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Influence of regional and local winds on urban ventilation in Cologne, Germany

W. KUTTLER, D. DÜTEMEYER, A.-B. BARLAG, Essen

Summary. This study examines the influence of regional and local winds on urban ventilation during clear and calm summer nights with low exchange weather conditions, taking the city of Cologne in the Cologne Bay (Germany) as an example. Results of this study on cold air penetration in the city show a sensitive interaction between the structure and direction of open rural areas and the temporal pattern of local cold air movement and regional wind. During the first half of calm summer nights, directly linked ventilation areas are unable to ensure the horizontal exchange of locally formed cold air between the surrounding countryside and the urban area as a result of the long distance from the city centre and large obstacles obstructing the ventilation areas. Time-scale analyses of the wind field carried out at nine meteorological stations show that the ventilation areas function independently from each other. In rural ventilation areas a flow of cold air from neighbouring slopes is observed during the whole night. During the second half of calm summer nights, the wind direction in the ventilation areas follows a path running downstream parallel to the River Rhine, caused by advected cold air formed and accumulated in the upstream section of the Cologne Bay. Advected cold air is superimposed on microscale circulation of cold air in the ventilation areas, allowing a horizintal transport of air from the surrounding countryside into the city. Depending on the direction and extent of the ventilation areas, regional wind can strengthen or replace the local air transport in the city of Cologne.

Einfluß regionaler und lokaler Winde auf die städtische Belüftung von Köln

Zusammenfassung. Diese Studie untersucht den Einfluß regionaler und lokaler Winde auf die städtische Belüftung während austauscharmer Sommernächte am Beispiel der Stadt Köln. Ergebnisse dieser Untersuchung zur Kaltluftversorgung der Stadt zeigen eine empfindliche Wechselwirkung zwischen der Struktur und Ausrichtung von Umlandfreiflächen und dem zeitlichen Muster lokaler Kaltluftbewegungen und regionalem Wind. Während der ersten Hälfte windschwacher Sommernächte wird ein horizontaler Austausch lokal gebildeter Kaltluft zwischen Umland und Stadt über direkt aneinandergrenzende Ventilationsflächen durch die große Innenstadtentfernung und Querhindernisse verhindert. Zeitreihenanalysen des Windfeldes an neun meteorologischen Stationen zeigen eine funktionale Unabhängigkeit der Ventilationsflächen. In den Ventilationsflächen des Umlandes werden während der ganzen Nacht Kaltluftabflüsse von angrenzenden Hängen beobachtet. In der zweiten Hälfte windschwacher Sommernächte folgt die Windrichtung in den Ventilationsflächen einer rheinparallelen, flußabwärts gerichteten Strömung, verursacht durch advehierte Kaltluft, die in flußaufwärts liegenden Teilen der Kölner Bucht gebildet und akkumuliert wurde. Die die mikroskalige Luftzirkulation in den Ventilationsflächen überlagernde advehierte Kaltluft ermöglicht einen horizontalen Lufttransport vom Umland in die Innenstadt. In Abhängigkeit von der Ausrichtung und Ausdehnung der Ventilationsflächen kann der regionale Wind den lokalen Kaltlufttransport nach Köln hinein verstärken oder ersetzen.

1. Introduction

One of the most serious problems in urban climatology, along with urban air pollution, is the thermal stress for the urban population, which is occasionally very high (MAYER 1993). The urban heat island should be examined as a possible cause. Its occurrence is most noticeable during low exchange weather conditions and is closely connected with the diurnal course of wind velocity. This sharply decreases with ground inversion in the surrounding countryside which builds up particularly in the evening and at night. The ground level wind system therefore functions predominantly independent from the wind regime above the inversion (KUTTLER 1988). This ground level wind system is based on the transport of cold air from the surrounding area into the warmer city. This process can improve unfavourable thermal situations. The transport of cold air in topographically flat terrain mainly takes place thermally as country breeze (BARLAG and KUTTLER 1990/1991) and in distinct relief by gravitational cold air flow (FREYTAG 1988). Depending on the structure of the relief, gravitational cold air flow can strengthen, overlap or replace thermally induced winds as a function of the amount and speed of the transported air (KUTTLER et al. 1996). The effectiveness of the two cold air transport mechanisms depends on the size of cold air production areas in the surrounding countryside, their distance from the city centre and on the existence of smooth ventilation lanes (KUTTLER 1996, MAYER 1996). Furthermore, the cold air which is transported should be clean so that the air quality of a city can be improved at the same time (KUTTLER and ZMARSLY 1995, ELIASSON and HOLMER 1990).

In this study the investigated area east of the city of Cologne as a cold air production area is of particular interest

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owing to its topographical location in the Rhine valley, situated between the eastern bordering highlands and the Lower Rhine Lowland, and also to its land use structure. These conditions could result in three different ventilation systems during clear summer nights with calm winds:

1. Local winds thermally induced by the urban heat island with the transport of cold air from suburban cool open areas into the city (country breeze),
2. Cold air which can flow from the foot of the eastern bordering slope over the surrounding open area into the city (local down-slope wind),
3. Cold air which flows from the Rhine valley south of the Cologne Bay over the flat, slightly sloping river terraces to the north-west (regional down-valley wind).

This investigation is concerned with the spatial and temporal interaction of these three possible ventilation mechanisms with a view to determine the most important ventilation variants for Cologne.

2. Description of the investigation area

The investigation area is situated in the eastern part of the City of Cologne (φ = 50°52′ N, λ = 7°05′ E) within the Cologne Bay (Figure 1). This forms a flat inclined geomorphological delta, widening to the north-west and falling off at the Lower Rhine Lowland. The Cologne Bay is bounded in the east and south by the foothills of the highland Rhenish Slate Mountains (Bergisches Land in the east and Siebengebirge in the south-east). The investigation area is situated east of the River Rhine, which flows from south-east to north-west through the Cologne Bay with a width of about 370 m and at a longitudinal inclination of about 1.2 m/km.

The decrease in altitude of the investigation area is less than 2 m/km perpendicular to the River Rhine. The investigation area can be characterized as a wedge-shaped, predominantly green area entering the developed area of Cologne from the east (Figure 2). The wooded foot of the slope directly to the east of the investigation area at the so-called Königsforst (see Figure 1) has an inclination of 17 m/km.

The Cologne Bay narrows to the south-east and comes to an end where the River Rhine leaves the Siebengebirge. Here the valley width is mainly 2 km and the maximum slope height ist about 150 m.

3. Investigation methods

The following results are based on stationary measurements of air temperature, air humidity, net radiation at 2 m a.g.l. as well as wind velocity and wind direction at 4 m a.g.l. and on mobile measurements. The stationary measuring network consists of eight ground stations and a rooftop station. For location and characteristics see Figure 2 and Table 1.

