Doctoral Thesis

Wind tunnel modelling of turbulence and dispersion above tall and highly dense urban roughness

Author(s):
Feddersen, Berend

Publication Date:
2005

Permanent Link:
https://doi.org/10.3929/ethz-a-004941441

Rights / License:
In Copyright - Non-Commercial Use Permitted

This page was generated automatically upon download from the ETH Zurich Research Collection. For more information please consult the Terms of use.
Wind tunnel modelling of turbulence and dispersion above tall and highly dense urban roughness

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY
ZURICH

for the degree of
Dr. sc. ETH Zürich

presented by
BEREND FEDDERSEN

Dipl.-Phys.
University of Hamburg

born 15.05.1973
citizen of Germany

accepted on the recommendation of
Prof. Dr. Hans Richner, examiner
Prof. Dr. Ulrike Lohmann, co-examiner
PD Dr. Mathias Rotach, co-examiner
Prof. Dr. Michael Schatzmann, co-examiner

April 2005
Contents

Symbols and abbreviations v

Operators v
Latin symbols v
Greek symbols viii

Abstract 1

Kurzfassung 5

1 Introduction 9

2 Theoretical background 13

2.1 Remarks on notation 13
2.2 Budget equations for turbulent fluids 14
2.3 Similarity theory and the scaling approach 16
2.4 Reynolds number similarity and independence 17
2.5 Boundary layer approximations 25
2.6 Rough-wall boundary layer flows and the logarithmic wind profile 26
2.7 Spatially averaged RANS equation 31
2.8 Integral scales and spectral representation of turbulence 32
2.9 Turbulent dispersion 35
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Introduction to urban turbulence and dispersion</td>
<td>41</td>
</tr>
<tr>
<td>3.1</td>
<td>Shear vs. thermal contributions to TKE production</td>
<td>41</td>
</tr>
<tr>
<td>3.2</td>
<td>Some findings from urban turbulence field studies</td>
<td>42</td>
</tr>
<tr>
<td>3.3</td>
<td>Urban dispersion modelling efforts</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>Experimental setup</td>
<td>49</td>
</tr>
<tr>
<td>4.1</td>
<td>Wind tunnel 'WOTAN' and measurement equipment</td>
<td>49</td>
</tr>
<tr>
<td>4.2</td>
<td>Principles of laser Doppler anemometry</td>
<td>54</td>
</tr>
<tr>
<td>4.3</td>
<td>Principles of flame ionization detection</td>
<td>57</td>
</tr>
<tr>
<td>4.4</td>
<td>Urban model of Kleinbasel</td>
<td>58</td>
</tr>
<tr>
<td>4.5</td>
<td>Measurement locations within and above the urban model</td>
<td>63</td>
</tr>
<tr>
<td>5</td>
<td>Flow boundary conditions</td>
<td>69</td>
</tr>
<tr>
<td>5.1</td>
<td>Mean wind profile of the approach flow from field measurements</td>
<td>69</td>
</tr>
<tr>
<td>5.2</td>
<td>Approach flow of the wind tunnel model</td>
<td>79</td>
</tr>
<tr>
<td>6</td>
<td>Modelled urban turbulence in Kleinbasel</td>
<td>87</td>
</tr>
<tr>
<td>6.1</td>
<td>Flow adaptation to the urban model</td>
<td>87</td>
</tr>
<tr>
<td>6.2</td>
<td>Integral statistics above roof level</td>
<td>91</td>
</tr>
<tr>
<td>6.3</td>
<td>Turbulence intensities and angular fluctuations of the wind vector</td>
<td>101</td>
</tr>
<tr>
<td>6.4</td>
<td>Conditional statistics of Reynolds fluxes above roof level</td>
<td>105</td>
</tr>
<tr>
<td>6.5</td>
<td>Spectra and integral length scales at Basel-Sperrstrasse</td>
<td>112</td>
</tr>
<tr>
<td>6.6</td>
<td>Terms of the TKE budget</td>
<td>117</td>
</tr>
<tr>
<td>6.7</td>
<td>Local turbulence within and above the street canyon Basel-Sperrstrasse</td>
<td>125</td>
</tr>
<tr>
<td>6.8</td>
<td>Horizontal ISL inhomogeneity and dispersive stresses above roof level</td>
<td>132</td>
</tr>
<tr>
<td>6.9</td>
<td>Comparison to turbulence field data</td>
<td>137</td>
</tr>
</tbody>
</table>
Symbols and abbreviations

The urban model represents part of the City of Basel (the area of Kleinbasel). Most of the urban model measures including the wind tunnel coordinates are given in full scale dimensions. The wind tunnel measures can be inferred by multiplication with 1/300 (the geometric scale factor). Height measures are given both in full scale measures and in multiples of the mean building height h. The following list of symbols and abbreviations gives an overview over the nomenclature used in this work.

Operators

\( \overline{\ldots} \) Time average over a time series
\( \langle \ldots \rangle \) Horizontal spatial average
\( \ldots' \) Deviation of the instantaneous value from the time average, e.g.
\[ u_i' = u_i - \overline{U}_t \]
\( \ldots'' \) Deviation of the local time average from the horizontal spatial average, e.g.
\[ U_i'' = U_i - \langle U_i \rangle \]
\( \ldots\ast \) Quantity made non-dimensional by suitable combination of \( U_{ref} \), \( L_{ref} \) and Q

Latin symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABL</td>
<td>Atmospheric boundary layer</td>
</tr>
<tr>
<td>BKLH</td>
<td>Basel-Kleinhüningen</td>
</tr>
<tr>
<td>BSPR</td>
<td>Basel-Sperrstrasse</td>
</tr>
<tr>
<td>BUBBLE</td>
<td>Basel urban boundary layer experiment</td>
</tr>
<tr>
<td>c</td>
<td>Instantaneous concentration</td>
</tr>
<tr>
<td>C</td>
<td>Mean concentration (time average)</td>
</tr>
<tr>
<td>( C_{max}^{\ast} )</td>
<td>Peak non-dimensional mean concentration as a function of ( x_{DST} ) determined from a Gaussian fit to the lateral ( C^{\ast} ) profile measured at ( x_3 = 27m ) (1.8h)</td>
</tr>
</tbody>
</table>
CYL  Cylinder source
\( d_0 \)  Zero plane displacement
DD  Wind direction degree, \( 0^\circ = \text{north and counting clockwise} \)
\( f \)  Circular frequency, i.e. \( [f] = 1/s \)
FFID  Fast Flame Ionization Detection
FID  Flame Ionization Detection
Flat \( u_i \)  Flatness of the distribution of the \( i^{th} \) velocity component
\( g \)  Acceleration due to gravity
\( h \)  Mean building height
\( h_{IBL} \)  Height of the internal boundary layer
\( h_{SRC} \)  Height of the gas release point
\( I_i \)  Turbulence intensity in the \( i^{th} \) velocity component, \( I_i = \sigma_i/U_1 \)
\( I_i() \)  Indicator function of the \( i^{th} \) quadrant in the \( u'_i u'_3 \) plane
IBL  Internal boundary layer
ISL  Inertial sublayer
\( k \)  von Karman constant, set to \( k = 0.4 \)
\( L \)  Monin-Obukhov length scale
\( L_i \)  Integral length scale derived from the \( i^{th} \) velocity component
\( L_{ref} \)  Reference length scale
\( L_{uz}, L_{uy}, L_{uz} \)  \( L_1, L_2, L_3 \)
LDA  Laser Doppler anemometry
LTS  Large tube source
\( n \)  Non-dimensional frequency \( n = f(x_3 - d_0)/U_1 \)
\( n_{u_{i,peak}} \)  Non-dimensional peak frequency of the velocity spectrum \( nS_i(n) \)
NNW  North-north-westerly wind sector from DD = 326.25\(^\circ\) to 348.75\(^\circ\)
NS  Navier-Stokes equation
NW  North-westerly wind sector from DD = 303.75\(^\circ\) to 326.25\(^\circ\)
p  Instantaneous pressure minus hydrostatic pressure \( p_{hyd} \)
P  Time average of pressure minus hydrostatic pressure \( p_{hyd} \)
\( p_{hyd} \)  Hydrostatic pressure with \( \partial_3 p_{hyd} = -\rho g \)
\( q \)  Turbulent kinetic energy
\( Q \)  Source strength at the gas release point
RANS  Reynolds averaged Navier-Stokes equation
R  Straight line distance between the source and the sampling locations
\( R_{ii}() \)  Spatial autocorrelation function of the \( i^{th} \) velocity function
R1  Source location for the dispersion experiment
RAD  Radius of homogenization
Re  Reynolds number \( Re = U_{ref} L_{ref}/\nu \)
RSL  Roughness sublayer
S1, etc.  Field sampling locations during the tracer experiment modelled in the wind tunnel (S1, S3a, S3b, S3c, S4, S8, S9)
\( s_{ij} \)  Instantaneous rate of strain tensor \( s_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i) \)
\( s'_{ij} \)  Fluctuating rate of strain tensor \( s'_{ij} = s_{ij} - S_{ij} \)
\( S_{ij} \)  
Time averaged rate of strain tensor \( S_{ij} = \frac{1}{2}(\partial_i U_j + \partial_j U_i) \)

\( S_i \)  
Relative contribution of the \( i \)th quadrant in the \( u'_i u'_3 \) plane to \( u'_i u'_3 \)

\( \tilde{S}_i() \)  
One-dimensional energy density of the \( i \)th velocity component

\( \hat{S}_i() \)  
Fourier transform of \( \sigma_i^2 \rho_i() \)

SFID  
Slow flame ionization detection

Skew \( u_i \)  
Skewness of the distribution of the \( i \)th velocity component

SLK  
Schweizer Landeskoordinaten

STS  
Small tube source

t  
Time coordinate (generic)

T  
Travel time

\( T_i \)  
Integral time scale derived from the \( i \)th velocity component

\( T_L \)  
Lagrangian time scale

TKE  
Turbulent kinetic energy

\( u_* \)  
Friction velocity (generic)

\( u_{*\text{flux}} \)  
Friction velocity estimated from the horizontally averaged Reynolds fluxes

\( u_{*\text{local}} \)  
Friction velocity determined from local Reynolds flux dependent on horizontal and vertical location

\( u_{*\text{local flux}} \)  
Friction velocity determined from the local Reynolds flux profile dependent on the horizontal location

\( u_{*\text{local log}} \)  
Friction velocity determined from the logarithmic profile fit to the local mean wind profile dependent on the horizontal location

\( u_{*\text{log}} \)  
Friction velocity estimated from the logarithmic profile fit to the horizontally averaged mean wind profile

\( u_{*\text{transport}} \)  
Velocity scale associated with the vertical turbulent TKE flux divergence

\( u_f \)  
Convective velocity scale

\( u_i \)  
Instantaneous \( i \)th velocity component

\( u_i' \)  
Fluctuating \( i \)th velocity component \( u_i' = u_i - U_i \)

\( U_i \)  
Time average of the \( i \)th velocity component ('mean wind speed')

\( U_{1,\text{ref}} \)  
Reference mean wind speed at \( x_{3,\text{ref}} \) for the power profile of the mean wind

\( U_{1,\text{eff}} \)  
Effective advection velocity in the Gaussian plume model

\( U_{\text{ref}} \)  
Reference velocity scale (generic)

\( U_{\text{CYL}} \)  
Gas exit velocity at the cylinder source

\( U_{\text{LTS}} \)  
Gas exit velocity at the large tube source

\( U_{\text{WT}} \)  
'Free stream' wind speed in the wind tunnel

\( U_{\text{STS}} \)  
Gas exit velocity at the small tube source

\( x_{2,\text{CNTR}} \)  
x_2 coordinate of the plume centreline as a function of \( x_{\text{DST}} \)

\( x_{3,\text{ref}} \)  
Reference height level for the power law for the mean wind profile

\( x_{\text{DST}} \)  
Downstream distance to the gas release point (source)

\( x_i \)  
Spatial coordinate (\( i = 1 \): longitudinal, \( i = 2 \): lateral, \( i = 3 \): vertical)

\( z_0 \)  
Roughness length
### Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
</table>
| $\alpha$ | (i) Exponent of the power law for the mean wind profile  
(ii) Kolmogorov constant, set to $\alpha = 0.55$ |
| $\zeta$ | Stability parameter $\zeta = (x_3 - d_0)/L$ |
| $\Delta S$ | Difference between sweeps and ejections, $\Delta S = S_4 - S_2$ |
| $\partial_i$ | Spatial partial derivative $\partial/\partial x_i$ |
| $\delta$ | Boundary layer height |
| $\varepsilon$ | Dissipation rate $\varepsilon = 2\nu s_{ij}s_{ij}$ |
| $\dot{\varepsilon}$ | Pseudo dissipation rate $\dot{\varepsilon} = \nu \partial_j u'_i \partial_j u'_i$ |
| $\eta$ | Kolmogorov length scale $\eta = (\nu^3/\varepsilon)^{1/4}$ |
| $\lambda_F$ | Frontal area index, i.e. flow facing roughness area per unit horizontal area |
| $\lambda_P$ | Plan area index, i.e. horizontal built-up area per unit horizontal area |
| $\lambda_{ui,peak}$ | Peak wave length of the velocity spectrum $\lambda_{ui}(n)$ calculated by applying Taylor's 'frozen turbulence' hypothesis |
| $\nu$ | Kinematic viscosity of air |
| $\rho$ | Density of air |
| $\rho_i(\cdot)$ | Time autocorrelation coefficient of the $i^{th}$ velocity function |
| $\sigma_\theta$ | Standard deviation of the lateral angular fluctuations of the wind vector |
| $\sigma_\varepsilon$ | Standard deviation of the vertical angular fluctuations of the wind vector |
| $\sigma_h$ | Standard deviation of the building height distribution |
| $\sigma_i$ | Standard deviation of the $i^{th}$ velocity component, also called the 'ith turbulent velocity' |
| $\sigma_y$ | (i) Lateral spread parameter of the Gaussian plume model  
(ii) Lateral standard deviation of a fluid element's path in a turbulent fluid in G.I. Taylor's analysis |
| $\sigma_z$ | Vertical spread parameter of the Gaussian plume model |
| $\tau$ | Time interval |
| $\omega$ | Angular frequency, i.e. $[\omega] = \text{rad/s}$ |
Abstract

The goal of the first part of this work is the analysis of local as well as horizontally averaged turbulence characteristics in the urban surface layer above roof level. The motivation is that those characteristics are of immediate importance for urban dispersion modelling and numerical turbulence model validation. Up to now main insights are typically only available from wind tunnel studies utilizing grossly idealized roughness models or from field studies with limited horizontal and vertical reach. Those approaches are faced with concerns either about their applicability to real urban scenarios or about their representativeness for other locations within an urban environment.

The present study was conducted within the wind tunnel 'WOTAN' at the Meteorological Institute of the University of Hamburg. It is based on a wind tunnel model of Kleinbasel (Switzerland) which represents urban roughness typical for many western European cities and belongs to the roughness category 'tall and high density' according to the classification scheme proposed by Grimmond and Oke (1999). Scale of the model is 1:300, total size of the modelled urban area is 2.4km x 1.2km (downstream length and width in field measures). The main body of turbulence data was recorded above a horizontal area of 345m x 210m (field measures) in the core part of the model 1.4km downstream of the model inflow edge. This area is characterized by a mean building height of \( h = 14.6\text{m} \) and a plan area index of \( \lambda_P = 0.54 \). Velocity measurements were done by the means of laser Doppler anemometry. The flow was neutrally stratified.

Turbulence analysis reveals a roughness sublayer (RSL) extending up to 3.3h and characterized by its large degree of horizontal variability. Above the RSL the inertial sublayer (ISL) is identified by the significantly reduced horizontal variability, the constant Reynolds fluxes and the logarithmic wind profile. It extends from 3.3h to 5.5h. Surprising and to the knowledge of the author not available from the literature is the finding that horizontally averaged Reynolds fluxes within the RSL continue to be constant at least down to 1.8h (lowest measurement level). This is despite the fact that local Reynolds flux profiles show a great variability in the upper part of the RSL ranging from large peaks to downward decreasing fluxes. The variability of local fluxes around the...
horizontal average is found to be up to 50% which sets important limitations to the representativeness of local profiles with regard to a 'typical profile'. A quadrant analysis of Reynolds fluxes shows that in contrast to statements in the literature the RSL is not characterized by the domination of sweeps which start to prevail over ejections only below 2.3h. Also in this height range the vertical turbulent TKE flux turns from positive (i.e. upwards) to negative (i.e. downwards) close to roof level. To the knowledge of the author this substructure of the urban RSL above roof level has not been identified and analysed in other studies yet. Increasing horizontal variability close to roof level cause an increase of dispersive stresses. They are observed to be about 6% of the horizontally averaged Reynolds fluxes at 1.8h (lowest measurement level), at this height level their vertical divergence is found to be greater than the vertical divergence of horizontally averaged Reynolds fluxes. This suggests that dispersive stresses are not negligible in the overall momentum balance around roof level. Due to experimental difficulties this study did not attempt horizontaly representative measurements below 1.8h.

With height increasing vertical turbulent TKE flux contributions to the TKE budget are observed within the ISL. This is interpreted as the characteristic of a flow not completely adapted to the urban roughness in these heights. As judged from the height range of lowest vertical turbulent TKE flux contributions the height of flow adaptation is estimated to coincide with the RSL height. The incomplete adaptation in greater heights is considered to be the reason for the difference in the friction velocity estimates based on the logarithmic profile fit or on Reynolds flux measurements. This difference has also been observed in other wind tunnel studies but, to the knowledge of the author, without a convincing explanation yet. Incomplete flow adaptation offers such an explanation with the consequence that the mere existence of a logarithmic wind profile and a constant flux layer are not sufficient to detect a completely adapted flow including local equilibrium of TKE dissipation and production. Turbulent TKE flux contributions should also been included in such an analysis of flow adaptation.

The comparison to field measurements shows a very good reproduction of local field turbulence characteristics. This supports the applicability of the findings given above to full scale urban scenarios of comparable roughness.

The second part of this work focuses on modelling a field tracer experiment conducted in Kleinbasel in the context of the BUBBLE experiment. For this a passive non-buoyant tracer ($C_2H_6$) was released from a continuous source closely above roof level (at about 1.5h) and sampled systematically above roof level at downstream source distances between 384m and 864m and up to a height of 102m above ground (field measures). Mean concentrations and concentration time series were measured by the means of fast flame ionization detection.
The horizontal mean concentration distribution is well-represented by a Gaussian parameterization while close to roof level the vertical concentration profiles decrease less rapid with increasing height than assumed by the Gaussian model. The lateral and vertical spread parameters of the plume are found to be smaller and less rapid increasing than suggested by the urban Gaussian parameterization formulas proposed by Briggs (1973). To give an adequate representation of the observed concentration field the advection wind speed parameter for the Gaussian model should be taken as an increasing function with increasing source distance. This is due to the physical inadequacy of the assumptions of the Gaussian model in the strong wind shear close to the urban surface which leaves this model as 'a model to be tuned' in the studied dispersion scenario.

The field mean concentrations are consistently found to be overestimated by the wind tunnel concentrations, typically by a factor up to 10 (and even larger at some locations). This is attributed to stability effects, the regime was strongly unstable during the field experiment while the wind tunnel flow was always neutrally stratified.
Kurzfassung


Die vorliegende Studie wurde im Windkanal 'WOTAN' am Meteorologischen Institut der Universität Hamburg durchgeführt. Sie basiert auf einem Windkanalmodell von Kleinbasel (Schweiz), das repräsentativ ist für städtische Rauigkeit vieler westeuropäischer Städte und zur Rauigkeitskategorie 'tall and high density' gemäß der Klassifikation von Grimmond und Oke (1999) gehört. Der Modellmaßstab ist 1:300, das modellierte Stadtgebiet umfasst 2.4km x 1.2km (Länge in Strömungsrichtung mal Breite). Der wesentliche Teil der Turbulenzdaten wurde über einem horizontalen Gebiet der Größe 345m x 210m (Originalmaßstab) im Kernbereich des Modells 1.4km stromabwärts vom Modellanfang gewonnen. Dieses Gebiet ist charakterisiert durch eine mittlere Gebäudehöhe von \( h = 14.6 \)m und eine Bebauungsdichte von \( \lambda_p = 0.54 \). Geschwindigkeitsmessungen wurden mittels Laser Doppler Anemometrie durchgeführt. Die Strömung war neutral geschichtet.

Die Turbulenzanalyse ergibt eine Rauigkeitsschicht (RS) mit einer Höhe von 3.3h, diese ist charakterisiert durch die hohe horizontale Variabilität. Oberhalb der RS liegt die Inertialschicht (IS) identifiziert anhand der deutlich reduzierten horizontalen Variabilität, der konstanten Reynoldsflüsse und des logarithmischen Windprofils. Sie erstreckt sich von 3.3h bis 5.5h. Überraschend und nach Kenntnis des Autors nicht bekannt in der Literatur ist die Erkenntnis, dass die horizontal gemittelten Reynoldsflüsse innerhalb der RS konstant bleiben mindestens bis hinab zu 1.8h (unterstes Messniveau). Dies gilt trotz der Tatsache, dass lokale Profile von Reynoldsflüssen eine große Variabilität im oberen Teil
der RS zeigen, von deutlichen Extrema bis hin zu mit abnehmender Höhe abnehmenden Flüssen.

Die Variabilität der lokalen Flüsse um das horizontale Mittel beträgt bis zu 50%, was eine wichtige Einschränkung der Repräsentativität lokaler Profile hinsichtlich 'typischer Profile' darstellt. Im Gegensatz zu Aussagen in der Literatur ergibt eine Quadrantenanalyse der Reynoldsflüsse, dass die RS nicht charakterisiert ist durch die Dominanz von Sweeps, diese setzen sich erst unterhalb von 2.3h gegenüber Ejections durch. In diesem Höhenbereich wechselt auch das Vorzeichen der vertikalen turbulenten TKE-Flüsse von positiv (d.h. aufwärts) nach negativ (d.h. abwärts) in Dachnähe. Nach Kenntnis des Autors haben andere Studien diese Unterstruktur der RS bisher nicht identifiziert und analysiert. Zunehmende horizontale Variabilität in Dachnähe bedingt eine Zunahme der dispersiven Spannungen. Sie betragen ungefähr 6% der horizontal gemittelten Reynoldsflüsse in 1.8h (unterstes Messniveau), in dieser Höhe ist ihre vertikale Divergenz größer als die vertikale Divergenz der horizontal gemittelten Reynoldsflüsse. Dies legt den Schluss nahe, dass dispersive Spannungen nicht vernachlässigbar sind in der gesamten Impulsbilanz auf Dachniveau. Wenn experimenteller Schwierigkeiten wurden in dieser Studie keine horizontal repräsentativen Messungen unterhalb von 1.8h durchgeführt.


Der Vergleich mit Feldmessungen zeigt eine sehr gute Reproduktion der lokalen Turbulenzcharakteristiken. Dies unterstreicht die Anwendbarkeit der oben angegebenen Erkenntnisse auf reale Stadtszenarien vergleichbarer Rauigkeit.

Der zweite Teil dieser Arbeit widmet sich der Modellierung eines Feld-Tracer-
Experiments durchgeführt in Kleinbasel im Rahmen des BUBBLE-Projekts. Dafür wurde ein passiver, nicht-auftriebsbehafteter Tracer (C$_2$H$_6$) von einer kontinuierlichen Quelle knapp über Dachniveau (ca. 1.5h) freigesetzt. Seine Konzentration wurde systematisch oberhalb des Dachniveaus in Quellentfernungen stromabwärts zwischen 384m und 864m und bis in eine Höhe von 102m über dem Boden (Feldmaßstab) vermessen. Mittlere Konzentrationen und Zeitserien wurden mit Hilfe der Technik der 'fast flame ionization detection' gemessen.


Die mittleren Konzentrationen im Feldexperiment sind durchweg geringer als die mittleren Konzentrationen im Windkanal, typischerweise um einen Faktor 10 (und größer an einzelnen Lokationen). Dies wird auf Stabilitätseffekte zurückgeführt. Im Feldexperiment herrschte starke Instabilität vor, während die Strömung im Windkanal stets neutral geschichtet war.
Chapter 1

Introduction

By now the investigation of turbulence and pollutant dispersion in urban areas has already some history. According to Pasquill (1974, p. 301), one of the earliest systematic and thoroughly documented field investigation of air pollution took place in Leicester in 1937-9. Since then the sophistication of measurement equipment and modelling approaches has increased steadily. Nevertheless, owing to the physical complexity of the phenomena and the technical challenges associated with the mathematical modelling as well as with the experimental studies, research is ongoing and important issues are still either not completely understood or not incorporated adequately in corresponding models. Over the decades the motivations to study those phenomena have remained essentially the same and have become a standard part in the introduction of many dispersion studies. This study is no exception. Quoting WMO (1958, p. 37), the motivation is "that under certain meteorological conditions the local air pollution levels may become serious social, economic, or health problems, particularly in industrialized urban regions". The problems may be judged by "sensory responses such as reduced visibility, offensive odour, or by respiratory discomfort, etc.". It has become custom to augment those motivational statements with data documenting the increasing levels of worldwide urbanization. This data is compiled and readily available from the United Nations (see e.g. the Global Environment Outlook (2002) from UNEP). The huge regulatory body, concerned with air quality management and in place in many parts of the world, documents the wide acknowledgement of the importance of those issues. The more important is a reliable and experimentally verified scientific basis for problem solving and decision making.

The Basel urban boundary layer experiment (BUBBLE) provides the context and large parts of the funding for the present wind tunnel study. One major activity within BUBBLE was an one-year observational period of turbulence characteristics in the greater area of Basel, Switzerland (2001/2002). With
the motivation to realize the benefits of synchronized efforts in field observations and modelling studies, the present wind tunnel study was initiated. Consequently, the urban area to be modelled in the wind tunnel was selected according to the location of one of the key measurement towers in the field whose data was analysed extensively. Thus Kleinbasel was chosen to be put into the wind tunnel. An excellent opportunity was opened for a direct comparison of field observations and wind tunnel modelling results.

While being restricted to neutral flow stratification, this wind tunnel study focuses on two topics which are apparently still open or under discussion in the literature:

1. Horizontally averaged urban turbulence profiles above roof level within the surface layer
2. Mean concentration field above urban roof level of a conserved, passive, non-buoyant scalar released from a point source closely above roof level at source distances roughly between 400m and 900m

The essential, but rather general qualification 'urban' is made more specific by reference to the urban roughness classification scheme proposed by Grimmond and Oke (1999). Given this classification the urban roughness of Kleinbasel belongs to the category 'tall and high density'. General qualitative and quantitative characteristics of this roughness class can be found in the cited study. Seemingly this type is characteristic for many western European cities. Therefore the turbulence characteristics investigated in this study may also apply to other urban areas with similar roughness characteristics and topography. No significant elevations are present in the model area Kleinbasel, therefore the topography is described as 'flat'.

A standard conceptual framework used in urban turbulence studies is depicted in Fig. 1.1. Given this framework, the following questions are analysed in this study with regard to the first focus on turbulence:

1.1. What is the state of flow adaptation to the urban roughness above the core area of the wind tunnel model about 1.6km downstream of the model inflow edge? (This is the location of the measurement tower in the field.)

1.2. What are the characteristics of the horizontal turbulence layers (the inertial sublayer and the roughness sublayer, see Fig. 1.1) with particular emphasis on horizontally averaged properties?

In the course of this study various turbulence characteristics are analysed (as it is apparent from a quick look at the table of contents).
The approach flow is coming from lower, non-urban roughness. Estimates of the roughness sublayer height range from 2h to 5h (Raupach et al. (1991)), the inertial sublayer constitutes the upper part of the surface layer typically reaching up to 10% of the total boundary layer height (Stull (1988)). A rule of thumb for the equilibrium layer height is 1% of the upstream fetch of (approximately) homogeneous roughness characteristics (Roth (2000)).

During the BUBBLE project, dispersion field experiments were conducted (June/July 2002). Tracer gas was released and sampled closely above roof level at source distances between a few hundred metres and about one kilometre. The wind tunnel model is designed to reproduce this setup (but under neutral conditions) with the following key questions under investigation:

2.1. What is the mean concentration field above roof level and how may it be related to the turbulence characteristics?

2.2. How do the wind tunnel measurements compare to the field measurements given wind direction fluctuations in the field and effects due to instability?

The analysis of urban turbulence uses to a large extend the standard notions and theoretical concepts of turbulence research, i.e. statistical quantities, budget equations, fluctuation spectra, characteristic length scales etc.. These concepts are summarized in chapter 2 including some more detailed discussions of rough wall turbulence and the logarithmic wind profile. This chapter also contains a discussion of the similarity laws which allow for the fascinating possibility to put an urban area into the wind tunnel. Having laid those foundations, some particularities of urban turbulence and dispersion are touched upon in chapter 3 with a short reference to present day focus of urban turbulence studies and the corresponding state of knowledge. It does not have to be mentioned (and therefore it is mentioned) that particularly in this chapter the gap between what is said and what could be said is large. But this admittedly
discomforting gap is not taken as an excuse to say nothing at all. Chapter 4 goes straight to the description of the experimental setup. The wind tunnel and the measurement equipment are introduced, the urban model is specified and the measurement locations are identified. An important boundary condition for the wind tunnel model is the approach flow with its turbulence characteristics. Chapter 5 describes the efforts to extract those characteristics from Basel field data. Only then the stage is prepared for the two central chapters of this work, chapter 6 dealing with the turbulence characteristics and chapter 7 describing the dispersion results from this study. The findings are summarized in the conclusions at the end of each chapter. The insights gained from this study are wrapped up in the summary chapter 8. Additional data and specifications can be found in appendices A to F.
Chapter 2

Theoretical background

In the following a brief overview over the basic notions and concepts of turbulence and dispersion theory is given as far as it is of immediate relevancy for the present study. Thorough derivations and more detailed interpretations are given elsewhere (e.g. Batchelor (1967), Pope (2000), Rodean (1996), Tennekes and Lumley (1972), Townsend (1976)).

2.1 Remarks on notation

The wind tunnel coordinate system is defined as follows: The positive longitudinal direction is given by wind tunnel axis in flow direction, the positive vertical direction is given upwards from the surface with the origin at the material surface of the wind tunnel floor and the lateral direction is defined in such a way to give a right-handed orthogonal coordinate system. Further specifications, in particular about the longitudinal and lateral origins, are given when the experimental setup is introduced. The longitudinal, lateral and vertical coordinate axes are labelled by \( i = 1, 2 \) and 3 respectively giving the coordinates \( x_1, x_2, x_3 \) with the instantaneous Eulerian flow velocities \( u_1, u_2 \) and \( u_3 \). Mean quantities are referred to with capital letters, e.g. \( U_i \), turbulent quantities have a prime, e.g. \( u'_i \). The functional dependency on the coordinates is frequently suppressed, i.e. \( u_i \) generally means \( u_i(x_1,x_2,x_3) \) etc..

The tensor notation is adopted throughout this work with Einstein’s summation convention applied, i.e. repeated indices are summed over from 1 to 3. Partial derivatives are abbreviated by

\[
\partial_i = \frac{\partial}{\partial x_i}
\]
2.2 Budget equations for turbulent fluids

This study is based on the Newtonian fluid model with fluid density and kinematic viscosity independent of space and time as it is standard practice in low speed wind tunnel modelling under neutral conditions. The fluid of choice is air. Under the given constant wind tunnel boundary conditions the turbulence is assumed to be in a steady state, i.e. $\partial / \partial t = 0$ for all statistical moments.

The dynamics in an inertial frame of reference including the gravitational force density $\rho g$ are given by the momentum budget, also known as the equations of motion or the Navier-Stokes (NS) equations in the fluid mechanical context, which read in Eulerian coordinates for the instantaneous $i^{th}$ velocity component $u_i$

$$u_j \partial_j u_i = -\frac{1}{\rho} \partial_t p + 2\nu \partial_j s_{ij}$$  \hspace{1cm} (2.1)

with

$\begin{align*}
s_{ij} & \equiv \frac{1}{2}(\partial_i u_j + \partial_j u_i) & \text{: instantaneous rate-of-strain tensor} \\
p & \text{: instantaneous pressure minus hydrostatic pressure} \\
    & p_{hyd} = p_0 - \rho g z_3 \\
\rho & \text{: density of air (constant)} \\
\nu & \text{: kinematic viscosity of air (constant)}
\end{align*}$

In general treatments of the atmospheric boundary layer another body force term, the Coriolis force, is included in Eqn. (2.1) due to the non-inertial nature of a frame of reference attached rigidly to the earth's surface. Since the present modelling focus is on the surface layer with restricted horizontal extension, this term is ignored based on two arguments:

- Within the surface layer it is an observational finding and frequently remarked in introductory books (e.g. Holton (1992), p.131, Garrat (1994), pp.1-2 and Fig. 3.2 on p.46, Schatzmann (2001), pp.129-130) that the effects of the Coriolis force are very small in comparison to the surface momentum flux. Its turning effect on wind direction is negligible. Therefore the flow dynamics within the atmospheric surface layer are very similar to flows in non-rotating frames of reference.
• In his review of flow modelling practices and results Snyder (1981, p.10) states that for characteristic horizontal scales below 5km the Coriolis force can be neglected. The argument is formulated in terms of Rossby number similarity. In the non-inertial equations of motions (i.e. including the Coriolis force) the Rossby number plays a similar role for Coriolis effects as the Reynolds number plays for viscous effects. The present wind tunnel model has a full scale horizontal extension of approximately 2.5km, therefore Coriolis effects are neglected (for a discussion and review see also Snyder (1972)).

