expected.

4. RIVERS AND URBAN WATERS

- very low z_0-values
- in the daytime hardly warming up
  - stabilization of the air layers near the ground
  - reduction of the low frictional resistance
- development of small scale circulations possible (city-/waterwindsystem resp. city-/riverwindsystem)
- no release of emissions
- absorber for atmospheric gases and aerosols

Valuation: Utilization recommended. An improvement of air quality is expected: the thermal effect, however, is reduced because of the relatively warm waterbody at night.

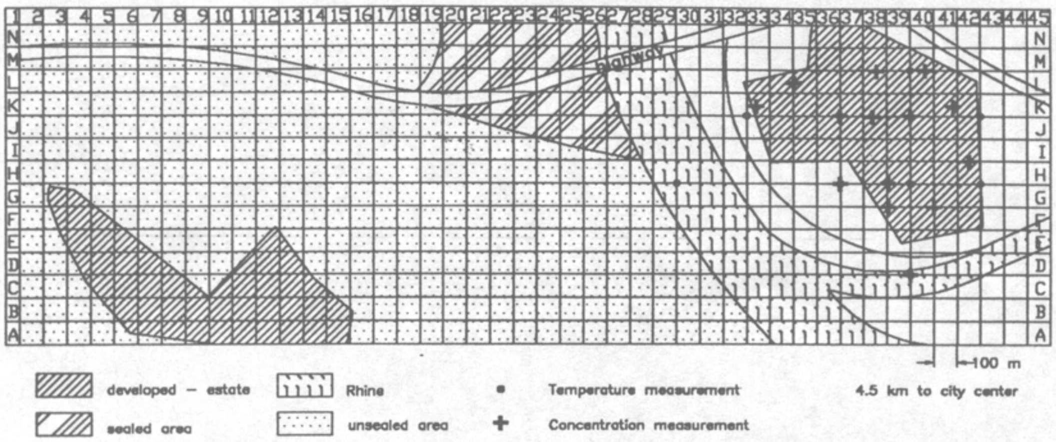

FIGURE 4. Map of the wind tunnel investigation area with measuring points (located near the city of Duisburg, Germany).

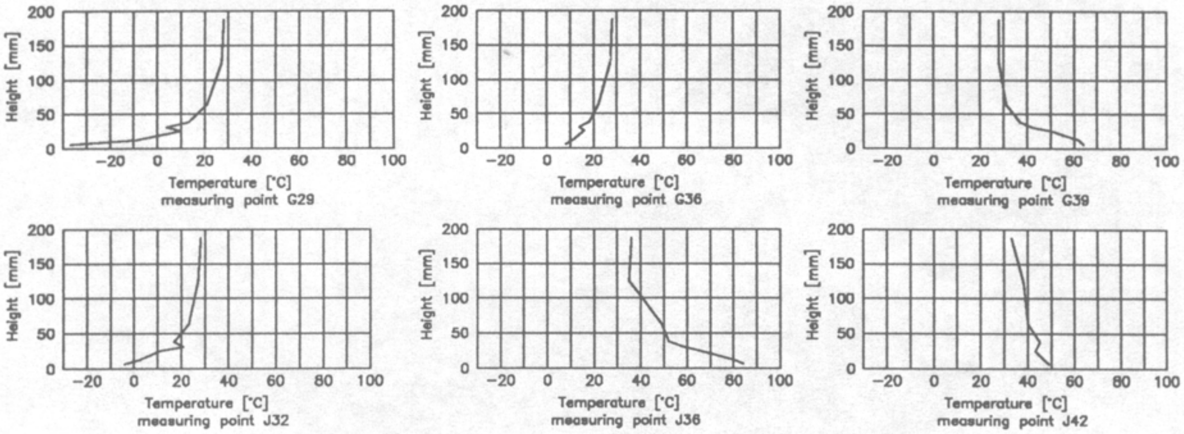

FIGURE 5. Temperature profiles measured in the wind tunnel.