The ground stations were positioned depending on the respective land uses. Data was registered with electronic data loggers. Each station recorded around 2100 three-minute mean values for 25 clear and calm summer nights with low exchange weather conditions in July and August

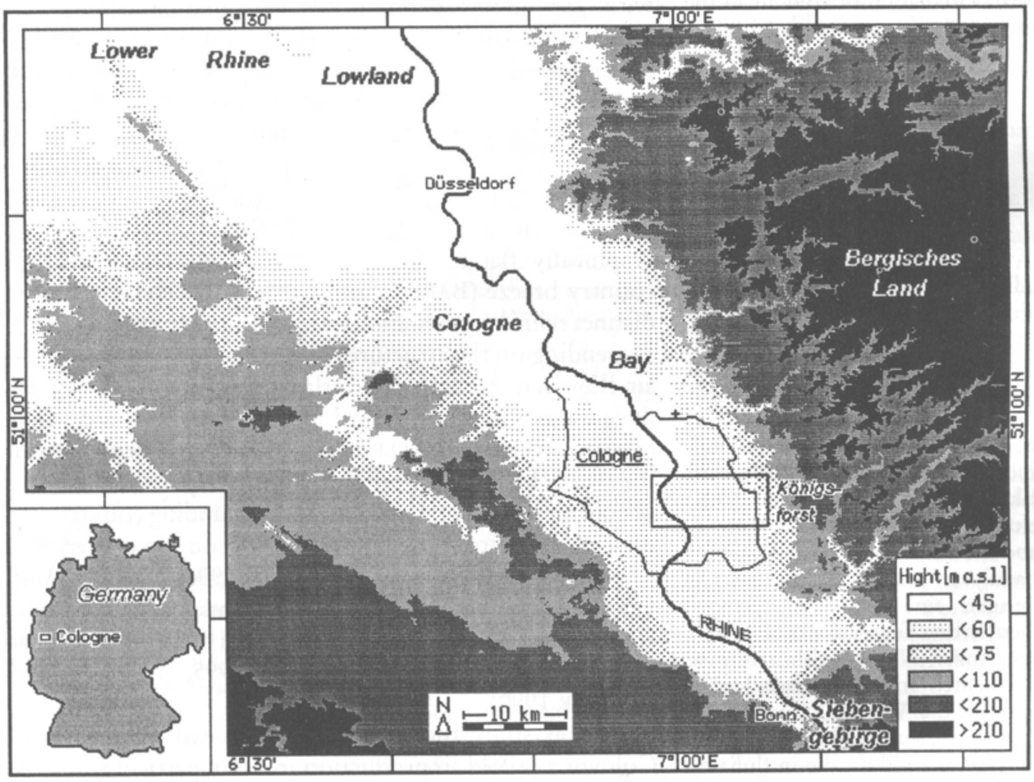


Fig. 1. Regional view of the investigation area. River and city border sketched in. Rectangle: Map of the investigation area (see Fig. 2).

Abb. 1. Regionaler Überblick über das Untersuchungsgebiet. Fluß und Stadtgrenze skizziert. Rechteckiger Ausschnitt: Untersuchungsgebiet (siehe Abb. 2).

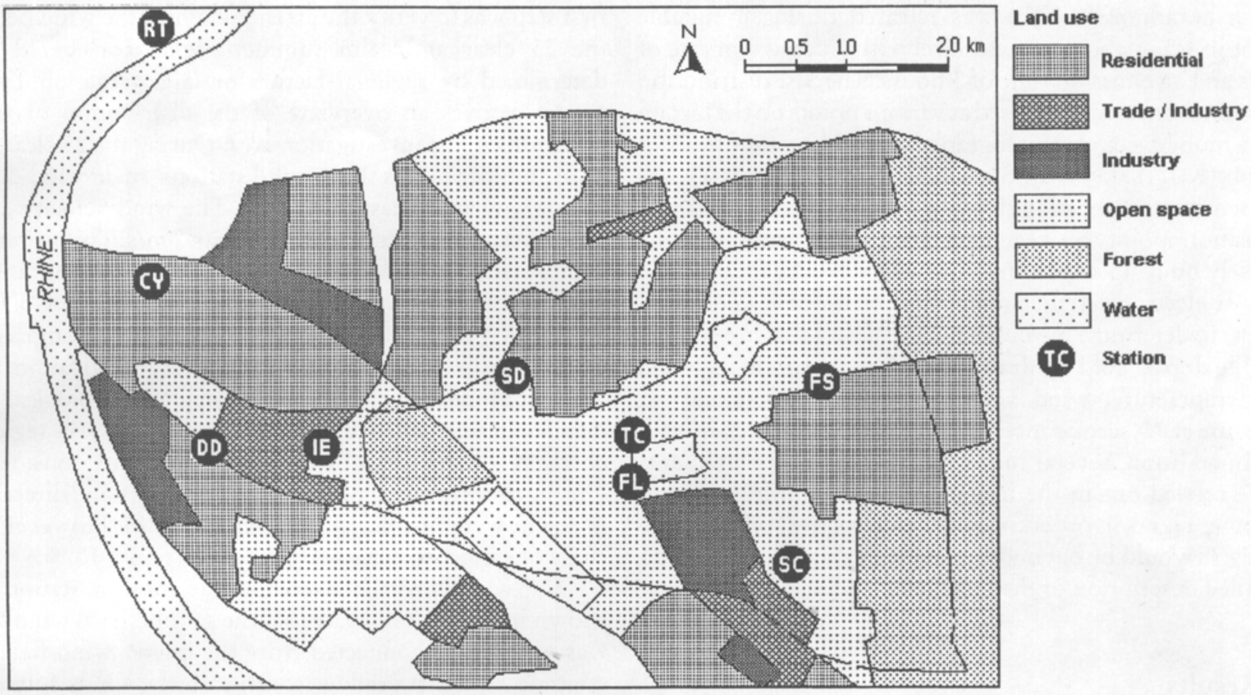


Fig. 2. Simplified map of the investigation area in Cologne including land utilization and stations (white areas are no investigation area).

Abb. 2. Generalisierte Darstellung des Untersuchungsgebietes Köln einschließlich der Flächennutzung und Stationsstandorte (Weiße Flächen liegen außerhalb des Untersuchungsgebietes).

1995. The classification system for stability proposed by PASQUILL (1961) with modifications by POLSTER (1968) was used to quantify the degree of turbulent diffusion. A clear and calm summer night is defined here as a night with a strong to moderate stratification prevailing for at least 75 % of night hours; the nights were only taken into consideration if the cloud cover on the preceding day had not exceeded 2/8. 76 % of the selected nights were under the influence of the large-scale meteorological situation types NEa, BM and HNFa.