The mass budget under the assumption of incompressibility reduces to the continuity equation

$$\partial_t u_i = 0. \quad (2.2)$$

The statistical treatment of turbulent flows distinguishes the mean flow $U_i$ and the turbulent flow $u'_i$ (with $u_i = U_i + u'_i$) which interact according to the Reynolds-averaged Navier-Stokes (RANS) equations

$$U_j \partial_j U_i = -\frac{1}{\rho} \partial_i P + \partial_j (2\nu S_{ij} - u'_j u'_i) \quad (2.3)$$

introducing thereby the Reynolds stresses $-u'_j u'_i$. They provide the turbulent mechanism for momentum transport within a turbulent fluid. The continuity equations for the mean and turbulent flow components are

$$\partial_t U_i = 0 \quad \text{and} \quad \partial_t u'_i = 0. \quad (2.4)$$

The kinetic energy of the mean flow $\frac{1}{2} U_i U_i$ is subject to the budget equation

$$U_j \partial_j \left( \frac{1}{2} U_i U_i \right) = -\partial_j \left( \frac{1}{\rho} U_j P + \overline{u'_j u'_i} U_i - 2\nu U_i S_{ij} \right) + \overline{u'_j u'_i S_{ij}} - 2\nu S_{ij} S_{ij}, \quad (2.5)$$

the budget for the turbulent kinetic energy (TKE) $q = \frac{1}{2} u'_j u'_i$ is given by

$$U_j \partial_j q = -\partial_j \left( \frac{1}{\rho} \overline{u'_j u'_i} + \overline{u'_j u'_i u'_i} - 2\nu \overline{u'_i S_{ij}} \right) - \overline{u'_j u'_i S_{ij}} - 2\nu S_{ij} S_{ij}. \quad (2.6)$$

For a thorough interpretation and order-of-magnitude estimation of the individual terms refer to Tennekes and Lumley (1972). In short, under steady-state conditions the budget of $q$ consists of a balance of, in order of appearance in the above budget equation, (a) advection by the mean flow, (b) transport by pressure, turbulent and viscous mechanisms, (c) production through coupling
to the mean rate of strain, which has an analogous loss term in the budget for \( \frac{1}{2}U_i U_i \), and (d) dissipation \( \varepsilon = 2\nu \overline{s'_{ij} s'_{ij}} \) to the molecular level.

Remark: The above given form of the mean and turbulent kinetic energy budgets in Eqns. (2.5) and (2.6) is chosen to emphasize their structural similarity. The term \( 2\nu \overline{s'_{ij} s'_{ij}} \) readily allows the identification as dissipation to heat (Batchelor (1967), p.153). A different form of the TKE budget can be found in the literature based on the identity

\[
2\nu \overline{u'_i s'_{ij}} = \nu \overline{\partial_j q} - \nu \overline{u'_i \partial_j u'_i}. \quad (2.7)
\]

The RHS shows an appealing, i.e. easy to interpret, viscous diffusion term for TKE. The drawback is that the dissipation \( \varepsilon \) is replaced by the pseudo-dissipation \( \bar{\varepsilon} = \nu \overline{\partial_j u'_i \partial_j u'_i} \). It is stated in the literature that under 'virtually all circumstances' it is \( \varepsilon \approx \bar{\varepsilon} \) (Pope (2000), p.132). Therefore some authors simply refer to \( \bar{\varepsilon} \) as 'dissipation' (e.g. Stull (1988), p. 123).

### 2.3 Similarity theory and the scaling approach

The compact notation of the budget equations (2.3), (2.5) and (2.6) given above is rather deceptive: No general solution exists in turbulent fluid dynamics, i.e. given arbitrary physical boundary and initial conditions, generally it is not feasible to determine exact solutions (neither in the classical nor in the weak sense) for the equations of motion with the currently available mathematical methods. Within the RANS approach this complexity is illustrated by the closure problem linked to the non-linearity of the NS equations. For the complete specification of a general joint probability distribution (e.g. for the \( u'_i \)'s) the countable but infinite number of its statistical moments must be specified. These moments and their temporal evolutions are determined by an infinite number of differential equations, which are known and could be deduced in principal, but which are entangled in such an unfortunate way that it is not possible to take a finite subset of equations specifying the same number of statistical moments. The number of unknowns always exceeds the number of equations. Every finite subsystem of those equations remains open in this sense and that is how the closure problem got its name. Based on more or less physical reasoning a multitude of closure schemes have been introduced in the literature to 'cut short' the infinite set of equations (for an introduction see e.g. Stull (1988)) which all have their specific and prior to the experimental test not always easy to identify range of applicability.

To deal with a specific turbulent flow the equations of motion have to be augmented with additional physical insights which may not be valid in general
but only for a (small) subclass of turbulence scenarios. Similarity theory (and in particular Buckingham Pi theory, see e.g. Stull (1988)) is one way to formalize the application of those insights which otherwise rely on experimental experience and physical intuition of the individual. Objective of this kind of 'theory' is the construction of non-dimensional quantities. The focus of research is thereby restricted to relations which do not suffer from dimensional inconsistencies. Necessary prerequisite for this approach is the optimism (or hypothesis) that all dimensional quantities relevant to the problem are known. The 'non-dimensionalization' is based on the identification of 'scales' which may lead to a simplified set of physical observables appropriate for guiding experimental studies or direct solution. For a thorough application of the scaling approach to turbulence see Tennekes and Lumley (1972).

Indeed, the description of turbulent flows makes extensive use of scales. Especially within the domain of wind tunnel modelling, which utilizes geometrically shrunk urban roughness models, the insights appropriate for comparison to full scale scenarios are presented in non-dimensional form, i.e. the dimensional findings are set in relation to suitable scales of the same physical dimension. The assumption of transferability of well-chosen non-dimensional wind tunnel findings to full scale scenarios constitutes the fundamental paradigm of this modelling approach. By comparing non-dimensional, i.e. appropriately scaled, wind tunnel results to field measurements, this study offers the opportunity to check this paradigm.

The general phenomenological relationships discovered by the application of similarity theory are plentiful, nevertheless it should always be kept in mind that the 'scaling ballet' which can be found in some treatises on turbulence is a rather poor (though sometimes astonishingly insightful) substitute for a completely solved theory of turbulence which is still to come.

### 2.4 Reynolds number similarity and independence

Why can wind tunnel turbulence model the atmospheric surface layer? It is clear that within the wind tunnel 'some kind of turbulence' can be produced, but why should that be an appropriate model of atmospheric turbulence? Instead of just referring to the empirical findings which provide a 'proof of concept' of the wind tunnel modelling approach (see e.g. Snyder (1981)), the conceptual foundations of this approach are hopefully made clear in the following. Central themes are the concepts of 'Reynolds number similarity' and, more important, 'Reynolds number independence'.
Starting point of the discussion is the RANS equation (2.3). It is clear that a mathematical analysis of turbulence must somehow solve this equation for a non-divergent velocity field (fulfilling Eqn. (2.4), thereby assuming constant density). The mathematician (or the courageous physicist or the very courageous meteorologist) assigned to deal with this problem will probably think about it in terms of some real-valued functions defined on some subset of some $\mathbb{R}^n$ with some given boundary conditions which in turn are also most probably specified in terms of some real-valued functions. When the problem is solved the mathematician returns some real-value solution functions to the grateful physicist (or very grateful meteorologist) who assigns some physical units to those functions and interprets them as velocities, pressures, etc. The important point is that, in principle, the mathematician does not care about the physical interpretations and units of the considered functions. He likes those functions ‘naked’ with all physical units being stripped off. Knowing (and accepting) these mathematical preferences, the RANS equation (2.3) should be formulated in a mathematically efficient way, i.e. in terms of intrinsically non-dimensional variables. Therefore some velocity scale $U_{ref}$ and some length scale $L_{ref}$ are introduced (they should be, of course, determined by the given turbulence scenario) and the following non-dimensional instantaneous variables are constructed:

\[ u_i^* = u_i/U_{ref} \]  \hspace{1cm} (2.8)
\[ x_i^* = x_i/L_{ref} \]  \hspace{1cm} (2.9)
\[ \left( \frac{p}{\rho} \right)^* = \left( \frac{p}{\rho} \right)/U_{ref}^2 \]  \hspace{1cm} (2.10)

with the corresponding mean and fluctuating variables defined analogously. If the RANS equation (2.3) is formulated in terms of these non-dimensional variables and then multiplied by $U_{ref}^2/L_{ref}$ to make the whole equation non-dimensional, one gets the non-dimensional RANS equation

\[ U_j^* \partial_j^* u_i^* = -\partial_i^* \left( \frac{p}{\rho} \right)^* + \partial_j^* \left( \frac{2}{Re} S_{ij}^* - \overline{u_i^* u_j^*} \right) \]  \hspace{1cm} (2.11)

and the incompressibility expressed as

\[ \partial_j^* u_j^* = 0 \]  \hspace{1cm} (2.12)

with $\partial_i^* = \partial/\partial x_i^*$ and $Re \equiv U_{ref} L_{ref}/\nu$. All equations for the higher order moments can also be formulated in terms of non-dimensional quantities as well. The insight from this simple transformation is huge: All turbulence scenarios with geometrically and kinematically similar boundary conditions and initial values and the same Reynolds number Re should have the same
non-dimensional turbulence characteristics because their equations of motion (i.e. the non-dimensional RANS equation (2.11)) are exactly the same. For a mathematician those turbulence scenarios are indistinguishable and he might describe this phenomenon by saying that 'on the set of all turbulence scenarios an equivalence relation is defined whose equivalence classes consist of all those turbulence scenarios obeying exactly the same non-dimensional equations of motions under the same non-dimensional boundary and initial conditions'. Physicists (and meteorologists) call this phenomenon simply 'Reynolds number similarity'.

The principle of 'Reynolds number similarity' offers a great potential for efficient problem solving. For each of the above introduced equivalence classes only one turbulence scenario has to be analysed to understand the complete class. Therefore the desire is to maximise the size of each equivalence class. Hopefully, the larger the classes, the less individual turbulence scenarios have to be analysed. The desire to maximise the equivalence classes leads to the requirement that \( U_{\text{ref}} \) and \( L_{\text{ref}} \) should be 'characteristic velocity and length scales of the turbulence system'. In principle, \( L_{\text{ref}} \), say, could be any length, e.g. the height of the researcher studying the turbulence system. This choice of \( L_{\text{ref}} \) would give a different Reynolds number \( Re \) and different non-dimensional coordinates \( x^* \) for a short and a tall researcher respectively and the efforts of the (poor) mathematician having to work for both of them might be doubled. (Unless he is clever enough to notice the equivalence by an appropriate scale transformation, but why should the glories of this discovery be reserved for him, the non-physicist?) The classes of equivalent turbulence scenarios would be very small. Therefore this choice of \( L_{\text{ref}} \) would not be 'wrong' in the strict sense (it is perfectly possible for each researcher to work with his length scale), but it would be terribly inefficient and therefore simply stupid. No straightforward exchange of insights from studies of seemingly different turbulence scenarios would be possible. To avoid this kind of inefficiency and stupidity, researchers like to choose 'characteristic' and 'physically relevant' length and velocity scales of the studied turbulence scenario. The choice of those scales can then be made subject to scientific discussion based on the criteria of efficiency and unification of experimental observations. As a side remark it is noticed, that due to the non-dimensional coordinates \( x_i^* \) all non-dimensional turbulence length scales are also given in units of \( L_{\text{ref}} \).

Do the wind tunnel turbulence modelled in this study and the full scale atmospheric surface layer turbulence belong to the same equivalence class of turbulence scenarios? To calculate the respective Reynolds numbers and by anticipating some of the measurements presented later in this study, the following scale choices are made:
$L_{\text{ref}}$ : The mean building height $h$ is assumed to be a characteristic length scale within the surface layer and closely above roof level, although other length scales may also play their role in this complex flow scenario. Instead of $h$, the (equivalent) length scale $2.2h$ is taken for $L_{\text{ref}}$, since at this height level velocity measurement both in the field and in the wind tunnel are available.

$U_{\text{ref}}$ : The mean wind speed measured at $x_3 = L_{\text{ref}}$ at the location Basel-Sperrstrasse (BSPR, the locations are introduced in chapter 4.5, see in particular Fig. 4.12 on page 66) is taken for $U_{\text{ref}}$. At this height level the velocity profile is assumed to be strongly influenced by the urban roughness of scale $h$, therefore $L_{\text{ref}}$ and $U_{\text{ref}}$ are both assumed to be characteristic scales for the 'urban surface layer, closely above roof level' turbulence scenario.

Taking typical values for the flow in the field ($L_{\text{ref}} = 31.7\text{m}, U_{\text{ref}} = 2\text{m/s}$ as a characteristic velocity during the field tracer experiments) and in the wind tunnel ($L_{\text{ref}} = 0.106\text{m}, U_{\text{ref}} = 3.37\text{m/s}$), one gets

$$Re_{\text{field}} = 4,226,667$$

and

$$Re_{\text{wind tunnel}} = 23,815.$$  

It is seen that the Reynolds number in the field is about a factor 177 larger than in the wind tunnel. The above outlined criterion of 'Reynolds number similarity' is therefore not fulfilled and both turbulence scenarios are not equivalent in the above given sense. This comes not at all surprising because with a geometric scale reduction of, say, 1/300 (as in this study) the velocity scale had to be increased by a factor 300 to ensure 'Reynolds number similarity'. This is not possible in the given wind tunnel. Nevertheless it is remarked that in both cases, due to the magnitude of the Reynolds number, the viscous term in the RANS is strongly suppressed by the factor $2/Re$. This strong suppression at sufficiently high Reynolds numbers (where it should make no big difference whether the viscous term is very much suppressed or very, very much suppressed) gives way to a second phenomenon, 'Reynolds number independence', which is discussed now.

Focus of this wind tunnel study is on the analysis of turbulence characteristics as e.g. the mean wind field, turbulent Reynolds fluxes, turbulent velocities $\sigma_i$ and terms of the TKE budget. These characteristics are closely related to the anisotropy of turbulence (e.g. the turbulent Reynolds fluxes would be zero in isotropic turbulence) and are determined by the 'most energetic structures' within the turbulence. At least since the works of Kolmogorov it has become standard practice in turbulence research to decompose turbulent
flows heuristically in different ranges of eddy length scales and to assign typical prevalent dynamics to each of those ranges. Without going too much into detail (it can all be found in the standard text books), the flow decomposition (for sufficiently large Reynolds numbers) distinguishes a range of small eddy length scales, whose dynamics and characteristics are basically the same for all turbulent flows and can be described universally, and a range of large eddy length scales, which show a clear dependency on the given boundary conditions and which are therefore different for different flow scenarios. The small scale turbulence is assumed to be isotropic (since there appears to be no reason for a kind of 'universal anisotropy'), while the large scale turbulence reflects the (an)isotropy of the boundary conditions.

Given this heuristic picture of turbulence, two experimental findings in turbulent flows at sufficiently large Reynolds numbers are key to the understanding of 'Reynolds number independence':

- The largest fraction of the total TKE is deposited in the larger scale eddy structures which are characteristic for the given turbulence scenario and which are therefore mostly anisotropic. Only a comparatively small fraction of energy is stored in the universal, small scale eddy structures. This insight results from a spectral analysis of turbulent flows.

- With increasing Reynolds number certain non-dimensional characteristics of turbulent flows evolve until they reach a 'final state' at a certain threshold Reynolds number. Above this threshold these characteristics are independent of the Reynolds number and stay constant. The standard textbook example for this phenomenon is the drag coefficient in turbulent rough wall pipe flow (see e.g. Stull (1988), pp. 353-354).

Given the observed constancy of certain integral characteristics above a certain threshold Reynolds number and given the energetic dominance of the larger scale structures (which should therefore be dominant contributors to these integral characteristics), the following heuristic picture appears: Up to the threshold Reynolds number the larger scale eddy structures evolve and change their characteristics, while above the threshold Reynolds number these structures appear to be fully developed (in terms of scaled characteristics) with further development prohibited by the given boundary conditions (e.g. rigid walls). The major consequence of further increasing the Reynolds number above its threshold value appears to be a 'down-sizing' of the smallest eddy structures. E.g. it is known that the Kolmogorov scale defined by

$$\eta = \left( \frac{\nu^3}{\varepsilon} \right)^{1/4}$$  \hspace{1cm} (2.13)
associated with the smallest eddy scales decreases continuously with increasing Reynolds number (see e.g. Tennekes and Lumely (1972)).

Wind tunnel modelling of atmospheric turbulence exploits this phenomenon of 'Reynolds number independence'. The goal is to get the larger scale turbulence structures right while being somewhat neglectful with the smaller scale structures. The latter carry only a small fraction of the total kinetic energy and do not bear the characteristic anisotropies of the system. The Reynolds number in the wind tunnel has to be large enough (to be above the threshold), but does not have to match the field Reynolds number. The small scale structure of atmospheric turbulence is not modelled in the wind tunnel, i.e. questions like 'what is the smallest eddy size in the field' can not be answered by direct measurements in the wind tunnel. (Nevertheless, as stated above, this range of small eddy scales has universal characteristics, therefore modelling 'characteristic small(est) scale atmospheric turbulence' is not really meaningful, these scales behave universally in all turbulence systems.)

Now that the foundations for the appropriateness of wind tunnel modelling are clarified and a bath in heuristic notions has been taken, two important questions remain:

1. What is the size of those 'larger scale energetic eddy structures characteristic for the anisotropies of the turbulence system'?

2. Are those 'larger scale structures' represented correctly in the wind tunnel model?

Concerning the first question it is noted that the range of eddy scales, where universal behaviour sets in, is termed the inertial subrange. It is identified by the characteristic '-2/3 slope' in the velocity spectra. Simiu and Scanlan (1986, p.54) report that this inertial subrange is height dependent and starts at eddy length scales around and below $5(x_3 - d_0)$ (for $d_0$ see chapter 2.6). As remarked by Garrat (1992, p.76), the upper length scale end of the inertial subrange does not coincide with the onset of local isotropy. Kaimal et al. (1972) conclude from their data that local isotropy starts at eddy length scales below $0.6(x_3 - d_0)$ (for neutral conditions, see Fig. 23 in their publication). Given these rough estimations and anticipating $d_0 = 10.2m (0.7h)$ and a height level of, say, $x_3 = 19.5m (1.3h)$ in the field scenario, it follows that at this height level the inertial subrange length scales may start closely below 50m and local isotropy sets in at eddy scales of about 5m. Although the details of those 'rule of thumb' estimations could be questioned (e.g. the estimation in Kaimal et al. (1972) is derived from turbulence data above a flat and homogeneous surface), they define a rough order of magnitude expectation. The implication for wind tunnel modelling is that eddy length scales should
be modelled adequately at least down to the range 5m - 50m (in field measures). It is observed in field experiments that in this range the contributions of eddies to turbulent velocities $u_i$ and turbulent fluxes $\overline{u_i u_j}$ decrease significantly with decreasing scale which supports the modelling approach to focus on the larger scale structures (see e.g. Garrat (1992)).

Turning to the second question and anticipating estimations of the dissipation rate $\varepsilon$ in the wind tunnel (presented in more detail later in this study) it is noted that the lower limit of wind tunnel eddy scales, the Kolmogorov scale $\eta_{\text{wind tunnel}}$, is about $0.2 \cdot 10^{-3}m$ as calculated from Eqn. (2.13). Bearing in mind the geometric scale factor, this length scale corresponds to $0.2 \cdot 10^{-3}m \cdot 300 = 6 \cdot 10^{-2}m$ in the field. Comparing this minimal eddy length present in the wind tunnel to the field Kolmogorov scale $\eta_{\text{field}}$, which might be expected to be in the order of $10^{-3}m$ (see e.g. Stull (1988, p. 167)), it is clear that the wind tunnel model applies a high frequency cut off, i.e. the smallest field eddy scales are not present in the wind tunnel. In the light of the above given scale estimations for the inertial subrange and the range of isotropic turbulence, this cut off should have no effect on the integral characteristics of the turbulent flow (i.e. mean wind field, turbulent velocities, turbulent fluxes, etc.) and no effect on the representation of the larger scale eddy structures. Concerning the correct representation of these larger scale structures in the wind tunnel, the assessment approach is straightforward: Compare the wind tunnel data to the field data! To the knowledge of the author there is no theoretic argument which predicts a priori the exact numerical value of the critical Reynolds number above which 'Reynolds number independence' prevails. Instead, a huge body of empirical evidence has been amassed which supports the expectation that with due care 'Reynolds number independence' can be established in the wind tunnel (see e.g. the list of references given in VDI (2000) and the discussion in Snyder (1981)). By the use of vortex generators and floor roughness, atmospheric turbulence characteristics in the approach flow for a given wind tunnel model can be established with turbulence integral length scales corresponding to the scale of the model. This allows the study of realistically scaled atmospheric turbulence above the model and constitutes an empirical fact which is made plausible by the phenomenon of 'Reynolds number independence'.

Summarizing the foundations of modelling atmospheric surface layer turbulence in the wind tunnel, it has been stated that

- for geometrically and kinematically similar turbulence scenarios the Reynolds number provides a classification scheme for equivalent scenarios having the same Reynolds number,

- the wind tunnel turbulence and the atmospheric surface layer turbulence do not belong to the same equivalence class since they have different
Reynolds numbers, therefore the argument of 'Reynolds number similarity' cannot be applied to this kind of wind tunnel modelling,

- the wind tunnel model with the appropriate boundary conditions can be expected to produce the same integral and, over large parts except the smallest length scales, the same spectral characteristics if it is operated in the range of 'Reynolds number independence'. This empirically observed independence is related to the strong suppression of the viscous term in the non-dimensional RANS equation at sufficiently large Reynolds numbers.

Every wind tunnel study of atmospheric turbulence has to give account of its state of 'Reynolds number independence', either by plausible reference to other studies or by direct comparison to field data. In this study the opportunity of available field data is exploited. Further discussion of the application of similarity criteria to fluid modelling is provided in Snyder (1972).

In the context of scale reduction within the wind tunnel model it is instructive to note also the time scale reduction. This is due to the geometric scale reduction as well as to the fact that the wind speeds in the wind tunnel are roughly the same as those in the atmosphere. The most straightforward demonstration of time scale reduction may be given by the observation that for a given wind speed the time, which a fluid particle needs to pass by a given geometry of length $L_{\text{ref}}$, is proportional to exactly this $L_{\text{ref}}$. Therefore if $L_{\text{ref}}$ is reduced by a factor of, say, 300, then the travel time scales of the fluid particles are also reduced by the same factor (in the sense that everything happens much faster to the fluid particles in the reduced geometry). The demonstration of time scale reduction can be made more elaborated by considering the TKE budget. Since the wind speeds are roughly the same in the wind tunnel and in the atmosphere, the TKE is also roughly the same. So are the Reynolds fluxes. But due to the geometric scale reduction, spatial derivatives of, e.g., the mean wind $U_1$ are increased corresponding to the scale factor, therefore the TKE production term $-\bar{u}'_1\bar{u}'_2\partial_3U_1 \left(-\bar{u}'_1\bar{u}'_2S_{ij} \text{ in Eqn. (2.6)}\right)$ is increased roughly by the geometric scale factor. For a model scale of, say, 1:300 the same amount of TKE is produced 300 times faster in the wind tunnel than in the atmosphere. Concerning the dissipation rate $\varepsilon$ and following Snyder (1972, formula (16)), it can be shown that the Kolmogorov length scale $\eta$ scales with $L_{\text{ref}}^{1/4}$. (As a side remark it is noted that, for a model scale of 1:300 as it is used in this wind tunnel study, one should expect $\eta_{\text{field}} \approx 4.2\eta_{\text{wind tunnel}}$. This appears to be in accordance with the above made quantifications of $\eta_{\text{field}}$ and $\eta_{\text{wind tunnel}}$.) As it was introduced in Eqn. (2.13), $\varepsilon$ scales with $\eta^{-4}$ and therefore with $L_{\text{ref}}^{-1}$. It follows that the dissipation rate scales inversely with the geometric scale, i.e. in the above numeric example the energy is dissipated 300 times faster. Summarizing, it is shown that according to the geometric scale reduction the
'TKE life cycle' is much faster in the wind tunnel than in the atmosphere, while the absolute levels of TKE are roughly the same. The wind tunnel time scale is reduced according to the geometric scale factor.

2.5 Boundary layer approximations

Phenomenological discoveries of general relationships between non-dimensional quantities are one line of attack on turbulence, another approach is the analysis of simplified equations of motion. Especially powerful simplifications are the boundary layer approximations of the RANS equation (2.3) which give for the dominating $U_1$ component

$$U_1 \partial_t U_1 + U_3 \partial_3 U_1 = -\frac{1}{\rho} \partial_t P - \partial_3 u' \partial_3 u'. \quad (2.14)$$

They are applicable to flows at large Reynolds numbers within boundary layers where flow symmetries and dominant directions of flow variation allow an identification of dominating terms within the complete RANS equation. Only those terms are retained in the above given approximation (2.14), for a derivation see e.g. Townsend (1976). One immediate insight is that for slow longitudinal variation (i.e. small $\partial_t U_1$), small $U_3$ close to the impermeable surface and vanishing pressure gradient $\partial_t P$ a vertically constant flux layer should be expected since then $\partial_3 u' \partial_3 u' \approx 0$. This constant value $u_2^2 = -u_1' u_3'$ close to the surface is denoted the (square of the) friction velocity and represents an omnipresent velocity scale. This constancy is in agreement with atmospheric boundary layer observations (see e.g. Stull (1988), p.357) and characterizes the so-called 'constant flux layer' or inertial sublayer. Turning the argument around one implication for wind tunnel modelling is that the axial pressure gradient should vanish to obtain a constant flux layer within a slowly developing boundary layer.

The simplified budget equation for the TKE $q$ within the boundary layer approximation is

$$U_1 \partial_t q + U_3 \partial_3 q = -\partial_3 \left( \frac{1}{\rho} u' \partial_3 u' - \frac{1}{2} u_3' u_2' \right) - \partial_3 u_1' \partial_3 U_1 - \varepsilon \quad (2.15)$$

(see e.g. Raupach et al. (1991)). In this wind tunnel study the TKE production term, the vertical turbulent transport term and the dissipation rate are estimated from measurements.
2.6 Rough-wall boundary layer flows and the logarithmic wind profile

Atmospheric boundary layer flows, and in particular urban boundary layer flows, are a subclass of general rough-wall boundary layer flows bounded on one side by a rigid, impermeable and rough wall. A 'rough wall' is distinguished from a 'smooth wall' by comparing the roughness element height $h$ to the viscous length scale $v/u_\ast$. $hu_\ast/v < 5$ (with non-zero $u_\ast$) characterizes smooth walls, 'dynamically fully rough' flows are obtained for $hu_\ast/v > 70$ (always the case in the atmospheric context), see Raupach et al. (1991). It is appropriate to give a short summary of the general characteristics of rough-wall boundary layer shear flows with focus on the surface layer. Many more details can be found in the comprehensive review by Raupach et al. (1991).

A simple approach to boundary layers distinguishes an inner layer (other terms for the same region are 'wall layer' or 'surface layer'), an outer layer and the overlap region of the two layers, the latter existing as a physically distinct layer in many, but probably not all flow scenarios. The inner layer being close to the wall accounts for roughly 10% to 20% of the total boundary layer height. It is characterized by steep velocity gradients and therefore high turbulence levels, i.e. high turbulence intensities and large production rates of TKE. The outer layer occupies the rest of the boundary layer and exhibits only small velocity gradients with an accordingly low shear TKE production which sometimes has been described as 'tired turbulence'.

Common to all boundary layer flows is that they exert a drag force on the bounding wall. This drag force is the most immediate characteristic of the dynamic flow-wall interaction. The wall acts as a momentum sink which is readily fed by the flow via viscous and turbulent transport of fluid momentum towards the wall. The rate of momentum transport at the wall per surface area should be reflected in the magnitude of the near-wall turbulent momentum transport within the flow towards the wall, i.e. in the magnitude of the Reynolds flux $-u'_i u'_3$. Therefore it is not surprising that the square root of this Reynolds flux turns out to be an omnipresent turbulent velocity scale, the friction velocity $u_\ast$ (assumed equivalent to the definition given in the preceding section), driving the dynamics near the wall.

Inner layer and outer layer scalings are distinctly different although in both cases $u_\ast$ is a relevant velocity scale: In the outer layer the difference of the mean velocity to the free stream velocity is scaled by $u_\ast$ ('velocity defect law') while in the inner layer the mean velocity itself is scaled with $u_\ast$ ('law of the wall'). The relevant length scale in the outer layer is the boundary layer thickness while in the inner layer relevant length scales are either the characteristic height and shape dimensions of the wall roughness (rough wall) and/or the distance from
The surface layer above rough walls (from now on the inner layer will be called surface layer as it is more common in the atmospheric context) can be subdivided in the upper part, which is the overlap region with the outer layer, and the lower part, the roughness sublayer. The distinct feature of the roughness sublayer is the 3-dimensional structure of the turbulence. This layer is found to reach up to 2 to 5 times the mean roughness height $h$ (Raupach et al. (1991)), individual roughness elements have their respective imprints in the turbulence structure, hence the 3-dimensionality.

The overlap region is of immediate importance in the context of the present study. The standard term for this region is the inertial sublayer, but other terms such as logarithmic layer or constant flux layer are also used almost interchangeably. This region within the boundary layer flow is either characterized by its kinematic and dynamic characteristics, as they are a logarithmic mean wind profile and approximately constant Reynolds stresses, or as a flow region where the simultaneous applicability of inner layer and outer layer scalings allow an elegant theoretical deduction of the just mentioned flow properties. From an experimentalist's and observer's point of view this study frequently uses the first, i.e. the kinematic and dynamic characterization of the inertial sublayer.

Since the existence of an inertial sublayer above urban roughness is a central theme of this work, three different lines of theoretic arguments are briefly reviewed which are commonly used to explain the logarithmic wind profile and the approximately constant Reynolds flux: (i) scaling arguments ('asymptotic matching'), (ii) arguments based on the RANS equation (2.3) under boldly simplifying assumptions concerning the flow symmetries and (iii) a mixture of scaling and order of magnitude arguments applied to the boundary layer approximated RANS equation (2.14).

The first line of arguments, asymptotic matching, argues that within the overlap region the length scales of the inner layer as well as those of the outer layer are applicable with the corresponding length scales being considered as independent variables which could be altered independently from each other depending on the specific flow realization. E.g. inner layer length scales could be held constant while the outer layer length scales could be changed giving different flow realizations. As a consequence, at a fixed height level within the overlap region a quantity expressed in terms of inner layer length scales does not change while the same quantity expressed in outer layer length scales might be subject to a change due to the different outer layer length scales. One solution to the apparent paradox is that the considered quantity depends on neither the inner nor the outer length scales but scales just with height $x_3$ (properly adjusted by the zero plane displacement $d_0$ due to the upward
flow displacement by the roughness elements). Taking \( u_* \) as the only relevant velocity scale (which might not be correct in case of significant external pressure gradients, but here approximately zero-pressure-gradient is assumed) and considering, e.g., the mean flow shear one arrives at the scaling relation \( dU_1/dx_3 \sim u_*/(x_3 - d_0) \) which integrates to the logarithmic flow profile. Since there is no other velocity scale which could serve as a scale for the Reynolds stress or for the deviation of the Reynolds stress from \( u_*^2 \), one concludes that \( -u'_1 u'_3 \sim u_*^2 \) and therefore the turbulent fluxes are approximately constant within the overlap region. The same consideration applied to the dissipation rate gives \( \varepsilon \sim u_*^2/(x_3 - d_0) \). The validity of these arguments relies on the existence of a height range where the independence of inner layer and outer layer length scales is physically plausible, i.e.

inner layer length scales \( \ll x_3 \ll \) outer layer length scales.

