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Article

Cold-air ventilation and the nocturnal boundary layer structure above an urban ballast facet

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Abstract

The ballast facet of a goods station with its railway track leading towards the rural surroundings of the city of Osnabrück, Germany, was studied in terms of its thermal behaviour and its significance as an urban ventilation path for nocturnal cold-air transport from the rural surroundings. The investigations are based on sulfurhexafluoride (SF_6) tracer experiments, tethersonde soundings and energy-balance measurements. Although the ballast facet absorbs much of the incoming solar radiation during the day it is able to cool significantly throughout the night. The dispersion of nocturnal cold-air about the urban centre of Osnabrück is shown to be spatially and temporally variable and affected by the vertical structure of the nocturnal boundary layer. Even in moderate topography the near-surface flow is able to partly decouple from the flow aloft resulting in a two-layered structure of the nocturnal boundary layer above the goods station area. The bottom part can be attributed to the cold-air flow from the eastern surroundings with a vertical extension of about 20–30 m while the upper part is influenced by the larger scale orography.

Zusammenfassung

Die Schotterfläche mit der ins östliche Umland führenden Gleisanlage des Güterbahnhofes der Stadt Osnabrück wurde hinsichtlich ihres thermischen Verhaltens sowie der Bedeutung als urbane Luftleitbahn für nächtlichen Kaltlufttransport aus dem Umland untersucht. Als Untersuchungsmethoden kamen Schwefelhexafluorid (SF_6)-Tracerexperimente, Vertikalsondierungen mit einem Fesselballon sowie Energiebilanzmessungen zum Einsatz. Trotz der starken Absorption der Einstrahlung im Tagesverlauf ist die Schotterfläche in der Lage, während der Nacht stark auszukühlen. Die Ausbreitung nächtlicher Kaltluft in das Stadtgebiet Osnabrücks zeigt sich als räumlich und zeitlich variabel und von der nächtlichen Grenzschichtstruktur beeinflusst. Die trotz moderater Topographie zeitweilig abgekoppelte bodennahe Strömung führt zu einer zweigeschichteten Struktur der nächtlichen Grenzschicht über dem Güterbahnhofbereich in Osnabrück. Der untere Teil wird von der Kaltluftströmung aus dem östlichen Umland mit einer vertikalen Mächtigkeit von 20–30 m charakterisiert, während der obere Teil von der großräumigeren Orographie beeinflusst wird.

1 Introduction

The urban heat island (UHI) belongs to the best-known and most intensively studied phenomena in the field of urban climatology. However, the spatial and temporal behaviour of the UHI is highly variable and dependent on the geographic and topographic setting, on the geometric shape, height and density of the buildings as well as on the building materials of the city under consideration – to name just a few. In recent years applied urban research focused on better understanding of the phenomenon but also on possible ways to mitigate nocturnal urban warming. Adequate urban ventilation through open spaces or ventilation paths is thought to be helpful in decreasing the UHI-intensity by drainage and transport of colder air from rural surroundings especially during clear and calm summer nights but also to reduce trace substance concentration due to dilution and mixing (KUTTLER, 2000).

In this context railway tracks are believed to serve as potential ventilation paths since they combine advantageous geographic exposition – in most cases they lead from rural environment into the urban centre – with favourable aerodynamic properties for air drainage and transport (small roughness length z_0, negligible displacement height z_d, sufficient length to width ratio, no barriers (MAYER et al., 1994)). The impact of different ventilation paths or inner-urban open spaces on cold-air transport and UHI-intensity are described for a couple of cities (e.g. GROSS et al., 1996; THORSSON and ELIASSON, 2003) whereas fewer studies deal with the thermal properties and the energy-balance of the specific facets and ventilation paths with regard to their influence on the air transported above. ASAEDA et al. (1996) and ANANDAKUMAR (1999) conducted research on different pavement-types. ANANDAKUMAR (1999) showed that asphalt with a thermal conductivity of 1.7 W m^{-1} K^{-1} rapidly conducts the heat received during the day to deeper layers releasing it during night leading to upward sensible heat fluxes due to high surface temperatures throughout summer nights. This feature was

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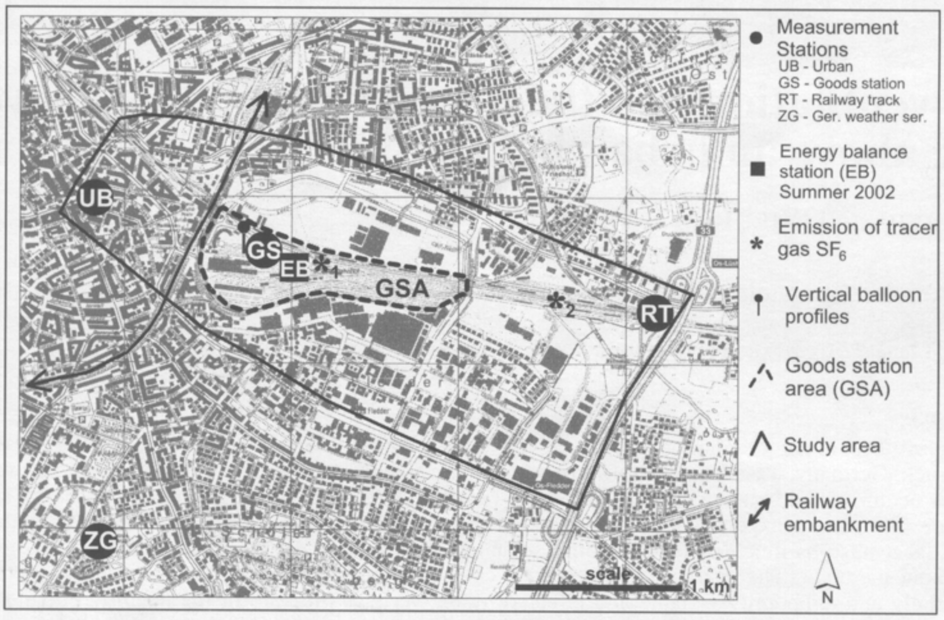