The Essen DWD-meteorological station, located outside Cologne Bay, was taken as a comparison station without local influences. Hourly average wind speed measurements at 10 m a.g.l. where available for the time period considered (DEUTSCHER WETTERDIENST 1997).

Cold air production areas were defined as vegetation areas such as unsealed open surfaces, fallow land and forests.

To determine open areas which appear suitable for effective ventilation, the surface roughness of the heterogeneously structured investigation area was mapped as z_0 according to the method proposed by LETTAU (1969). Following MATZARAKIS and MAYER (1992), $z_0 < 0.5$ m and a length to width ratio of 1000 m : 50 m were chosen as sufficiently low roughness and area extension for undisturbed cold air transport.

The depth of penetration of cold air into the city centre was determined with a tracer gas spreading test. Tracer gas

Table 1. Characteristics of the measuring stations in the investigation area in Cologne/Germany.

Tab. 1. Beschreibung der Meßstationen im Untersuchungsgebiet Köln.

Station	Altitude (m a.s.l.)	Measuring quantities*	Characteristics of the surroundings
FS (Foot of the slope)	50	ϑ_a, U, u, WD	Agricultural land use, light development
SC (Surrounding countryside)	50	ϑ_a, U, u, WD	Agricultural land use, industrial estate
TC (Transition from countryside to city)	54	ϑ_a, U, u, WD	Situated on banks of earth, grass areas
FL (Fallow land)	50	ϑ_a, U, u, WD	Open fallow land, flooded quarries, industrial estates
SD (Development in the surroundings)	50	ϑ_a, U, u, WD	Farmland, wood and light development
IE (Industrial estate)	45	ϑ_a, U, u, WD, Q	Industrial estate
DD (Dense development)	45	ϑ_a, U, u, WD	Cemetery, garden allotments, multi-storey buildings
CY (City)	43	ϑ_a, U, u, WD	Gravel areas, railway embankment, multi-storey buildings
RT (Rooftop)	179 (137 m a.g.l.)	u, WD	Highest point, no surrounding high rise buildings

* ϑ_a = Air temperature in 2 m a.g.l. [°C]
U = Relative humditiy of air in 2 m a.g.l. [%]
u = Wind velocity in 4 m a.g.l. [m/s]
WD = Wind direction in 4 m a.g.l. [degree]
Q = Net radiation in 1.7 m a.g.l. [W/m^2]
a.s.l. = above sea level
a.g.l. = above ground level

sulfur-hexafluoride (SF_6) was released during a suitable night in 1.5 m above ground level with an emission rate of 2 g/s and an emission time of 3 hours. The SF_6-distribution was simultaneously analysed at various points on the terrain by a mobile gas chromatograph with a detection limit of 1 ppb (KUTTLER 1996). Station IE (industrial estate) was chosen as the location for the emission source at the transition point between the ventilation areas and the densely built-up city centre.

An electronic tethersonde was set up over individual nights to determine the meteorological elements in a vertical profile during cold air drainage. The tethersonde recorded air temperature, wind velocity, wind direction and air pressure at 10-second intervals up to a height of 200 m a.g.l.

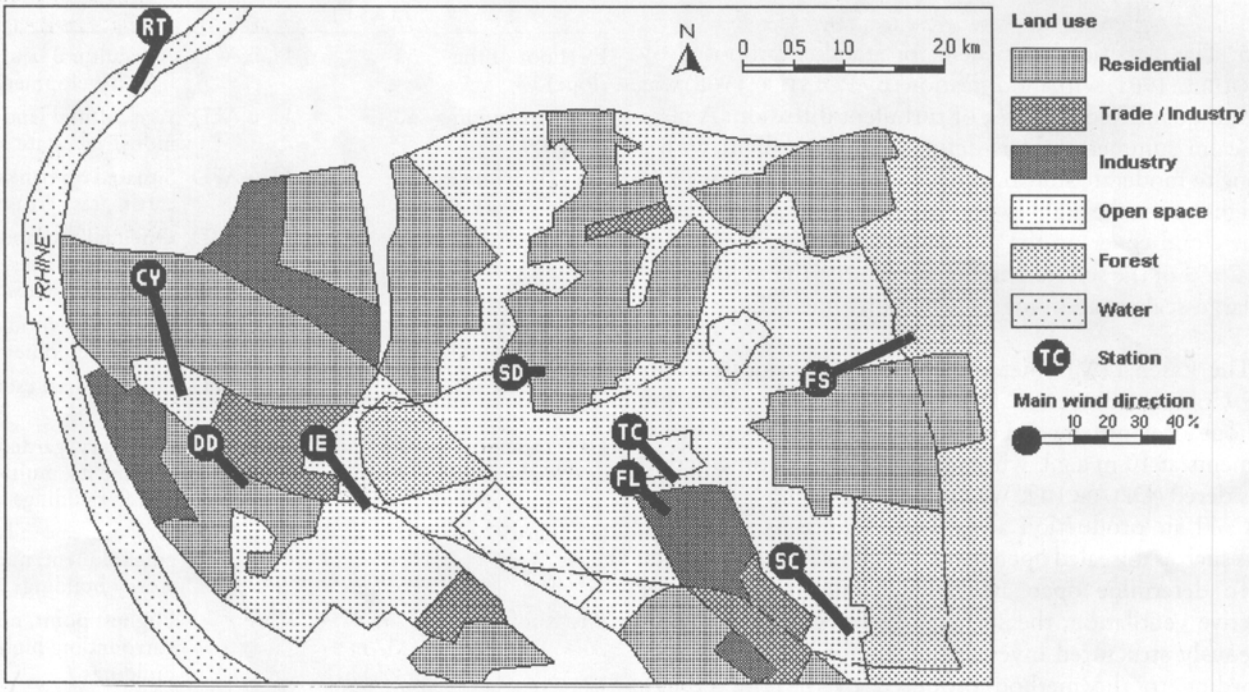
In addition, several mobile temperature measurements were carried out in the investigation area during selected summer nights in order to record ground level temperature fields. It would be beyond the scope of this article to give a detailed description of these surveys.

4. Results

In order to determine the three wind systems in the investigation area postulated in section 1, country breeze, down-slope wind and down-valley wind, and to distinguish the times at which these systems are active, mainly the wind measurements at the temporary stations were analysed. The first step was to verify the extend to which the wind field of the 25 clear and calm summer nights considered was determined by regional factors or larger-scale air flows. Figure 3 gives an overview of the distribution of wind directions in the investigation area. During the 25 clear and calm summer nights the ground stations' main wind directions show south easterly winds. The wind velocity at all ground stations usually totals less than 2 m/s. The prevailing south-easterly wind direction in the investigation area is largely due to the orographical conditions of the Cologne Bay (BAND 1961, EBEL 1962, GROBER 1973). A comparison of the south-easterly wind field in the investigation area with wind measurements at the Essen meteorological station, located outside the Cologne Bay, confirms the regional character of the wind field during the nights considered. During the measuring period, the prevailing wind directions in Essen were northerly to easterly (79 %). However, the share of easterly to southerly winds was only 15 %.