Turning to the second line of argument, the RANS equation (2.3) states that the total time derivative of a flow particle's velocity is equal to the negative pressure gradient plus a divergence of the full stress tensor including the Reynolds stresses. Assuming horizontal homogeneity, i.e. \( \partial_1 = \partial_2 = 0 \), mass conservation gives \( \partial_3 U_3 = 0 \) and therefore, knowing that \( U_3 = 0 \) at the wall, \( U_3 = 0 \) throughout the whole flow region under consideration. Further assuming stationarity, i.e. \( \partial_t = 0 \), the material derivative \( \partial_t U_i + U_j \partial_j U_i \) equals zero, i.e. in this approximation the total force acting on the fluid particle vanishes. Assuming zero-pressure-gradient all stress tensor divergences must vanish and since horizontal homogeneity has been assumed anyway this gives a zero vertical change of stress. Neglecting the viscous stress part in high Reynolds number flow scenarios one arrives at the constancy of Reynolds stresses with height. Invoking a mixing length model with the mixing length proportional to height above \( d_0 \) the logarithmic wind profile is readily derived. The validity of this line of arguments apparently relies on the validity of the stated boldly simplifying symmetry assumptions.

The third reasoning somewhat loosens the strong assumptions made in the second line of arguments. It starts from the boundary layer approximated RANS equation (2.14) for large Reynolds numbers and vanishing pressure gradient:

\[
U_1 \partial_1 U_1 + U_3 \partial_3 U_1 = -\partial_3 u'_1 u'_3. \tag{2.16}
\]

The continuity equation in the boundary layer approximation reduces to \( \partial_1 U_1 + \partial_3 U_3 = 0 \). Assuming slow variation of \( \partial_1 U_1 \) with height one may estimate \( U_3 \) scaling with height \( x_3 \). Assuming further slow streamwise development and assuming that vertical derivatives scale with the inverse boundary layer height \( 1/\delta \) one arrives at \( -\partial_3 u'_1 u'_3 \to 0 \) as \( x_3/\delta \to 0 \) (\( x_3 \) remaining above the
roughness canopy since within the canopy the above stated boundary layer approximation is not valid any more). Therefore an approximately constant flux layer is obtained under the stated provisions. Raupach et al. (1991) remark that 'in practice' a constant flux layer is roughly the region

\[ h - d_0 < x_3 - d_0 < \delta/10 \] (2.17)

with \( h \) being the mean roughness height and \( \delta \) the boundary layer height. The lower limit of this estimation has to be questioned and checked in the urban context.

Arguments in the context of atmospheric boundary layers are conceptually similar to the last reasoning, they rely on horizontal homogeneity approximations of the atmospheric flow with a consequent order of magnitude estimation of the individual terms utilizing values typical for the Prandtl layer (yet another name for the surface layer in the atmospheric context), see e.g. Tennekes and Lumley (1972). Based on those arguments it is also found that the vertical variation of \( u_1' u_3' \) within the Prandtl layer should be very small. Employing a turbulence viscosity and mixing length model, the logarithmic wind profile is derived. These consideration also show that the turning effects of the Coriolis force within the surface layer are very small and can be generally neglected (Tennekes and Lumley (1972), p.169).

For completeness and because it will have some relevancy in chapter 6.6 it is noted that not only a mixing length model but also the TKE budget (2.15) in combination with scaling arguments could be used to 'derive' the logarithmic wind profile. Within the inertial sublayer it is frequently observed that local production is approximately balanced by local dissipation, i.e.

\[ \varepsilon \approx -\overline{u_1' u_3'} \partial_3 U_1. \] (2.18)

Knowing \( -\overline{u_1' u_3'} = u_3'^2 \) and employing dissipation scaling as \( \varepsilon \approx u_3'^2/k(x_3 - d_0) \) the logarithmic wind profile is obtained.

Given that armoury of arguments and the fact that an inertial sublayer has been observed in many boundary layer flows the question arises why there should be any difference in the case of an urban boundary layer. The reason is that some, if not all, assumptions on which the above outlined arguments rely could be questioned in the urban context:

- The height of the roughness elements (viz. buildings) might be tens of meters while the height commonly attributed to the surface layer is about 100m. Therefore scaling arguments which rely on the smallness of surface scales in comparison to boundary layer scales (e.g. the simple height scale \( x_3 - d_0 \) in the ISL) could be questioned.
Due to the large height and highly irregular arrangement of roughness elements in particular urban environments the range of 3-dimensional turbulence is extended significantly into the boundary layer (as compared to, e.g., comparatively regular vegetation roughness). Therefore arguments relying on the horizontal homogeneity approximation close to the surface might be challenged.

Urban roughness characteristics are frequently changing: Parks, backyards, streets with different orientation to the mean flow direction, narrow and wide street canyons and different, more or less randomly distributed roof shapes alternate and force the flow to be in a state of 'constant adaptation', at least close to roof level. Therefore the assumption of slow streamwise flow development, at least in this height range, is doubtful and the existence of a flow layer where only aggregate measures of the underlying roughness are relevant has to be checked explicitly.

Indeed, wind tunnel modelling using idealized urban roughness (e.g. Cheng and Castro (2002)) has indicated a significantly squeezed inertial sublayer and has contributed to the discussion about the existence of an inertial sublayer over realistic urban roughness.

Now that the ISL has been discussed for some length it is time to formally state the logarithmic wind profile:

\[ U_1(x_3) = \frac{u_*}{k} \ln \left( \frac{x_3 - d_0}{z_0} \right) \]  

with

- \( u_* \): Friction velocity,
- \( k \): von Karman constant, set to 0.4 in this work,
- \( z_0 \): Roughness length,
- \( d_0 \): Zero plane displacement.

The role of the friction velocity \( u_* \) has been discussed above. Besides the momentum flux towards the wall, expressed through the scaling of the mean wind shear with \( u_* \), the flow is retarded which the logarithmic wind profile takes into account through a subtractive constant. The profile is shifted uniformly to lower wind speeds with the shift being parameterised by the roughness length \( z_0 \) and scaling, again, with \( u_* \). \( z_0 \) accounts for all those effects of the roughness on the mean wind speed which are not incorporated in the mean wind shear (which is independent of \( z_0 \)). It is assumed to be a function of only the roughness geometry. It is convenient (and fortunate) that a single roughness length scale, \( z_0 \), is sufficient to describe the effects of the roughness geometry within
the inertial sublayer. The zero plane displacement $d_0$ denotes the dynamic origin of the flow as it is felt by the logarithmic wind profile within the inertial sublayer. It can be interpreted as the centroid of the vertical drag distribution within the canopy layer and constitutes therefore the mean height level of drag force action on the surface (see Jackson (1981)). It should be mentioned that the notion of a 'dynamic origin' depends on the dynamic quantity under investigation, e.g. Reynolds fluxes might 'feel' another 'dynamic origin' (see Kastner-Klein and Rotach (2004)).

A final remark goes to the von Karman constant $k$. In rough-wall flows it has been observed that the friction velocity $u_{\text{log}}$ determined from logarithmic profile fits to the mean wind profile is larger than $\left(-u'_1 u'_3\right)^{1/2}$ measured within the constant flux layer (e.g. Cheng and Castro (2002), Kastner-Klein and Rotach (2004)). Therefore a discussion exists whether $u_{\text{log}}$ should generally just be interpreted as a scaling velocity for the mean wind profile rather than as an estimate for the true shear stress velocity (Kastner-Klein and Rotach (2004)) or whether the von Karman constant $k$ is changing in a rough environment (therefore making $u_{\text{log}}$ and $\left(-u'_1 u'_3\right)^{1/2}$ equal again). Since this discussion does not seem to have reached a conclusion in the literature, $k$ is set to 0.4 in this study. An alternative explanation for the differences in the estimated friction velocities is considered in this study when the horizontally averaged TKE budget as measured above the urban model is presented (chapter 6.6).

### 2.7 Spatially averaged RANS equation

The canonical treatment of boundary layer flows assumes horizontal homogeneity. In the lower regions of the urban boundary layer this assumption has to be modified. Vertical profiles are either of local nature or refer to horizontally averaged quantities. The procedure of time averaging has produced extra terms in the momentum balance for the time-averaged quantities, therefore it is not surprising to find that horizontal averaging produces modified equations of motion for the horizontally and time-averaged quantities.

Following Raupach and Shaw (1982), the horizontal averaging operator is denoted by angle brackets $(\ldots)$. Local time averages are decomposed into the respective horizontal mean and the local deviation from this mean, the deviation is denoted by double primes, e.g. $U_i = \langle U_i \rangle + U''_i$, etc.

Horizontal averaging applied to the RANS equation gives the horizontally averaged equations of motion
Comparing these equations to the original RANS equation (2.3) and following the interpretations of Raupach and Shaw (1982) and Wilson and Shaw (1977), three new terms are readily identified:

\[ \partial_j \langle U'' U'' \rangle : \] The divergence of the dispersive stresses \( \langle U'' U'' \rangle \), which contributes to momentum transfer due to spatial correlations of horizontal deviations of the \( U_i \)'s from their respective horizontal mean values.

\[ -\frac{1}{\rho} \langle \partial_i P'' \rangle : \] Form drag imposed by material bodies within a vegetation or urban canopy.

\[ \nu \langle \partial_i \partial_j U'_i \rangle : \] Viscous drag, also imposed by material bodies within the flow, e.g. vegetation or buildings.

The dynamic role of the dispersive stress is frequently found to be rather small above the canopy layer of a rough surface (see e.g. Castro and Cheng (2002) for a wind tunnel study above fairly regular roughness). In the present study, dispersive stresses \( \langle U'' U'' \rangle \) above the urban model are estimated (chapter 6.8).

### 2.8 Integral scales and spectral representation of turbulence

An important tool in experimental investigations of the non-local nature of turbulent flows are the one-point temporal autocorrelation functions defined as

\[ \rho_i(\tau) = \frac{u'_i(t)u'_i(t + \tau)}{\sigma_i^2} \] (2.21)

symmetric in \( \tau \) and independent of \( t \) due to stationarity (and not to be confused with the fluid density \( \rho \)). Integral time scales \( T_i \) are defined as

\[ T_i = \int_0^\infty \rho_i(\tau) d\tau \] (2.22)

The temporal autocorrelation functions and integral scales can be transformed to spatial dimensions by utilizing Taylor's hypotheses of 'frozen turbulence': If the mean flow moves much faster than the turbulence, i.e. \( U_1 \gg \sigma_i \), the
turbulence advected past a point \((x_1, x_2, x_3)\) fixed in space could be considered as an approximately instantaneous (on turbulent time scales) snapshot of the turbulence at the points \(x_1 - U_1 t\) in space. This allows the calculation of approximate spatial autocorrelation functions from one-point measurements according to the transformation

\[
R_{ii}(0, \Delta x_1, 0, 0) := \frac{u'_i(t, x_1, x_2, x_3)u'_i(t, x_1 + \Delta x_1, x_2, x_3)}{\sigma_i^2 \rho_i(\Delta x_1/U_1)}
\]

using the symmetry of \(\rho_i(\tau)\) in \(\tau\). The corresponding integral spatial length scales \(L_i\) are given by

\[
L_i := \frac{1}{\sigma_i^2} \int_0^\infty R_{ii}(x, 0, 0) dx
\]

\[
\approx \int_0^\infty \rho_i(x/U_1) dx = U_1 \int_0^\infty \rho_i(\tau) d\tau = U_1 T_i. \tag{2.24}
\]

Instead of \(L_1, L_2\) and \(L_3\) the notations \(L_{ux}, L_{uy}\) and \(L_{uz}\) are commonly used to emphasize that they are derived from one-point time series 'advected' by the mean wind \(u\) (here denoted by \(U_1\)).

The (slightly modified, see below) Fourier transform \(S_i(f)\) of \(\sigma_i^2 \rho_i(\tau)\) in frequency space facilitates a conceptual decomposition of turbulence into different eddy time scales \(1/f\) (and therefore, by the virtue of Taylor's Hypothesis, eddy length scales \(U_1/f\)). This decomposition is in the spirit of the heuristic notions of 'large eddies' and 'small eddies', which are mainly based on first-sight impressions of the fluctuating movements in turbulent fluids, it proves to be a useful concept in structuring turbulence phenomena. \(S_i(f)\) is defined by

\[
S_i(f) = 2 \cdot 2\pi \cdot \frac{1}{2\pi} \int_{-\infty}^\infty u'_i(t)u'_i(t+\tau) exp(-2\pi\tau f) d\tau \tag{2.25}
\]

to give

\[
\sigma_i^2 = \int_0^\infty S_i(f) df. \tag{2.26}
\]

\(S_i(f)\) is related to the Fourier transform \(\hat{S}_i(\omega)\) of \(\sigma_i^2 \rho_i(\tau)\) through (see Kaimal and Finnigan (1994))

\[
S_i(f) = 2 \cdot 2\pi \cdot \hat{S}_i(\omega) \quad \text{with} \quad \omega = 2\pi f. \tag{2.27}
\]
The factor of 2 is due to the restriction to non-negative frequencies, the factor $2\pi$ stems from the conversion from angular frequency $\omega$ to circular frequency $\omega$.

$S_i(f)$ cannot be interpreted exactly as the contribution of the infinitesimal frequency interval $df$ at the frequency $f$ to the total TKE in the $i^{th}$ velocity component since it is based only on the 1-dimensional spectrum. Nevertheless due to its accessibility in experimental measurements, it is an important observable which serves the spectral characterization of turbulence. Standard parameterizations of the three velocity spectra above a flat homogeneous surface within the atmospheric surface layer for neutral conditions were provided by Kaimal et al. (1972). Kaimal and Finnigan (1994) give them slightly modified as

$$\frac{nS_1(n)}{u_*^2} = \frac{102n}{(1 + 33n)^{5/3}}$$

$$\frac{nS_2(n)}{u_*^2} = \frac{17n}{(1 + 9.5n)^{5/3}}$$

$$\frac{nS_3(n)}{u_*^2} = \frac{2.1n}{(1 + 5.3n^{5/3})}$$

with the non-dimensional frequency $n = f(x_3 - d_0)/U_1$, $U_1$ being the mean wind speed at the observational height level $x_3$. Those parameterizations serve as a frequently quoted reference, urban spectra are frequently discussed in comparison to those flat surface spectra (see below and chapter 3.2).

Three remarks concerning the spectral parameterizations (2.28) to (2.30): Firstly, the parameterizations given in Kaimal et al. (1972) differ slightly from the above given parameterizations quoted from Kaimal and Finnigan (1994). In Kaimal et al. (1972) the numerators in the parameterizations for the $u_1$ and $u_3$ spectra are $105n$ and $2n$ respectively. The reason for the deviations is that the parameterizations originally proposed by Kaimal et al. (1972) do not give $4/3$ for the ratios $S_2(n)/S_1(n)$ and $S_3(n)/S_1(n)$ in the inertial subrange as required by local isotropy. Therefore Kaimal and Finnigan (1994) seem to have modified the parameterizations slightly to yield the desired $4/3$ ratios in the inertial subrange. Nevertheless, certain other publications (e.g. VDI (2000)) still quote the parameterizations from Kaimal et al. (1972). Secondly, other parameterizations exist as well, of course. E.g. in the context of wind engineering and the estimation of wind effects on buildings, Simiu and Scanlan (1978) give slightly different parameterizations with the main difference being a somewhat higher energy density in the low frequency part of the $u_1$ spectrum and the $u_1$ spectral peak shifted to lower frequencies. Unfortunately, the $u_1$, $u_2$ and $u_3$ spectral parameterizations proposed by Simiu and Scanlan (1978, as
well as in their 2nd edition 1986), with the $u_2$ spectral parameterization taken to be a modified version of the parameterization from Kaimal et al. (1972) and the $u_3$ spectral parameterization taken from Lumley and Panofsky (1964), do not appear to give the 4/3 ratio in the inertial subrange (although Simiu and Scanlan (1978, p.62) claim differently). Despite the existence of certain alternative spectral parameterizations the reference from Kaimal et al. (1972) and their modified version seem to be a common starting point for spectral discussions in urban meteorology (see e.g. Roth and Oke (1993), Feigenwinter et al. (1999), Roth (2000)). Thirdly, the parameterizations (2.28) to (2.30) from Kaimal and Finnigan (1994) imply constant spectral peaks (in terms of the non-dimensional frequency $n$) with $n_{u_1,peak} = 0.0455$, $n_{u_2,peak} = 0.158$ and $n_{u_3,peak} = 0.469$. In greater heights this constancy is subject to discussion and an increasing peak frequency $n_{u_1,peak}$ is observed (see e.g. Simiu and Scanlan (1978, p.55) and Roth (2000)). Therefore the above given parameterizations should by applied with due caution to heights greater than those from which they were originally derived ($x_3 = 5.66m$, $11.3m$ and $22.6m$, see Kaimal et al. (1972)).

2.9 Turbulent dispersion

Up to this point the picture of turbulence has been happily outlined in Eulerian colours, i.e. turbulence has been described in terms of observables assigned rigidly to each point in space. This is a natural approach given the nature of standard measurement devices which are mostly fixed in space. On the other hand this approach is not necessarily natural given the derivation of the NS equations (2.1) which are frequently deduced as the momentum balance for an individual fluid element. (For a general discussion of the notion 'fluid element' and the associated continuum hypothesis refer to Batchelor (1967), pp. 4-6.) The fluid element is moving in space and its instantaneous velocity at a specific point on its trajectory defines the instantaneous Eulerian velocity at that particular point in space. From this point of view the Eulerian velocity field rigidly assigned to the points in space is really based on the velocities of all the fluid elements on their respective trajectories. This so-called Lagrangian approach to assign velocities to fluid elements and not to space points is in a sense 'closer to the physics' of the fluid system, the fluid elements are the bearer of the dynamics and not the points in space. But painting in Lagrangian colours is more difficult and does not correspond nicely to the type of measurements normally made in turbulent fluids, therefore Eulerian drawings are far more common in turbulence research. Nevertheless, working within the Eulerian framework comes with certain costs, the least being the necessity to get used to material derivatives, which are the Eulerian counterparts of Lagrangian time derivatives, while a more severe drawback is the questionable or
only approximate physical relevancy of some Eulerian time and length scales. This is illustrated by turning now to the phenomenon of turbulent dispersion.

The study of turbulent dispersion is basically the study of the movements of fluid elements (or particles, as they are frequently termed in this context) within a turbulent fluid. In general the particles under investigation are chemically and/or physically distinct from the surrounding turbulent fluid. A common experimental arrangement is the release of those particles from a well-defined point in space (the 'source') and the subsequent measurement of time-averaged particle concentrations at certain distances from the source. These concentration patterns are the material realization of the probability distributions determining the chance to find a single particle at a given point in space after it has been released from the source. Since in general large quantities of particles are released from the source, turbulent dispersion is described in statistical terms.

Famous results were obtained by G.I. Taylor (1921) and describe the lateral spread of a plume downstream of a point source within a moving turbulent fluid. The spread is given by the lateral standard deviation \( \sigma_y \) of the particle trajectories from the downstream centreline of the plume after a given particle travel time \( t \) and depends on the turbulent fluctuations of the lateral particle velocities given by the standard deviation \( \sigma_v \). For short travel times it is found that

\[
\sigma_y^2 \approx \sigma_v^2 t^2
\]

(2.31)

while for long travel time the analysis gives

\[
\sigma_y^2 \approx 2 \sigma_v^2 T_L t
\]

(2.32)

(see e.g. Hanna et al. (1982)). It is plausible to relate the travel time \( t \) directly to the distance from the source. Therefore the insight is that close to the source the plume should spread linearly with increasing distance while far away from the source the plume should spread as the square root of the distance. The 'Lagrangian time scale' \( T_L \) appearing in the second relation measures how long the particle memorizes its past, i.e. over what temporal periods its velocities are significantly correlated (in this case its velocities lateral to the plume centreline). This Lagrangian time scale intrinsic to the motion of an individual particle can be estimated only roughly from Eulerian measurements (see e.g. Hanna et al. (1982), pp. 9-10) indicating thereby the qualitative difference between the Eulerian and the Lagrangian frame of reference.

Two different approaches to turbulent dispersion modelling are stochastic modelling and parametric modelling. The aim of stochastic modelling is to get as close as possible and as necessary to the trajectories of individual particles.
and simulate the dispersion process by tracing the movements of a sufficiently large number of single particles. This approach promises to be a very versatile and powerful method, which is already an indication for its potential complexity and mathematical sophistication (see e.g. Rotach et al. (1996) or Luhar and Britter (1989)). Essential inputs to those stochastic models are the probability distributions which govern the random particle trajectories. The moments of those distributions have to be determined and/or verified from experimental observations. Lack of this experimental data leaves a certain amount of hypothesizing within this modelling approach, therefore the urban turbulence data presented in this and other studies could be used as input for those stochastic models.

The parametric or phenomenological approach starts with the observation that for a certain class of dispersion scenarios (e.g. release from a point source over a flat surface) the resulting concentration patterns have very similar shapes depending in a regular fashion on the exact boundary conditions of the realization (e.g. the mean wind speed, atmospheric stability, source strength). Needless to say that those shapes will then be parameterized as functions of these relevant boundary conditions. This approach treats the details of turbulent dispersion as a black box and strives (just) for an economic linkage between the relevant boundary conditions and the resulting concentration patterns.

Since the focus of this study is on the measurement of concentration patterns, certain preference is given to the parametric approach to summarize the data effectively. To that aim and encouraged by the findings of e.g. Davidson et al. (1995, 1996) and Theurer (1995) the omnipresent Gaussian plume model is used which parameterizes the concentration field downstream of a continuous point source within a uniform wind field along the $x_1$ direction as follows (see e.g. Hanna et al. (1982), p.25):

$$\frac{C}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U_1} \exp\left(-\frac{x_2^2}{2\sigma_y^2}\right) \cdot \exp\left(-\frac{(x_3 - h_{SRC})^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(x_3 + h_{SRC})^2}{2\sigma_z^2}\right)$$  

(2.33)

with

- $C$ : Concentration field $C \equiv C(x_1, x_2, x_3)$,
- $Q$ : Source strength,
- $U_1$ : Wind speed of the uniform wind field,
- $\sigma_{y,z}$ : Lateral/vertical spreads of the plume as functions of $x_1$,
- $h_{SRC}$ : Height of the source.

A conceptual sketch of the Gauss model is given in Fig. 2.1.

The physical modelling assumptions behind the Gaussian plume model are clear. Lateral and vertical particle displacements are assumed to be the sum
over a large number of small random vertical and lateral movements. According to the central limit theorem the sum over a large number of random variables converges to a Gaussian distribution under quite general conditions (e.g. if the real random variables are integrable, have positive variance and are independent and identically distributed, see e.g. Bauer (1968), pp. 224-226). The vertical distribution is simply reflected at $x_3 = 0$ modelled by a virtual source at $x_3 = -h_{SRC}$. Integrating the concentration over a thin layer of thickness $dx_1$ from $x_2 = -\infty$ to $\infty$ and from $x_3 = 0$ to $\infty$ gives a particle number (or total particle mass) of $Qdx_1/U_1$ within that thin layer. This particle number is independent of $x_1$, i.e. net longitudinal dispersion is assumed to vanish, and corresponds to the number of particles which the thin layer picks up during its passage time $dx_1/U_1$ at the source of strength $Q$. Nevertheless it is also clear that the Gaussian plume model is unphysical with respect to the infinite extension of the concentration field from $x_2 = -\infty$ to $\infty$ and up to $x_3 = \infty$. This would imply an infinite velocity of concentration propagation. Whenever this Gaussian model is applicable, the challenge is to determine the functional forms of $\sigma_y(x_1)$ and $\sigma_z(x_1)$.

The assumptions behind the Gaussian plume model are also its constraints (for further discussion see e.g. Beychok (1994, chapter 2)). In the context of near-surface dispersion a severe constraint appears to be the assumption of an uniform wind field which is in contrast to the logarithmic wind profile in the surface layer and the strong wind shear above very rough surfaces (then e.g. the appropriate choice for $U_1$ in the above given parameterization is not obvious and, in practical applications, it is apparently determined by convention, 'intuitive guess' and/or data availability, see e.g. discussion in Beychok
Therefore efforts have been made to derive solutions for dispersion equations applicable to general turbulent shear flow (see e.g. Huang (1979), for a brief review of analytical solutions to diffusion models see e.g. Tirabassi (1989)). The resulting formulas contain the Gaussian model as a special case for an uniform wind field. Despite those achievements the Gaussian model provides the by far simplest means to describe a concentration field, on a phenomenological basis it has been found suitable even for dispersion in shear wind fields close to rough surfaces (see discussion and cited studies in chapter 3.3). Since its lack of a sound physical basis in these 'shear cases', the practice to use the Gaussian model anyway as an operational model (as e.g. stated in Helbig at al. (1999) and Hanna et al. (1982)) blurs the distinction between a physical model and a parameterization scheme subject to empirical parameter fitting.

Knowing those important qualifications, this study uses the Gaussian parameters (the 'sigmas') to describe the measured mean concentration field. This may be justified by the omnipresence and the descriptive power of the Gaussian plume model and the availability of empirically determined parameterizations for $\sigma_x(x_1)$ and $\sigma_z(x_1)$ which could be used for comparison.
Seite Leer / Blank leaf
Chapter 3

Introduction to urban turbulence and dispersion

Urban turbulence and dispersion is a rich area of ongoing research. After justifying the focus of this study on neutral conditions, a few remarks are made about the present research context.

3.1 Shear vs. thermal contributions to TKE production

It seems intuitively clear and has been frequently remarked (e.g. by Britter and Hanna (2003)), that urban roughness with its large obstacles causes increased drag forces, i.e. the urban surface is a more insatiable momentum sink than e.g. a rural surface. The turbulent flow reacts with increased turbulence intensities and an increased turbulent momentum transfer towards the surface, the urban friction velocity $u_*$ and the corresponding skin-friction coefficient are increased in comparison to non-urban surfaces. It is standard practice to classify flow stabilities by the height dependent stability parameter $\zeta = (x_3 - d_0)/L$ with $\zeta = 0$ being identified with neutral conditions ($L$ being the Monin-Obukhov length scale, see e.g. Stull (1988)), in field scenarios small deviations of $\zeta$ from zero are considered acceptable for neutrality, e.g. $|\zeta| \leq 0.05$ or $|\zeta| \leq 0.1$ as in Roth (2000)). It is $L \sim u_*^2$, i.e. the larger $u_*$, the smaller $\zeta$. Given the large urban $d_0$ and the restricted range of $x_3$ above roof level within the surface layer it is plausible to assume the urban surface layer or at least the height range close to roof level to be well-described by (near-)neutral stratification for common wind scenarios.

Another approach to analyse the relative importance of shear turbulence in
comparison to convective turbulence, as e.g. applied by Rotach (1993b), is to investigate the scaling of the vertical turbulence velocity $\sigma_3$ according to the relation

$$\sigma_3^3 = C_1 u_*^3 + C_2 u_f^3$$

(3.1)

where it suffices here to know that $u_f$ is another, convective velocity scale which reflects the magnitude of thermal turbulence production (see Rotach (1993b) for definition and discussion). The quantity $C_1/C_2$ could be seen as a rough measure of the relative contributions of shear production and thermal production to $\sigma_3$. It is observed that within urban scenarios this ratio is increased by a factor 1.5 to 2 in comparison to rural settings (Rotach (1993b)). This supports the assumption that shear TKE production dominates thermal TKE production more easily close to urban surfaces than close to rural surfaces.

Nevertheless it must be noted that thermal TKE production might also be enhanced above urban surfaces. As Hertig (1995) reviewed, urban surfaces may have a smaller heat capacity than rural surfaces implying higher urban surface temperatures and correspondingly larger temperature differences above the urban surface. During calm wind periods with reduced horizontal advection also due to large surface roughness it may be argued that thermal TKE contributions may exceed shear contributions (see Fig. 1 in Hertig (1995)).

Therefore summarizing, urban TKE production in comparison to non-urban TKE production is characterized by larger 'swings of the pendulum' from shear contributions to thermal contributions and vice versa. For calm winds and high levels of insolation on sunny days thermal TKE contributions might be expected to dominate, whereas for sufficiently strong winds shear (or mechanical) TKE production can be assumed to prevail.

Given this discussion it is concluded that the restriction of wind tunnel modelling efforts to neutral scenarios has a sufficient chance to reproduce realistic urban turbulence within the surface layer for sufficiently strong, but not uncommon wind scenarios. Since the requirement of 'Reynolds number independence' necessitates sufficiently strong winds (in the wind tunnel) anyway, the natural focus of wind tunnel studies like the present one is on neutral scenarios.

### 3.2 Some findings from urban turbulence field studies

Various aspects of urban turbulence have been studied in the field despite the technical challenges of urban campaigns to acquire comprehensive data sets.
Due to the subject of the present wind tunnel study the focus is on findings concerning above roof level turbulence. The following aspects of non-convective urban turbulence within the surface layer above roof level have been and are still in the spotlight of field research activities:

- **Reynolds stresses** $u'v'$ and turbulent velocities $\sigma_i$. Given the size of the roughness (i.e. buildings) the roughness sublayer (RSL) takes a non-negligible part of the urban surface layer, its turbulence conditions might even be seen as more characteristic for urban surface layer turbulence than inertial sublayer (ISL) turbulence. Depending on the building heights the ISL might be squeezed to just a thin height range at the top of the surface layer. Therefore appropriate RSL scaling relations and typical vertical profiles of Reynolds fluxes and turbulent velocities are of interest. Högström et al. (1982) suggested that ISL scaling relations for $\sigma_i$ are also obeyed in the RSL provided that the scale $u_*$ is determined from the local Reynolds fluxes. This suggestion was studied further by Rotach (1993b) and Oikawa and Meng (1995), their data has been found supportive for this concept of local scaling. This gives importance to the finding that the Reynolds fluxes are not necessarily constant with height within the RSL as demonstrated by Rotach (1993a) and further supported by Oikawa and Meng (1995) and Feigenwinter et al. (1999). In those studies the turbulent momentum fluxes increase with increasing height within the RSL, reach a peak above roof level (Feigenwinter et al. (1999) reported a peak height of $x_3/h = 2.1$, Oikawa and Meng (1995) observed a peak at $x_3/h = 1.5$) and decrease subsequently to the assumed ISL value. Unfortunately the somewhat limited height range, limited vertical resolution and locality of urban field measurements make an exact identification and general appreciation of this Reynolds flux peak quite difficult. Extending the analysis of Reynolds fluxes, further insights in the turbulent momentum transfer can be gained by a quadrant analysis (also introduced later in this study, see chapter 6.4) which determines the relative importance of upward transport of momentum deficit ('ejections') in comparison to the downward transport of momentum excess ('sweeps'). Oikawa and Meng (1995) report a dominance of ejections above the urban canopy ($x_3/h = 1.5, 2.6, 5.0$ and $6.4$), while within their urban canopy sweeps dominate ($x_3/h = 0.8$). Rotach (1993a) observes sweep dominance up to $x_3/h = 1.55$ (measurements at $x_3/h = 0.71, 0.91, 1.27$ and $1.55$) with this dominance decreasing with increasing height. Feigenwinter (2000) observes dominance of ejections above the mean building height ($x_3/h = 1.5, 2.1$ and $3.2$) with this dominance decreasing with decreasing height.

- **Estimation of $z_0$ and $d_0$ from morphometric and/or typological characteristics of the urban roughness.** The flow parameters $z_0$ and
$d_0$ are essential to describe the retardation and upward displacement of the mean flow in terms of the logarithmic wind profile. To understand the estimation challenge it is important to distinguish between flow parameters of fluid dynamic origin (viz. $z_0$ and $d_0$) and roughness parameters of morphometric origin assigned to the surface boundary conditions (e.g. the mean roughness height $h$ or the frontal area index $\lambda_F$, which is a measure of flow facing roughness area per unit horizontal area, see e.g. Grimmond and Oke (1999)). If the functional dependency of $z_0$ and $d_0$ on any suitable (and empirically collectible) set of roughness parameters were known, this would amount to a major step in linking boundary conditions to flow dynamics, a step which can be done ultimately only by a more advanced mathematical theory for the RANS equation. Given the mathematical complexity of the RANS equation such an empirically verified functional relationship would be a great tool in flow studies without a full mathematical theory. The expectation to find such a relationship is not completely unreasonable since the logarithmic flow region is assumed to be far enough away from the rough surface not to depend on every nitty-gritty roughness detail. Although, of course, in these greater heights flow adaptation to the roughness characteristics requires a sufficiently long fetch of approximately uniform roughness. The state of research has been reviewed by Grimmond and Oke (1999). They come to the somewhat disappointing conclusion that among the many suggested relationships no single superior formula has been devised yet, although some general rules of thumb are known. Part of the challenge lies in the identification of a sufficiently large number of well-documented urban field studies to cover a wide range of different roughness configurations necessary for a detailed analysis of a functional dependency. Research continues.