Figure 1: Overview of the study area in Osnabrück.

also reported from other urban energy-balance studies (Grimmond and Oke, 1995; Piringer et al., 2002; Arnfield, 2003).

To assess the effect of the cold-air flow it is important not only to understand how cold-air flow interacts with the nocturnal boundary layer (NBL) structure but also how far the cold-air is able to penetrate into the built-up urban centres. The influence of the topography on the NBL structure is very important in complex terrain or study areas with marked topography (Arritt and Pielke, 1986; Piringer and Baumann, 2001), but also better knowledge is needed from areas with moderate topography as is the case for the area studied here. Besides cold-air drainage from gently inclined slopes it is necessary to study how the cold-air is transported via relevant ventilation paths and how the flow interacts with the ambient wind and the NBL structure. In valleys with marked topography the near-surface flow is reported to decouple from the flow aloft under strong stability (Holden et al., 2000). On a smaller scale a near-surface drainage flow was observed to decouple even if the flow aloft was of opposite direction (Marth et al., 2001; Soler et al., 2002).

This study reports measurements that were performed at a goods station and its ballast surface in Osnabrück, Germany. Cold-air dynamics were studied by means of tracer dispersion and tethersonde soundings. The purpose of this paper is to figure out the thermal behaviour of the ballast facet on the diurnal cycle as a prerequisite for cold-air formation, how the NBL is structured in the vicinity of the urban ventilation path and how it effects cold-air transport in an area with moderate topography. First of all the study area and the topographic setting will be specified (section 2). A description of the methods follows in section 3. In section 4 results concentrating on the thermal behaviour of the ballast facet, on cold air dispersion into the urban centre of Osnabrück and vertical structure of the NBL will be presented.

2 Study area

The urban area of Osnabrück is situated at the bottom of the east-west exposed valley marked by the river Hase which lies between the height ranges of the Teutoburger Wald in the north with surface heights up to 331 m a.s.l. and the Wiehengebirge in the south with heights up to 320 m a.s.l. The horizontal distance between Osnabrück and the heights of Teutoburger Wald and Wiehengebirge is around 20 km to the north and south.

The ballast facet of the goods station area (GSA) lies roughly within the centre of the urban area of Osnabrück (52° 16' N, 8° 04' E), Germany and covers a surface area of approx. 0.45 km^2 (Fig. 1). The goods station is situated to the east of the city centre. At the western border of the GSA a railway embankment with a height of 9 m running from N to S marks a transition between the GSA and the urban centre. The GSA is located on relatively flat terrain (66 m a.s.l.) with the railway track leading from the goods station towards the eastern periphery. It is bordered by the urban centre in the west (building heights on average 12–16 m), a commercial area in the south and a residential district in the north (building heights on average 8–12 m). The eastern surroundings of the study area are characterised by large percentages of unsealed natural surfaces like meadow, agricultural crop land and pasture. The surface is favourable to cold-air production during clear and calm summer nights. The elevation in the vicinity of the ballast facet (north and south of the railway track) rises to 138 m a.s.l. with an average slope of less than 2° resulting in a relief energy of 60–80 m in the vicinity of the study area. The topography can therefore be characterised as moderate.

3 Material and methods

From April to October 2001 three meteorological stations (UB, GS, RT) measuring wind speed (u) and wind direction (ϕ) in 4 m a.g.l., air temperature (t_L) and relative humidity (f) in 2 m a.g.l. were installed in the study area (Fig. 1). Additional data from a German Weather Service station (ZG) situated to the south of the study area has been available (u, ϕ, t_L, f). The station is situated on a higher terrain level 30 m above the stations UB, GS and RT giving information on the flow structure at some height above the railway track.

To analyse nocturnal cold-air dispersion tracer experiments with SF_6 have been conducted during the nights of 26/27 July, 2001, 27/28 July, 2001 and 15/16 August, 2001. The tracer concentration and dispersion was evaluated by means of a mobile gas chromatograph in 2 m a.g.l. (Autotrac 101, Tracertech, Immenstaad a. B., Germany) to estimate the horizontal penetration of cold-air into the urban area. Tracer concentration measurements at each single point which were performed by gas chromatography lasted for < 2 min. Sequential measurements at different points of the study area were not time-corrected since we were interested in quantifying SF_6 dispersion rather than the temporal SF_6-dynamics. The SF_6 was emitted approximately 100 m to the east of station GS in 1.5 m a.g.l. during 26/27 July and 27/28 July ($*_1$, Fig. 1) with a mass flux of 0.2 g s^{-1} and was emitted more than 1.5 km further to the east on 15/16 August, 2001 ($*_2$, Fig. 1) with a mass flux of 0.35 g s^{-1}. The campaigns did last for about 2,5–3 h each night while roughly 35–40 SF_6 concentration measurements at a height of 2 m a.g.l. were performed within the urban centre. Prior to the measurements the natural background concentration of SF_6 was measured with 0.035 ppb (26/27 July) and 0.037 ppb (15/16 August) respectively.