The wind directions recorded at rooftop station RT shown in Figure 3 indicate that the ground level wind field was possibly disconnected from the higher wind field. In contrast to the prevailing south-easterly winds found at ground level, there is a strong south-westerly component in the wind direction at station RT.

In the following sections, the ground level wind field for low exchange summer nights in the investigation area is considered in terms of country breeze, down-slope wind and down-valley wind.



Calms at stations [%]: RT: 0,6 CY: 14,0 DD: 56,5 IE: 23,9 SD: 50,2
TC: 5,7 FL: 10,0 FS: 11,2 SC: 6,1

Fig. 3. Main wind directions at the Cologne measuring stations for 25 clear and calm summer nights in July and August 1995. Data: 2065 three-minute mean values.

Abb. 3. Hauptwindrichtungen an den Kölner Meßstationen für 25 austauscharme Sommernächte im Juli und August 1995. Datengrundlage: 2065 Drei-Minuten-Mittelwerte.

4.1. Country breeze

In order to distinguish a possible country breeze from the other two wind mechanisms postulated above, the first step was to determine whether the three prerequisites of a country breeze are given in the investigation area. These are an urban heat island, cold air production areas in the nearby countryside and ventilation paths.

The temperatures measured during the 25 summer nights from the eight ground stations were used to detect a possible urban heat island necessary for probably local, thermally induced wind (Table 2). These data reflect the decrease of temperature between the city centre and the surroundings. Station CY was identified as the warmest city station ($\overline{\vartheta}$ = 20.6° C) and station FS ($\overline{\vartheta}$ = 17.2° C) as the coldest station in the surroundings. The horizontal temperature difference $\Delta\vartheta_{u-r}$ between these two stations averaged 3.4 K and reached up to 5.7 K during individual nights. The formation of an urban heat island can therefore be observed in the city of Cologne during low advection summer nights. Between the transition of the densely built-up areas and outer open spaces, there is a largely uniform temperature level of $\overline{\vartheta} \approx$ 18.8° C. Mobile temperature measurements confirmed that this applies over a large area.

Table 2. Air temperatures at the measuring stations of the investigation area in Cologne for 25 clear and calm summer nights in July and August 1995.

Tab. 2. Lufttemperatur der Meßstationen im Untersuchungsgebiet Köln für 25 austauscharme Sommernächte im Juli und August 1995.

		Station								
		FS	SC	TC	FL	SD	IE	DD	CY	Average
$\overline{\vartheta}_a$	[°C]	17.2	17.4	18.9	18.7	18.7	18.9	18.9	20.6	18.7
$s_{\vartheta a}$	[K]	3.8	3.7	3.3	3.3	3.3	3.4	3.3	3.0	3.4
$\vartheta_{a\ max._{abs.}}$	[°C]	26.5	26.1	26.9	26.5	26.5	27.4	27.4	28.2	26.9
$\vartheta_{a\ min._{abs.}}$	[°C]	8.6	8.9	11.1	10.8	10.8	11.1	10.8	12.8	10.6

Data: 2065 three-minute mean values
$\overline{\vartheta}_a$ = average air temperature
$s_{\vartheta a}$ = standard deviation of air temperature
$\vartheta_{a\ max._{abs.}}$ = absolute measured maximum air temperature
$\vartheta_{a\ min._{abs.}}$ = absolute measured minimum air temperature

The cold air production areas in the surroundings which are necessary for the formation of country breezes were determined by mapping as green and wooded areas (Figure 4). These 14 km^2 cold air production areas stretch from the foot of the slope of the Bergisches Land into the built-up area of Cologne, however, never reaching the city centre.

Connected ventilation paths reaching as far as possible into the densely built-up area are necessary to direct this cold air effectively into the city centre. The ventilation areas found in the investigation area are also shown in Figure 4. Four ventilation areas (No. I to IV), together totalling 12 km^2, are situated within the cold air production areas but are separated by obstacles with a height h > 10 m, such as industrial estates, wooded areas and motorway embankments which could obstruct the flow of cold air (KING 1973). As a result, there are no closed continuous ventilation paths from the surroundings into the city centre, but rather subdivided areas. Moreover, since the ventilation areas do

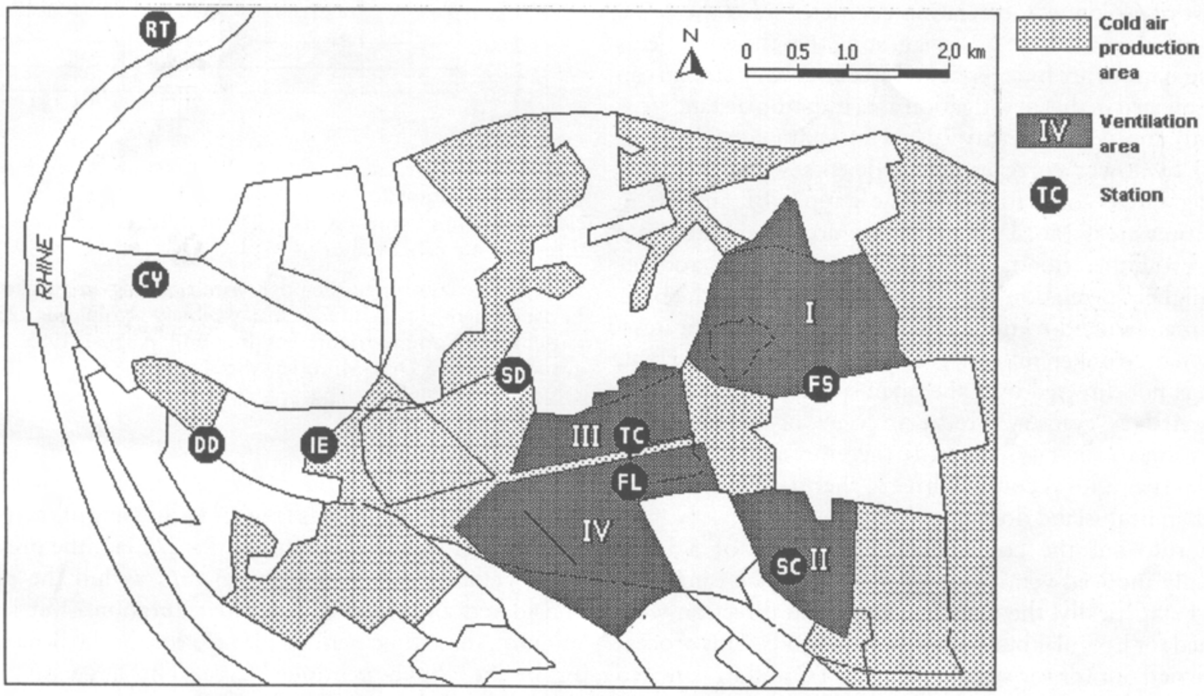


Fig. 4. Cold air production areas and ventilation areas in the investigation area in Cologne.