- **Characteristics of urban turbulence spectra.** For a flat homogeneous surface detailed analysis and parameterizations of turbulent velocity spectra are available, see e.g. Kaimal at al. (1972) based on the Kansas experiment from 1968 and quoted slightly modified in Eqns. (2.28) to (2.30) on page 34. Urban spectra are mostly discussed in terms of deviations from those 'flat surface spectra'. For the velocity spectra Roth and Oke (1993) found only minor deviations, as they are e.g. a slight shift of the $u_3$ spectral peak towards lower frequencies and a slight shift of the $u_1$ spectral peak towards higher frequencies ($x_3/h = 1.7$ and 2.6 in their study). Feigenwinter et al. (1999) also report shapes of the velocity spectra similar to those above flat surfaces ($x_3/h = 1.5, 2.1$ and 3.2 in their study) with the deviations being a shift of the peak frequencies in all velocity spectra towards lower frequencies with decreasing height, a trend which is most visible in the their $u_3$ spectra. Their findings in the $u_1$ spectra are in contrast to the observations of Roth and
Oke (1993). In his review Roth (2000) points out that 'the overall shapes of the urban spectra are remarkably similar to the (rural) references for both $u_1$ and $u_3$'. Deviations are the shift of $u_3$ spectral peaks towards lower frequencies and the greater scatter in the flat-surface-scaled urban spectral curves below $x_3/h < 3$. This indicates that below this height level additional length scales (presumably dictated by the roughness elements) become influential.

This rough overview sets the stage for this wind tunnel study. Urban field campaigns face certain constraints: One constraint is their local nature and the subsequent uncertainty concerning the horizontal representativeness of their findings. In practice, this constraint is somewhat dealt with by averaging over (all) wind directions. Another constraint is their vertical reach and resolution which is dictated by availability of resources and technical feasibility. Also instationarity of meteorological boundary conditions must be considered, resulting in a need for data detrending and limiting the length of averaging periods (e.g. to one hour). Wind tunnel studies are not subject to those constraints, therefore they can contribute by filling the respective gaps in the field data.

### 3.3 Urban dispersion modelling efforts

Urban dispersion modelling might be referred to different horizontal scales of interest. Britter and Hanna (2003) distinguish four scales: the regional scale (up to 100 or 200km), the city scale (up to 10 or 20km), the neighbourhood scale (up to 1 or 2km) and the street scale (less than 100 to 200m). The larger the scale the less detailed the roughness has to be modelled. This classification of scales incorporates of course some amount of simplification, e.g. street canyon dispersion can take place on scales greater than just 200m with plumes meandering through various street canyons and city districts while still being very sensitive to the local building geometry. Given the present dispersion scenario above roof level with source distances roughly between 400 to 900m and using the suggested nomenclature, the present scale of interest is the neighbourhood scale.

The neighbourhood scale can be thought of as a transitional scale where the necessity to model the roughness details (on the street scale) passes over to the luxury of considering only aggregated effects of the roughness (on the city or regional scale). The step from taking into account individual building structures to considering only an increased urban roughness length $z_0$ and an increased urban friction coefficient is a rather bold one which may leave considerable room in between. It is the challenge on the neighbourhood scale.
to find adequate modelling strategies for this transitional region. One approach could consist of being somewhat neglectful with regard to the geometric details of the roughness while modelling the turbulence structure more detailed (e.g. by taking into account characteristic Reynolds flux profiles within the RSL, see below). The rewards of successful research could be modelling approaches which are less resource intensive than those on street scale and show a better performance than those based on city scale roughness representations applied to the neighbourhood scale.

At this point the observation is helpful that most of the neighbourhood dispersion takes place within the urban surface layer, therefore the characteristics of RSL turbulence (determining assumingly most of the urban surface layer turbulence) should be taken into account. As it is summarized by Rotach (1999), dispersion models which ignore the RSL turbulence and only take into account ISL turbulence characteristics have a common tendency to underestimate ground level concentrations. Rotach (1999) reports improved model performances if the varying Reynolds fluxes within the RSL are explicitly included in the model. The main improvements are a less pronounced roll-off of surface concentrations beyond the surface concentrations peak and a less rapid growth of plume width and height. The peak concentrations themselves are found to be very similar in location and magnitude to the 'pure-ISL' models. The cited improvements are intuitively comprehensible since reduced Reynolds fluxes (as employed in the cited models) in combination with local scaling lead to reduced turbulent velocities $\sigma_z$ and a reduced mean wind gradient giving larger mean wind speeds close to the surface in comparison to 'pure-ISL' models (see Rotach (1999)). This results in a plume being more narrowed around the plume centreline with correspondingly larger concentrations.

The RSL parameterizations for the Reynolds fluxes used in the improved dispersion models are based on monotonously increasing fluxes with increasing height within the RSL and make a simplification by ignoring the Reynolds flux peak close to roof level observed in field measurements (e.g. Oikawa and Meng (1995)). Since the success factor of the enhanced modelling approach consists in smaller Reynolds fluxes below the ISL, the role of the peak has to be clarified with regard to its somewhat counteracting impact on the up to now assumingly discovered improvement mechanism for urban dispersion models. Research is ongoing and includes wind tunnel studies, especially for analysing scaling concepts based on the Reynolds flux peak value and for estimating the peak significance for horizontally averaged turbulence (see e.g. Kastner-Klein and Rotach (2004)). This is a point where the present wind tunnel study also intends to make a contribution.

Besides the Lagrangian modelling approach used in the studies cited above semi-empirical approaches exist, an interesting one described e.g. by Theurer (1995). He describes the dispersion from a point source within or closely above
an idealized urban canopy as observed in a wind tunnel study. A distinction is made between distances from the source where the concentration pattern is comparatively easy to describe (the so-called 'far field') and those distances close to the source where the dispersion process depends significantly on the roughness details (the so-called 'near field' which can be readily compared to the 'street scale'). The so-called 'radius of homogenization' (RAD) demarcates the near field from the far field. According to Theurer (1995) one of the defining characteristics of the far field is the possibility to describe the concentration pattern in terms of a Gaussian plume model (see Eqn. (2.33) on page 37). Now the interesting question is the actual size of the RAD. Theurer (1995) reports that for a source height of 1.5h, city centre roughness (configuration S0 in his publication) and approach flow directions of 0° and 45° to the orientation of the building rows the RAD is roughly 25h (Fig. 7 in his publication). Beyond this distance the concentration pattern is well-described by a Gaussian plume model. Theurer (1995) remarks that the RAD decreases with increasing aerodynamic roughness of the building arrangement. The semi-empiricism of this approach stems from the fact that spreading parameters and possible shift parameters of the Gaussian plume have to be determined from wind tunnel or field experiments, they are the input of subsequent concentration calculations in the far field. Again the details of the turbulent dispersion mechanism are largely treated as a black box, thereby allowing an easy to use model. In the present wind tunnel study with 'real' urban roughness, the source height is between 1.3h and 1.7h and focus is on source distances from approximately 30h to 60h. The findings of Theurer (1995) provide the motivation to expect Gaussian concentration patterns. Further motivation is provided by the study of Davidson et al. (1995). In their field experiment, dispersion within an array of cubes was studied with the source height being at half cube height and concentration measurements within and closely above the cubes. Lateral and vertical Gaussian concentration profiles are reported, for details see their publication.

A final remark goes to the performance of present-day operational and/or commercially available urban dispersion models with respect to their capability to include complex urban scenarios. Recently the results of a major dispersion model comparison exercise have been published including 24 modellers from 21 institutions (the 'Podbielski-exercise', see Lohmeyer et al. (2002)). Summarizing the results concerning the various pollutant predictions within a given street canyon it is said that no standard modelling procedure exists and the predictions clearly depend on the modelling approach used, even when different modellers use the same model the results may vary. Nevertheless the outcome was found encouraging enough to recommend further collaboration with a need for continuing standardization and guidance. Given the difficulties to incorporate correctly the effects of urban roughness on a neighbourhood scale, further research seems to be worthwhile.
Chapter 4

Experimental setup

This wind tunnel study is based on two measurement campaigns. The first campaign, from June 10th to August 15th 2003, focused on approach flow configuration and turbulence measurements. The second campaign, from February 9th to May 7th 2004, focused on dispersion modelling.

4.1 Wind tunnel ’WOTAN’ and measurement equipment

The wind tunnel ’WOTAN’ of the Meteorological Institute at the University of Hamburg has been constructed under the guidance of B. Leitl and came into operation in 2001. It is a 25m long boundary layer wind tunnel with a 18m long interior test section (see Fig. 4.1). Its rectangular cross section is 4m wide and 2.75 to 3.25m high (variable ceiling). Variation of the ceiling height can be done at 9 positions along the wind tunnel axis, downstream distance between two neighbouring positions is 1.5m with the first position being 6m from the inflow edge of the test section. The flexible ceiling adjusts smoothly to the set height configuration. Inside the wind tunnel 22 pressure probes are installed pairwise at opposing side walls, i.e. pressure measurements can be done at 11 locations along the wind tunnel axis. Height of the pressure probes is 1.34m above the wind tunnel floor, separation between the probes along the wind tunnel axis is 1.5m starting 0.75m from the inflow edge of the test section. Inside the wind tunnel a traverse system allows automatic positioning of LDA or FFID probes (see below for an explanation of those techniques). The system is operated by a positioning software installed on a PC outside the wind tunnel. The traverse system was used with a positioning accuracy of 1mm in each space dimension. During the measurement campaigns a Prandtl tube was mounted 4.5m from the upstream edge of the test section at a height
of 1.65m above the wind tunnel floor and at a side wall distance of 0.52m to measure the wind tunnel free stream velocity.

The test section was divided into two 9m long sub-sections. The upstream sub-section was covered by idealized roughness elements, the urban model was installed in the downstream sub-section (see Fig. 4.2). At the inflow edge of the test section vortex generators were installed. Due to their somewhat technical nature, the descriptions of these vortex generators, the roughness elements and their configuration used during the campaigns is exiled to appendix A. In the following, whenever reference is made to the inflow edge of the model (not to be confused with the inflow edge of the test section) the border line between the upstream and the downstream sub-section is meant (i.e. the separation line between the dark and the light surface in Fig. 4.2).

Turbulence measurements, i.e. flow velocity measurements, were made by laser Doppler anemometry (LDA). The equipment included a laser unit from Spectral-Physics Lasers (model 177-G0232, two lasers with wavelengths of 488nm and 514.5nm respectively) and a LDA system from Dantec Measurement Technologies A/S (transmitter-based FibreFlow optical system 60X40, Flow Processor BSA F70 and BSA Flow Software v2 (2.00.29)). The laser probe inside the wind tunnel was connected to these components outside the wind tunnel by an optical fiber (Fig. 4.3). Due to probe availability the first campaign was conducted using a laser probe with 50mm focal length, while during the second campaign a laser probe with 80mm focal length was used. Seeding particles (see 'Principles of LDA' below) were provided by the 'Tour-Hazer' from Smoke Factory using Tour-Hazer-Fog.

For the dispersion experiments a point source was operated with ethane ($C_2H_6$,
Figure 4.2: Urban model of Kleinbasel installed in the wind tunnel (looking upstream in the upper picture and downstream in the lower picture). The lower picture also shows the traverse system above the model and the Prandtl tube to the right above the roughness elements to measure the wind tunnel free stream velocity. The row of 'dots' on each side wall between the lights and the windows indicate the positions of the pressure probes.
Figure 4.3: The laser unit and the FibreFlow optical system from DANTEC outside the wind tunnel (upper picture). The laser probe installed to the traverse system inside the wind tunnel and connected to the outside components by an optical fibre (lower picture).
Figure 4.4: The FFID used for concentration measurements (upper picture) and the FFID probe inside the wind tunnel for concentration measurements above the urban model at the tip of the thin needle (lower picture).
Ethan 2.5 from Linde Gas) as tracer gas. The mass flow controller Brooks\(^{(R)}\) 5850S from Emerson (20-1000ln/h AIR) was used which had been calibrated between the first and second measurement campaign. Background concentrations were measured with the slow flame ionization detector (SFID) Rosemount\(^{(R)}\) Analytical Model 400A from Emerson, concentration measurements within and above the urban model were made with the fast flame ionization detector (FFID) HFR400 from Cambustion Ltd. (Fig. 4.4). The SFID and FFID were calibrated at least twice a day with calibration gases corresponding to four reference ethane concentrations as given by the manufacturer: 0ppm (synthetic air), 256ppm, 777ppm and 1207ppm. The highest reference concentration (1207ppm) was used for FFID calibration only since background concentrations never reached that concentration range. The FFID signal was amplified and filtered using the Kemo VBF44 multi-channel filter/amplifier system from Kemo Inc.. The FFID probe was mounted with a needle of length 146mm (±0.5mm) and an inner diameter of 0.22mm (±0.02mm) (Fig. 4.4). Given the pressure difference between ambient pressure and pressure inside the combustion chamber (see 'Principles of FID' below) of about 110mmHg (±2mmHg) and a combustions chamber temperature of about 183°C (±7°C), the maximal FFID frequency response to concentration fluctuations as given by the manufacturer was about 125Hz (±5Hz).

### 4.2 Principles of laser Doppler anemometry

The straightforward principles of LDA as given in the technical LDA manual by the manufacturer can be summarized as follows. Two coherent laser beams of the same wavelength are arranged to intersect in a certain measurement volume thereby producing a fringe pattern (i.e. interference pattern) of high and low intensity (Fig. 4.5a). If the wavelengths are exactly equal the fringe pattern is stationary and the regions of high and low intensities form parallel planes. Seeding particles, i.e. fog droplets, are introduced into the flow, they act as non-disturbing markers of turbulent air parcels. Any droplet of appropriate size travelling through the measurement volume scatters laser light whenever it passes through one of the high intensity planes thereby producing a flickering scatter signal on its way through the volume. This flickering scatter signal is termed a 'Doppler burst' as shown somewhat idealized in Fig. 4.6, each peak in the burst corresponds to the passage through one plane of high intensity. The frequency of this flickering signal depends on the particle’s velocity component perpendicular to the parallel planes and allows thereby a determination of this particular velocity component. By analysing the scattered signals any chosen velocity component can be measured by careful adjustment of the fringe pattern’s orientation.
Figure 4.5: (a) Two intersecting coherent laser beams produce an interference pattern of high and low intensity planes in the intersection volume. (b) The measurement volume is approximated by an ellipsoid (shaded area). The orientation in the sketches is chosen as if the velocity component $u_1$ were measured.

Figure 4.6: The scattered 'Doppler burst' signal from a particle crossing the measurement volume (conceptual). Each peak corresponds to the passage through a plane of high laser light intensity (graphic taken from the LDA manual by DANTEC).
A trick is needed to distinguish the two possible velocity directions perpendicular to the parallel planes. By shifting the frequency of one laser beam by a small amount (40Mhz in the present study) the fringe pattern is not stationary but moves continuously through the measurement volume in a direction perpendicular to the planes. Thus any particle with the respective velocity component exactly equal to the fringe pattern's velocity has a vanishing 'flickering frequency' of the scattered laser light, the fringe pattern's velocity constitutes a threshold velocity. Particle velocity directions can be determined uniquely in all those flows where all particle velocities stay strictly on one side of this threshold velocity (either smaller or larger). It is shown in the technical LDA manual that for the given shift frequency the expected instantaneous flow velocities in this study are easily within that range of unique direction determination.

A 2-dimensional laser probe was used during the campaigns which allowed the simultaneous determination of two instantaneous velocity components perpendicular to each other. This explains why two lasers of different wavelengths were used. The light from each of the two lasers was split (and frequency shifted) into two beams giving a total of four laser beams to measure two velocity components simultaneously. The above given LDA principles apply to each pair of split beams separately. Therefore, conceptually, two measurement volumes were created, a blue one (for the wavelength equal to 488nm) and a green one (for the wavelength equal to 514.5nm), of essentially the same size and at the same location (the focal length of the laser probe applies to both colours).

Due to the Gaussian intensity profile within each of the beams the measurement volume forms approximately an ellipsoid as illustrated together with a definition of measures in Fig. 4.5b. The measures \( \Delta x_1, \Delta x_2, \Delta x_3 \) of the ellipsoid depend on the intersecting angle of the two beams and thereby on the focal length of the laser probe. Tab. 4.1 summarizes the geometric specifications of the measurement volumes as given by the manufacturer. With this LDA setup it is found that mean velocities can be measured with an accuracy of ±0.08m/s. Further discussion of the measurement accuracy is provided in appendix B.

There are at least two challenges when operating the LDA equipment. Firstly, the seeding particles (i.e. fog droplets) must be of appropriate size. As given in Tab. 4.1, the fringe spacing was about 3\( \mu \text{m} \) (5\( \mu \text{m} \)) during the first (second) campaign. This sets the optimal seeding particle's size, since larger particles imply a reduced 'flickering' (some part of the particle is always in a high intensity region and scatters light), while smaller particles imply less intense scatter intensity. Unfortunately the seeding particle's size is not under complete control of the experimenter, thus the LDA data rate may vary depending on environment conditions. Secondly, an appropriate level of scatter signal
amplification has to be found. Too much amplification increases the noise and renders the signal useless for statistical analysis. Too low amplification decreases the data rate (i.e. detected particles per second), thereby either reducing significantly the sample size of instantaneous velocity measurements or requiring inefficient long acquisition times. The allowable and necessary amplification levels depend on the signal quality and may vary daily. Based on the experience gained during the two measurement campaigns confidence was established to have dealt appropriately with those challenges.

### 4.3 Principles of flame ionization detection

Again the principles as given in the SFID/FFID manuals are straightforward. Central component of the SFID and the FFID is the combustion chamber where a flame is constantly maintained by the continuous insertion of fuel ($H_2$) and air. The combustion chamber is at low pressure created by a vacuum pump. Concentration samples of ethane are sucked into the chamber through a thin needle (FFID) or tube (SFID) from the sampling location. The subsequent combustion process creates significant quantities of positive ions and electrons where the number of ions is nearly proportional to the number of carbon atoms burnt in hydrocarbon form. The ions and electrons are collected and produce an electrical signal which can be converted to a concentration value by the use of an appropriate calibration curve. The essential construction difference between a SFID and a FFID is the insertion point of the sample into the combustion chamber. Within a SFID the sample is mixed with the fuel before it gets into the combustion chamber. This process allows fluctuation response times of typically one second. Within a FFID the sample and the fuel are brought together only at the location of the flame within the combustion chamber, no mixing occurs before the actual combustion. This modification allows fluctuation response times of about 1/100 second or even smaller with the

<table>
<thead>
<tr>
<th>LDA Parameter</th>
<th>1st campaign</th>
<th>2nd campaign</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength [nm]</td>
<td>488</td>
<td>514.5</td>
</tr>
<tr>
<td>Focal length [mm]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Number of fringes</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Fringe spacing [$\mu$m]</td>
<td>3.060</td>
<td>3.226</td>
</tr>
<tr>
<td>Probe volume - $dx_1$ [mm]</td>
<td>0.115</td>
<td>0.122</td>
</tr>
<tr>
<td>Probe volume - $dx_2$ [mm]</td>
<td>1.443</td>
<td>1.521</td>
</tr>
<tr>
<td>Probe volume - $dx_3$ [mm]</td>
<td>0.115</td>
<td>0.121</td>
</tr>
</tbody>
</table>

Table 4.1: Specification of the optical LDA characteristics (see Fig. 4.5b for definition of measures).
response times depending mainly on the speed of sample intake (and thereby on the difference between chamber and ambient pressure) and the needle length along which concentration diffusion blurs the concentration signal. The measurement accuracy is such that dimensionless concentrations $C^*$ (introduced in chapter 7.1) are measured with an accuracy of $\pm 6 \cdot 10^{-4}$. Further discussion of the measurement accuracy is provided in appendix B.

Of course, besides the simplicity of principles, operational challenges are also present. Transformation of FID signal output to concentration values depends sensitively on the pressure difference mentioned above, the temperature within the combustion chamber and possible impurities inside the thin needle which alter the sample intake characteristics. These and other influence factors typically change during the day and/or with increasing time of operation. Therefore careful and frequently repeated signal calibrations are indispensable, they were done during the whole dispersion measurement campaign at least twice a day (typically in the morning and at noon).

4.4 Urban model of Kleinbasel

The urban model is specified by the model area, the approach flow direction, the model scale and the details of the urban roughness. The model area and the modelled approach flow direction are shown in Fig. 4.7. This particular area was chosen for two reasons. Firstly, the field measurement tower Basel-Sperrstrasse (BSPR) was located in the centre of this area. Extensive turbulence measurements were made from August 2001 to July 2002, the recorded field data provides a good opportunity for comparison to the wind tunnel measurements. Secondly, the field tracer experiments were conducted in this part of Basel (Kleinbasel) with sampling stations distributed throughout the area (see e.g. Gryning et al. (2004)). The wind tunnel dispersion experiment is designed to model those tracer experiments, again with the motivation to compare field data to wind tunnel measurements. The chosen approach flow direction (DD $= 330^\circ$) corresponds roughly to the prevailing wind directions during the tracer experiments. It is a favourable circumstance that close to the upstream border of the chosen model area another field measurement station was operated from June 10th to July 9th 2002 (RASS measurements). This station at Basel-Kleinhüningen (BKLH) provided wind and temperature profile data up to $x_3 = 200$m which are used for approach flow modelling in the wind tunnel (see chapter 5).

To provide further motivation for the chosen approach flow direction, it is instructive to take a quick look at the typical wind conditions over Kleinbasel. Data is taken from the time period when both measurement stations, at BSPR
and BKLH, were operated (June 10th to July 9th 2002). Fig. 4.8 shows the wind directions (10-minutes-averages) as they were measured simultaneously at BKLH and BSPR with the scenarios selected according to the horizontal wind speeds as measured at BSPR at $x_3 = 31.7$ m (2.2h). Besides the dominant wind sectors, which are easily identified, it is observed that the wind directions were well-aligned, no significant turning of the wind direction between BKLH and BSPR is identified. As an additional insight, strong winds came preferably from north-westerly directions corresponding to the approach flow direction modelled in the wind tunnel.

The model scale has been chosen to be 1:300. This applies to the urban roughness scales as well as to the turbulence integral length scales. Modelling experience of the Hamburg wind tunnel group supported the expectation that this degree of scale reduction is feasible in the chosen wind tunnel. Therefore the (small) risk was taken to construct the urban model before turbulence measurements confirmed the correct geometric scaling of turbulence length scales (as e.g. $z_0$ and $L_{uw}$). For the chosen scale the wind tunnel model area of about 4m x 8m (width x length) translates to a full scale area of about 1.2km x 2.4km. (In section 4.1 a length of 9m was assigned to the
Figure 4.8: Correlation of 10-minutes-averaged wind directions measured simultaneously at Basel-Kleinhüningen (BKLH) and Basel-Sperrstrasse (BSPR) between June 10th and July 9th 2002. The wind directions at BSPR are measured at $x_3 = 31.7m$ (2.2h), the wind directions at BKLH are taken as the average over the levels $x_3 = 40m$, 60m, 80m and 100m to obtain an 'approach flow wind direction'. The scenarios are selected according to the wind speeds measured at BSPR at $x_3 = 31.7m$ (2.2h) ((a) to (f)).
model area. The 'last', i.e. the most downstream, meter was not covered with houses, so the actual urban model area was just about 8m long.) The model scale has also implications for the time scale. Since wind tunnel velocities are of comparable magnitude as their field counterparts, flow particles in the wind tunnel need only about 1/300 of the corresponding field time to pass a given shrunk roughness element. Therefore wind tunnel turbulence time scales are about 1/300 of the corresponding field turbulence time scales (see end of chapter 2.4 for further discussion).

The topography of Kleinbasel is essentially flat, therefore no elevations were modelled. This is supported by the topographical data provided by the University of Basel as well as by the on-site impression during a visit in Basel. The greater area of Basel is of course influenced by hills, mountains and valleys. The dominant wind sectors can be explained by those mesoscale structures. But the influence of this greater area topography is not assumed to be relevant for the present microscale study except for the existence of the mentioned dominant
<table>
<thead>
<tr>
<th>Location coordinates BSPR (SLK) (easting, northing)</th>
<th>(611890, 268365)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean building height $h$ (inside 250m circle around BSPR)</td>
<td>14.6m</td>
</tr>
<tr>
<td>Variation of building height $\sigma_h$ (inside 250m circle around BSPR)</td>
<td>6.9m</td>
</tr>
<tr>
<td>Local mean building height (inside 10m circle around BSPR)</td>
<td>14.0m</td>
</tr>
<tr>
<td>Plan aspect ratio $\lambda_P$ (inside 250m circle around BSPR)</td>
<td>0.54</td>
</tr>
<tr>
<td>Frontal plan aspect ratio $\langle \lambda_F \rangle$ (inside 250m circle around BSPR and averaged over all wind directions)</td>
<td>0.37</td>
</tr>
<tr>
<td>Land use</td>
<td>Dense urban, mainly residential, 3 to 4 storey buildings in blocks, flat commercial / light industrial, buildings in the backyards</td>
</tr>
</tbody>
</table>

Table 4.2: Morphological specifications of the urban roughness in the vicinity of the field measurement tower Basel-Sperrstrasse (BSPR) (taken from the BUBBLE website). In the wind tunnel coordinate system BSPR is located at $x_1 = 1634m$ and $x_2 = 0m$.

The details of the urban roughness of Kleinbasel, i.e. the shapes, measures and arrangement of buildings, were extracted from a digital model provided by the authorities of Basel. The digital model was checked for plausibility and consistency by an extensive collection of photos (>200 photos) taken during a visit in Basel. In only a few cases modifications to the digital building arrangement had to be made. Great care was taken to include as many details as feasible down to a few meters. The complete model comprises over 3,200 houses hand made by Gerken Architektur-Modellbau (www.mod-ger.de). The houses were constructed from Styrodur® which has certain favourable properties such as a roughened surface to counteract flow laminarization close to the surfaces. Fig. 4.9 shows two locations within the wind tunnel model compared to their full scale counterparts. Based on random checks the measures of the model houses are estimated to correspond within 1-2mm (i.e. full scale within about 0.5m) to the digital blueprint. Based on the same digital data set certain roughness parameters were calculated by Andreas Christen from the University of Basel and published on the BUBBLE project website, they are summarized in Tab. 4.2. In particular the mean building height $h = 14.6m$ around BSPR serves as a frequently cited height scale in this work.
Figure 4.10: Map of the wind tunnel model with the origin of \( x_1 \) \((x_2)\) defined to be at the model inflow edge (wind tunnel centreline). Wind tunnel side walls are at \( x_2 = \pm 600\)m (in full scale measures). Systematic turbulence measurements are made within the small rectangle (upstream edge at \( x_1 = 1364\)m), concentration measurements are made within the large rectangle (upstream edge at \( x_1 = 1334\)m). Array of points gives the concentration measurement locations covering the large rectangle. The nine small crosses within and at the border of the large rectangle indicate the vertical concentration profile locations, the large cross close to the model inflow edge indicates the location for background concentration measurements. Release point of the gas is at R1, field sampling stations are at S1, S3 (at three height levels S3a, S3b, S3c), S4, S8 and S9.

4.5 Measurement locations within and above the urban model

The model measures (full scale), the wind tunnel coordinate system and an overview over the measurement locations are given in Fig. 4.10.

To allow a straightforward presentation of the turbulence measurement results the following standard expressions are introduced denoting turbulence measurement locations above the urban model:

- The five horizontal profiles
- The ten vertical profiles
• The street level profile

• The Feigenwinter location

In the following chapters reference is made to those profile locations without detailing again their exact coordinates. They are defined now.

With the goal to get representative horizontal averages five height levels above roof level were chosen and covered respectively by a rectangular grid of horizontally distributed measurement points. Location of the five horizontal layers was from \( x_1 = 1364\text{m} \) to \( 1709\text{m} \) (1694m), from \( x_2 = -120\text{m} \) to 90m and respectively at \( x_3 = 27\text{m} \) (1.8h), \( x_3 = 33\text{m} \) (2.3h), \( x_3 = 39\text{m} \) (2.7h), \( x_3 = 45\text{m} \) (3.1h) and \( x_3 = 69\text{m} \) (4.7h). Their location above the urban model is given in Figs. 4.10 to 4.12. At the three lower height levels the measurement points were arranged on a rectangular grid at a downstream and cross-stream separation of 30m with one additional measurement point at the centre of each square and an additional row of measurement points downstream of the grid, giving a total of 180 measurement points per layer and a downstream extension of 345m (Fig. 4.12). Due to decreasing horizontal variability the measurement points at the centre of each square and the additional row of measurement points downstream of the grid were skipped on the two upper height levels, giving a total of 96 measurement points per layer and a downstream extension of 330m on the two upper height levels. The upstream edge of these horizontal layers was at a distance of about 1.3km from the model inflow edge. Whenever reference is made to 'the five horizontal profiles' those five horizontal layers are meant.

With the intention to increase the vertical resolution and to analyse the variability of local turbulence ten vertical profiles were measured within the area covered by the five horizontal profiles (Fig. 4.11 and Fig. 4.12). Eight of these ten vertical profiles (with one of the eight at BSPR) were measured above street canyons, the remaining two vertical profiles were taken at backyard locations characterized by particularly high and low turbulence intensities. Whenever reference is made to 'the ten vertical profiles' those ten locations are meant. The focus on locations above street canyons was motivated by the intention to compare alternative locations for the measurement tower BSPR which had not been realized in the field. From \( x_3 = 24\text{m} \) (1.6h) upwards wind tunnel turbulence measurements were made at the same height levels for all ten locations up to \( x_3 = 204\text{m} \) (14.0h). Thus it is possible to calculate horizontal averages over ten points per height level from \( x_3 = 24\text{m} \) (1.6h) upwards. Local roughness geometry determined the feasibility to make measurements below \( x_3 = 24\text{m} \) (1.6h). This was possible only at some locations (see appendix D), averages over those reduced horizontal samples were not calculated due to their reduced significance.
Figure 4.11: (a) Flower sticks inserted into the model indicate the ten vertical profile locations and the Feigenwinter location (right location). Full scale height of the flower sticks is approximately 200m. Rectangle indicates the horizontal area covered by the five horizontal profiles. (b) Close up of the 10 vertical profile locations indicated by tooth sticks. White plastic wool models vegetation.
Figure 4.12: Area covered by the five horizontal profiles and locations of the ten vertical profiles in the central part of the urban model. At the two upper levels of the five horizontal profiles the density of measurement points was reduced (96 instead of 180 measurement points). The ten vertical profile locations and the Feigenwinter location (thick cross) are shown on the street map, the nomenclature of the ten vertical profiles locations is given below.
Owing to the size of the laser probe in relation to the narrow street canyons it proved to be difficult to measure turbulence below roof level. Only at one location within Basel-Sperrstrasse it was possible to measure turbulence profiles from street level upwards, see Fig. 4.12. The notion 'the street level profile' refers to this location. Another single location is the 'Feigenwinter location' which corresponds to the field measurement location analysed by Christian Feigenwinter from the University of Basel in his PhD thesis (Feigenwinter (2000)), see also Figs. 4.11a and 4.12.

To document the flow adaptation to the urban model, profile measurements were made for increasing urban fetches. Those profile locations, which are all on the wind tunnel centreline, are shown in Fig. 4.13. Their increasing distances from the model inflow edge, where the approach flow profile was measured, were $x_1 = 809m$, 1034m, 1334m and 1634m.

The horizontal mean concentration distribution is resolved by measurements made systematically on a horizontal grid of measurement points (Fig. 4.10). The grid starts 384m downstream of the source (at $x_1 = 1334m$), extends to 864m downstream of the source (to $x_1 = 1814m$) and has a lateral extension of 420m (from $x_2 = -76m$ to $x_2 = 344m$), roughly symmetric around the

Figure 4.13: Profile locations to document flow adaptation to the urban model. Marks on the sticks indicate full scale $x_3 = 100m$ and $x_3 = 200m$. 
expected plume centreline. This grid was measured at three height levels, \( x_3 = 27\text{m (1.8h)} \), 45m (3.1h) and 69m (4.7h), 135 horizontal measurements points (= 9 longitudinal x 15 lateral equally spaced locations) per height level were covered, giving a total of 405 grid measurement points (= 3 x 135).

The vertical mean concentration distribution is documented by vertical profiles measured at the estimated plume centreline (Fig. 4.10). These positions were determined based on the estimated locations of maximal concentrations at \( x_3 = 27\text{m (1.8h)} \) as observed from the horizontal grid measurements. A plume deflection has been noticed explaining the somewhat tilted arrangement of the vertical profile locations. The measurement levels were from \( x_3 = 21\text{m (1.4h)} \) up to 102m (7.0h) every 9m giving a total of 10 levels per vertical profile. At some locations the lowest measurement level had to be shifted upwards due to local building height.

To allow a direct comparison to the field measurements, concentration time series were recorded at the field sampling stations covered by the wind tunnel model (Fig. 4.10). The exact coordinates of the source location R1 and the sampling stations are given in Tab. 4.3 (taken from Gryning et al. (2004)). These time series were recorded for continuous gas releases as well as for source off/on transitions to estimate travel times.

The source location R1 as well as the location for background concentration measurements at about \( x_3 = 20\text{m (1.4h)} \) are indicated in Fig. 4.10 as well.
Chapter 5

Flow boundary conditions

In this chapter a description is given of the efforts to determine the characteristics of the approach flow from field measurements. The wind tunnel approach flow, i.e. the turbulence characteristics at the model inflow edge, is documented.