On the same nights tethersonde profiles (u, ϕ, pressure, dry and wet bulb temperatures) up to a height of 250 m a.g.l. were conducted with a balloon manufactured by AIR, Boulder, Colorado, USA. The balloon ascents and descents were performed with a speed of 0.25 m s^{-1}. 10 m-layer averages were calculated for each profile. For purposes of visualisation the profiles are centred on the starting time of each ascent. The gradient Richardson numbers (Ri) for the layer-averages have been calculated according to (3.1)

$$Ri = \frac{\frac{g}{\Theta} \cdot \frac{\Delta\Theta}{\Delta z}}{\left(\frac{\Delta u}{\Delta z}\right)^2 + \left(\frac{\Delta v}{\Delta z}\right)^2} \qquad (3.1)$$

with g the acceleration due to gravity in m s^{-2}, Θ the potential temperature in K, Δu and Δv the horizontal wind vectors in m s^{-1} and Δz the layer thickness in m.

This paper will only take into account tracer and tethersonde results from the nights 26/27 July and 15/16 August, 2001 describing typical case-studies of clear and calm nights. To gain insights into the energy-balance of the ballast facet an energy-balance station (EB) was operated at the GSA from June to September 2002 (there was only little operational work at the goods station during that period). The site surroundings and surface conditions have to be considered heterogeneous with a mixture of ballast, gravel, railway tracks and sparse vegetation in the flux footprint as well as light and electricity masts in the field of the flow. The actual measurement point offered the maximum possible fetch with at least > 100 m (west) and up to > 600 m from the east.

Half-hourly flux estimates of the sensible heat flux Q_H and latent heat Q_E were calculated by a modified Bowen-ratio which uses direct buoyancy flux estimates of a sonic with a sampling rate of 10 Hz (USA-1, METEK, Elmshorn, Germany) and dry and wet bulb temperatures measured at two levels (0.45 m and 2.1 m) above the ground (LIU and FOKEN, 2001). Ground temperatures (t_B) were measured with a thermistor profile at –0.05, –0.1 and –0.3 m below ground level. The ballast surface temperature (T_0) was calculated according to the approach proposed by SOZZI et al. (1999). The modelled surface temperature has been verified against temporary measurements performed with a handheld infrared thermometer (I-Tec 2003, Novasens, Lüneburg, Germany) and showed good agreement with a slope of linear regression of 1.04 ($r^2 = 0.98$). The thermal conductivity of the ballast bulk was determined with $\lambda = 0.45$ W m^{-1} K^{-1} by laboratory measurements (WEBER, 2004). Mean meteorology and soil temperatures were sampled at 1 Hz and stored as 3 min averages.

Cold-air dynamics are most intensively expressed during clear and calm summer nights. To categorise those nights for the analysis of cold-air dynamics half-hourly data of wind speed and net radiation were classified according to dispersion categories of Pasquill – Polster (PASQUILL, 1961; POLSTER, 1969). Nights are defined as clear and calm here when at least 50% of daytime data were classified as moderately to strongly instable and 75 % of night-time data were strongly to moderately stable. In 2001 27 nights, in 2002 21 nights belonged to the category clear and calm nights.

4 Results and discussion

4.1 Thermal behaviour of the ballast facet

Due to the relatively small thermal conductivity of the porous ballast bulk incoming heat is not rapidly conducted to deeper layers of the ballast so that during

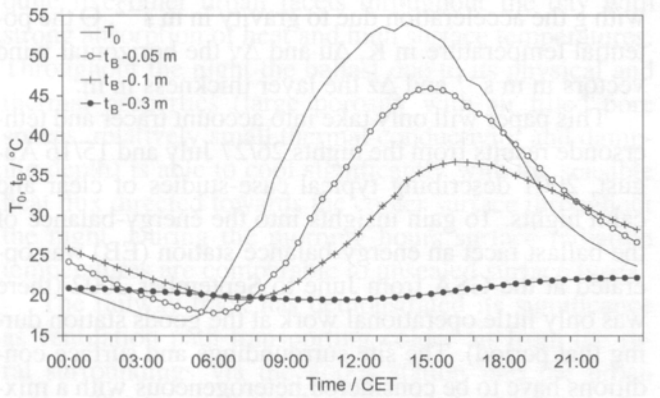

Figure 2: Diurnal variation of the modelled surface temperature (T_0) and ground temperatures (t_B) of the ballast facet at the good station in Osnabrück during a clear and calm summer day (29 July, 2002).