Abb. 4. Kaltluftproduktionsflächen und Ventilationsflächen im Untersuchungsgebiet Köln.

not completely cover the cold air production areas and are relatively far from the city centre, it is questionable whether cold air formed by the cold air production areas can be directed into the city centre over these ventilation areas.

The south-easterly wind directions at the stations in Figure 3 run from open areas into densely built-up areas, so it seems that local cold air is transported by thermal induction from the surrounding area into the city, although this is unlikely in view of the subdivisions in the terrain.

However, it is not possible to determine with this interpretation if the corresponding wind directions at the stations occur simultaneously. This would be expected in the case of a cold air ventilation of the city centre by thermally induced winds or down slope winds. In view of the given urban heat island and wind field, temporally connected local cold air dynamics are expected to occur for shorter or longer periods during the nights. For that purpose, the temporal structure of the urban heat island and wind field in the investigation area was analysed by cross correlations of the wind direction and air temperature time sequences from open area stations. As part of this analysis, correlation coefficients were calculated and interpreted depending on the station distances and wind velocities. The results demonstrate whether and with which time delay wind directions and air temperature measured at the stations near to the city correspond to those of the stations in the surrounding area. In addition, it can be determined whether local cold air transport, possibly thermally induced, occurs between the surrounding and the city centre.

In Figure 5, the cross correlations of wind direction were done with the stations FS and TC, and SC and FL respectively, located radially around the city and along the northern and southern ventilation areas at the suburb situated to the east of Cologne. Correlation coefficients for the equal time period are low ($r < 0.2$), suggesting that the wind fields at these stations are independent. No connecting stream can be established in the investigation area if station distance ($d \approx 2200$ m) and wind velocity ($u \approx 1$ m/s) are considered as shown by lower correlation coefficients with increasing time lag. Cross correlation with the stations FL and TC in ventilation areas No. IV and III (Figure 4), situated in a north-south direction tangential to the city, shows a somewhat higher correlation coefficient of $r \approx 0.5$. On the basis of the main wind directions of both stations this indicates a somewhat stronger influence of a south-easterly current, which is not directed over the open spaces and can not be interpreted as country breeze in view of its tangential orientation to the city centre. It therefore appears consequently, that a local country breeze thermally induced by the urban heat island does not occur.

To rule out the coincidental appearance of a local, thermally induced ventilation of the city which cannot be proved statistically, the time series of wind direction were searched for irregular but suitable time periods. This process was carried out for the stations FS, SC, TC and FL situated in the rural ventilation areas No. I to IV. The three-minute values of wind directions which show a theoretical cold air outflow from the open spaces around the eastern suburb to

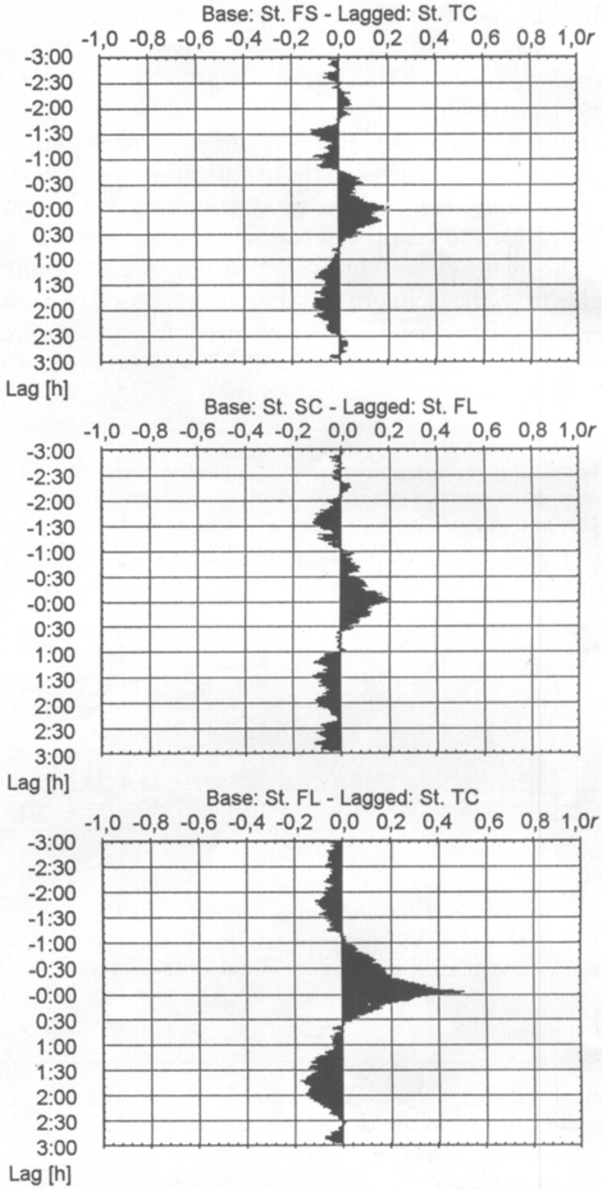


Fig. 5. Cross correlation of the wind direction between selected permanent stations of the investigation area in Cologne for 25 clear and calm summer nights in July and August 1995. Data: 2065 three-minute mean values.

Abb. 5. Kreuzkorrelationen der Windrichtung an ausgewählten Feststationen des Untersuchungsgebiets Köln für 25 austauscharme Sommernächte im Juli und August 1995. Datengrundlage: 2065 Drei-Minuten-Mittelwerte.

the open spaces at stations TC and FL were filtered and grouped into time periods (Figure 6). In view of the average distance between the stations of $d \approx 2200$ m, the prevailing wind velocity of $u \approx 1.0$ to 1.5 m/s within the periods considered and the resulting flow duration of at least 36 minutes, these time periods play no role in the flow of cold air in the above-mentioned area. The large number of three-minute time periods alone suggests that the stipulated wind direction constellation between stations FS, SC, TC and FL appears coincidentally and therefore gives no indi-

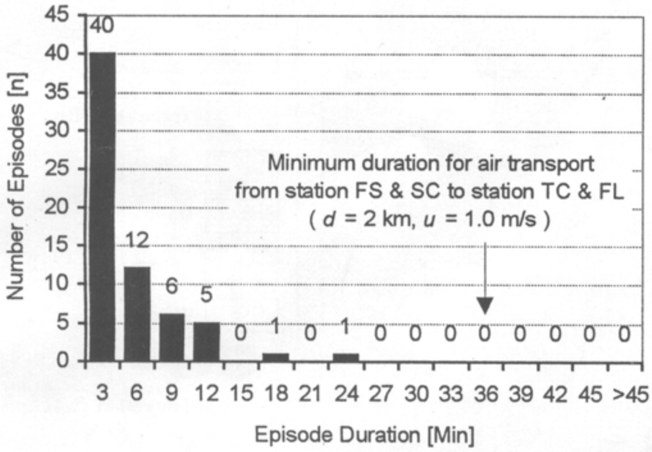


Fig. 6. Duration and number of time periods for the simultaneous appearance of the general north-easterly wind direction at permanent stations FS, SC, TC and FL in Cologne for 25 clear and calm summer nights in July and August 1995. Data: 2065 three-minute mean values.