5.1 Mean wind profile of the approach flow from field measurements

In the wind engineering context it is common practice to parameterize the mean wind profile by the so-called power law which is given by

\[ \frac{U_1(x_3)}{U_{1,\text{ref}}} = \left( \frac{x_3 - d_0}{x_{3,\text{ref}} - d_0} \right)^\alpha \]  

where \( U_{1,\text{ref}} \) is the velocity at some chosen reference height \( x_{3,\text{ref}} \) and \( \alpha \) is an exponent depending on the roughness of the surface. In contrast to the logarithmic profile (Eqn. (2.19) on page 30) the power law is found to be an appropriate parameterization for far greater height ranges even beyond the surface layer. The exponent \( \alpha \) is usually taken as a unique function of the roughness length \( z_0 \) (see e.g. Plate (1995), also Fig. 8 in Counihan (1975)). Since the field data measured near the model inflow edge at Basel-Kleinhüningen (BKLH) is available up to \( x_3 = 200 \text{m} \) and the vertical resolution of the field data below \( x_3 = 100 \text{m} \) is rather low, the power law is taken instead of the logarithmic profile to parameterize the wind profile up to \( x_3 = 200 \text{m} \). Therefore the focus of approach flow characterization from field data is on the exponent \( \alpha \). Nevertheless, owing to its conceptual importance, the roughness length \( z_0 \) is also estimated from logarithmic profile fits up to \( x_3 = 100 \text{m} \). Since the
lowest field measurement level at BKLH was rather high (at $x_3 = 40m$) with comparatively low vertical resolution from that level upwards, variation of the zero plane displacement $d_0$ has no or only very little impact on the overall profile fits. Therefore it is not possible to estimate $d_0$, it is set to zero which corresponds roughly to the verbal description of the immediate surroundings of BKLH ('very flat railway tracks only', A. Christen from the University of Basel). This vanishing $d_0$ corresponds formally to the result obtained when $d_0$ is included in the profile estimation as a free parameter, in this case $d_0$ is estimated to be close to zero. Nevertheless, the physical implication of this estimation is somewhat limited (see e.g. Blackadar (1997), p.34).

Wind and potential temperature measurements were made at BKLH from June 10th to July 9th 2002 and were provided by METEK GmbH as 10-minutes-averages (RASS measurements). The field data used for wind tunnel approach flow modelling covers the height range from $x_3 = 40m$ up to $x_3 = 200m$, the vertical resolution is 20m. Thus 3938 10-minutes-profiles of simultaneously measured wind speed, wind direction and potential temperature were available. The RASS data was checked for consistency by comparison to simultaneously measured profiles taken by a nearby located captive balloon, the data sets were found to be reasonably consistent with each other (private communication with R. Vogt, University of Basel). A first glance at the BKLH data indicates two dominant wind sectors in the height range up to $x_3 = 100m$ (see Fig. 4.8 on page 60 as well as Fig. 5.1): from approximately 100° to 160° and from approximately 270° to 360°. The first sector typically corresponds to nighttime/early morning episodes, while the second sector typically prevails during daytime/early afternoon scenarios (see Fig. 5.2).

To determine the power law exponent $\alpha$ the relevant 10-minutes-periods are selected according to the three criteria:

(i) Wind direction in a sufficiently narrow sector around 330° (approach flow direction to be modelled in the wind tunnel)

(ii) Wind speed sufficiently high to focus on turbulence scenarios with significant shear turbulence production

(iii) Stratification sufficiently neutral to minimize thermal turbulence production

Regarding the first two criteria the notion 'sufficiently' is made operational as follows:

(ad i) The admissible wind sector is chosen to represent approximately uniform surface roughness since the mean wind profile is a function of upwind
Figure 5.1: Wind speeds versus wind directions measured at Basel-Kleinhüningen (BKLH) at $x_3 = 40\text{m}$ between June $10^{th}$ and July $9^{th}$ 2002. Each point represents a 10-minutes-average, a total of 3938 10-minutes episodes are shown. Two dominant wind sectors are identified, roughly between $DD = 100^\circ$ and $160^\circ$ and between $DD = 270^\circ$ and $360^\circ$.

surface roughness. Eyesight inspection of the map (Fig. 4.7 on page 59) indicates presumably uniform roughness in a sector between $300^\circ$ and $360^\circ$. Therefore only those profiles are retained which have wind directions in the sector between $300^\circ$ and $360^\circ$ at all nine levels from $x_3 = 40\text{m}$ to $x_3 = 200\text{m}$.

(ad ii) Wind speeds of at least $3\text{m/s}$ at roof level (approximately at $x_3 = 20\text{m}$) are considered 'strong enough'. (The notion of 'strong wind' is somewhat vague. The chosen speed is taken after personal communication with B.Leitl and by taking into account the experience within the Hamburg wind tunnel group.) From this the threshold value for the lowest measurement level ($x_3 = 40\text{m}$) is estimated to be $4.4\text{m/s}$. Only those profiles were retained which had a wind speed of at least that threshold magnitude at $x_3 = 40\text{m}$. The resulting analysis should of course not depend on the precise threshold value, but nevertheless this value has to be set explicitly to allow for a transparent application of the 'sufficiently strong wind' criterion.

On the basis of the given field data the state of stratification can be determined only approximately. In the case of the power law the dependence of the estimated exponent $\alpha$ on stratification is found to be rather weak. With hindsight this is taken as a justification to apply criterion (iii) rather boldly.
Figure 5.2: Relative occurrence of dominant wind sectors. Only those 10-minutes episodes are included which have wind directions within one of the dominant wind sectors at all height levels up to $x_3 = 200m$.

(ad iiia) Static stratification is given by the slope of the potential temperature profile. Neutral stratification corresponds to a constant potential temperature with height. Therefore the potential temperature profile from $x_3 = 40m$ to $200m$ is approximated by a linear fit to determine its 'average slope'. The steepness of this average slope, i.e. the average 'temperature change per height', is taken as a selection criterion according to 'the smaller the absolute slope the more neutral the stratification'. Different threshold slopes are set and only those time periods are considered when the absolute value of the average potential temperature change per height (between $x_3 = 40m$ and $200m$) does not exceed the given threshold. The variation of the estimated $\alpha$'s from the thus constructed mean wind profiles is found to be rather small. The obvious shortcomings of this 'average slope' approach are somewhat controlled by visual inspection of samples of thus selected temperature profiles. None of the selected profiles had been rejected by (subjective) inspection.

It is acknowledged that in the presence of increased turbulence levels, as it is the case above urban roughness, the potential temperature gradient tends to be diminished due to increased vertical mixing (as already remarked, e.g., in WMO (1958, p. 40)). Therefore the classification of stability based on the potential temperature gradient becomes somewhat ambiguous. Nevertheless, at the time of approach flow evaluation no other appropriate 'thermal data'
Figure 5.3: Mean wind profiles averaged over 10-minutes episodes fulfilling the indicated 'potential temperature threshold slope' criterion (see text). Solid lines are respectively fitted power law profiles (Eqn. (5.1), parameters as given in Tab. 5.1). Horizontal shift in the profiles is due to varying $x_{3,\text{ref}}$.

ready for analysis was available. For the estimation of the roughness length $z_0$ from logarithmic profile fits, additional approaches to identify neutral periods are also pursued (see below).

To estimate $\alpha$, the power law from Eqn. (5.1) is fitted to the wind profile obtained by averaging over all scaled wind profiles stemming from those 10-minutes-periods selected according to the above stated criteria. Height range of the fit is from $x_3 = 40\text{m}$ to $x_3 = 200\text{m}$. The reference height level $x_{3,\text{ref}}$ for the scaling velocity $U_{1,\text{ref}}$ is the same for all included scaled 10-minutes-profiles as well as for the final power law fit. Nevertheless the chosen $x_{3,\text{ref}}$ may vary for the different potential temperature threshold slopes depending on which reference height level gives the best fit. The resulting scaled mean wind profiles are shown in Fig. 5.3, Tab. 5.1 summarizes the statistics. The apparent horizontal shifts of the profiles are merely a consequence of different reference height levels $x_{3,\text{ref}}$.

Two remarks can be made. Firstly, the mean wind profiles are well parameterized up to $x_3 = 200\text{m}$ by the power law with $\alpha = 0.14$ to 0.17. Secondly, with increasing threshold temperature slope the mean wind profile varies only
<table>
<thead>
<tr>
<th>threshold slope [°C/100m]</th>
<th>α</th>
<th>d₀ [m]</th>
<th>z_{ref} [m]</th>
<th>R²</th>
<th>No. of included 10-min episodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.17</td>
<td>0</td>
<td>40</td>
<td>0.95</td>
<td>10</td>
</tr>
<tr>
<td>0.2</td>
<td>0.16</td>
<td>0</td>
<td>60</td>
<td>0.94</td>
<td>17</td>
</tr>
<tr>
<td>0.3</td>
<td>0.14</td>
<td>0</td>
<td>200</td>
<td>0.95</td>
<td>32</td>
</tr>
<tr>
<td>0.4</td>
<td>0.14</td>
<td>0</td>
<td>180</td>
<td>0.97</td>
<td>35</td>
</tr>
<tr>
<td>0.5</td>
<td>0.14</td>
<td>0</td>
<td>200</td>
<td>0.98</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 5.1: Estimated power law exponent α (Eqn. (5.1)) for different potential temperature threshold slopes. Range of the power law fit is from \( x_3 = 40 \text{m} \) to \( 200 \text{m} \).

Slightly (with respect to the physically plausible α range from 0.08 to 0.40, see e.g. VDI guideline 3783 (2000)), with a somewhat decreasing α. This decrease can be explained by noting that with increasing potential temperature threshold slope the reference level \( x_{3,ref} \) moves upwards. It is a known effect that low reference levels may lead to an overestimation of α (see e.g. Counihan (1975)).

These findings indicate that for the chosen threshold velocity of 4.4m/s at \( x_3 = 40 \text{m} \) the influence of stratification on the mean wind profile (as far as it is represented by the 'potential temperature slope criterion') is of minor importance in the given field data set. It is noted that a manual selection of the 'most neutral' potential temperature profiles by subjective criteria does not yield a different result (not shown) (in that manual approach the profiles were inspected visually, only those profiles with the 'most constant' potential temperature were retained). The data is interpreted as being most supportive for \( α \sim 0.15 - 0.16 \).

Estimation of roughness length \( z_0 \) is hampered by a large profile-to-profile variability based on 10-minutes-averages. Therefore the first step is to construct mean profiles over 30 and 60 minutes respectively. Whenever 3 (6 respectively) successive 10-minutes-profiles fulfil the wind direction criterion, the profile data is averaged per height level to give a 30-minutes-profile (60-minutes-profile respectively). From these profiles only those are retained which fulfil the wind speed criterion as stated above. In addition to the above stated 'potential temperature slope criterion' with somewhat restricted potential temperature threshold slopes, two other approaches in the search for neutral periods are applied.
(ad iiib) According to Monin-Obukhov similarity theory wind profiles stemming from non-neutral time periods should show deviations from the logarithmic shape. Therefore the quality of the logarithmic profile fit to the wind profile up to $x_3 = 100m$ is taken as a selection criterion. It was quantified by the (somewhat arbitrary) definition of a minimal admissible $R^2$ thereby filtering for the 'most logarithmic' profiles. The chosen threshold values for $R^2$ were 0.99 and 0.95.

(ad iiic) A particular time period, the morning hours of June 28th 2002, shows some eye-catching characteristics of neutral stratification, it is therefore taken as a case study. These favourable characteristics are

- an approximately constant potential temperature with height,
- a logarithmic shape of the mean wind profile,
- Richardson bulk numbers comparatively close to zero (otherwise the scatter of Richardson bulk numbers over adjacent height layers is simply too large to be a meaningful selection criterion),
- a stability parameter $\zeta = x_3/L$ (as measured at BKLH at $x_3 = 10m$) of approximately -0.09 and therefore comparatively close to zero (otherwise no favourable correlation is observed between $\zeta$ measured at $x_3 = 10m$ and the temperature and wind profiles from $x_3 = 40m$ upwards, therefore $\zeta$ is not used as a general selection criterion).

For a fourth estimation approach of $z_0$ the scaled mean wind profiles from the power law fits are taken which were constructed as averages over multiple, not necessarily successive 10 minutes periods. Four samples of 10-minutes episodes are obtained by setting the threshold temperature slope to 0.1°C/100m, 0.2°C/100m, 0.3°C/100m and 0.5°C/100m (the threshold slope 0.4°C/100m is not included because the resulting profile sample covers essentially the same 10 minutes episodes as the threshold slope 0.3°C/100m). Each of the four samples gives an average wind profile (shown in Fig. 5.3). An estimation of $z_0$ is obtained by fitting the logarithmic law once to all those four profiles collectively.

The results of the four $z_0$ estimation approaches (based respectively on the
Criterion Averaging Parameter Estimated No. of 
time [min] $z_0$ [m] profiles

<table>
<thead>
<tr>
<th>Potential temperature</th>
<th>30</th>
<th>0.1°C/100m</th>
<th>0.08</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
<td>0.1°C/100m</td>
<td>0.04</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2°C/100m</td>
<td>0.08</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3°C/100m</td>
<td>0.82</td>
<td>6</td>
</tr>
<tr>
<td>Threshold slope</td>
<td>30</td>
<td>0.2°C/100m</td>
<td>0.04</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.2°C/100m</td>
<td>0.08</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3°C/100m</td>
<td>0.82</td>
<td>6</td>
</tr>
<tr>
<td>Best log fit</td>
<td>30</td>
<td>$R^2 = 0.99$</td>
<td>0.31</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>$R^2 = 0.99$</td>
<td>0.10</td>
<td>1</td>
</tr>
<tr>
<td>Mean wind profiles</td>
<td>10</td>
<td>0.1°C/100m</td>
<td>0.19</td>
<td>4</td>
</tr>
<tr>
<td>from power law fits</td>
<td>10</td>
<td>0.2°C/100m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.3°C/100m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.5°C/100m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case study</td>
<td>30</td>
<td>7:40am-8:10am</td>
<td>0.23</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>7:40am-8:40am</td>
<td>0.18</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.2: Summary of the estimation approaches for $z_0$.

'potential temperature slope criterion', the '$R^2$ criterion', the case study and on the mean wind profiles from power law fits) are summarized in Tab. 5.2. Fig. 5.4 shows the logarithmic profiles (Eqn. (2.19) on page 30) fitted to the mean wind profiles from the case study and to those wind profiles also used for the power law fits.

The four estimation approaches for $z_0$ differ in their criteria for a neutral stratification. Three of them realize an algorithmic procedure while the fourth, the case study approach, relies on the 'eye of the observer'. The scatter of the resulting $z_0$ estimations is quite large, ranging from 0.04m to 0.82m. Nevertheless it is noted that the mean wind profiles from the power law fit, which have already observed to be well-shaped up to $x_3 = 200$m, give an estimation of $z_0$ (0.19m) rather close to estimations from the case study (0.18m and 0.23m respectively) where there is good evidence of neutral stratification. Therefore it is assumed that an appropriate estimation of $z_0$ might be in the range from 0.18m to 0.23m. This compares reasonably well with the estimates from the best log fit approach applied to the 60-minutes-profiles (0.10m to 0.36m).

Compared to reference values reported for the adiabatic ABL it is noted that
Figure 5.4: (a) Logarithmic profile fit (Eqn. (2.19) on page 30) to the wind profiles also used for the estimation of the power law exponent. (b) Fit of the logarithmic profile to the two case studies stemming from the morning hours of June 28th 2002.
The estimated power law exponent $\alpha \sim 0.15-0.16$ and the estimated roughness length $z_0 \sim 0.18\text{m}-0.23\text{m}$ are within the range of the functional relationship between these two parameters as proposed e.g. in Counihan (1975) for adiabatic conditions (Fig. 5.5). Both parameters give a consistent roughness classification as 'moderately rough' (cf. e.g. Counihan (1975), VDI guideline 3783 (2000)),

- the roughness classification 'moderately rough' which is used for mainly rural roughness appears to be at the lower end of the roughness range one might expect by eyesight inspection of the fetch which gives a more suburban type of roughness. Nevertheless it is noted that the immediate surrounding of the measurement location BKLH at the inflow edge of the wind tunnel model is described as 'very flat railway tracks', so the data is not considered inconsistent with the surroundings of the measurement location.

Based on these findings and within the limits of the indicated estimation uncertainties, the estimated parameters $\alpha$ and $z_0$ are considered to describe reasonably well the approach flow under (near-)adiabatic conditions. Combining these quantitative findings with the visual roughness impression and using the classification scheme introduced by Davenport (1960) (which is supported by the more up-to-date study by Wieringa (1993)), the approach flow is supposed
to correspond to roughness class 5. In the parlance of VDI (2000) the roughness is assumed to be at the transition from 'moderately rough' to 'rough'. Therefore the parameters deduced from the field data are taken as lower limits with somewhat larger values also considered appropriate for wind tunnel modelling.

5.2 Approach flow of the wind tunnel model

Based on the findings presented in the last section the VDI guideline 'Physical modelling of flow and dispersion processes in the atmospheric boundary layer' (VDI (2000)) is used as a reference to model the turbulence characteristics at the model inflow edge (in the following termed 'the approach flow'). The goal is set by the turbulence characteristics corresponding to the transition from 'moderately rough' to 'rough' (VDI (2000) classification). The data presented in the following refers exclusively to wind tunnel measurements.

As argued in the chapters 2.5 and 2.6, an important boundary condition for modelling atmospheric surface layers in the wind tunnel is a negligible pressure gradient along the wind tunnel axis. Only then it could be expected to model a constant flux layer as observed in the field and predicted by the boundary layer approximated RANS equation (2.14). The sensitivity of the constant flux layer on the pressure gradient has also been observed in other turbulence studies conducted by the Hamburg wind tunnel group (internal discussion). The pressure gradient is controlled by varying the wind tunnel ceiling with the urban model installed in the wind tunnel. Fig. 5.6 shows the scaled axial pressure gradients as set for the first and the second measurement campaign. Also shown is the recommended upper pressure gradient threshold according to VDI (2000). Except at the beginning of the test section, where no ceiling adjustment is possible, the recommended maximal axial pressure gradient is never exceeded.

The approach flow characteristics are set by a suitable configuration of vortex generators at the inflow edge of the test section and roughness elements in the first half of the test section. Finding the appropriate configuration is a painstaking activity requiring patience and good fortune. The final configuration of vortex generators and roughness elements is documented in appendix A. The profile of mean wind $U_1$ as measured at the model inflow edge on the wind tunnel centreline is shown in Fig. 5.7. The corresponding profile parameters are $\alpha = 0.19$ (fit from $x_3 = 24m$ to $204m$), $z_0 = 0.19m$ (fit from $x_3 = 24m$ to $108m$ with this height range determined by the seemingly good fit of the logarithmic law (Eqn. (2.19) on page 30) and based on height range expectations for atmospheric logarithmic profiles) and $d_0$ set to 0.00m (not included
Figure 5.6: Scaled pressure gradient along the wind tunnel axis (a) during the first measurement campaign and (b) during the second measurement campaign.
Figure 5.7: Mean wind profile of the approach flow at the wind tunnel centreline (a) with the power law fit for $\alpha = 0.19$ and $d_0 = 0$ m ($x_{3,ref} = 144$ m, height range of the fit $x_3 = 24$ m to 204 m) and (b) with the logarithmic profile fit for $z_0 = 0.19$ m and $d_0 = 0$ m (height range of the fit $x_3 = 24$ m to 108 m). Dashed horizontal lines give roughness element height of 12 m (corresponding to 0.04 m on model scale).
in the estimation). The friction velocity as estimated from the logarithmic profile fit is \( u_{\text{el}} = 0.40 \text{m/s} \). The family portrait (always at the model inflow edge on the wind tunnel centreline) continues with the turbulence intensities \( \sigma_i / U_1 \) (Fig. 5.8) compared to the VDI (2000) reference and the Reynolds flux \( u'_i u'_3 \) profile (Fig. 5.9a). By eye-sight inspection a constant flux layer is identified from \( x_3 = 36 \text{m} \) to \( 144 \text{m} \), the estimated friction velocity from the flux profile is \( u_{\text{flux}} = 0.44 \text{m/s} \). The three turbulent velocities \( \sigma_i \) scaled with \( u_{\text{flux}} \) are shown in Fig. 5.9b. Lateral homogeneity of turbulence at the model inflow edge is documented in Fig. 5.10 for the height levels \( x_3 = 36 \text{m}, 108 \text{m} \) and \( 180 \text{m} \). It is noted that lateral homogeneity is well-established up to \( x_3 = 108 \text{m} \) (the focal height range of the modelling efforts) with a somewhat decreasing lateral homogeneity at \( x_3 = 180 \text{m} \).

Time series of all three velocity components are recorded at the model inflow edge at the height levels \( x_3 = 36 \text{m}, 72 \text{m}, \) and \( 108 \text{m} \). The velocity spectra are shown in Fig. 5.11 together with the reference spectra from Kaimal et al. (1972). Integral length scales \( L_{ux} \) are also calculated, they are compared to the urban \( L_{ux} \) and to the reference from Counihan (1975) in chapter 6.9 (Fig. 6.44 on page 144).

Summarizing the presented turbulence characteristics at the model inflow edge, it is remarked that the approach flow roughly represents turbulence characteristics corresponding to the roughness transition from 'moderately rough' to 'rough'. The mean wind profile, the turbulence intensities and the constant flux layer are modelled very well in comparison to the VDI (2000) reference. Deviations are identified for the scaled turbulent velocities \( \sigma_i / u_{\text{flux}} \) (for \( i = 1 \) and \( 2 \) the reference values of 2.5 and 1.8 are somewhat larger, for \( i = 3 \) the reference 1.25 is a bit smaller) and the low frequency part of the spectra while the integral length scales \( L_{ux} \) correspond again well to the Counihan (1975) reference. Given the time spent on approach flow modelling (more than one month) and the difficulty to modify single turbulence parameters in isolation from the other parameters (in fact each reconfiguration of e.g. the roughness elements influences the whole set of turbulence parameters), it is decided to take the achieved configuration as the flow boundary condition for the urban model. The expectation is that, beyond a sufficient urban model fetch and for the studied height range, memory effects of the stated deviations from atmospheric reference turbulence should not be relevant for the intended urban turbulence measurements.
Figure 5.8: Turbulence intensity of the approach flow at the wind tunnel centreline in the (a) longitudinal, (b) lateral and (c) vertical velocity component. Reference is taken from VDI (2000).
Figure 5.9: (a) Reynolds fluxes $u'_1u'_3$ with the constant flux value $u_{*\text{flux}}$ indicated and (b) turbulent velocities scaled by $u_{*\text{flux}}$ of the approach flow at the wind tunnel centreline.
Figure 5.10: Lateral homogeneity of the approach flow measured at three height levels: (a) Mean wind, (b) longitudinal turbulence intensity and (c) Reynolds fluxes with dotted lines indicating linearized lateral trends. Lateral homogeneity in lateral and vertical turbulence intensities look similar.
Figure 5.11: Approach flow velocity spectra at the wind tunnel centreline of $u_1$ (left column), $u_2$ (middle column) and $u_3$ (right column) measured at $x_3 = 36\text{m}$ (lower row), $x_3 = 72\text{m}$ (middle row) and $x_3 = 108\text{m}$ (upper row). Shown is $nS_i(n)/\sigma_i^2$ versus non-dimensional frequency $n = f x_3/U_1$, straight curves give the reference spectra from Kaimal at al. (1972).
Chapter 6

Modelled urban turbulence in Kleinbasel

The turbulence measurements presented in the following sections have the purpose to identify and characterize the ISL and the RSL above the urban roughness of Kleinbasel. But first the adaptation of the flow to the urban model is discussed.

6.1 Flow adaptation to the urban model

The model inflow edge constitutes a roughness change. Flow response to a roughness change is usually discussed in terms of an internal boundary layer (IBL) which includes different states of flow adaptation (the transitional state in the upper IBL part and the equilibrium state in the lower IBL part), see e.g. Garrat (1990).

The impact of the roughness change on the mean wind profile at the wind tunnel centreline with increasing urban fetch is shown in Fig. 6.1. Also shown are estimations of the IBL height $h_{IBL}(x_1)$ based on the formula proposed by Wood (1982) and cited in Simiu and Scanlan (1986):

$$h_{IBL}(x_1) = 0.28 \cdot z_0 \left( \frac{x_1}{z_0} \right)^{0.8}.$$  \hspace{1cm} (6.1)

Anticipating the results presented in the next section, the urban roughness length $z_0$ is set to 2.8m±0.8m (now referring to the urban model roughness which is distinct from the approach flow roughness discussed in the last chapter). The uncertainty in the thus calculated $h_{IBL}(x_1)$ due to the uncertainty in
Figure 6.1: Adaptation of the mean wind profile to the urban model along the wind tunnel centreline. Locations A to D are 809m, 1034m, 1334m and 1634m downstream of the model inflow edge. Straight lines indicate IBL top estimated by Woods formula (Eqn. 6.1), dashed lines indicate uncertainty of this estimation due to uncertainty in \( z_0 \).
Figure 6.2: Adaptation of the Reynolds fluxes to the urban model along the wind tunnel centreline. Symbols as in the case of the mean wind adaptation (Fig. 6.1).
$z_0$ is indicated in Fig. 6.1 by the dashed lines, they give $h_{IBL}(x_1)$ calculated for $z_0 = 2.0\text{m}$ and $3.6\text{m}$ respectively. It may be noted that the formula (6.1) from Wood (1982) is one out of several proposed for IBL height growth downstream of an abrupt roughness change (see e.g. Kaimal and Finnigan (1994)). Fig. 6.2 elucidates the impact on the $u'u_3$ profiles at the wind tunnel centreline. A 'shear shock' immediately downstream of the roughness change is obvious as it is commonly observed for smooth-rough transitions (see e.g. Garrat (1990)). Subsequently the Reynolds fluxes adapt successively to the urban roughness. For the mean wind profiles as well as for the flux profiles it is observed that the influence of the roughness change appears to extend to somewhat greater heights than predicted by Wood’s formula (6.1). This may be explained by the observation that between the model inflow edge and, say, $x_1 = 1034\text{m}$ (i.e. location B in Fig. 6.1) the mean building height is somewhat larger than between $x_1 = 1517\text{m}$ and $x_1 = 1664\text{m}$ where the ten vertical profile have been measured to determine $z_0$ (see photos in Fig. 4.9 on page 61 and Fig. 4.11a on page 65). Therefore the above used $z_0$ to calculate $h_{IBL}(x_1)$ underestimates the roughness immediately downstream of the model inflow edge. There the taller buildings may accelerate the IBL height growth.

The main body of urban turbulence measurements stems from roughly between the two most downstream locations C and D, 1334m and 1634m downstream of the model inflow edge. Here the comparison of the mean wind profiles shows no further significant profile adaptation between $x_3 = 48\text{m}$ (3.3h) and 96m (6.6h), variations below $x_3 = 48\text{m}$ (3.3h) should be attributed to roughness sublayer inhomogeneity. Above $x_3 = 96\text{m}$ (6.6h) up to $x_3 = 180\text{m}$ (12.3h) a transitional state of the mean wind profile may still be diagnosed. A conclusive comparison of the Reynolds flux profiles at these two locations is made ambiguous by the somewhat larger values of $u'u_3$ at location C (1334m downstream of the model inflow edge) at the height levels $x_3 = 60\text{m}$ (4.1h) and $x_3 = 72\text{m}$ (4.9h). Therefore the longitudinal $u'u_3$ profile taken at the wind tunnel centreline at the upmost level ($x_3 = 69\text{m}$ (4.7h)) of the five horizontal profiles is consulted, see Fig. 6.3. No significant systematic downstream change of $u'u_3$ can be observed. Therefore at least the large upstream value of $u'u_3$ at $x_3 = 72\text{m}$ (4.9h) (at location C in Fig. 6.2) is interpreted as an outlier. Based on the longitudinal profile it is concluded that at $x_3 = 69\text{m}$ (4.7h) the Reynolds fluxes show no indication of further adaptation to the urban model with increasing urban fetch. Based on the vertical profiles at $x_1 = 1334\text{m}$ and $x_1 = 1634\text{m}$ this state of adaptation appears to extend up to $x_3 = 120\text{m}$ (8.2h). This height level corresponds roughly to 9% of the upstream urban model fetch (1334m). Flow adaptation is further discussed in section 6.6 in the context of the TKE budget.

In the next sections the focus will be on the height range up to $x_3 = 81\text{m}$ (5.5h) between $x_1 = 1364\text{m}$ and $x_1 = 1709\text{m}$. Given this focus in combination
with the above stated observations concerning the state of flow adaptation it is reasonable to expect turbulence characteristics typical for the Kleinbasel urban roughness without significant distortions originating from approach flow properties. As noted, further qualifications of the state of flow adaptation are made when the TKE budget is discussed.

### 6.2 Integral statistics above roof level

Since the profiles of Reynolds flux $\overline{u'_1 u'_3}$ are instructive for the identification of a layered turbulence structure, they are discussed first. Fig. 6.4a shows the ten vertical $\overline{u'_1 u'_3}$ profiles (given one by one in appendix D), Fig. 6.4b their horizontal averages together with the horizontally averaged values of the five horizontal profiles. The following observations are made:

- The horizontal mean values of $\overline{u'_1 u'_3}$ over the five horizontal profiles stay approximately constant at all five height levels. This indicates that the 'true' horizontal averages of $\overline{u'_1 u'_3}$ may stay constant down to at least the lowest measurement level of the five horizontal profiles, i.e. $x_3 = 27m$ (1.8h).
Figure 6.4: 10 vertical profiles of Reynolds fluxes (top) and horizontally averaged Reynolds fluxes (bottom). Dotted scatter bars refer to min-max range at each height level of the 10 vertical profiles, solid scatter bars give the standard deviation over each of the 5 horizontal profiles. See text for the estimated ISL height range.
• The horizontal mean values of \( \overline{u_1' u_3'} \) over the ten vertical profiles stay approximately constant from \( x_3 = 48 \text{m} \) (3.3h) to \( 81 \text{m} \) (5.5h) (including these two levels). Above \( x_3 = 81 \text{m} \) (5.5h) \( -\overline{u_1' u_3'} \) decreases markedly while below \( x_3 = 48 \text{m} \) (3.3h) \( -\overline{u_1' u_3'} \) increases. This increase is in contrast to the constancy of the averages over the five horizontal profiles. It may be seen as a consequence of the fact that the ten vertical profiles are mostly located above street canyons. They may therefore represent corresponding turbulence characteristics at the lower height levels.

• Above \( x_3 = 48 \text{m} \) (3.3h) the averages over the five horizontal profiles and the ten vertical profiles collapse which is seen as an indication for the horizontal representativeness of the ten vertical profiles from \( x_3 = 48 \text{m} \) (3.3h) upwards.

• Below \( x_3 = 48 \text{m} \) (3.3h) the horizontal scatter within the vertical profile data and the horizontal profile data increases markedly. Above \( x_3 = 48 \text{m} \) (3.3h) the horizontal scatter stays roughly constant. This is seen as an indication for the onset of pronounced 3-dimensional turbulence close to roof level below \( x_3 = 48 \text{m} \) (3.3h).

The constant flux behaviour and the constancy of horizontal scatter with height make the height range from \( x_3 = 48 \text{m} \) (3.3h) to \( 81 \text{m} \) (5.5h) a candidate height range for the modelled ISL. The uncertainty of this estimation, stemming from the vertical profile resolution and the subjective profile inspection, is estimated to be approximately \( \pm 3 \text{m} \) (0.2h). The constant vertical Reynolds flux within this height range is estimated to be \( -\overline{u_1' u_3'} = 0.28 \pm 0.01 \text{m}^2/\text{s}^2 \) with the error estimation based on the vertical scatter of \( -\overline{u_1' u_3'} \) within the estimated ISL height range. It follows \( u_{\text{flux}} = (-\overline{u_1' u_3'})^{1/2} = 0.53 \pm 0.01 \text{m}/\text{s} \).

The contribution of \( u_2' u_3' \) to \( u_{\text{flux}} \) has not been measured and is considered to be negligible within the ISL as it is suggested by the BUBBLE field data, see Christen et al. (2003).)