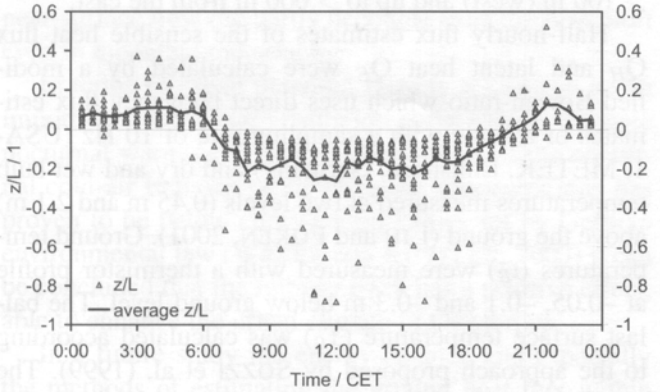

Figure 3: Diurnal variation of the stability parameter z/L (triangles) and the average z/L (line) during 21 clear and calm summer days at the energy-balance station in Osnabrück during the study period from 12 June–23 September, 2002.

clear and calm days with high solar radiation input the surface temperature increases rapidly. On the 29 July, 2002 T_0 reached a maximum of about 53° C at 14:00 CET (Fig. 2). The near-surface temperature recordings showed high daily temperature amplitudes of 36.7 K (T_0), 28.1 K (t_B –0.05 m) and 17.2 K (t_B –0.1 m) indicating strong warming and cooling of the near surface ballast bulk on the daily cycle. At –0.3 m below the surface no distinct diurnal temperature change was visible. The amplitude on 29 July, 2002 at –0.3 m was only 1.4 K in magnitude indicating that the incoming heat was stored within a shallow layer of the ballast bulk. These findings clearly correspond to the estimated shallow damping depth of only 0.09 m.

During the evening transition period the near-surface temperatures started to decrease. At around 21:00 CET the upper 5 cm were colder than t_B–0.1 m. At the end of the night the whole ballast bulk cooled so that the temperature in –0.3 m was the highest. This fact is also obvious in thermal imagery of urban areas where ballast facets at stations and railway tracks often belong to the warmest surface-types in the early evening (~ 20:00 CET) but to the coldest surfaces during the morning hours. Ballast facets have been characterised as the surface-type with the strongest cooling rates of all urban surfaces in terms of surface radiation temperature with an average of about 1.6 K h^{-1} (DÜTEMEYER, 2000). This is about the same order of magnitude compared to the results for the night 28/29 July 2002 which amount to a surface cooling rate of $\Delta T_0/\Delta t = 1.3$ K h^{-1}.

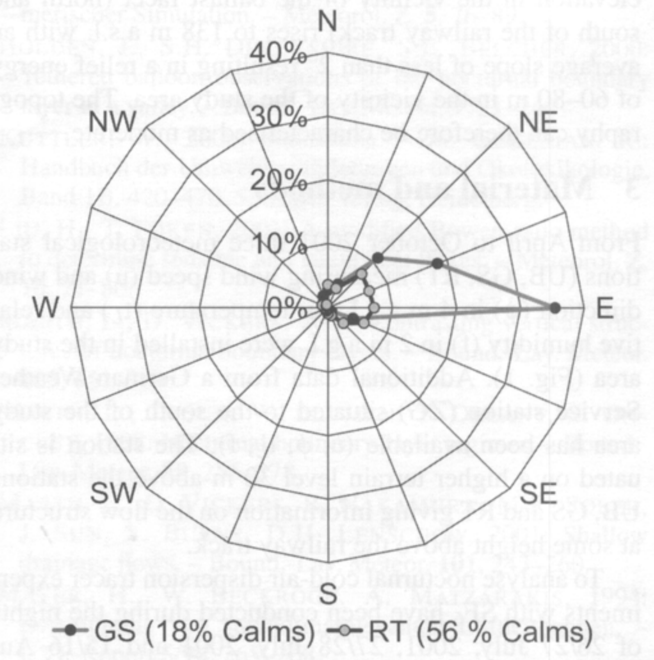

Figure 4: Wind frequency distributions at stations GS and RT during 27 clear and calm nights in the study period from 26 April–31 October, 2001 on the basis of 3 min averages.

The specific thermal behaviour of the ballast facet contributes to the evolution of downward nocturnal Q_H which are relatively small by magnitude (~ 5–10 W m^{-2}) but consequently directed downward during night. This is in contrast to other urban facets and volumes still showing upward sensible heat fluxes during the night (ASAEDA et al., 1996; ANANDAKUMAR, 1999). In consequence the air-layers adjacent to the ballast are able to cool during the night. This is an important characteristic of an urban ventilation path that has not only the potential to transport air masses due to its aerodynamically smoothness but also does not thermally affect the air masses transported above by warming due to nocturnal heat release as is the case for most other urban surface types.

In terms of atmospheric stability expressed by the stability parameter $\zeta = z/L$, with z the measurement height a.g.l. and L the Obukhov-length, the near surface atmosphere above the ballast shows slight to moderate stable conditions ($z/L > 0$, Fig. 3) during night which is also not common to urban areas and urban facets re-