Abb. 6. Andauer und Anzahl von Perioden mit gleichzeitigem Auftreten nordöstlicher Windrichtungen an den Feststationen FS, SC, TC und FL in Köln für 25 austauscharme Sommernächte im Juli und August 1995. Datengrundlage: 2065 Drei-Minuten-Mittelwerte.

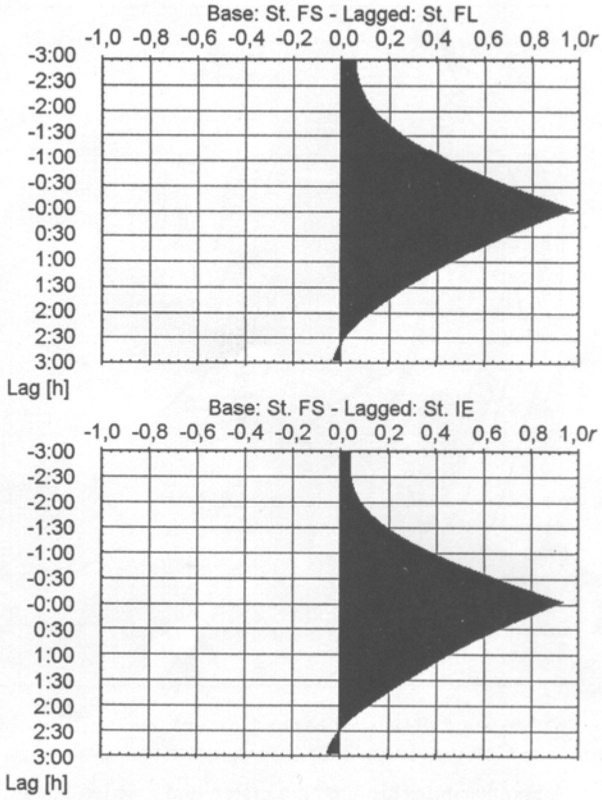


Fig. 7. Cross correlation of air temperature at selected stations of the investigation area in Cologne for 25 clear and calm summer nights in July and August 1995. Data: 2065 three-minute mean values.

Abb. 7. Kreuzkorrelationen der Lufttemperatur an ausgewählten Feststationen des Untersuchungsgebiets Köln für 25 austauscharme Sommernächte im Juli und August 1995. Datengrundlage: 2065 Drei-Minuten-Mittelwerte.

cation of a general thermally induced local transport of cold air in this area.

This suspicion is confirmed by air temperature cross correlation which was carried out along the entire open spaces between stations FS, FL and IE (Figure 7). The temperature field between these stations has approximately the same average value. Without time-lagging the correlation coefficients are very high ($r > 0.9$), i.e., at each given time approximately the same temperature prevails at the stations considered. Cold air dynamics of the type expected in a thermally induced wind system therefore do not occur here. This assumption is confirmed by lower correlation coefficients with increasing time lag.

On preliminary basis, it can therefore be concluded that the country breeze does not reach the city centre, although the thermic prerequisites are met.

4.2. Down-slope wind

As shown in Figure 3, at the slope bottom stations FS and SC in the surrounding area, there is a large share of winds from ENE and SE, respectively, with relatively few calms (8 % on average). These winds represent down-slope winds from the Königsforst. Especially the location of station FS, shielded against south-easterly airflow by the housing estate in the south, confirms this assumption. If the winds in the first and second halves of the nights are considered separately (Figure 8; for a definition of "halves of the nights", see section 4.3), cold air inflow to ventilation areas I and II was proved at both stations FS and SC especially between sunset and 01:00 CET.

In view of the separation of the ventilation areas and the fact that there is no air flow via ventilation areas III and IV to the city centre, these down-slope winds play no significant role in the ventilation of the city centre.

It can be supposed, therefore, that the prevailing east to south-easterly wind direction in the whole investigation area is not controlled by country breezes and local down-slope winds.

4.3. Regional down-valley wind

Regional cold air flow from the southern part of the Cologne Bay could determine the wind field in the investigation area in Cologne. During a clear and calm summer night accumulated cold air from the relatively narrow and deeply carved Rhine valley from the south flows into the opening Cologne Bay (KLAUS 1988) as "Siebengebirgswind" (LUFT 1938), where cold air has been formed since the beginning of the night in corresponding meteorological conditions in suitable open spaces. During the advancing night both cold air masses begin to flow down-valley as Rhine Valley Wind in a north-westerly direction following the lightly sloping Rhine terraces. For the northern Rhine