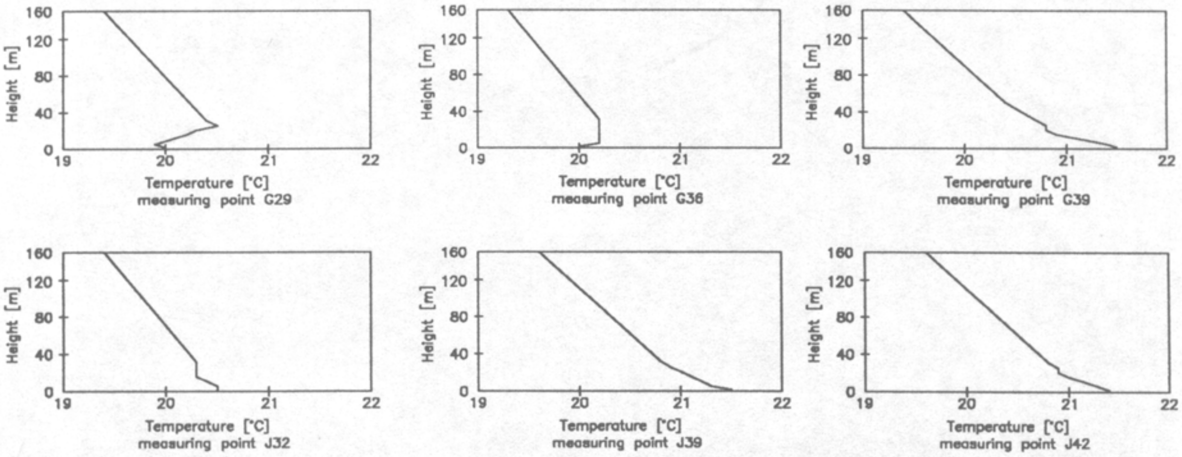

FIGURE 6. Temperature profiles measured in the wind tunnel and transferred to nature.

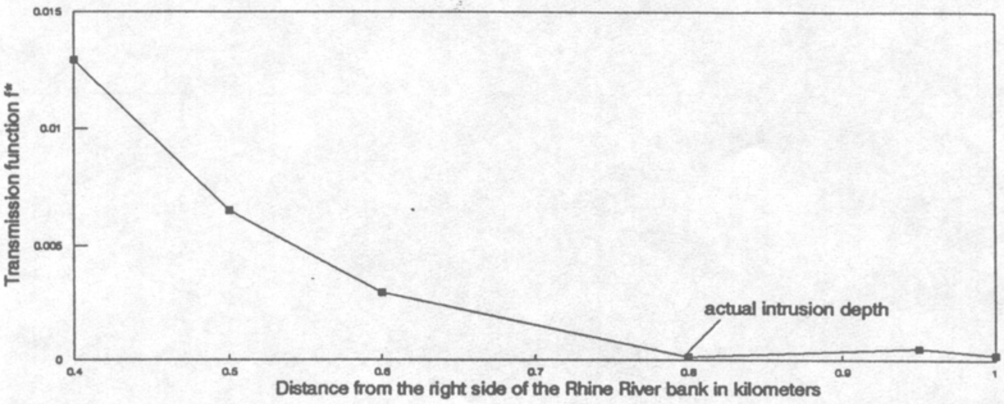

FIGURE 7. Transmission profiles for cold air intrusion at cross section G.

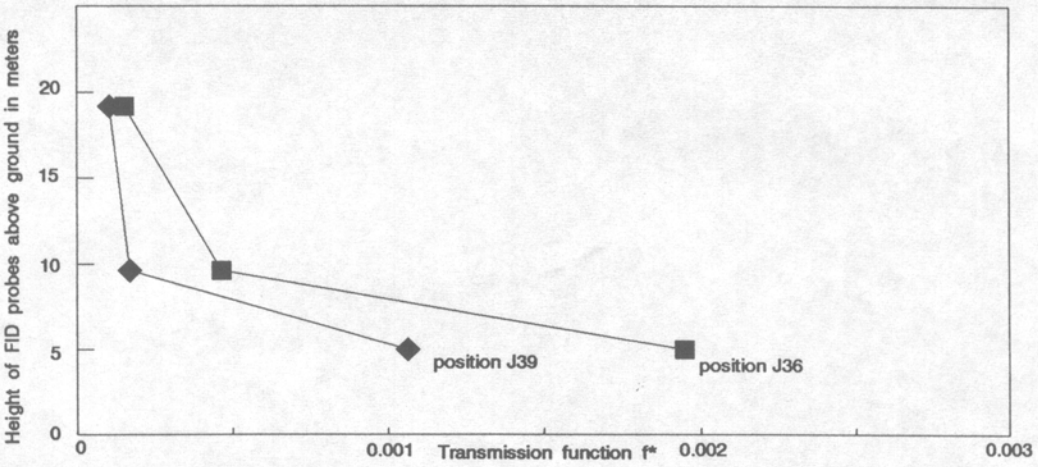

FIGURE 8. Altitude profiles of cold air transmission.