The picture is more diverse when the ten vertical \( \overline{u_1' u_3'} \) profiles are inspected individually. Tab. 6.1 summarizes the local ISL estimations based on the constant flux criterion (with 'local' meaning that only the local vertical \( \overline{u_1' u_3'} \) profile is considered in the respective estimations), the individual profiles (aggregated in Fig. 6.4) are given separately in appendix D. Compared to the horizontally averaged data it is observed that for all parameters the mean values over all local estimations correspond well to the estimations based on the horizontal averages within the given accuracy (as they should), while the scatter in the locally estimated \( z_0 \) and the lower boundary of the ISL is significant. The latter indicates that the transitional region from the RSL to the ISL has a rather wobbly shape. Inspecting Tab. 6.1 shows that this transitional region covers roughly the height range from \( 33 \text{m} \) (2.7h) to \( 63 \text{m} \) (4.3h). Nevertheless, within the given estimation accuracy, 6 out of 10 vertical \( \overline{u_1' u_3'} \) profiles show...
<table>
<thead>
<tr>
<th>Location</th>
<th>Lower ISL limit [m]</th>
<th>Upper ISL limit [m]</th>
<th>$u_{local \ flux}$ [m/s]</th>
<th>$u_{local \ log}$ [m/s]</th>
<th>$z_0$[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>45</td>
<td>81</td>
<td>0.52</td>
<td>0.65</td>
<td>2.5</td>
</tr>
<tr>
<td>M</td>
<td>51</td>
<td>87</td>
<td>0.54</td>
<td>0.73</td>
<td>4.1</td>
</tr>
<tr>
<td>Q</td>
<td>45</td>
<td>87</td>
<td>0.52</td>
<td>0.68</td>
<td>3.0</td>
</tr>
<tr>
<td>P</td>
<td>51</td>
<td>93</td>
<td>0.53</td>
<td>0.69</td>
<td>3.4</td>
</tr>
<tr>
<td>R</td>
<td>33</td>
<td>93</td>
<td>0.54</td>
<td>0.64</td>
<td>2.7</td>
</tr>
<tr>
<td>T</td>
<td>36</td>
<td>69</td>
<td>0.53</td>
<td>0.63</td>
<td>2.3</td>
</tr>
<tr>
<td>S</td>
<td>63</td>
<td>81</td>
<td>0.49</td>
<td>0.68</td>
<td>2.6</td>
</tr>
<tr>
<td>high</td>
<td>39</td>
<td>93</td>
<td>0.53</td>
<td>0.73</td>
<td>3.9</td>
</tr>
<tr>
<td>low</td>
<td>42</td>
<td>87</td>
<td>0.51</td>
<td>0.61</td>
<td>2.0</td>
</tr>
<tr>
<td>BSPR</td>
<td>54</td>
<td>84</td>
<td>0.53</td>
<td>0.63</td>
<td>2.6</td>
</tr>
<tr>
<td>Average</td>
<td>$46 \pm 9$</td>
<td>$86 \pm 7$</td>
<td>$0.52 \pm 0.01$</td>
<td>$0.67 \pm 0.04$</td>
<td>$2.9 \pm 0.7$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Lower ISL limit [m]</th>
<th>Upper ISL limit [m]</th>
<th>$u_{local \ flux}$ [m/s]</th>
<th>$u_{local \ log}$ [m/s]</th>
<th>$z_0$[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>45</td>
<td>81</td>
<td>0.52</td>
<td>0.65</td>
<td>2.5</td>
</tr>
<tr>
<td>M</td>
<td>51</td>
<td>87</td>
<td>0.54</td>
<td>0.73</td>
<td>4.1</td>
</tr>
<tr>
<td>Q</td>
<td>45</td>
<td>87</td>
<td>0.52</td>
<td>0.68</td>
<td>3.0</td>
</tr>
<tr>
<td>P</td>
<td>51</td>
<td>93</td>
<td>0.53</td>
<td>0.69</td>
<td>3.4</td>
</tr>
<tr>
<td>R</td>
<td>33</td>
<td>93</td>
<td>0.54</td>
<td>0.64</td>
<td>2.7</td>
</tr>
<tr>
<td>T</td>
<td>36</td>
<td>69</td>
<td>0.53</td>
<td>0.63</td>
<td>2.3</td>
</tr>
<tr>
<td>S</td>
<td>63</td>
<td>81</td>
<td>0.49</td>
<td>0.68</td>
<td>2.6</td>
</tr>
<tr>
<td>high</td>
<td>39</td>
<td>93</td>
<td>0.53</td>
<td>0.73</td>
<td>3.9</td>
</tr>
<tr>
<td>low</td>
<td>42</td>
<td>87</td>
<td>0.51</td>
<td>0.61</td>
<td>2.0</td>
</tr>
<tr>
<td>BSPR</td>
<td>54</td>
<td>84</td>
<td>0.53</td>
<td>0.63</td>
<td>2.6</td>
</tr>
<tr>
<td>Average</td>
<td>$46 \pm 9$</td>
<td>$86 \pm 7$</td>
<td>$0.52 \pm 0.01$</td>
<td>$0.67 \pm 0.04$</td>
<td>$2.9 \pm 0.7$</td>
</tr>
</tbody>
</table>

Table 6.1: Locally estimated ISL parameters per vertical profile location (see appendix D for the individual profiles). The average values are given with the standard deviations, for the logarithmic profile fits $d_0$ is always set to 10.2m (0.7h) (as argued in appendix C).

ISL behaviour at or below 48m (3.3h), with another 3 showing ISL behaviour closely above. Therefore the above given ISL height estimation based on the horizontally averaged data is retained.

The ISL height estimation is based solely on the analysis of $\overline{u'_1 u'_3}$ profiles and will appear frequently in the following diagrams, its foundation are summarized as follows:

- Vertical constancy of the horizontally averaged Reynolds stress $\overline{u'_1 u'_3}$
- Attenuation of the horizontal scatter to an approximately constant scatter range with increasing height
- Conformity of the ten local $\overline{u'_1 u'_3}$ profiles to the constant flux behaviour within the estimated ISL height range

It is instructive to compare the present RSL height estimate of 3.3h for realistic urban wind tunnel roughness to results from other studies. Cheng and Castro (2002a) use the same definition of the RSL height above their regular wind tunnel roughness, i.e. the height of convergence of vertical turbulence profiles. For a rough surface consisting of regular cubes (arranged either in an aligned or in a staggered fashion) they find RSL heights between 1.7h and 1.9h (table III in their publication). For block-shaped roughness elements with varying heights they estimate the RSL to be 2.5h, where h is the mean roughness element height. Kastner-Klein and Rotach (2004) study the turbulence above
a realistic urban wind tunnel model and estimate the height of the layer, where
the influence of building pattern irregularities on the turbulence is clearly
noticeable, to be about 3h. The results of Cheng and Castro (2002a), Kastner-
Klein and Rotach (2004) and of the present study support the intuitively clear
expectation that increasing roughness irregularity increases the RSL height.
In his review of urban turbulence Roth (2000) finds the RSL height estimates
from several studies above various types of roughness to correspond well to
the (rather wide) height range of 2h to 5h brought forward by Raupach et al.

A remark concerning the notion of a 'local ISL' in the context of local $\overline{u_1''u_3'}$
profiles: Strictly speaking the ISL should reflect the aggregated effects of the
underlying roughness and the upstream fetch, therefore the combination of
'local' and 'ISL' appears to be paradoxical or requires at least a 'spatially
extended notion of locality'. Being aware of that 'paradox' it is nevertheless
instructive with regard to local urban field measurements to distinguish 'local
conclusions' from 'horizontally averaged conclusions'. Therefore, employing
the standard field ISL detection criterion (i.e. constancy of Reynolds fluxes
with height), it makes sense to talk about 'local ISL behaviour'. The horizontal
variability of the local transition height range from RSL to ISL, where vari¬
able flux behaviour changes to constant flux behaviour with increasing height,
is an interesting but not surprising outcome of the presented measurements.
Including the criterion of (approximate) horizontal homogeneity in the ISL
characterisation leads to the conclusion that the locally detected lowest height
level of flux constancy with height is only a somewhat rough proxy for the
true lower height limit of the ISL. Local measurements can be elusive in this
regard. Some field studies construct profiles averaged over all wind directions
to overcome this locality constraint, thereby postulating some sort of 'angular
ergodicity', i.e. the equivalence of angular and horizontal area averages. The
validity of this assumption is not subject of this study since the modelled wind
direction is not changed. The point of horizontal (in)homogeneity within the
ISL is further discussed in section 6.8.

Next the mean wind profile is analysed. Fig. 6.5 shows the fit of the loga¬
rithmic law (Eqn. (2.19) on page 30) to the horizontally averaged wind profile
calculated from the ten vertical profiles. The fit is based solely on the data
points within the estimate ISL height range, nevertheless it is observed that the
thus estimated parameters describe the profile very well down to at least $x_3 =
24m (1.6h)$. Above $x_3 = 100m (6.8h)$ the quality of the fit decreases markedly.
The applicability of the logarithmic profile even below the ISL has also been
observed by Cheng and Castro (2002a) above regular wind tunnel roughness
(cubes and blocks of varying height). As quoted by Cheng and Castro (2002a),
Ploss et al. (2000) make a similar observation by stating that, by spatial aver¬
aging, the logarithmic region can be extended to the RSL. These statements
must be opposed by the observations made by Raupach et al. (1986) above a model plant canopy and by Raupach et al. (1980) close to a cylinder-roughened surface. They observe a less than logarithmic profile slope within the RSL, i.e. in their studies the mean flow is accelerated close to the roughness elements in comparison to the downwards extrapolated logarithmic profile within the ISL. Therefore the existence of a logarithmic wind profile within the RSL does not appear to be of general nature but depends on the roughness type.

Though the profile clearly has a logarithmic shape within and below the ISL, the estimation of the parameters \(d_0\), \(z_0\) and \(u_{* \text{log}}\) is less well-defined. Appendix C gives a detailed discussion of the adopted estimation procedures and the findings. It is decided to give the parameters as \(d_0 = 10.2\) m (0.7h), \(z_0 = 2.8\) m±0.8 m (0.19h±0.05h) and \(u_{* \text{log}} = 0.66\) m/s±0.05 m/s. Thereby the zero plane displacement \(d_0\) has been set (not estimated) to correspond to the rule of thumb \(d_0 = 0.7\) h (see Grimmond and Oke (1999), with the mean building height \(h = 14.6\) m), other values for \(d_0\) give equally good profile fits (judged by \(R^2\)) with \(z_0\) and \(u_{* \text{log}}\) varying as it is indicated by their respective uncertainty (see appendix C).
The logarithmic law can also be fitted to the individual ten mean wind profiles within the locally determined ISL height range. With $d_0 = 10.2\text{m (0.7h)}$ kept fixed, Tab. 6.1 summarizes the local parameter estimations. The averages over all local estimations, $z_0 = 2.9\text{m (0.20h)}$ and $u_{\text{log}} = 0.67\text{m/s}$, correspond well to the estimations based on the horizontally averaged wind profile. Taking into account the variability of local ISL height ranges the scatter in the local parameter estimations is not surprising.

Comparing the estimations $u_{\text{flux}}$ and $u_{\text{log}}$ it is observed that $u_{\text{flux}}$ is about 20% smaller than $u_{\text{log}}$. Even if the estimation uncertainty is taken into account it is evident that the mean wind gradient in the ISL 'feels' a different, i.e. somewhat larger, scaling velocity $u_{\text{log}}$ than the turbulent motions themselves. This phenomenon over rough surface has been observed also in other studies (see the discussion at the end of chapter 2.6). It is remarked that the observed relative difference between $u_{\text{log}}$ and $u_{\text{flux}}$ agrees roughly with the findings in the urban wind tunnel study conducted by Kastner-Klein and Rotach (2004), although care has to be taken since their approach to determine $u_{\text{flux}}$ is somewhat different (see their publication). In this context the analysis of Cheng and Castro (2002a) is of interest. They investigated the problem of the most appropriate estimate for the friction velocity $u_*$ to parameterize the logarithmic wind profile. Besides Reynolds flux measurements in the RSL and ISL they also measured the surface drag to obtain a 'direct estimate' of the friction velocity. They conclude that the best estimate (in terms of parameterizing the logarithmic wind profile) is obtained from the surface drag measurements and not from the Reynolds flux measurements within the ISL. A further instructive observation of Cheng and Castro (2002a) is that the friction velocity obtained from the surface drag measurements is about 10% to 15% larger than the friction velocity calculated from flux measurements within the RSL and ISL (see Table IV in their publication). In the light of these results the present finding of $u_{\text{log}} > u_{\text{flux}}$ appears to be plausible for the simple reason that $u_{\text{flux}}$ might be only a poor (lower) estimate of the 'true friction velocity' (corresponding to the surface drag). A better estimate might be provided by $u_{\text{log}}$. The present study did not attempt to directly measure the surface drag, so this interesting question has to remain undecided. Since the Reynolds flux $u'$ and the (square of the) turbulent velocities $\sigma_1$ are combined within the Reynolds stress tensor, $u_{\text{flux}}$ is considered to be the relevant scale for the turbulent motions within the ISL. When the TKE budget is presented a possible explanation for the different scaling velocities $u_{\text{flux}}$ and $u_{\text{log}}$ is discussed.

Now that the turbulent velocity scale $u_{\text{flux}}$ is determined, the turbulent velocities $\sigma_1$ and $\sigma_3$ are analysed. Fig. 6.6 shows the horizontally averaged profiles of $\sigma_1/u_{\text{flux}}$ and $\sigma_3/u_{\text{flux}}$ (ISL-scaling) and $\sigma_1/u_{\text{local}}$ and $\sigma_3/u_{\text{local}}$ (local scaling) with $u_{\text{local}} = (\langle u_1^3 u_3^3 \rangle)^{1/2}$ determined at the same point in space as $\sigma_1$ and $\sigma_3$. $\sigma_2$ was measured only on the lowermost level $x_3 = 27\text{m (1.8h)}$ (with 80 hor-
Figure 6.6: Horizontally averaged turbulent velocities scaled by $u_{*\text{flux}}$ (ISL scaling, top) and by $u_{*\text{local}}$ (local scaling, bottom). Dotted lines as in Fig. 6.5.
horizontal data points). It is observed that in both scalings the marked increase of the horizontal scatter below $x_3 = 48m (3.3h)$ level indicates the onset of the pronounced 3-dimensional character of RSL turbulence. It is noted that down to $x_3 = 24m (1.6h)$ both scalings exhibit roughly the same degree of horizontal scatter, therefore in this height range neither of them appears to be superior in collapsing the turbulent velocities onto a single curve within the RSL. The same statement applies if $\sigma_1$ and $\sigma_3$ are scaled separately for each of the ten vertical profiles with the respective locally estimated $u_{local \_flux}$ (not shown), i.e. the same increase of scatter within the RSL is observed. At $x_3 = 27m (1.8h)$ it is observed that for $\sigma_2$ the horizontal scatter increases significantly with local scaling in comparison to ISL scaling. Based on the ten vertical profiles it is found that $\sigma_1/u_*\_flux = 2.00 \pm 0.04$ and $\sigma_3/u_*\_flux = 1.26 \pm 0.02$ within the ISL height range with the uncertainty giving by the vertical scatter. The single data point for the horizontally averaged lateral turbulent velocity at $x_3 = 27m (1.8h)$ gives $\sigma_2/u_*\_flux = 1.58$.

Summarizing, it is noted that the horizontal averages of both the ISL scaled as well as the locally scaled turbulent velocities $\sigma_1$ and $\sigma_3$ continue to be approximately constant well below the ISL down to at least $x_3 = 24m (1.6h)$. In both scalings the respective profiles show a markedly increased horizontal scatter within the RSL.

Fig. 6.7 shows the horizontally averaged skewness of $u_1$ and $u_3$ respectively. With the aid of conditional analysis presented in section 6.4, it is possible to demonstrate a strong correlation (and a linear relationship) between (i) any one of the triple moments of the joint distribution of the standardized $u_1$ and $u_3$ and (ii) the dominant mechanism of vertical momentum transport (i.e. either the transport of momentum deficit upwards or the transport of momentum excess downwards). This provides the appropriate context to appreciate the roles of Skew $u_1$ and Skew $u_3$. Here it is remarked that from within the RSL to the ISL top Skew $u_1$ consistently decreases from slightly positive to slightly negative values whereas Skew $u_3$ stays constant and slightly positive within the RSL and increases throughout the ISL. For regular wind tunnel roughness Raupach (1981) observes the same tendencies (Figure 4 in his publication) but with Skew $u_3$ assuming negative values close to the roughness elements. Also in his study Skew $u_1$ and Skew $u_3$ appear to be closer to zero than in the present study (see also Figure 3 in his study). In the surface layer above a model plant canopy (vertical aluminium strips) Raupach et al. (1986) make similar observations for Skew $u_1$ and Skew $u_3$, i.e. Skew $u_1$ decreases from positive to negative values (but does not stay as close to zero as in Raupach (1981)) while Skew $u_3$ is positive immediately above the canopy (as in the present study) and increases consistently throughout the surface layer (Figure 7 in their publication). Further discussion is provided in the context of the turbulent TKE flux in section 6.6.
The horizontally averaged flatness of $u_1$ and $u_3$ are given in Fig. 6.8. The value of 3 for a Gaussian distribution might serve as a reference point. In the ISL height range the flatness of $u_1$ is approximately 2.7, the flatness of $u_3$ is approximately 3.2. This constancy of flatness is in contrast to the clear systematic variation of the skewnesses within the ISL height range. Referring again to Raupach (1981) and his study above regular wind tunnel roughness, he observes in the surface layer the flatness of $u_1$ to be about 2.6 while the flatness of $u_3$ is only very little larger than 3 (Figure 5 in his publication). In his data as well as in the present study the flatness of both velocity components is observed to increase closer to the roughness elements. Above a model plant canopy Raupach et al. (1986) find the flatness of $u_1$ to be approximately 2.5, while the flatness of $u_3$ is estimated to be about 3.5. For both velocity components the flatness clearly increases within the canopy layer (Figure 8 in their publication). Brunet et al. (1994) make similar observations in their wind tunnel study above 'waving wheat', again the flatness of $u_1$ is slightly smaller than 3 while the flatness of $u_3$ is slightly larger than 3 (Figure 10 in their publication). Their findings concerning Skew $u_1$ and Skew $u_3$ coincide with the observations noted above. Therefore summarizing, the findings of the present study are in accordance with the observations in other rough wall turbulence studies.
6.3 Turbulence intensities and angular fluctuations of the wind vector

The horizontally averaged turbulence intensities $I_i = \sigma_i/U_i$ (for $i = 1, 3$) are given in Fig. 6.9 together with the reference from VDI (2000). It is instructive to compare these urban profiles to the turbulence intensity profiles for the approach flow (Fig. 5.8 on page 83). Two observations can be made:

- The turbulence intensities are influenced by the urban fetch up to roughly $x_3 = 140\text{m} \ (9.6\text{h})$. Above that height level the turbulence intensities measured above the urban model are the same as those of the approach flow.

- Up to roughly $x_3 = 50\text{m} \ (3.4\text{h})$ both turbulence intensities, $I_1$ and $I_3$, are within the range assigned to the roughness category 'very rough' by VDI (2000).

The turbulence intensity $I_2$ ($I_3$) can be interpreted as a rough measure of the average absolute value of the tangent of the lateral (vertical) direction fluctuations of the instantaneous wind vector around the mean wind direction.
Figure 6.9: Horizontally averaged turbulence intensities (a) $I_1$ and (b) $I_3$. The reference is taken from VDI (2000). Dotted lines as in Fig. 6.5.
Figure 6.10: Distribution of (a) vertical and (b) lateral angular fluctuations of the instantaneous wind vector around the $x_1$ axis. Narrow peaks are measured at $x_3 = 69m$ (4.7h), wider peaks at $x_3 = 31.8m$ (2.2h) at the location BSPR.
The arc tangent of \( I_2 \) (\( \theta \)) may serve as an estimate for the standard deviation \( \sigma_{0} \) (\( \sigma_{e} \)) of the lateral (vertical) angular fluctuations of the wind vector. The appropriateness of this interpretation decreases with increasing turbulence intensity (then the respective geometric and statistical approximations, on which the interpretation is based, become less accurate).

Lateral and vertical angular fluctuations of the wind vector, \( \sigma_{0} \) and \( \sigma_{e} \), are analysed at the location Basel-Sperrstrasse (BSPR). Fig. 6.10 shows the estimated distributions at \( x_3 = 31.8 \text{m} \) (2.2h), the topmost height level of the field measurement tower at BSPR, and \( x_3 = 69 \text{m} \) (4.7h) with positive and negative angular fluctuations defined according to the orientation of the \( x_2 \) and \( x_3 \) axis respectively (e.g. positive vertical angular fluctuations point upward, etc.). As expected, the fluctuations increase markedly closer to the roughness. The slightly positive skewness of the distributions of the vertical angular fluctuations are directly related to the existence of the material surface at \( x_3 = 0 \text{m} \) (Oh). Based on these angular distributions per height level, vertical profiles of \( \sigma_{0} \) and \( \sigma_{e} \) can be determined. Fig. 6.11 shows these lateral and vertical standard deviations based on the angular distributions as measured at BSPR.

Figure 6.11: Standard deviations of lateral (\( \sigma_{0} \), triangles) and vertical (\( \sigma_{e} \), squares) angular fluctuations of the wind vector at the location BSPR. Shown are estimations based on the angular distributions (full symbols) and based on the arc tangents of \( I_2 \) and \( I_3 \) at BSPR (empty symbols). Dotted lines as in Fig. 6.5.
The arc tangents of $I_2$ and $I_3$ (also measured locally at BSPR) are included in Fig. 6.11 to clarify the accurateness of the above given interpretation of these quantities. It is observed that the estimations based on $I_2$ and $I_3$ systematically underestimate the 'true' standard deviations of lateral and vertical angular fluctuations. E.g. at $x_3 = 19.5m$ (1.3h), it is $I_3 = 0.31$ and arc tangent of $I_3$ is equal to 17.1°, while the standard deviation $\sigma_v$ determined from the vertical angular distribution of the wind vector equals 22.7°. This gives an underestimation by 5.6° or 25%. With increasing height and therefore decreasing turbulence intensities the estimations based on the turbulence intensities get closer to the 'true' angular standard deviations.

6.4 Conditional statistics of Reynolds fluxes above roof level

Non-zero Reynolds fluxes $\overline{u'_1 u'_3}$ indicate vertical turbulent transfer of longitudinal momentum. The sign of $\overline{u'_1 u'_3}$ gives the direction of this momentum flux. The findings of the preceding section reveal the expected downward momentum transport towards the urban surface. To refine the analysis, a distinction is made with respect to the transport of momentum deficit upwards and momentum excess downwards, both resulting in a net downward transport of momentum. The benefit of such an analysis is twofold: Firstly, dominant motion patterns can be identified, e.g. slow fluid ejected upwards or fast fluid sweeping downwards over the ground. Secondly, the relative contributions of momentum deficit transport and momentum excess transport to the total momentum flux serve as an additional characteristic to describe the turbulent boundary layer flow above roof level. Such an analysis of relative contributions of the different momentum transport mechanisms provide an additional meaningful characterization of the urban model flow suitable for a comparison to field data. The tool for this investigation is conditional analysis (or quadrant analysis), a short introduction is given in the following. Further reference is provided e.g. in Raupach (1981).

Starting point is the segmentation of the individual $u'_1 u'_3$ contributions to $\overline{u'_1 u'_3}$ into four quadrants, see Fig. 6.12. With $i$ indicating the number of the quadrant, the individual contributions are labelled outward interactions ($i = 1, u'_1 > 0, u'_3 > 0$), ejections ($i = 2, u'_1 < 0, u'_3 > 0$), inward interactions ($i = 3, u'_1 < 0, u'_3 < 0$) and sweeps ($i = 4, u'_1 > 0, u'_3 < 0$). Based on a sample (i.e. time series) of $N$ measurements, the total contributions from each quadrant are estimated by
Figure 6.12: Characterization of $u'_1u'_3$ time series by conditional analysis (conceptual).

\[
\begin{align*}
\left( u'_1u'_3 \right)_i &= \frac{1}{N-1} \sum_{k=1}^{N} u'_{1,k}u'_{3,k}I_i(u'_{1,k}, u'_{3,k}) \\
S_i &= \frac{\left( u'_1u'_3 \right)_i}{u'_1u'_3} \\
S_1 + S_2 + S_3 + S_4 &= 1
\end{align*}
\]

with $I_i()$ being the indicator function of the $i$th quadrant. Defining further the relative contributions from each quadrant $i$ as

\[
S_i = \frac{\left( u'_1u'_3 \right)_i}{u'_1u'_3}
\]

gives

\[
S_1 + S_2 + S_3 + S_4 = 1
\]

with

\[
S_1, S_3 < 0 \quad \text{and} \quad S_2, S_4 > 0.
\]

It is seen that the relative contributions from ejections and sweeps to the total momentum flux dominate the other two interactions (since $u'_1u'_3 < 0$). Ejections correspond to the upward transport of longitudinal momentum deficit, sweeps represent the downward transport of longitudinal momentum excess. To get a measure of the relative importance of sweeps over ejections, the quantity

\[
\Delta S = S_4 - S_2
\]

is defined with $\Delta S > 0$ ($\Delta S < 0$) indicating the prevalence of sweeps over ejections (ejections over sweeps).

It is remarked that if the joint distribution of $u_1$ and $u_3$ were Gaussian, then $\Delta S = 0$ for symmetry reasons. It is further remarked that the analysis could
be even more refined by segmenting the individual contributions $u'_1u'_3$ further according to their magnitude, thereby introducing a variable threshold value $H$ and counting only those events with $|u'_1u'_3| > H$ per quadrant. This would allow the assessment of the contribution and frequency of peak events. Since here the focus is on the analysis of the relation between (i) sweep and ejection contributions to the total momentum flux and (ii) the standardized triple moments of the joint distribution of $u_1$ and $u_3$, $\Delta S$ suffices for this analysis.

Fig. 6.13 shows the horizontally averaged profile of $\Delta S$. It is observed that $\Delta S$ decreases continuously with increasing height throughout the upper part of the RSL and the whole ISL. At the lowest level, $x_3 = 24m$ (1.6$h$), $\Delta S = 0.04$, i.e. slightly positive, while within the ISL it is $-0.1 \leq \Delta S \leq 0$. It follows that with increasing height ejections (i.e. upward transport of slow fluid) slightly prevail over sweeps, while downward extrapolation suggests a prevalence of sweeps (i.e. $\Delta S > 0$) close to roof level. This impression is further supported by a local case study at and below roof level (see section 6.7). Relating the observed horizontally averaged $\Delta S$ profile to the estimated RSL height it is noted that $\Delta S > 0$ is not a characterizing property of the whole RSL. In the present case $\Delta S > 0$ is observed only below $x_3 = 33m$ (2.3$h$), while in the upper part of the RSL from $x_3 = 33m$ (2.3$h$) to $x_3 = 48m$ (3.3$h$) $\Delta S \leq 0$ is found. This is in
Figure 6.14: Horizontally averaged $\Delta S$ versus horizontally averaged $\overline{u'_1 u'_1 u'_1/\sigma_1^3}$. Dashed line corresponds to linear fit as given in Eqn. (6.14). Height $x_3$ increases as indicated.

Contrast to the statement made by Raupach (1981) who considers the sweep domination to be 'one of the main distinguishing features of the roughness sublayer'. In the present urban case the height range of $\Delta S > 0$ does not coincide with the height range of horizontally inhomogeneous turbulence. Here the latter characteristic is used for RSL identification.

As remarked above, a Gaussian distribution implies $\Delta S = 0$ and therefore, turning the implication around, $\Delta S \neq 0$ implies a non-Gaussian distribution. Taking that as a heuristic motivation one may hypothesize that small deviations of $\Delta S$ from zero may indicate a near-Gaussian distribution. It is remarked further that the deviations of the standardized triple moments $\overline{u'_1 u'_1 u'_1/\sigma_1^3}$, $\overline{u'_1 u'_1 u'_3/\sigma_1^2 \sigma_3}$, $\overline{u'_1 u'_3 u'_3/\sigma_1 \sigma_3^2}$ and $\overline{u'_3 u'_3 u'_3/\sigma_3^3}$ from zero are another indication for non-Gaussian distributions (all triple moments are zero in the Gaussian case). Since it is known from the theory of analytic functions that small deviations are (sometimes) a good place to look for linear relationships one may hypothesize that $\Delta S$ and the standardized triple moments may depend linearly on a parameter which parameterises the deviation of the joint distribution from a Gaussian distribution. Whatever that parameter might be, it may be then concluded that also the relation between $\Delta S$ and any one of the standardized triple moments (and, of course, between the standardized triple moments themselves) might be linear.
This heuristic line of arguments based on the near-Gaussian character of the joint distribution of $u_1$ and $u_3$ provides a rough intuitive understanding of the relations shown in Figs. 6.14 to 6.17 where vertical profiles from $x_3 = 24m$ (1.6h) to $x_3 = 204m$ (14.0h) of the respective quantities are plotted against each other (therefore the height information is given just implicitly). $\Delta S$ and Skew $u_1 = \overline{u_1'u_1'/\sigma_1^3}$ are clearly correlated. This correlation is well-described by a linear relationship. The same applies to the relations between the standardized joint triple moments of $u_1$ and $u_3$. This comes not entirely surprisingly. Raupach (1981) conducted a similar analysis within a turbulent boundary layer flow above regular roughness (regularly arranged cylinders) and found in the surface layer the relationships

$$\Delta S = 0.37 \cdot \overline{u_1'u_1'/u_3^3/\sigma_1^3}$$  \hspace{1cm} (6.7)$$

and

$$\overline{u_1'u_1'/u_3^3/\sigma_1^3} = -2.02 \cdot \overline{u_1'u_1'u_3'/\sigma_1^3\sigma_3}$$  \hspace{1cm} (6.8)$$
$$= 1.97 \cdot \overline{u_1'u_3'u_3'/\sigma_1^2\sigma_3}$$  \hspace{1cm} (6.9)$$
$$= -1.70 \cdot \overline{u_3'u_3'u_3'/\sigma_3^3}$$  \hspace{1cm} (6.10)$$

Supporting these findings, Raupach et al. (1986) observed in the surface layer...
Figure 6.16: Horizontally averaged $\frac{\langle u'_1 u'_1 u'_1 \rangle}{\sigma_1^3}$ versus horizontally averaged $\frac{\langle u'_3 u'_3 u'_3 \rangle}{\sigma_1 \sigma_3^2}$, dashed line corresponds to linear fit as given in Eqn. (6.16).

Figure 6.17: Horizontally averaged $\frac{\langle u'_1 u'_1 u'_1 \rangle}{\sigma_1^3}$ versus horizontally averaged $\frac{\langle u'_3 u'_3 u'_3 \rangle}{\sigma_3^3}$, dashed line corresponds to linear fit as given in Eqn. (6.17).
above a model plant canopy (vertical aluminium strips) in the wind tunnel

\[
\frac{\bar{u}_1' u_1' u_1' / \sigma_1^3}{\approx -2 \cdot \frac{\bar{u}_1' u_1' u_3' / \sigma_1^2 \sigma_3}{(6.11)} \\
\approx 2 \cdot \frac{\bar{u}_1' u_3' u_3' / \sigma_1 \sigma_3^2}{(6.12)} \\
\approx -1.5 \cdot \frac{\bar{u}_3' u_3' u_3' / \sigma_3^3}{(6.13)}.
\]

The present turbulence study above urban roughness gives

\[
\Delta S = 0.38 \cdot \frac{\bar{u}_1' u_1' u_1' / \sigma_1^3}{-0.06} (6.14)
\]

and

\[
\frac{\bar{u}_1' u_1' u_1' / \sigma_1^3}{\approx -2.52 \cdot \frac{\bar{u}_1' u_1' u_3' / \sigma_1^2 \sigma_3 + 0.14}{(6.15)} \\
\approx 2.25 \cdot \frac{\bar{u}_1' u_3' u_3' / \sigma_1 \sigma_3^2 + 0.14}{(6.16)} \\
\approx -1.91 \cdot \frac{\bar{u}_3' u_3' u_3' / \sigma_3^3 + 0.31}{(6.17)}.
\]

It is noticed firstly, that the linear relationships are reproduced and the order of magnitude of the constants of proportionality agree for all relationships though the exact numerical values are clearly different, and secondly, that the present data shows affine-linear relationships between the quantities with a clearly identifiable affine part which is not reported by Raupach (1981). Thus summarizing, the results for isolated cylindrical roughness elements and urban roughness arranged around backyards and spaced by street canyons qualitatively agree though with clear quantitative variations (referring thereby to the upper part of the RSL and to the estimated ISL height range).