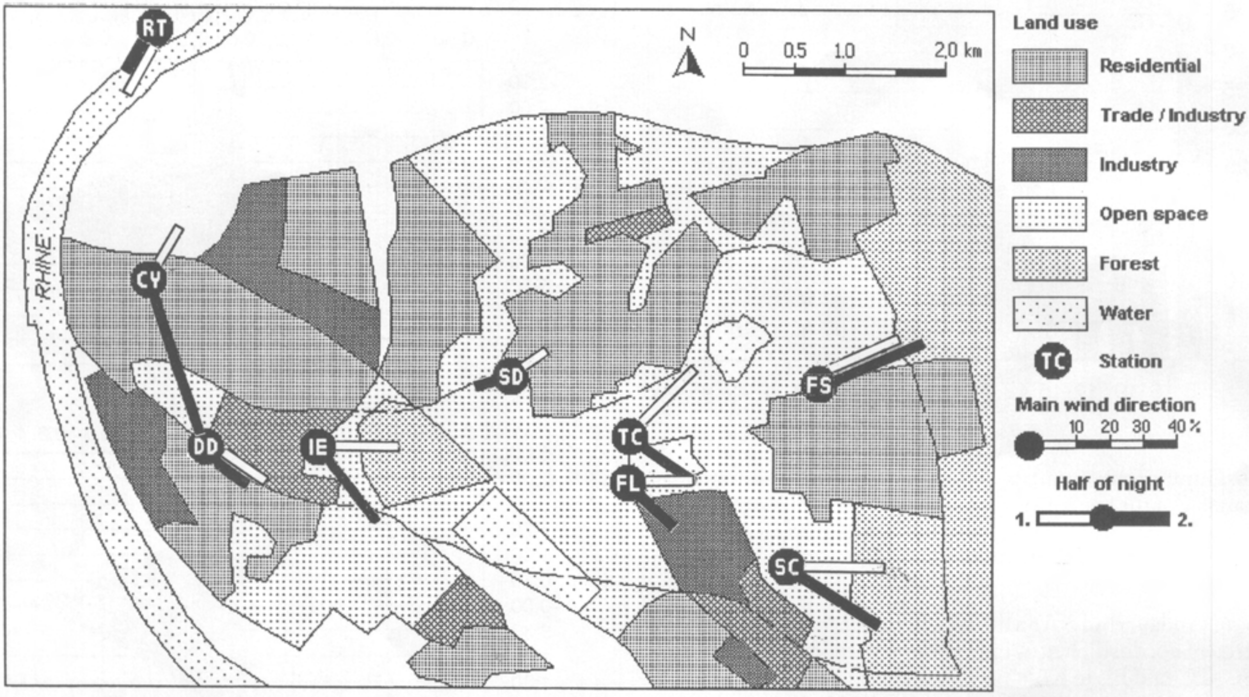


Fig. 8. Main wind directions of the first and second halves of the 25 clear and calm summer nights in July and August 1995 at the stations in Cologne. Data: 2065 three-minute mean values.

Abb. 8. Hauptwindrichtungen der ersten und zweiten Nachthälfte für 25 austauscharme Sommernächte im Juli und August 1995 an den Kölner Stationen. Datengrundlage: 2065 Drei-Minuten-Mittelwerte.

Valley EBEL (1962) was able to prove the regional character of this south-easterly down-valley wind by considering the wind field in Düsseldorf separately for the two halves of clear nights. He found that the wind turned from NE in the first half to SE in the second half of the night. The advected regional cold air is superimposed and mixed on the local cold air flow in the Cologne investigation area and directed into the city centre.

This process is made clear by the stations' main wind directions from first and second halves of the 25 low exchange summer nights (Figure 8). This halves are defined here as the time periods from sunset to 01:00 CET and between 01:00 CET and sunrise, respectively. 01:00 CET was selected as middle of the night due to the earliest time for the onset of the Rhine Valley Wind on the basis of the data available. In contrast to the main wind directions for the whole night (see Figure 3) which indicated the transport of cold air from the surroundings into the city, the wind directions from the first half of the night point to a mutual microscale air exchange taking place between the individual open spaces and their neighbouring built-up areas. Especially the relatively high share of calms must be taken into consideration (see Figure 3). The wind field of station DD is determined by the channelling effect of straight rows of buildings which cannot be shown on the map. The south-westerly component at station SD is due to the slight north-easterly slope of the terrain and the shielding effect of a narrow strip of coppice to the south.

However, in the second half of the night, in particular at stations SC, TC, FL, IE, and CY, it can be proved that the Rhine Valley Wind flows in the direction of the city. After midnight the wind at these stations takes a direction which, depending on the location of the stations, runs parallel to the River Rhine. The Rhine Valley Wind carries along the cold air which was formed in the open spaces of the investigation area in the early night. It is important to study its spatial effectiveness with regard to penetration and vertical extension.

An investigation of cold air distribution with SF_6-tracer gas combined with vertical soundings was therefore carried out at Station IE at the transition point between the surrounding and densely built-up area in the low exchange summer night from 9 to 10 August 1995 which was influenced by extensive high pressure over the British Isles. For the SF_6-measuring period between 01:49 and 04:47 CET the main wind directions at selected stations near to the river reflect the air stream parallel to the River Rhine (Figure 9). The distribution of SF_6-tracer gas concentration in 1.5 m above ground level shows that cold air was transported across an area of about 7 km^2 from the surrounding area into the city up to the River Rhine in the second half of the night in spite of the densely built-up area. During the second half of the night it can therefore be assumed that the air formed in the cold air production areas within the investigation area, the cold air based on local down-valley wind, and the air transported up from the southern part of the Cologne Bay is directed by the Rhine Valley Wind through the investigation area into the densely built-up area.

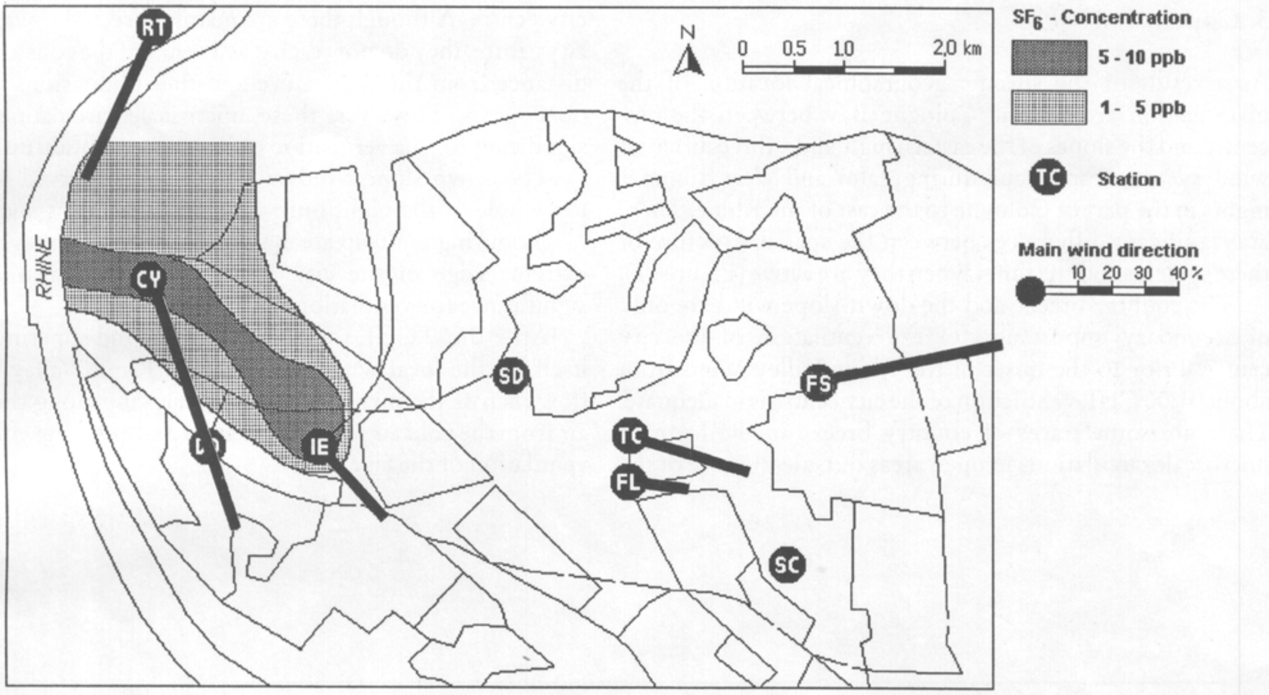


Fig. 9. SF_6-distribution and main wind directions at selected stations between 01:49 and 04:47 CET during the clear and calm summer night from 09 to 10 August 95 in Cologne. Data: three-minute mean values.