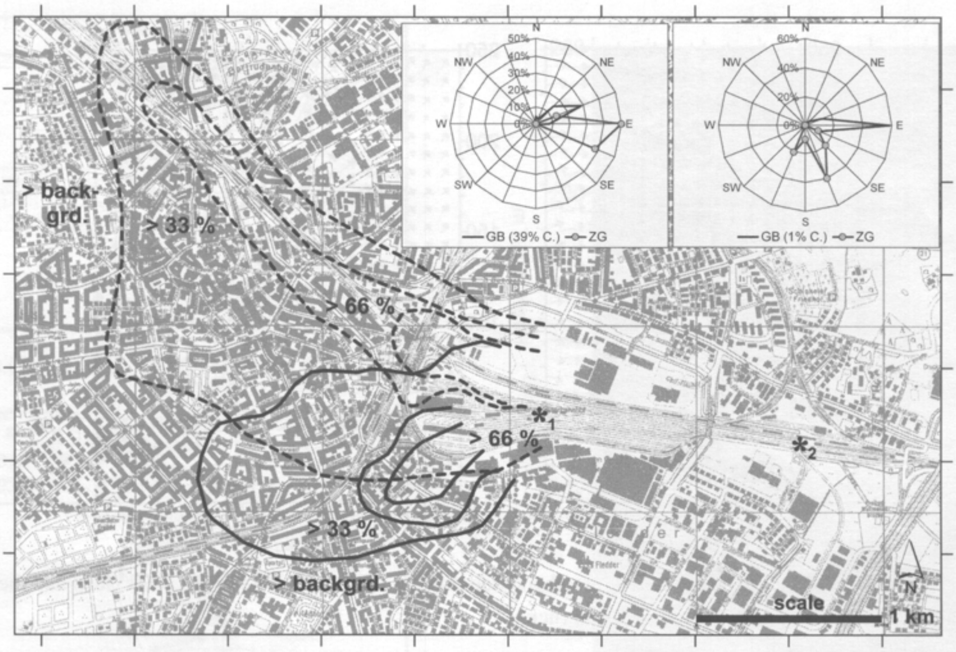

Figure 5: Dispersion of the tracer SF_6 on the 26/27 July, 2001 (solid lines) and the 15/16 August, 2001 (dashed lines) as detected by mobile measurements with a gas-chromatograph covering the urban centre of Osnabrück. For the definition of SF_6-isolines see text. The wind frequency distributions in the upper half of the figure refer to the 26/27 July, 2001 (left) and the 15/16 August, 2001 (right).

spectively (GRIMMOND and OKE, 1995; GRIMMOND and OKE, 2000).

4.2 Cold-air dynamics and nocturnal boundary layer structure

During 27 clear and calm nights in the study period from 26 April–31 October, 2001 cold-air drainage induced by the moderate relief in the NE and SE of station RT is indicated by varying wind directions from 0°–180° at RT (Fig. 4). The drainage flow was observed to be intermittent and clearly correlated to horizontal wind speed fluctuations at RT. Easterly wind directions at the goods station GS ($\overline{u} = 1.1$ m s^{-1}) demonstrate that cold-air is transported via the GSA into the direction of the urban centre of Osnabrück (cf. Fig. 1). The UHI-intensity during the 27 nights evaluated as the horizontal temperature difference between stations UB and RT was on average 2.1 K with a maximum of 4.8 K based on 3 min averages.

SF_6 is a powerful tool to study the dispersion of the cold-air during the nights of 26/27 July, 2001 and 15/16 August, 2001 in more detail (Fig. 5).

Three isolines of SF_6-concentrations are given for each night which are defined regarding the maximum concentration of SF_6 analysed for the given night. All concentration values which are greater than the background concentration are labelled > backgrd. whereas concentration values greater than 33 % or 66 % of the maximum are labelled > 33 % and > 66 % respectively. With this method it is possible to identify two patterns: First, the maximum dispersion of the tracer (> backgrd.) giving information on the horizontal penetration distance of cold-air into the urban centre. Second, it is possible to identify areas of higher concentrations (> 66 %) which are not easily interpreted owing to the complex structures of urban areas but indicate near-surface accumulation areas of cold-air.

During the night of the 26/27 July, 2001 near surface nocturnal wind speeds were weak with an average of $\overline{u_{GS}} = 0.4$ m s^{-1}. The wind direction frequency distribution indicates north-easterly directions at GS throughout the night with $\overline{\phi_{GS}} = 53°$ (see inset in Fig. 5). This was not the case for the lowest 20–30 m of the NBL which experienced wind directions from E during the first part of the night (Fig. 6 left). It is also clearly visible that the wind directions from NE in the upper part of the NBL > 150 m a.g.l. observed from the early tethersonde profiles between 21:26 –00:16 CET are of no consequence for the near-surface flow in the lowest 20–30 m a.g.l. which remained constantly from E. However, during the span of the tracer experiment (00:00–02:20 CET) the flow structure of the upper-part of the NBL did affect the near-surface wind direction distribution. The flow in the lowest 20–30 m turned to north-easterly directions diverting the SF_6-tracer cloud into the south-western parts of the urban centre of Osnabrück (Fig. 5). The area of higher tracer concentrations > 66 % reached a distance of approximately 0.9 km from the emission source but was located at the eastern side of the railway embankment whereas maximum dispersion could be estimated with 1.9 km in that night.

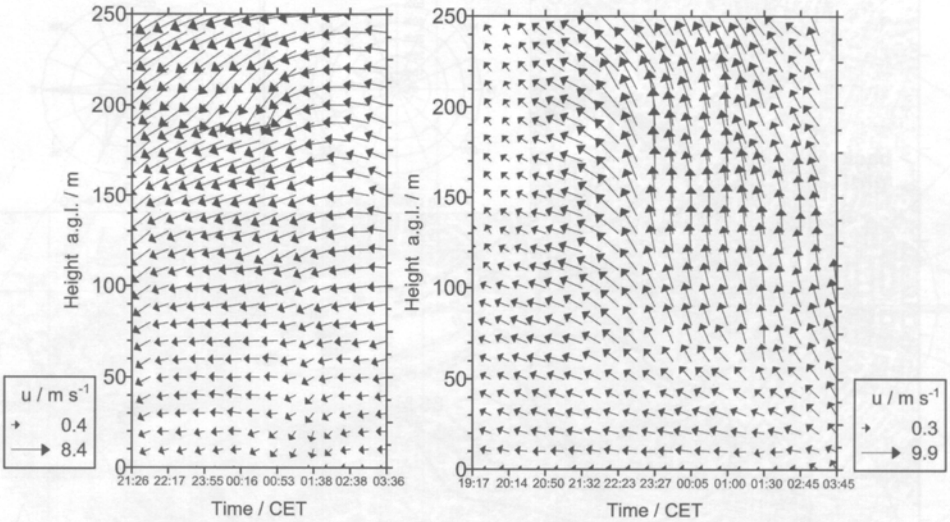

Figure 6: Wind speed and wind direction as estimated by tethersonde profiles during the 26/27 July, 2001 (left) and the 15/16 August, 2001 (right) above the ballast facet at the goods station in Osnabrück.