These quantitative differences are not unexpected since the ejection-sweep behaviour close to the roughness is speculated to depend on the roughness geometry, in particular on the 'd-type' or 'k-type' nature of the roughness (for a discussion of the different types of roughness refer to Perry, Schofield and Joubert (1969)). Townsend (1976) stated that

'k-type' roughness behaviour "is shown by surfaces with irregular corrugations and protuberances, e.g. sandpaper"

while

"the 'd' type behaviour is shown by rough surfaces composed of similar rectangular bars laid transversely to the direction of flow with spacing equal to the width of the bars" and mostly stable vortices in the channels between the bars.
Raupach (1981) observed a sweep-dominated layer close to his more 'k-type'-like roughness of isolated cylinders. His data shows a surface layer dominated by sweeps for his roughest configuration (Fig. 9, configuration F, in his publication). This differs from the present findings above urban roughness where the ISL is slightly dominated by ejections, sweeps may get important only close to the roof level. Indeed, Townsend (1976, p.142) suggested that ejections should play a more pronounced role in the momentum transfer above 'd-type' roughness. Since stable vortex structures within street canyons perpendicular to the mean flow are one characteristic of 'd-type' roughness as interpreted by Townsend (see the picture on p. 142 in his book), the shift from sweep domination (Raupach (1981)) towards a prevalence of ejections within the surface layer in the urban case is consistent with Townsend's speculation. The slight prevalence of ejections over sweeps in the Basel urban surface layer is also found in the Basel field data (see the comparison to the field data in section 6.9).

A final remark goes to a more mathematical dress of the presented heuristic arguments based on the near-Gaussian nature of the joint distribution of $u_1$ and $u_3$. As it is noted by Raupach the predictions of a cumulant-discard approach are "in acceptable agreement" (Raupach (1981)) with his results which in turn are qualitatively similar to the present findings. The cumulant-discard method is based on the assumption that the distribution under investigation can be approximated by considering only a finite number of cumulants (usually those of low order) and discarding the rest, i.e. setting the remaining cumulants equal to zero (for a brief introduction see e.g. Antonia and Atkinson (1973)). Thereby the Gaussian distribution (with all cumulants equal to zero except those of first and second order) is modified in 'small steps' giving in this sense non- but near-Gaussian distributions. This appears to be one alley to follow in mathematical terms.

## 6.5 Spectra and integral length scales at Basel-Sperrstrasse

Above the urban model velocity time series were recorded at Basel-Sperrstrasse (position BSPR) at four height levels, $x_3 = 22.5m$ (1.5h), 31.8m (2.2h), 72m (4.9h) and 108m (7.4h), to analyse the spectral energy distributions $S_i(f)$ in longitudinal, lateral and vertical direction respectively. The spectra measured in the wind tunnel are compared to the rural reference spectra given by Kaimal et al. (1972) and cited slightly modified in chapter 2.8 (Eqns. (2.28) to (2.30) on page 34). The essential characteristics to compare are, firstly, the overall shape of the spectra, i.e. the relative energetic contributions from different time and length scales, and, secondly, the locations of the spectral peaks to
identify energetically dominant time and length scales. It is noted that those characteristics are not affected by the choice of normalization. Kaimal et al. (1972) originally proposed $u_*^2$ as a normalizing factor, equally well $\sigma_1^2$ could be used as it is done in the following (and also in VDI (2000)). The rural spectral parameterizations of Kaimal et al. (1972) are multiplied with the ratio $u_*^2/\sigma_1^2$ as measured in the wind tunnel. The interpretation of $u_*^2$ in the rural parameterization scheme is somewhat ambiguous within the urban RSL (the rural parameterizations were originally not derived for those urban scenarios, they stem from the Kansas experiment in 1968 and were measured at $x_3 = 5.66\text{m}, 11.3\text{m}$ and $22.6\text{m}$ above a flat homogeneous surface). One may take $u_*^2$ as a purely local value, as a horizontal average or simply and always as $u_{flux}^2$ as it is determined from the constant flux within the ISL. (Here, of course, it is dwelled on the luxury of wind tunnel data availability.) In this study the following choices for $u_*^2$ have been made:

- At $x_3 = 22.5\text{m}$ (1.5h): Horizontal average of $\left(-\overline{u_1 u_3}\right)^{1/2}$
- At $x_3 = 31.8\text{m}$ (2.2h): Local value $u_{local}$
- At $x_3 = 72\text{m}$ (4.9h) and $108\text{m}$ (7.4h): ISL value $u_{flux}$

This choice is plausible within the ISL height range. At the two lower height levels the choice is mainly motivated by the correspondence of the measured spectra to the rural references although the differences between the three options are small. As stated above, the overall interpretation of the spectra is not affected.

The wind tunnel velocity spectra are given in Figs. 6.18 to 6.20, the characteristics of the respective time series are listed in Tab. 6.2. Only at $x_3 = 31.8\text{m}$ (2.2h) all three spectra are available, at the other three levels the $u_1$ spectrum and either the $u_2$ or the $u_3$ spectrum were measured. The time series were recorded with irregular arrival times (LDA measurements) and regularized by sample and hold. The result of the subsequent fast Fourier transformation (FFT) is shown in the figures, no further filtering was applied. The non-dimensional frequency range shown in all the spectral diagrams is from $0.001$ to $4$ which is well below the respective (non-dimensional) Nyquist frequencies as calculated from the mean acquisition rates. Over all time series the (non-dimensional) Nyquist frequencies range roughly from $6$ to $14$. The high frequency parts of the spectra spoilt by aliasing effects are mostly cut off though small effects are still present at the upper levels since here the sampling frequency was slightly reduced. The integral length scales $L_{ux}, L_{uy}$ and $L_{uz}$ are obtained by integrating the autocorrelation functions estimated from the time series (see Eqn. (2.24) on page 33). The FFT and the integration are performed by a custom-made software package which is documented in
Table 6.2: Characteristics of the time series (300s) and spectra measured at BSPR. The spectral peak wavelength $\lambda_{u1,\text{peak}}$, $\lambda_{u2,\text{peak}}$ and $\lambda_{u3,\text{peak}}$ are estimated from the spectra by eyesight with the subjective estimation uncertainty indicated in square brackets.

Pascheke (2000). The spectral peaks and the corresponding peak length scales are estimated by eyesight inspection of the spectra, the indicated ranges refer to the subjective uncertainty in the peak identification.

With regard to the four $u_1$ spectra in Fig. 6.18 it is observed that at $x_3 = 22.5m$ (1.5h) the decrease of spectral energy to either side of the peak is more pronounced than in the rural reference. The spectrum is somewhat narrowed and squeezed with the peak slightly shifted to higher frequencies. At $x_3 = 31.8m$ (2.2h) the spectrum collapses very well with the rural counterpart. At the two upper levels, $x_3 = 72m$ (4.9h) and 108m (7.4h), the low frequency part is energetically diminished in comparison to the rural reference, the peaks are increasingly shifted to higher frequencies. It is remarked that the length scales with energetic deviations are roughly those larger than the wind tunnel length scales (width and height). In all four spectra the -2/3 slope of energetic decrease (as given by the reference spectra) is clearly identifiable in the higher frequency part, commonly taken as an indication for the existence of an inertial subrange.

The $u_2$ spectrum at $x_3 = 31.8m$ (2.2h) in Fig. 6.19 compares well to the rural reference. As in the case of the $u_1$ spectra, the low frequency energies at $x_3 = 72m$ (4.9h) and 108m (7.4h) are diminished in comparison to the rural reference, the peaks are increasingly shifted to higher frequencies. Again, the
length scales with energetic deviations are those larger than the wind tunnel length scales. At all three height levels the -2/3 slope range is well-established.

The eye-catching characteristic of the two $u_3$ spectra in Fig. 6.20 measured at $x_3 = 22.5m$ (1.5h) and 31.8m (2.2h) is the consistent shift to low frequencies while the overall shape is not markedly altered in comparison to the rural reference. It is observed that a non-dimensional frequency defined as $n = f x_3 / U_1$ (i.e. setting $d_0 = 0m$) collapses the $u_3$ spectrum nicely with its rural counterpart. This may provoke the interpretation that vertical turbulence penetrates well into the street canyons and backyards which makes the distance $x_3$ to the material surface a more appropriate length scale for vertical turbulence than $x_3 - d_0$. Further discussion about this spectral shift is given when the
Next, the ratios $S_2(n)/S_1(n)$ and $S_3(n)/S_1(n)$ are shown. The assumption of local isotropy within the inertial subrange predicts these ratios to be $4/3$ (see e.g. Kaimal and Finnigan (1994)). Fig. 6.21 shows the ratios per height level. It is observed that both ratios approach an approximately constant value at small scales, but both are clearly smaller than $4/3$. It is found that

- $S_3(n)/S_1(n) = 1.14 \pm 0.02$ at $x_3 = 22.5m (1.5h)$ and $31.8m (2.2h)$,
- $S_2(n)/S_1(n) = 1.21 \pm 0.02$ at $x_3 = 31.8m (2.2h)$ and $72m (4.9h)$ and
- $S_2(n)/S_1(n) = 1.17 \pm 0.02$ at $x_3 = 108m (7.4h)$. 

**Figure 6.19**: Velocity spectra of $u_2$ at BSPR taken at $x_3 = 31.8m (2.2h)$, 72m (4.9h) and 108m (7.4h). At the two upper levels dotted lines indicate the wind tunnel measures (4m width, 3m height). Straight curves correspond to the rural reference from Kaimal et al. (1972).
Figure 6.20: Velocity spectra of $u_3$ at BSPR taken at $x_3 = 22.5m$ (1.5h) and $31.8m$ (2.2h). Upper row shows the spectra with the non-dimensional frequencies $n = f(x_3 - d_0)/U_1$, while the lower row takes the non-dimensional frequencies as $n = fx_3/U_1$. Straight curves correspond to the rural reference from Kaimal et al. (1972).

The discussion of the spectra and length scales is continued when the comparison to the field data is made.

6.6 Terms of the TKE budget

The velocity spectra presented in the last section are used to estimate the local energy dissipation at the respective height levels. For this purpose the inertial subrange description as proposed by Kolmogorov (1941) is assumed to be applicable (see e.g. Kaimal and Finnigan (1994)), i.e.
Figure 6.21: Ratios $S_3(n)/S_1(n)$ (left column) and $S_2(n)/S_1(n)$ (right column) from lower to greater heights (bottom to top row). Theoretical local isotropy ratio 4/3 in the inertial subrange is given by the straight lines, estimated observed ratios are indicated by the dashed lines.
with the local energy dissipation $\varepsilon$ at the height level $x_3$ and the Kolmogorov constant $\alpha$ (not to be confused with the exponent $\alpha$ of the power law of the mean wind profile). Kaimal and Finnigan (1994) give $\alpha = 0.5-0.6$, thus $\alpha = 0.55$ is taken in this study. By fitting this parameterization to the inertial subrange, which is taken to be the $-2/3$ slope range, the energy dissipation is estimated. Fig. 6.22 shows the fit to the $u_1$ spectrum at $x_3 = 72m$ (4.9h) and indicates the range of uncertainty (fits were made by eyesight) which is estimated to correspond plausibly to $\pm 10\%$ of $\varepsilon$ (with $\alpha$ given, of course).

Based on scaling arguments within the ISL, $\varepsilon$ should obey the order of mag-
The relationship between the dissipation rates estimated from the spectral fit of Eqn. (6.18) and the local dissipation scales (i.e. $u_{*\text{local}}$ taken for $u_*$) is shown in Fig. 6.23. Indeed, the correspondence is very well at the height levels within and slightly above the ISL, while at the height levels within the RSL the local scales overestimate the dissipation rates determined from the spectra. Since (i) the scaling argument is designed only for the ISL height range and (ii) the -2/3 slope predicted by Kolmogorov's relation (6.18) is well-established in the RSL spectra which supports the appropriateness of this relation, the spectrally estimated dissipation rates are considered more plausible than those based simply on the scale.

Velocity spectra were measured only at the location BSPR. Nevertheless, if one assumes the empirical relationship shown in Fig. 6.23 to have a general applicability (which is plausible within the ISL, but a speculation within the RSL), the dissipation rates can also be estimated for other horizontal locations and at other than the four height levels of spectral measurements. Thus the local flux \( u_{*\text{local}} = \left(-u'_1u'_3\right)^{1/2} \) is used to estimate the local dissipation rates.
and subsequently the horizontally averaged dissipation rates.

The TKE production term \( -\overline{u_1' u_2'} \partial_3 \overline{U_1} \) can be calculated at each height level for each of the ten vertical profiles. Observing that for the majority of the ten horizontal locations the mean wind profiles are well-parameterised by the locally fitted logarithmic law even below the ISL, the local production rate is estimated by

\[
\text{production} \approx -\frac{u_1' u_3'}{k(x_3 - d_0)} u_{* \text{local \ log}}
\]

within the ISL and the upper part of the RSL \((u_{* \text{local \ log}} \text{ of course varying from location to location})\). Thereby horizontally averaged TKE production profiles are estimated.

To estimate the vertical turbulent flux of TKE, only measurements of \( u_2' u_3' u_3' \) and \( u_3' u_3' u_3' \) are available, the components \( u_2 \) and \( u_3 \) were not measured simultaneously. Other studies facing the same limitation estimate \( u_2' u_3' u_3' \approx 0.5 (u_3' u_1' u_1' + u_3' u_3' u_3') \), see e.g. Raupach (1981) or Antonia and Luxton (1971).

Here the same approach is pursued to estimate

\[
\text{vertical turbulent TKE flux} \approx 0.75 \left( u_3' u_1' u_1' + u_3' u_3' u_3' \right).
\]

Fig. 6.24 shows the horizontally averaged vertical turbulent TKE flux based on the ten vertical profiles together with an eyesight fit of a smooth interpolation. The smooth interpolation allows an estimation of the vertical derivative of the horizontally averaged vertical turbulent TKE flux which enters the TKE budget.

The thus estimated contributions to the horizontally averaged TKE budget are shown in Fig. 6.25 scaled either with the RSL length scale \( h \) or the ISL length scale \( k(x_3 - d_0) \). It is observed that within the ISL the residual term to close the TKE budget is small. Closer to roof level the residual increases. It is further observed that within the ISL the TKE budget is not closed simply by dissipation and production, but the upward turbulent transport of TKE constitutes a measurable loss term. I.e., local TKE production levels are too high to be fully dissipated locally, but some fraction of TKE is also removed upwards. Combining this observation with the finding, that within the ISL \( \varepsilon \) scales with \( u_{* \text{flax}}^3 \) as shown above, it is a necessary consequence that \( u_{* \text{log}} > u_{* \text{flax}} \). Indeed, one may formally assign a velocity scale

\[
u_{\text{transport}} = \frac{k(x_3 - d_0)}{u_{* \text{flax}}^2} \partial_3 \left( \frac{1}{\rho} \overline{u_3' p'} + \frac{1}{2} \overline{u_3' u_3' u_3'} \right)
\]

(6.22)

to the vertical turbulent TKE flux divergence and close the velocity gap à la \( u_{* \text{log}} = u_{* \text{flax}} + u_{\text{transport}} \). Therefore a difference between the velocity scales \( u_{* \text{flax}} \) and \( u_{* \text{log}} \) may indicate that the TKE budget within the ISL is not
closed simply by local dissipation and production, but the removal of TKE by vertical fluxes makes also a contribution. Since this removal mechanism may scale with vertically constant velocity scales (i.e. $u_{*_{\text{flux}}}$ and $u_{*_{\text{transport}}}$) and the ISL length scale $k(x_3 - d_0)$, the logarithmic shape of the wind profile is not spoilt. According to the studies cited at the end of chapter 2.6, which have observed $u_{*_{\text{flux}}} \neq u_{*_{\text{log}}}$, such contributions may not be uncommon above (very) rough surfaces as e.g. urban landscapes.

Another possible interpretation may start from the observation that the contribution of the vertical turbulent TKE flux divergence to the TKE budget is least at the top of the RSL, approximately between $x_3 = 42$ m (2.9h) and 48 m (3.3h), and increases downwards as well as upwards (Fig. 6.25). In particular the upward increase of TKE flux divergence may indicate a non-equilibrium state of the flow observable in the 3rd order statistical moments (equilibrium meaning here the adaptation of the flow to the rough surface without any further downstream development within the ISL). This is in contrast to the findings concerning the adaptation of the mean wind and the Reynolds fluxes which have been considered to be adapted up to at least $x_3 = 69$ m (4.7h).

Figure 6.24: Estimation of the horizontally averaged vertical turbulent TKE flux. Straight line gives smooth interpolation used to estimate the vertical derivative. Dotted lines as in Fig. 6.5.
Figure 6.25: Horizontally averaged terms of the TKE budget based on the 10 vertical profiles scaled with (a) the RSL length scale $h$ and (b) the ISL length scale $k(x_3 - d_0)$. Dotted lines as in Fig. 6.5.
to 96m (6.6h) (see chapter 6.1). One explanation could be that flow adaptation in the 'near-equilibrium height range' still continues, but so slowly that an additional fetch of 300m (the distance between the two most downstream measurement locations C and D, see Figs. 6.1 and 6.2 on pages 88 and 89) does not produce a resolvable profile change in this height range (Fig. 6.1). Indeed, if an urban fetch of 1.6km is necessary for local energetic equilibrium up to \( x_3 = 48m \) (3.3h) as judged by the decreasing TKE flux divergence contributions, then an additional 1.6km of urban fetch might be needed for the complete ISL up to \( x_3 = 81m \) (5.5h) being in local energetic equilibrium, i.e. with no TKE flux divergence contributions to the TKE budget. This leads to an estimation for the ratio of equilibrium layer height to necessary urban fetch of \((x_{3,\text{equilibrium}} - d_0) : \text{fetch} = (48m - 10.2m) : 1.6km = 0.02\). It may be compared with the common rule of thumb for neutral conditions that the ratio of fetch to observation height to ensure the measurement of adapted flow properties should be 100:1 (see e.g. Wieringa (1993), Roth (2000)).

Giving the observation of decreasing \( u_*\text{flux} \) with increasing urban fetch (Fig. 6.2), one may then hypothesize that \( u_*\text{log} \) decreases with increasing urban fetch, i.e. the 'equilibrium wind profile' in the ISL is less steep than observed at \( x_3 = 1634m \). Unfortunately, this discussion contains some speculation which can be resolved satisfactorily only by allowing longer urban fetches and analysing the subsequent flow development.

Summarizing it is stated, that \( u_*\text{flux} \neq u_*\text{log} \) indicates the non-closure of the TKE budget by local dissipation and production within the ISL, while it remains an open question whether that indicates a still adapting flow to the urban surface. If this were the case, then the observation of a constant flux layer and a logarithmic wind profile (as observed in this study) are not sufficient to diagnose a flow completely adapted to the urban roughness. The TKE budget should also be analysed. The turbulence in the surface layer may evolve further until assuming \( u_*\text{flux} = u_*\text{log} \) is established. This evolution appears to be 'continuously logarithmic', i.e. the shape of the wind profile may always be logarithmic with continuously decreasing \( u_*\text{transport} \) as defined in Eqn. (6.22).

As a final observation it is stated that below \( x_3 = 42m \) (2.9h) the loss of TKE due to vertical transport increases with decreasing height down to at least \( x_3 = 24m \) (1.6h). This indicates a layer close to roof level with high production levels of TKE which is not completely dissipated locally but transported away vertically. This layer close to roof level is characterized by large horizontal variability (as it is indicated e.g. by the increased scatter bars in Fig. 6.25). It will be further enlightened when a local turbulence scenario within and above the street canyon of Basel-Sperrstrasse is considered in section 6.7.
6.7 Local turbulence within and above the street canyon Basel-Sperrstrasse

Up to now horizontally averaged turbulence profiles above roof level have been presented. This approach has been pursued down to $x_3 = 24\text{m} (1.6h)$ which was the lowest height level accessible at all ten vertical profile locations. Continuing downwards and thereby skipping one or several locations would have weakened the significance of the horizontal averages.

The height range immediately above roof level is expected to be characterised by high levels of shear TKE production which show up most prominently as local Reynolds flux peaks close to roof level, see e.g. Rafailidis (1997). In the preceding sections it was demonstrated that also certain other turbulence characteristics change close to roof level, e.g. sweeps make an increasing relative contribution to the vertical momentum transfer and the downward turbulent TKE transport takes an increasing share in the TKE budget. Despite the measurement difficulties (densely covered surface with narrow street canyons hindering a convenient positioning of the measurement probe) one location within Basel-Sperrstrasse was accessible to measure local turbulence down to street level (the 'street level location', slightly off the street centre line towards the wind facing house wall, see Fig. 4.12 on page 66). Therefore the horizontally averaged turbulence profiles can be extrapolated downwards at least in terms of a local case study. For this case study the wind components $u_1$ and $u_3$ were measured simultaneously.

The local $u'_1 u'_3$ profile down to street level together with the horizontally averaged profile above roof level is given in Fig. 6.26a. It is instructive to compare it to the other two local $u'_1 u'_3$ profiles taken above Basel-Sperrstrasse at the positions BSPR and H respectively, see Fig. 6.26b. The two latter profiles have a distinctly different shape above roof level in the upper part of the RSL, for the obvious reasons this latter profile shape might be denoted the 's-shape' (positions BSPR and H) while the street level profile shape might be called the 'peak-shape'. Comparing the two $u'_1 u'_3$ profile shapes to the horizontally averaged profile of $u'_1 u'_3$ it is observed that they account for the large horizontal scatter of $u'_1 u'_3$ in the RSL above roof level. The reason for these different profile types may be elucidated by considering the roof shapes in the footprints of the considered height ranges at the measurement locations, (see Fig. 4.11b on page 65 with the street level location being close to location M) and recalling the results of Rafailidis (1997). In his wind tunnel study he found a distinct peak in the $u'_1 u'_3$ profile downwind of a slanted roof. No peak is observable in his data downwind of a flat roof with a slight indication of a 's-shape' although Rafailidis did not discuss this 's-shape' (Fig. 5, B/H=1, in his publication). Therefore the present observations are consistent with his findings and give an
Figure 6.26: (a) Local Reynolds flux $u'_1 u'_3$ profile measured at the street level location compared to the horizontally averaged Reynolds flux profile based on the 10 vertical profiles. Lower dashed line indicates local upwind roof height (16.3m) at the street level location. (b) Local Reynolds flux profiles measured at the locations H and BSPR within the same street canyon (Basel-Sperrstrasse) as the street level profile shown in (a).
illustration of the variability of turbulence even above the same street canyon only about 40m apart in lateral direction (distance between the street level profile and position BSPR). Christen et al. (2003) report that close to roof level and within the street canyon the contribution of $\overline{u_1' u_3'}$ to $u_{\text{local}}$ cannot be neglected any more. Therefore, in this height range the $\overline{u_1' u_3'}$ profile may give only an insufficient indication of the $u_{\text{local}}$ profile.

Next the local profile of $\Delta S$ (as defined in Eqn. (6.6)) down to street level is considered. Fig. 6.27a shows the local profile together with the horizontally averaged profile above roof level. The comparison to the $\Delta S$ profiles above roof level at the locations BSPR and H within Basel-Sperrstrasse is given in Fig. 6.27b. It is observed that the profile down to street level has a strong but comparatively narrow positive peak at and closely below roof level (Fig. 6.27a, narrow in comparison to the local $u_1' u_3'$ peak above roof level). This indicates a distinct dominance of sweeps over ejections in this thin height range, i.e. downward transport of momentum excess strongly dominates the upward transport of momentum deficit. Though the profiles at the positions BSPR and H do not reach far enough down to roof level one may infer from Fig. 6.27b a less strong local increase of $\Delta S$.

The picture of a thin height range around roof level characterised by an intense downward turbulent transport of momentum is complemented by the local vertical turbulent TKE flux profile. Again, the local profile down to street level is shown together with the horizontally averaged profile in Fig. 6.28a, Fig. 6.28b gives the comparison to the local profiles above roof level at the locations BSPR and H. A distinct and narrow negative peak is observed at local upwind roof level ($x_3 = 16.3m$ (1.1h)), i.e. closely above the height where $\Delta S$ has its positive peak. This is not surprising if the strong correlation between $\Delta S$ and the triple velocity moments is recalled from conditional analysis (chapter 6.4) Approaching roof level the joint distribution of $u_1$ and $u_3$ gets increasingly non-Gaussian. Therefore the energetic counterpart to the downward transport of momentum, i.e. sweep domination, is identified, TKE is also transported downwards intensely. Inspecting the local vertical turbulent TKE flux profile further it is observed that the flux is zero around approximately $x_3 = 30m$ (2.1h). This height coincides roughly with the peak in the local $\overline{u_1' u_3'}$ profile and therefore corresponds to the 'hot spot' (i.e. peak) of local shear turbulence production. From that height level TKE is transported upwards and downwards, with the flux divergence representing a loss term in the TKE budget above roof level and a gain term within the street canyon, i.e. TKE is deposited in the street canyon via turbulent transport from above roof level (as it is deduced from the change of sign of the vertical derivative in Fig. 6.28a). For 's-shape' RSL turbulence the necessary profile data close to and below roof level is not available from this study to come to similar conclusions but the indications are that if there are peaks in the $\overline{u_1' u_3'}$, $\Delta S$ or
Figure 6.27: (a) Local $\Delta S$ profile measured at the street level location compared to the horizontally averaged $\Delta S$ profile based on the 10 vertical profiles. Local scatter bars (solid) are based on two measurements per height level. (b) Local $\Delta S$ profiles measured at the locations H and BSPR.
Figure 6.28: (a) Local vertical turbulent TKE flux profile measured at the street level location compared to the horizontally averaged vertical turbulent TKE flux profile based on the 10 vertical profiles. (b) Local vertical turbulent TKE flux profiles measured at the locations H and BSPR.
vertical turbulent TKE flux profile, they must be more narrow and closer to roof level and probably less pronounced than in the case of 'peak-shape' RSL turbulence.

The mean wind profile (only $U_1$) down to street level is given in Fig. 6.29 together with a local fit of the logarithmic profile to the local ISL height range which in turn is estimated from the local constant flux height range in Fig. 6.26a ($x_3 = 48m$ (3.3h) to 93m (6.4h)). Again it is observed that although the parameters of the logarithmic profile are estimated from only the local ISL height range, the fit to the mean wind profile is very well down to roof level. Within the lower half of the street canyon a backflow $U_1 < 0$m/s is observable indicating a vortex structure which is further supported by the $U_1 - U_3$ vector plot in Fig. 6.30. Since the street canyon is not exactly perpendicular to the mean flow one may think of the vector plot as representing a cross section through a spiralling flow structure with a presumably positive component $U_2$ as it is suggested by the geometry, see Figs. 4.9 (p.61), 4.10 (p.63) and 4.11b (p.65). The existence of stable vortices (in the long-term mean) between the house rows perpendicular to the mean flow agrees with the qualitative characterisation of 'd-type' roughness given by Townsend (1976). According to the arguments of Townsend this might serve as a heuristic explanation for the non-dominant role of sweeps throughout large parts of the surface layer in contrast
Figure 6.30: $U_1 - U_3$ vector plot at the street level location. The length of the topmost velocity vector at $x_3 = 30m$ (2.1h) corresponds to 2.86m/s.

to the 'k-type' findings of Raupach (1981).

Summarizing, a consistent picture of local 'peak-shape' RSL turbulence has been drawn, thereby the RSL 'fine-structure' has been somewhat elucidated for those scenarios. At roughly $x_3 = 30m$ (2.1h) an intense TKE production layer exists from which TKE is transported upwards and downwards. At local roof level ($x_3 = 16.3m$ (1.1h)) a thin layer of intense downward turbulent transport of momentum and TKE is identified. One may say that for those scenarios street canyon turbulence is essentially above roof level turbulence transported downwards. As the analysis has made clear, the terms 'peak-shape' and 's-shape' RSL turbulence refer to somewhat extreme turbulence scenarios above street canyons approximately perpendicular to the mean flow. Taking the analysis of Rafailidis (1997) into account, an important determinant of RSL turbulence above those street canyons appears to be the upwind roof shape in the immediate neighbourhood and the footprint of the measurement location. One may sensibly expect that different roof shapes may lead to a more or less pronounced formation of 'peak-shape' or 's-shape' RSL turbulence. According to the presented data, horizontal changes between these two types can be expected on horizontal scales as small as 40m depending on the building structures and roof shapes. It might be reasonable to expect a significant influence of roof shapes on street ventilation patterns.
6.8 Horizontal ISL inhomogeneity and dispersive stresses above roof level

Increasing horizontal homogenization with increasing height is illustrated based on the five horizontal profiles for the turbulence intensity $I_1 = \sigma_1/U_1$ and the local friction velocity $u_{*\text{local}} = \left(-\overline{u'_1 u'_3}\right)^{1/2}$ in Fig. 6.31. The process of horizontal homogenization is clearly demonstrated, the variability between neighbouring points decreases significantly within the ISL (point-to-point distance is 30m in $x_1$ as well as in $x_2$ direction). Nevertheless, the horizontal ISL scatter bars, e.g. in Fig. 6.4 on page 92, indicate a still significant horizontal variability over the ten vertical profiles. To trace its origin, lateral turbulence profiles were measured at $x_3 = 69m$ (4.7h) at the downstream edge of the five horizontal profiles ($x_1 = 1694m$). Fig. 6.32 shows the lateral profiles of the mean wind $U_i$ and the Reynolds flux $u'_i u'_3$, Fig. 6.33 relates those lateral profiles to the urban model. The lateral variability is obvious and has not been present in the approach flow (see e.g Fig. 5.10a on page 85). It is noted that the five horizontal profiles cover roughly the lateral range from one extreme to the other. The origin of this lateral inhomogeneity is related to the inhomogeneity of the upstream roughness on a lateral scale of, say, a few hundred meters. In particular large industrial facilities around the wind tunnel centreline cause a significant flow retardation. This larger scale roughness inhomogeneity leaves its imprint in the ISL and might not be particularly uncommon in realistic urban environments. The small scale roughness inhomogeneity on a scale of, say, ten or twenty meters leaves its imprint in the RSL and is smoothed out in the ISL as it is supported by the significantly reduced point-to-point variability in Fig. 6.31. This more qualitative distinction between the '100m scale' and the '10m scale' with the corresponding roughness inhomogeneities adds a clear limitation to the notion of a 'horizontally homogeneous ISL'.

Dispersive stresses are introduced in the context of the horizontally averaged RANS equation (2.20) (page 32). These stresses are frequently found to be rather small above the roughness canopy. Cheng and Castro (2002a) find the dispersive stresses $\langle U''_1 U''_3 \rangle$ to be only 0.5% to 1% of $\langle u'_1 u'_3 \rangle$ (in the height range between 1h and 2h and depending on the (in their case quite regular) roughness geometry). Raupach et al. (1986) also find $\langle U''_1 U''_3 \rangle$ to be only about 1% of $\langle u'_1 u'_3 \rangle$ at 1h (model plant canopy consisting of vertical aluminium strips), while they estimate the ratio to be about 5% at 0.7h. In the present study the dispersive stresses $\langle U''_1 U''_3 \rangle$ are estimated for the five horizontal profiles, they are shown in Fig. 6.34 together with the already discussed horizontally averaged Reynolds fluxes $\overline{u'_1 u'_3}$. Indeed, it is found that those dispersive stresses above roof level are more than an order of magnitude smaller, i.e. 2% to 6%, than the horizontally averaged Reynolds fluxes (e.g. at $x_3 = 27m$ (1.8h) $\langle U''_1 U''_3 \rangle = -0.018m^2/s^2$ compared to $\langle \overline{u'_1 u'_3} \rangle = -0.28m^2/s^2$). Nevertheless, not the absolute
Figure 6.31: Increasing horizontal homogenization over the five horizontal profiles with increasing height for turbulence intensity $I_1 = \sigma_1/U_1$ (left) and local friction velocity $u_{*local} = \left(-u'_1u'_3\right)^{1/2}$ (right). Flow direction is along the positive $x_1$ direction.
Figure 6.32: Lateral inhomogeneity of (a) mean wind and (b) Reynolds fluxes measured at $x_3 = 69\text{m} (4.7h)$ at the downstream edge of the five horizontal profiles ($x_1 = 1694\text{m}$).
Figure 6.33: One peak in the lateral mean wind profile is related to a flat park presenting low roughness (light area to the left of the wind tunnel centreline in (a)), while the other peak may have its origin in a gap between large industrial facilities (indicated by the left arrow in (b)). The area covered by the five horizontal profiles is given by the rectangle in (a).
magnitude, but the (vertical) derivatives enter the horizontally averaged RANS equation (2.20) (page 32). Since the horizontally averaged Reynolds fluxes are approximately constant with height down to (at least) \( x_3 = 27\text{m} \) (1.8h), it is observed that below \( x_3 = 39\text{m} \) (2.7h) the vertical derivative of \( \langle U''_1 U''_3 \rangle \) makes a larger contribution to (2.20) in comparison to the vertical change of \( \langle u'_1 u'_3 \rangle \). Estimated from the two lowest height levels (\( x_3 = 27\text{m} \) (1.8h) and \( x_3 = 33\text{m} \) (2.3h)) the vertical change of \( \langle U''_1 U''_3 \rangle \) is about \( 1.4 \cdot 10^{-3}\text{m/s}^2 \) compared to essentially no change of \( \langle u'_1 u'_3 \rangle \). Therefore the conclusion for the Kleinbasel urban roughness is that below \( x_3 = 2\text{h} \) to \( 3\text{h} \) the contributions from the dispersive stress divergence to the dynamics of horizontally averaged turbulence is not negligible compared to the contributions from the horizontally averaged Reynolds flux divergence. This may be compared to the observations made by Böhm et al. (2000) in their wind tunnel study within a model plant canopy. They note that in the upper canopy layer above 0.6h the 'dispersive flux divergence increases rapidly to a maximum of almost (minus) one half of the turbulent flux divergence'. Therefore they consider the dispersive stress
Figure 6.35: Field measurement locations compared to wind tunnel measurement locations at Basel-Sperrstrasse (BSPR). Field data from the encircled wind sectors NW and NNW as measured at the topmost field measurement level are taken for comparison to wind tunnel measurements (wind tunnel approach flow direction given by the heavy dashed line).