Abb. 9. SF_6-Verteilung und Hauptwindrichtungen ausgewählter Stationen in Köln zwischen 01:49 und 04:47 MEZ der austauscharmen Sommernacht vom 09.–10.08.95. Datengrundlage: Drei-Minuten-Mittelwerte.

A vertical extension of around 100 m was determined at station IE by several vertical soundings in addition to tracer gas investigation for the south-easterly cold air stream, as can be seen from the vertical profiles illustrated in Figure 10, taken in the early morning (05.00 CET) on 10 August 1995. The absence of the relatively indifferent to unstable ground level stratification typical of industrial locations confirms that the effects of the Rhine Valley Wind penetrate to ground level. As a result, the cold air from the cold air production areas is carried along by the Rhine Valley Wind in the direction of the city. A distinct, calm, south-easterly wind stream was identified in the lowest 20 m within this inversion caused by the local surface roughness, as BARLAG (1993) also proved with vertical soundings in the Vichtbachtal near Aachen. Between 100 and 160 m above ground level an increase of 5.5 to 7.0 m/s in wind velocity was identified above the inversion, possibly pointing to the presence of a low level jet. ROTH (1987) was able to prove a frequent appearance of low level jets in the North-west German lowlands.

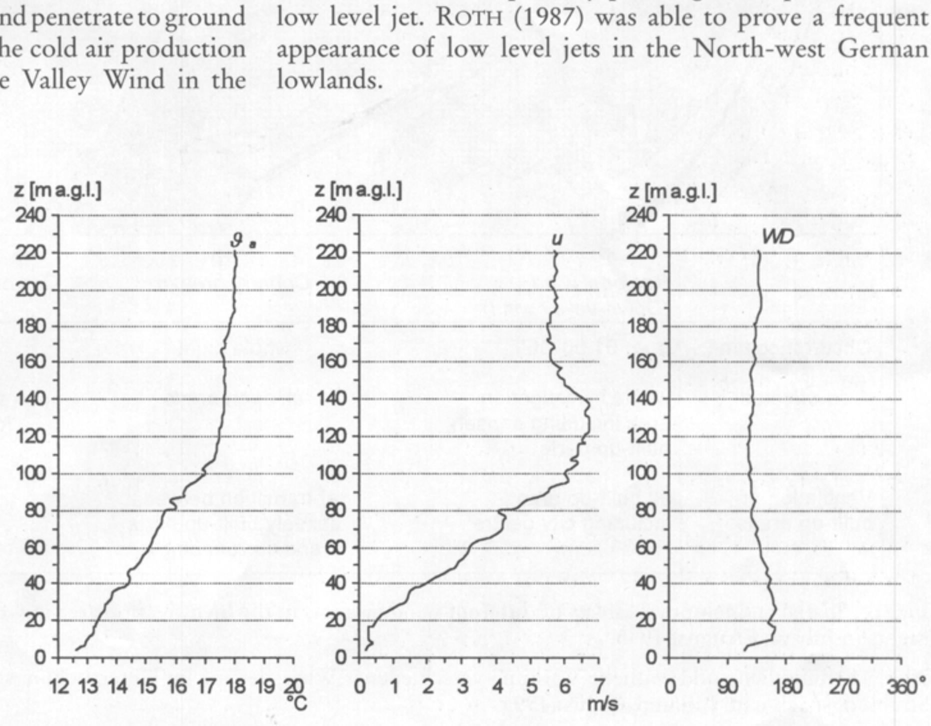


Fig. 10. Vertical profiles of air temperature ϑ_a, wind velocity u and wind direction WD at the outskirts of the built-up area (Station IE) on the morning of 10 August 95 at 05:00 CET. Data: 78 10-second interval measurements.

Abb. 10. Vertikalprofile der Lufttemperatur ϑ_a, Windgeschwindigkeit u und Windrichtung WD am Bebauungsrand (Station IE) am Morgen des 10.08.95 um 05:00 MEZ. Datengrundlage: 78 10-Sekunden-Intervallmessungen.

5. Conclusion

As a result of the specific geographical location of the investigation area in the Cologne Bay between the city centre and the slopes of the eastern highlands, three different wind systems can occur during calm and clear summer nights in the part of Cologne to the east of the Rhine. There are significant differences between the spatial structure of these systems and the times when they are active (Figure 11).

The country breeze and the down-slope wind are only of secondary importance for the ventilation of the city centre. Prior to the onset of the Rhine Valley Wind from about 01:00 CET, ventilation of the city centre is inadequate. There are some traces of country breeze in the form of microscale circulations in open areas outside the core of the city centre. Although these are mainly directed toward the city centre, they do not reach it as a result of the considerable distance from the city centre and the subdivisions of the open areas. However, these microscale circulations are significant for the ventilation of the outlying built-up areas.

The down-slope winds which can be observed during the whole of the night only ventilate open areas and their neighbouring built-up areas at the foot of the slopes on the extreme edge of the city and are therefore also of no significance for ventilation in the city centre.

After 01:00 CET, the Rhine Valley Wind superimposes itself on the local wind systems. The Rhine Valley Wind flows across the investigation area, carrying along the cold air from the cold air production areas and ensuring effective ventilation of the city centre.

	↑ Regional wind (Down-valley wind)	↑ Country breeze	↑ Down-slope wind
Occurrence time:	from 01:00 CET	whole night	whole night
Area affected:	whole investigation area including densely built-up parts	all open areas	open areas along foot of slope
Ventilation of built-up areas:	all built-up areas including city centre	at transition between densely built-up parts and surroundings	suburbs

Fig. 11. Spatial and temporal effects of different wind systems in the investigation area in Cologne during 25 clear and calm summer nights in July and August 1995.

Abb. 11. Räumliche und zeitliche Wirkung verschiedener Windsysteme im Untersuchungsgebiet Köln während 25 windschwacher Strahlungsnächte im Juli und August 1995.

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Prof. Dr. W. Kuttler
Dipl.-Geogr. D. Dütemeyer
Dr. rer. nat. A.-B. Barlag
Institute of Ecology, Department of Landscape Ecology
University of Essen
D-45117 Essen
Germany

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