During the 15/16 August, 2001 wind speeds of $\overline{u_{GS}} = 1.5$ m s^{-1} prevailed at GS with wind directions constantly from E throughout the night $\overline{\phi_{GS}} = 92°$. The wind directions in the upper part of the NBL were from south-easterly to southerly wind directions throughout the night as indicated by the tethersonde profiles (Fig. 6 right) as well as by the wind frequency distribution of station ZG (Fig. 5). This night showed a clear decoupling of the near surface flow (~ 20 m) from the flow aloft. The southerly wind direction did not affect the near-surface flow. Only the later profiles (from 01:00 CET onwards) showed south-easterly directions at a height-level of about 30–40 m a.g.l. The tracer experiment was carried out between 00:00–03:00 CET. The isolines (Fig. 5) indicate that the dispersion was not mainly affected by the surface-flow as indicated by station GS but by the wind directions at some height above ground level (~ 20 m a.g.l.). The isoline of higher concentrations > 66 % extends to a horizontal distance of 2.2 km from the emission source while maximum dispersion > backgrd. can be estimated with a distance of 4.2 km. With the emission source moved approx. 1.5 km further E during that night the significance of the railway track for cold-air transport is demonstrated. The differences in maximum horizontal and especially higher tracer concentration dispersion (> 33 %, > 66 %) between both nights are mainly attributed to the difference in ambient near-surface wind speed. The tracer experiments during both nights clearly indicate that not only the near surface wind direction affects cold-air dispersion but also the wind direction distribution within the bottom 20–30 m of the NBL has an effect. Despite the observed variability of cold-air dispersion about the urban centre it can be concluded that during all the nights studied central parts of the urban centre were covered by the cold-air transport from the rural surroundings. The railway embankment (h = 9 m) did obviously not block cold-air dispersion since the tracer experiments demonstrated that SF$_6$ horizontally penetrated into the urban centre up to a linear distance of approx. 0.9 km (> backgrd., 26/27 July, 2001) or rather 1.6 km (> backgrd., 15/16 August, 2001) as measured from the western edge of the railway embankment.

4.3 General remarks on the flow regime

Despite the attempt to classify a data collective characterising clear and calm nights with similar external meteorological conditions favourable to cold-air production there is always a degree of variability to be detected within in the nocturnal boundary layer structure which is not only evident in this study but is a common feature of the NBL (e.g. POULOS et al. 2002; MARTH and VICKERS, 2002). However, the tethersonde profiles exhibit an important feature of the flow structure within the Hase valley that can be somewhat generalised since it was also evident during other nights with tethersonde data.

An average vertical profile of the gradient Richardson number (Ri) was plotted for the 26/27 July, 2001 as well as for the 15/16 August, 2001 (Fig. 7). Richardson numbers greater than 1 were corrected to a value of 1 in the raw data to suppress large values of Ri in the averaging process. These large values can occur when the ratio is calculated from small numbers in the denominator which in case of Ri is attributed to small wind speed gradients between 10 m-layers. However, correcting larger Ri values to Ri = 1 is plausible since the turbulence characteristics of large Ri (e.g. Ri = 5 or Ri = 20) makes little physical difference (MARTH et al. 1998).

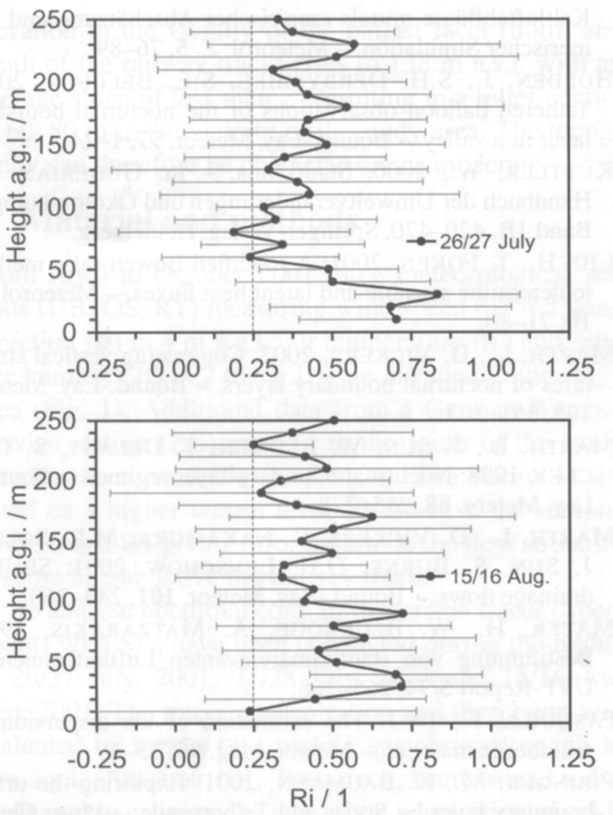

Figure 7: Average gradient Richardson number (Ri) for all tethersonde profiles for the nights of 26/27 July, 2001 (top) and 15/16 August, 2001 (bottom). Standard deviations of Ri are indicated by the grey horizontal lines. The dashed vertical line marks the critical Richardson number $Ri_c = 0.25$.

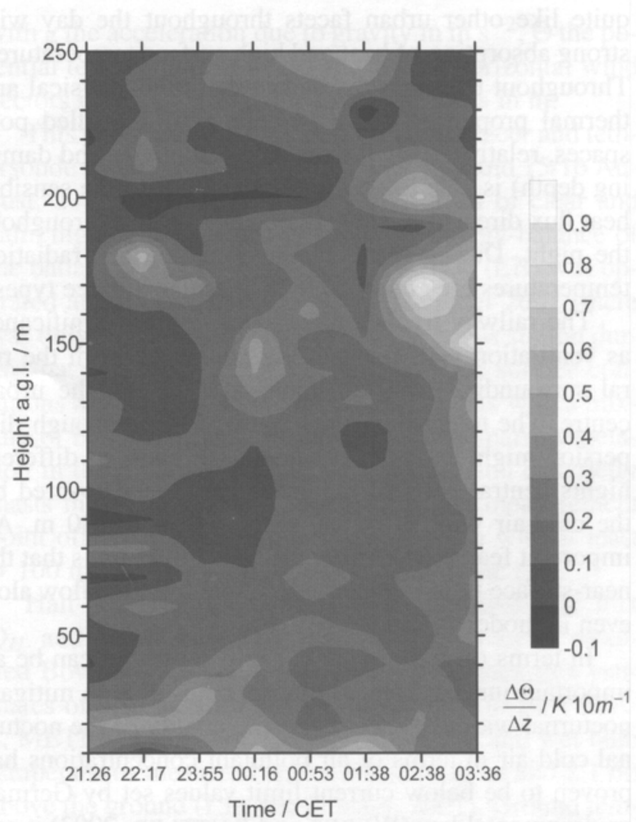

Figure 8: Gradients of potential temperature from tethersonde profiles taken at the goods station in Osnabrück during the night of 26/27 July, 2001. Gradients ($\Delta\Theta/\Delta z$) are calculated from 10 m-layer averages.

As mentioned before, marked wind direction changes in the upper boundary layer e.g. on 15/16 August, 2001 (Fig. 6) did not affect the flow in the lowest 20–30 m a.g.l. which stayed quite constant and showed easterly wind directions throughout the night. The decoupling of the near surface flow marks a somewhat two-layered structure of the NBL which is also indicated by the sharp edge in the Ri profile at a height level of about 30–40 m a.g.l. in both profiles shown (Fig. 7). This edge is believed to define the border between the near-surface cold-air flow which tended to partly decouple from the flow aloft as shown during both nights presented here. The decoupling can be explained by shelter effects of the adjacent topography as well as by the more stable regime near the surface with stronger positive temperature lapse rates (~ 0.5–0.7 K 10 m^{-1}, Fig. 8) than in the layer above due to strong cooling of the surface as described in section 4.1 in conjunction with cold-air advection from the eastern rural surroundings (see section 4.2). The decoupled near-surface flow extended to a height of nearly half the valley height ($z/h \approx 0.4$) when taking into account the surface heights of the adjacent topography ($h \approx 60$–80 m a.g.l.). These findings correspond to the decoupling depth observed by (HOLDEN et al., 2000) although it seems more coincidental than a general feature of valley flow systems. Some effect of the build-up areas N and S of the GSA on sheltering the cold-air flow can not be ruled out although the average building height (8–12 m) is considerably lower as is the height of the decoupled flow so that significant impact of buildings is less likely. The upper part of the NBL > 40–50 m a.g.l. was more prone to short-time changes of wind direction and wind speed which are believed to be related to the larger scale orography of Wiehengebirge and Teutoburger Wald as well as to mesoscale disturbances. It has to be noted that these average profiles can not account for the strong variability within the Ri-data which might occur temporally throughout the night especially in the upper-parts of the NBL but the transition between the near surface flow and the flow aloft is distinct and common to all nights.

5 Concluding remarks

The study presents findings about the thermal behaviour of an inner-urban ballast facet and analyses cold-air transport and NBL structure above a goods station area. The thermal behaviour of the ballast is somewhat unique within an urban area since it thermally behaves quite like other urban facets throughout the day with strong absorption of heat and high surface temperatures. Throughout the night the ballast due to its physical and thermal properties (large porosity with air filled pore spaces, relatively small thermal conductivity and damping depth) is able to cool significantly with the sensible heat flux directed towards the cooler surface throughout the night. During the morning hours surface radiation temperatures are comparable to unsealed surface types.

The railway track has demonstrated its significance as ventilation path transporting colder air from the rural surroundings via the goods station into the urban centre. The tracer dispersion showed that although dispersion might be spatially variable throughout different nights central parts of the urban centre are covered by the cold-air with a vertical extension of 20–30 m. An important feature regarding the NBL structure is that the near-surface flow can partly decouple from the flow aloft even in moderate topography.

In terms of urban planning railway tracks can be an important inner-urban ventilation paths able to mitigate nocturnal warming. Since also the quality of the nocturnal cold-air in terms of air pollutant concentrations has proven to be below current limit values set by German environmental law (Weber and Kuttler, 2003) it can be concluded that the railway track has a positive effect, able to enhance the urban climate of Osnabrück.

In a future study the energy-balance and especially the methods of estimating the ground heat flux within the heterogeneous ballast layer will be addressed in more detail.

References

Anandakumar, K., 1999: A study on the partition of net radiation into heat fluxes on a dry asphalt surface. – Atmos. Environ. **33**, 3911–3918.

Arnfield, J., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. – Int. J. Climatol. **23**, 1–26.

Arritt, R. W., R.A. Pielke, 1986: Interactions of nocturnal slope flows with ambient winds. – Bound.-Layer Meteor. **37**, 183–195.

Asaeda, T., V.T. Ca, A. Wake, 1996: Heat storage of pavement and its effect on the lower atmosphere. – Atmos. Environ. **30**, 413–427.

Dütemeyer, D., 2000: Urban-orographische Bodenwindsysteme in der städtischen Peripherie Kölns. – Essener Ökologische Schriften, Bd. **12**, Westarp Wissenschaften, Hohenwarsleben, 171 p.

Grimmond, C. S. B., T.R. Oke, 1995: Comparison of heat fluxes from summertime observations in the suburbs of four north american cities. – J. Appl. Meteor. **34**, 873–889.

—, —, 2000: Heat fluxes and stability in cities. Third AMS symposium on the urban environment 14.–18.08.2000. – Davis, 28–29.

Gross, G., T. Frey, T. Mosimann, P. Trute, R. Lessing, 1996: Die Untersuchung kleinräumiger Kaltluftabflüsse mittels empirischer Abschätzung und numerischer Simulation. – Meteorol. Z. **5**, 76–89.

Holden, J., S.H. Derbyshire, S.E. Belcher, 2000: Tethered balloon observations of the nocturnal boundary layer in a valley. – Bound.-Lay. Meteor. **97**, 1–24.

Kuttler, W., 2000: Stadtklima. – In: Guderian, R.: Handbuch der Umweltveränderungen und Ökotoxikologie, Band 1B, 420–470, Springer-Verlag, Heidelberg.

Liu, H., T. Foken, 2001: A modified Bowen-ratio method to determine sensible and latent heat fluxes. – Meteorol. Z. **10**, 71–80.

Marth, L., D. Vickers, 2002: Contrasting vertical structures of nocturnal boundary layers. – Bound.-Lay. Meteor. **105**, 351–363.

Marth, L., J. Sun, W. Blumen, T. Delany, S. Oncley, 1998: Nocturnal boundary-layer regimes. – Bound.-Lay. Meteor. **88**, 255–278

Marth, L., D. Vickers, R. Nakamura, M.R. Soler, J. Sun, S. Burns, D.H. Lenschow, 2001: Shallow drainage flows. – Bound.-Lay. Meteor. **101**, 243–260

Mayer, H., W. Beckröge, A. Matzarakis, 1994: Bestimmung von stadtklimarelevanten Luftleitbahnen. – UVP-Report **5/94**, 265–268.

Pasquill, F., 1961: The estimation of the dispersion of windborne material. – Meteor. Mag. **90**, 33–49

Piringer, M., K. Baumann, 2001: Exploring the urban boundary layer by Sodar and Tethersonde. – Phys. Chem. Earth (B) **26**, 881–885.

Piringer, M., C.S.B. Grimmond, S.M. Joffre, P. Mestayer, D.R. Middleton, M. Rotach, A. Baklanov, K. De Ridder, J. Ferreira, E. Guilloteau, A. Karppinen, A. Martilli, V. Masson, M. Tombrou, 2002: Investigating the surface energy balance in urban areas – recent advantages and future needs. – Water, Air, and Soil Pollution Focus **2**, 1–16.

Polster, G., 1969: Erfahrungen mit Strahlungs-, Temperaturgradient-, und Windmessungen als Bestimmungsgrößen der Diffusionskategorien. Meteor. Rundsch. **22**, 170–175.

Poulos, G. S., W. Blumen, D.C. Fritts, J.K. Lundquist, J. Sun, S. Burns, C. Nappo, R.M. Banta, R.K. Newsom, J. Cuxart, E. Terradellas, B. Balsley, M. Jensen, 2002: CASES-99: A comprehensive investigation of the stable nocturnal boundary layer. – Bull. Amer. Meteor. Soc. **83**, 555–581.

Soler, M. R., C. Infante, P. Buenestado, L. Marth, 2002: Observations of nocturnal drainage flow in a shallow gully. – Bound.-Layer Meteor. **105**, 253–273.

Sozzi, R., A. Salcido, R.S. Flores, T. Georgiadis, 1999: Daytime net radiation parameterisation for Mexico City suburban areas. – Atmos. Res. **50**, 53–68

Thorsson, S., I. Eliasson, 2003: An intra-urban thermal breeze in Göteborg, Sweden. – Theor. Appl. Climatol **75**, 93–104.

Weber, S., 2004: Energiebilanz und Kaltluftdynamik einer urbanen Luftleitbahn. – Dissertation FB 9, Universität Duisburg-Essen, Campus Essen, 207 pp.

Weber, S., W. Kuttler, 2003: Analyse der nächtlichen Kaltluftdynamik und -qualität einer stadtklimarelevanten Luftleitbahn. – Gefahrstoffe – Reinhaltung der Luft **63**, 381–386.