The measurement tower BSPR in Basel-Sperrstrasse is the primary field reference station for turbulence data. During the BUBBLE project field turbulence data was recorded within and above this street canyon at $x_3 = 3.6m (0.2h),$ $11.3m (0.8h),$ $14.7m (1.0h),$ $17.9m (1.2h),$ $22.4m (1.5h)$ and $31.7m (2.2h)$ from August 2001 to July 2002. Fig. 6.35 gives a schematic sketch of the field and model measurement arrangement. The field data is segmented into sixteen wind sectors based on the wind measurements at the topmost field measure-
Figure 6.36: Field and wind tunnel measurements of the mean wind $U_1$ at BSIR scaled by the wind speed at the topmost field measurement level ($x_3 = 31.7$m (2.2h)). See text for definition of 'neutral' and 'strong neutral'. Field scatter bars are given by the 25% and 75% quantile. Dashed line gives the local upwind building height ($x_3 = 14.3$m (1.0h)).

The comparison of the wind tunnel and the field mean wind profile scaled with $U_1(x_3=31.7$m) is given in Fig. 6.36. A good correspondence is observed. The Reynolds fluxes are compared in Fig. 6.37 in terms of the local friction velocities $u_{*local} = \sqrt{-\frac{u'_1 u'_3}{\gamma}}$ scaled by the local mean wind $U_1(x_3)$ per height.
level. Again a good correspondence is observed. The locally scaled turbulent velocities $\sigma_i/u_{*\text{local}}$ are compared in Figs. 6.38 to 6.40. It is observed that the correspondence for $\sigma_3/u_{*\text{local}}$ is again very good. A larger scatter over the wind sectors and stabilities is observed for $\sigma_2/u_{*\text{local}}$, the correspondence to the wind tunnel data for sector NNW is better than for sector NW, best correspondence is for sector NNW and $|\zeta| < 0.05$. The same tendency is observed for $\sigma_1/u_{*\text{local}}$, here the field data remains somewhat larger than the wind tunnel data even for the sector NNW and $|\zeta| < 0.05$. The larger values for the lateral and longitudinal turbulent velocities may be attributed at least partly to the instationarity of field boundary conditions, which include varying wind speeds and directions. Besides those variations a good overall correspondence between the wind tunnel and the field data is found for the mean wind profile, the Reynolds fluxes and the turbulent velocities. It is noted that values of $\sigma_1/u_*$ as low as $2$ have been observed in other field studies, see e.g. the remark in Simiu and Scanlan (1978, p. 54) as well as findings in Duchène-Marullaz (1975).

Next, the conditional analysis results for the Reynolds fluxes are compared.
Figure 6.38: Field measurements and wind tunnel measurements of $\sigma_1/u_{*\text{local}}$ at BSPR. Vertical dotted line indicates ISL reference value of 2.5 from Lumley and Panofsky (1964).

Figure 6.39: Field measurements and wind tunnel measurements of $\sigma_2/u_{*\text{local}}$ at BSPR. Vertical dotted line indicates ISL reference value of 1.9 from Lumley and Panofsky (1964).
Again referring to the location BSPR, Fig. 6.41 compares field $\Delta S$ to wind tunnel $\Delta S$. The observed field $\Delta S$ peak at roof level should also be compared to the wind tunnel case study conducted within Basel-Sperrstrasse (Fig. 6.27a on page 128). Feigenwinter (2000) has estimated $\Delta S$ at another location within Basel and at greater heights (up to $x_3 = 76m (5.2h)$). $\Delta S$ was measured at the corresponding location in the wind tunnel, the comparison is shown in Fig. 6.42. Feigenwinter (2000) included in his calculation all wind directions with $DD > 224^\circ$ and $DD < 103^\circ$ while the wind tunnel corresponds to $DD = 330^\circ$. The effect of the different upwind fetches should be most notably at the lowest level, $x_3 = 36m (2.5h)$, which may serve as an explanation for the deviation between the wind tunnel finding and the field finding at this level. Overall it is found again that the field findings of conditional analysis are well-reproduced in the wind tunnel model, at the Feigenwinter location up to $x_3 = 76m (5.2h)$.

To compare the spectral characteristics it is referred to the review by Roth (2000) who in turn based parts of his spectra review on the work done by Feigenwinter et al. (1999) in Basel within the BASTA project. Roth (2000) summarizes that "the shapes of the [urban] velocity spectra show good agreement with [rural] reference data" with the important qualification that the
Figure 6.41: Field measurements and wind tunnel measurements of $\Delta S$ at BSPR.

Figure 6.42: Wind tunnel measurements of $\Delta S$ at the Feigenwinter location compared to the data from Feigenwinter (2000).
peak frequencies in the $u_3$ spectra are consistently shifted towards lower values. Fig. 6.43 compares those peak frequencies as reviewed by Roth (2000) to the wind tunnel findings of the present study. Agreement in the order of magnitude of the shift is observed. Roth (2000) reviews further that the "spectra are only clearly affected by individual roughness characteristics close to and within the urban canopy". He concludes from the integral statistics and from the spectra that turbulent flows over cities and plant canopies bear strong similarities. For the wind tunnel $u_3$ spectra it is indeed observed that there is a close resemblance to the rural reference at $x_3 = 22.5 \text{m} (1.5h)$ (except the peak shift which is observed in the urban case with $d_0$ included in the non-dimensional frequency) and $x_3 = 31.8 \text{m} (2.2h)$, at this latter height level the resemblance also extends to the $u_1$ and $u_2$ spectra. The observed deviation of the $u_1$ spectrum at $x_3 = 22.5 \text{m} (1.5h)$ from the rural reference corresponds to the similarity of urban spectra to spectra above and within plant canopies as remarked by Roth (2000). Within plant canopies it is observed that the $u_1$ spectra exhibit a more rapid roll off towards higher frequencies (Finnigan (2000), Gardiner (1994)).

Concerning the increasing shift of the peak frequencies in the $u_1$ and $u_2$ spectra towards higher frequencies at $x_3 = 72 \text{m} (4.9h)$ and $x_3 = 108 \text{m} (7.4h)$ the interpretation is ambiguous. Roth (2000) reports a "consistent increase of the peak frequency with increasing height for all three velocity components" and it may be questioned whether the scalings of the peak length scales as implied by the parameterizations based on rural measurements up to $x_3 = 22.6 \text{m}$ (i.e.
Figure 6.44: Integral length scales $L_{ux}$ measured in the wind tunnel in the approach flow at the model inflow edge (empty triangles) and at BSPR (empty diamonds) compared to the reference from Counihan (1975) for neutral ABL (diagram taken from Counihan (1975)). Urban $L_{ux}$ correspond to those listed in Tab. 6.2 on page 114.

$\lambda_{u1,peak} = 22.0 \cdot (x_3 - d_0)$ and $\lambda_{u2,peak} = 6.3 \cdot (x_3 - d_0)$ are valid at considerably greater heights (e.g. at $x_3 = 72m$ (4.9h) and above). Therefore it might not be unreasonable to expect a peak frequency shift. This expectation is further supported by the discussion of Simiu and Scanlan (1978 p.55, the discussion seemingly disappeared in their 2nd edition from 1986) and by the findings of Busch and Panofsky (1968). The latter study reports that above $x_3 = 50m$ the peak wavelengths increase less than linear with height, i.e. the spectral peak frequencies are found to be shifted towards larger non-dimensional frequencies. Nevertheless the coincidence of the wind tunnel measures with the region of energetic deviations provokes some doubt and raises the concern about model artefacts. These concerns would imply an insufficient energetic representation of larger length scales at greater heights. To shed some light on this issue, the integral length scales $L_{ux}$ as obtained by correlation function integration (see...
Eqn. (2.24) on page 33) are estimated for the location BSPR as well as for the model inflow edge at the wind tunnel centreline, they are compared to the review given by Counihan (1975) in Fig. 6.44. Two conclusion can be drawn:

1. There is no convincing indication for an unnatural shift of wind tunnel integral length scales $L_{ux}$ to lower values up to $x_3 = 108m$ (7.4h) and the wind tunnel $L_{ux}$'s correspond roughly to the expected integral length scales as determined from field measurements (only roughly because the scatter in the empirical field data presented by Counihan (1975) is significant).

2. The urban $L_{ux}$ profile clearly shows a somewhat transitory state, the 'new' (i.e. urban) length scale information does not appear to have already been transported up to $x_3 = 108m$ (7.4h). This finding sheds some light on the discussion about flow adaptation (see discussion in chapter 6.6) which still seems to be underway at $x_3 = 72m$ (4.9h) at BSPR with respect to $L_{ux}$ adaptation (1634m downstream of the roughness change at the model inflow edge).

In the $u_2$ spectra the energetic drop-off at scales larger than the wind tunnel measures is particularly eye-catching at $x_3 = 108m$ (7.4h) (Fig. 6.19 on page 116). Despite the field finding of larger peak frequencies with greater heights this strong drop-off may be due to a model artefact which becomes increasingly observable in the $u_2$ spectra from $x_3 = 72m$ (4.9h) upwards to $x_3 = 108m$ (7.4h) and may constitute a limitation of this wind tunnel model. Nevertheless the results of the conditional analysis at $x_3 = 76m$ (5.2h) compared to the field data from Feigenwinter (2000) at the same height level does not indicate a significant effect of this limitation on the turbulence characteristics studied in this wind tunnel experiment within and below the ISL.

The observation of $S_3(n)/S_1(n)$ smaller than 4/3 is also made by Christen et al. (2004) and Feigenwinter et al. (1999). Christen et al. (2004) measured $S_3(n)/S_1(n)$ in the field at the same location (BSPR) as this study did in the wind tunnel. In the non-dimensional frequency range from $n = 1$ to 4 they report the ratio to be between 1.0 and 1.2 (at $x_3/h = 1.5$ and 2.2). Only around $n = 40$ $S_3(n)/S_1(n)$ is found to have a peak close to 4/3 at $x_3/h = 2.2$ (see Fig. 4 in their publication). Feigenwinter et al. (1999) report ratios of about 1.22 ($x_3 = 76m$ (3.2h), their chosen mean building height is $h = 24m$) and 1.23 ($x_3 = 50m$ (2.1h)) while at their lowest level $S_3(n)/S_1(n)$ reaches close to 4/3 from below ($x_3 = 36m$ (1.5h)).

Summarizing, the wind tunnel model is found to reproduce satisfactorily the cited field turbulence characteristics within and below the ISL. Particularly the comparison to the BSPR field data within the RSL is very encouraging
with regard to the applicability of the wind tunnel results to full scale field scenarios.

6.10 Reynolds number independence

For sufficiently large Reynolds numbers the modelling requirement of strict Reynolds number similarity is relaxed by the observation of Reynolds number independence (see discussion in chapter 2.4). It is found that many turbulence characteristics are independent of the exact Reynolds number as long as a certain threshold Reynolds number range is exceeded.

Reynolds number independence is exploited in the context of the present study, it is important for two reasons. The first reason is of course to assure the applicability of wind tunnel findings to full scale urban scenarios. Since the wind tunnel wind speeds and the full scale wind speeds are of the same order of magnitude, the Reynolds number difference is mainly determined by the geometric scale reduction which is 1:300. Therefore the wind tunnel Reynolds number, based e.g. on the mean building height and the wind speed at roof level, is about 1/300 of the corresponding full scale Reynolds number. The comparison to the field data presented in the last section indicates that for the studied turbulence characteristics the wind tunnel flow exceeds the threshold Reynolds number range for Reynolds number independence. The wind tunnel results are therefore expected to be transferable to full scale scenarios.

The second reason to check Reynolds number independence is the necessity to further reduce the wind tunnel wind speed for the dispersion experiment. Lower wind speeds imply higher concentration values which benefit the measurement accuracy and the resolution of the concentration field. Therefore Reynolds number independence has been checked at the location BSPR up to the top of the ISL (x₃ = 81m (5.5h)) for those parameters of most immediate relevancy for turbulent dispersion, i.e. the mean wind profile and the turbulent velocities. The wind tunnel turbulence results presented in the last sections were acquired at Uᵢ(x₃ = 81m, BSPR) = 5.18m/s. To check Reynolds number independence vertical turbulence profiles were measured at the location BSPR for two different wind speeds: Uᵢ(x₃ = 81m, BSPR) = 5.28m/s and Uᵢ(x₃ = 81m, BSPR) = 0.97m/s. Thereby a Reynolds number range corresponding roughly to a factor of five is covered. Fig. 6.45a shows the mean wind profile scaled by Uᵢ(x₃ = 81m, BSPR), Fig. 6.45b gives the turbulence intensities σ₁/Uᵢ and σ₃/Uᵢ. Since the profile scatter does not exceed the measurement scatter Reynolds number independence is concluded for wind speeds from Uᵢ(x₃ = 81m, BSPR) = 0.97m/s upwards. This finding coincides with the experience of the Hamburg wind tunnel group which includes low wind
Figure 6.45: Reynolds number independence check (a) for the mean wind profile and (b) for the longitudinal and vertical turbulence intensities.
speed measurements obeying Reynolds number similarity even within street canyons. Therefore the dispersion experiments made at \( U_1(x_3 = 81\text{m}, \text{BSPR}) = 1.25\text{m/s} \pm 0.09\text{m/s} \) are assumed to be within the range of Reynolds number independence.

### 6.11 Conclusions

The wind tunnel model reproduces very well the local field turbulence characteristics in Kleinbasel under neutral conditions. The field data used for direct comparison covers the height range up to \( x_3 = 31.7\text{m} \) (2.1h) at the location BSPR as well as the three height levels \( x_3 = 36\text{m} \) (2.5h), 50m (3.4h) and 76m (5.2h) at the Feigenwinter location. This finding encourages the conclusion that the wind tunnel modelling results are applicable to the neutrally stratified urban surface layer in the full scale scenario.

Based on horizontally averaged turbulence profiles measured between about 1.3km and 1.7km downstream of the model inflow edge, a layered turbulence structure could be clearly identified: The RSL reaching up to \( x_3 = 48\text{m} \) (3.3h) and the ISL reaching from \( x_3 = 48\text{m} \) (3.3h) to 81m (5.5h). The prominent characteristic of the RSL is the horizontal variability of various observed turbulence characteristics, individual roughness elements leave their imprints in the turbulence structure closely above roof level. In addition to the horizontal inhomogeneity of turbulence, other indicators for the given RSL height range are as follows:

- The ISL dissipation scale given in Eqn. (6.19) (page 120) corresponds well to the dissipation rates estimated from the velocity spectra at the height levels 72m (4.9h) and 108m (7.4h), while at the lower height levels 31.8m (2.2h) and 22.5m (1.5h) the ISL scale increasingly tends to overestimate the spectrally estimated dissipation rate (Fig. 6.23 on page 120).

- The contribution of the vertical turbulent TKE flux to the TKE budget is minimal and close to zero in the height range between \( x_3 = 40\text{m} \) (2.7h) and \( x_3 = 50\text{m} \) (3.4h). Above and below this height range the TKE flux contributions increase (Fig. 6.25 on page 123).

The criterion of sweep domination over ejections, i.e. \( \Delta S > 0 \), is not found to be typical for the whole RSL height range but characterizes the height layer closer to roof level below \( x_3 = 33\text{m} \) (2.3h) (Fig. 6.13 on page 107). This is in contrast to the observations made by Raupach (1981) above a cylinder-roughened surface. Also the role of dispersive stresses in the overall momen-
tum balance appears to become non-negligible only close to roof level and not throughout the whole RSL (see below).

The ISL is identified based on the following coexisting features:

- Markedly decreased horizontal variability in turbulence characteristics,
- constant profile of the horizontally averaged Reynolds fluxes \( \langle u_1 u_3 \rangle \),
- logarithmic wind profile of the horizontally averaged flow \( \langle U_1 \rangle \),
- good correspondence of the TKE dissipation rate \( \varepsilon \) estimated from the velocity spectra to the ISL dissipation rate scale.

The following observations concerning these characteristics are emphasized:

- The logarithmic shape of the horizontally averaged wind profile continues deep down into the RSL, at least down to \( x_3 = 27 \text{m} \) \((1.8h)\). This extension of the logarithmic region has also been observed in other studies (e.g. Cheng and Castro (2002a), Ploss et al. (2000)), while some studies (e.g. Raupach et al. (1986), Raupach et al. (1980)) have observed deviations from the logarithmic profile within the RSL. This feature appears to depend on the roughness type, urban roughness of the type investigated in this study apparently shows this characteristic.

- The constant horizontally averaged Reynolds flux profile continues deep down into the RSL, at least down to \( x_3 = 27 \text{m} \) \((1.8h)\). This confines potential deviations from constancy (including a peak as analysed by Kastner-Klein and Rotach (2004)) to the layer very close to roof level, i.e. at least below \( x_3 = 27 \text{m} \) \((1.8h)\). Given the estimated RSL layer height of 48m \((3.3h)\), such deviations are not seen as 'characteristic features' of the (above roof level) RSL in the investigated urban scenario.

- Local constancy of Reynolds fluxes with height may not be a reliable indicator of the ISL which also includes (approximate) horizontal homogeneity of turbulence.

Although the turbulence characteristics in the ISL height range are clearly distinct from those in the adjacent height layers (e.g. constancy of Reynolds fluxes and decreased horizontal variability), certain deviations from the 'canonically expected' ISL characteristics are observed. They are:
• Horizontal homogeneity of turbulence characteristics is not perfect, i.e. variations on a horizontal scale of, say, 100m are observed (Fig. 6.32 on page 134). These variations are attributed to upwind roughness inhomogeneity of the urban model.

• The TKE removing contributions from the vertical turbulent TKE flux are not negligible (Fig. 6.25 on page 123).

• The ratio of the spectral densities $S_2$ and $S_1$ in the assumed inertial subrange is not $4/3$ but about 1.2 (Fig. 6.21 on page 118).

Referring also to the observations of flow adaptation (Figs. 6.1 and 6.2 on pages 88 and 89), two conclusions are possible: Either the observed flow characteristics are adapted to the urban roughness (and fetch) up to about $x_3 = 96\text{m} (6.6h)$ and contributions of upward turbulent TKE flux to the TKE budget are part of the energetic equilibrium in the ISL above very rough surfaces, therefore 'local equilibrium' (i.e. contributions to the TKE budget only from production and dissipation) is not obtained. Or the observed flow characteristics are completely adapted only up to about $x_3 = 48\text{m} (3.3h)$ with the mean wind profile and the Reynolds fluxes in greater heights adapting very slowly without any discernible profile changes downstream of an additional 300m fetch of urban roughness. The latter conclusion is in better correspondence with common rules of thumb for the equilibrium layer growth close to the surface. In this case, a consequent conclusion is that a logarithmic wind profile and a vertically constant flux are not sufficient to diagnose an equilibrium layer, but the contributions of the vertical turbulent TKE flux should also be analysed. With increasing urban fetch the mean wind gradient may continuously decrease, while maintaining a logarithmic wind profile, until $u_{*\text{log}} = u_{*\text{flux}}$. Unfortunately, the wind tunnel model fetch was not long enough to allow for more precise conclusions.

Local Reynolds flux profiles within the RSL above roof level show a large variability, two extreme profile shapes have been identified ('s-shape' and 'peak-shape'). The dominant determinant for the local above roof level Reynolds fluxes appears to be the upwind roof and building geometry in the turbulence footprint. Focusing on the RSL height range above $x_3 = 27\text{m} (1.8h)$ (where horizontal averages were determined based on the horizontal grid measurements), it is found that by local measurements the horizontally averaged Reynolds flux of $-0.28\text{m}^2/\text{s}^2$ can be overestimated by at least up to 50% $(-0.42 \text{m}^2/\text{s}^2$ at location 'high' at $x_3 = 27\text{m} (1.8h)$) and underestimated by at least up to 18% $(-0.23 \text{m}^2/\text{s}^2$ at location 'Q' at $x_3 = 30\text{m} (2.1h)$). For the mean wind speed at $x_3 = 27\text{m} (1.8h)$ the horizontally averaged mean wind of 3.06$m/s$ is found to be overestimated by local measurements by up to at least 16% and underestimated by up to at least 23%. This degree of variability within the modeled urban RSL above roof level is considerably larger than observed by...
Raupach (1981) above more regular roughness (cylinder-roughened surface). E.g. within the RSL above the canopy he reports a scatter of $u'_1u'_3$ around the horizontal average of typically 5%.

In terms of a local case study above a street canyon it has been demonstrated that at roof level a turbulence layer exists characterised by intense downward momentum transport and downward turbulent TKE flux. Above roof level and in particular in the ISL height range the turbulent momentum transport is slightly dominated by ejections. This appears to be characteristic for urban roughness and is distinct from findings above more regular model roughness.

In contrast to findings in other turbulence studies (e.g. Cheng and Castro (2002a) and Raupach et al. (1986) for idealized wind tunnel roughness) the role of dispersive stresses above the canopy layer is found to be not negligible in comparison to the horizontally averaged Reynolds fluxes. Although the dispersive stresses $\langle U'_1U'_3 \rangle$ are found to be only 2% to 6% of the horizontally averaged Reynolds flux $\langle u'_1u'_3 \rangle$ in the height range from $x_3 = 27m$ (1.8$h$) to $x_3 = 69m$ (4.7$h$), the vertical change of $\langle U'_1U'_3 \rangle$ between the two lowest height levels ($x_3 = 27m$ (1.8$h$) and $x_3 = 33m$ (2.3$h$)) is found to be larger than the corresponding change of $\langle u'_1u'_3 \rangle$. Thus at least in this height range the dispersive stress divergence contribution to the horizontally averaged RANS equation is larger than the one from the horizontally averaged Reynolds stress.
divergence. Similar observations are made by Böhm et al. (2000) in the upper part of a model plant canopy.

In the upper RSL part and throughout the ISL strong correlations are observed between $\Delta S$ and $\bar{u_1}' \bar{u_1}' \bar{u_1}' / \sigma_1^3$ and among the triple moments of the joint distributions of $u_1$ and $u_3$. They are found to be qualitatively similar to findings above regular idealized roughness, but with clear quantitative variations. These variations as well as the finding of an ISL slightly dominated by ejections are discussed with reference to the concepts of 'd-type' and 'k-type' roughness. Urban roughness appears to belong to the 'd-type' category. Therefore the approach to model urban scenarios with idealized roughness configurations, which may exhibit 'k-type' turbulence characteristics, should be treated with care and caution. The observed correlations may serve as consistency criteria for theoretical velocity distributions used e.g. in Lagrangian stochastic particle models.

All velocity spectra are similar in shape to rural reference spectra. The $u_3$ spectra are observed to be moved to lower frequencies within the RSL, while the $u_1$ and $u_2$ spectra are moved increasingly to higher frequencies with increasing height within and slightly above the ISL. Analysis of integral length scales does not confirm the suspicion that the latter observation could be due to model artefacts.

The findings from horizontally averaged turbulence profiles above roof level are summarized in Fig. 6.46.
Chapter 7

Modelled urban dispersion in Kleinbasel

The wind tunnel dispersion experiment is designed to model the field tracer experiment conducted in Kleinbasel in June/July 2002 during the BUBBLE project. In the field scenario $SF_6$ was released from a point source closely above roof level (1.3h). The motivation for the wind tunnel experiment is to have similar dispersion scenarios looked upon from the field, the wind tunnel and subsequently also the numerical perspective. In the wind tunnel ethane ($C_2H_6$) is taken as the dispersing gas, its density is comparable to that of air and it is well-detectable by the SFID/FFID probes.

In the following the downstream distance from the source (i.e. the distance along the $x_1$ direction) is denoted by $x_{DST}$.

### 7.1 Similarity considerations and source configuration

To facilitate a comparison of wind tunnel and field concentration measurements, not the actual concentrations are compared but the non-dimensional concentrations $C^*$ which are defined as (see e.g. VDI (2000), also discussions in Schatzmann et al. (2001) and Schatzmann and Leitl (2002))

$$C^* = \frac{CU_{ref}L_{ref}^2}{Q}$$

(7.1)

with
This choice of a non-dimensional concentration is motivated by the non-dimensional mass conservation for the dispersing gas which reads in dimensional instantaneous integral form:

$$\int\int\int_{V} (\partial_t c + u_i \partial_i c) \, dV = Q$$  \hspace{1cm} (7.2)$$

where the volume $V$ includes the point source of strength $Q$. By introducing non-dimensional coordinates $x_i^* = x_i/L_{ref}$, non-dimensional velocities $u_i^* = u_i/U_{ref}$ and the non-dimensional time $t^* = t U_{ref} / L_{ref}$ and dividing by $Q$, one obtains over the non-dimensional volume $V^*$

$$\int\int\int_{V^*} \left[ \partial_t^* \left( \frac{c U_{ref} L^2_{ref}}{Q} \right) + u_i^* \partial_i^* \left( \frac{c U_{ref} L^2_{ref}}{Q} \right) \right] \, dV^* = 1 \hspace{1cm} (7.3)$$

or simply

$$\int\int\int_{V^*} (\partial_t c^* + u_i^* \partial_i c^*) \, dV^* = 1 \hspace{1cm} (7.4)$$

with $c^*$ defined analogously to $C^*$. For all volumes $V^*$ not including the point source the RHS is simply zero which gives the non-dimensional transport equation

$$\partial_t c^* + u_i^* \partial_i c^* = 0 \hspace{1cm} (7.5)$$

for all points except of course at the point source itself. (At the point source the RHS of the transport equation is formally infinity, i.e. the RHS should be considered a 3-dimensional Dirac distribution (also known as a 'delta function') which is just the mathematical representation of a point source density.) From this discussion it is seen that for all scenarios with identical non-dimensional geometries $x_i^* = x_i/L_{ref}$ and identical non-dimensional velocity fields $u_i^* = u_i/U_{ref}$ the solution $c^*$ for the transport equation should be the same. This is then of course also true for the mean values $C^*$.

In the present study geometric similarity is assured by the urban model and similarity of the velocity fields is given by Reynolds number independency as demonstrated in chapter 6.10. Therefore $C^*$ appears to be the appropriate non-dimensional quantity to compare with field measurements. $L_{ref}$ is taken
to be the mean building height $h$, the mean wind $U_1$ measured at the topmost level of the BSPR measurement tower ($x_3 = 31.7m (2.2h)$) is taken for $U_{ref}$, it is known in the wind tunnel and for the field scenarios. Given the convenient wind tunnel units for concentration and source strength, ppm and litres per hour ($l/h$), $C^*$ is calculated from

$$C^* = U_{ref} \cdot L_{ref}^2 \cdot 3.6 \cdot \frac{C[ppm]}{Q[l/h]}$$

(7.6)

with $U_{ref}$ in [m/s] and $L_{ref}$ in [m] as it is derived and discussed in appendix F.

Based on the results of the field experiment, expectations for $C^*$ at the field sampling stations are derived. In combination with the minimal $U_{ref}$ (to assure Reynolds number independency) and the minimal concentrations detectable by the FFID (assumed to be roughly in the order of 10ppm based on the experience of the Hamburg wind tunnel group) the minimal source strength required for the experiment can be estimated which turns out to be roughly 200 $l/h$. This volume flow rate has implications on the source design if jet effects due to large gas exit velocities are to be avoided. The maximal admissible gas exit velocity from the source is given by the mean wind speed $U_{R1}$ at the source location R1. During the dispersion experiment in the wind tunnel, the mean wind speed at R1 is estimated to be $U_{R1} = 0.60m/s$ which corresponds to a reference wind speed of about $U_{ref} = 0.82m/s$ at BSPR, $x_3 = 31.8m (2.2h)$ (to be used to calculate $C^*$) and a wind tunnel ‘free stream’ velocity as measured by the Prandtl tube of about $U_{WT} = 2.05m/s$. It is clear that the source design used in the field experiment cannot be replicated to scale in the wind tunnel. The field source was a thin rubber tube with an inner diameter of 8mm. Downscaling by the geometric scale factor of 300 gives for a volume flow rate of 200 $l/h$ a bulk exit velocity of about 100km/s (!). Even without downscaling the bulk exit velocity at the source would be about 1.1m/s. Both a bit too large to be desirable.

Therefore deviations from the field source design are unavoidable. Three different source designs are compared in the wind tunnel to check for the influence of source geometry on the concentration pattern. For the obvious reasons they are called the cylinder source (CYL), the large T-tube source (LTS) and the small T-tube source (STS) (Fig. 7.1a). The cylinder source consists of three rows with 20 openings in each row giving a total of 60 openings. Each opening has a diameter of 3mm giving a total source area of $60 \pi 1.5^2 mm^2 = 424 mm^2$. The height of the cylinder source is 20mm, its diameter is 30mm. Mounted on top of the roof as in Fig. 7.1b the middle row is at a height of $x_3 = 21.3m (1.5h)$, the total release height range is therefore roughly between $x_3 = 18.3m (1.3h)$ and $x_3 = 24.3m (1.7h)$ (in the field experiment the tracer gas release was at $x_3 = 18.3m (1.3h)$). The large and the small T-tube source are open at
Figure 7.1: The cylinder (CYL), the large tube (LTS) and the small tube (STS) source (a) mounted on the roof at the ethane release location R1 within the urban model (CYL in (b) and LTS in (c)).
Assumingly the concentration pattern in the vicinity of the source depends on the source geometry. In particular the different source designs presented above are not expected to model adequately the field experiment in the near-field of the release point. Nevertheless, based on the results of Schatzmann and Leitl...
(2003) the expectation is that the detailed source geometry has no effect on the concentration pattern at those source distances relevant for the present study ($x_{DST} \geq 384m$). This expectation is supported by the lateral $C^*$ profiles at $x_3 = 27m$ (1.8h) measured at $x_{DST} = 384m$ using all three source designs (Fig. 7.2). The lateral $C^*$ profile does not appear to depend on the source design at this source distance. A slight plume deflection is observed above Kleinbasel and to exclude any source artefacts Fig. 7.2 also includes the lateral $C^*$ profiles at $x_3 = 30m$ (2.1h) measured at $x_{DST} = 894m$ using the sources STS and CYL. The deflection is observed for both source geometries, so an influence of the source geometry on the plume deflection is not observed.

For the concentration measurements discussed in the following the LTS source has been used.

### 7.2 Mean concentration field above roof level

Mean concentrations are measured based on 3-minutes averages. Lateral $C^*$ profiles at $x_3 = 27m$ (1.8h) and vertical $C^*$ profiles (on the plume centerline) at the most upstream and most downstream measurement locations ($x_{DST} = 384m$ and $x_{DST} = 864m$) are shown in Fig. 7.3 together with a fit of the applicable part of the Gaussian plume parameterization (see Eqn. (2.33) on page 37). The lateral and vertical $C^*$ profiles at the intermediate locations are given in appendix E. The overall impression is that the lateral profiles are very well represented by the Gaussian distribution with the quality of fit $R^2$ being typically 0.99. The vertical profiles are a bit less well represented by the Gaussian formula, here $R^2$ varies between 0.96 and 0.98. As it is shown in appendix E, the height range of deviations appears to be close to roof level with the actual concentrations decreasing less rapidly with increasing height as assumed by the Gaussian parameterization (this is particularly apparent for the vertical profiles at $x_{DST} = 444m$ and $x_{DST} = 624m$).

The estimated lateral plume spreads $\sigma_y$ (as estimated at $x_3 = 27m$ (1.8h)) and vertical plume spreads $\sigma_z$ (as estimated from $x_3 = 21m$ (1.4h) or higher upwards) are shown in Fig. 7.4 together with reference curves from Briggs (1973) as cited in Hanna et al. (1982). Of course, several other reference schemes to determine the Gaussian 'sigmas' exist (for a comparison see e.g. Irwin (1983)), but Briggs' formulas belong to the apparently rare parameterizations particularly designed for urban scenarios. His formulas are based on data from the dispersion field experiment in St. Louis in 1968.

In the present wind tunnel study it is found that appropriate parameterizations of the measured $\sigma_y$ and $\sigma_z$ in terms of downstream distance $x_{DST}$ from the source are
Figure 7.3: (a) Lateral concentration profiles measured at the upstream and downstream edge of the rectangular concentration measurement area at $x_3 = 27m$ (1.8h) (see Fig. 4.10 on page 63) (quality of fit $R^2 = 0.99$ for both profiles). (b) Vertical concentration profiles measured at the estimated peak locations of the lateral profiles shown in (a) ($R^2 = 0.98$ at $x_{DST} = 384m$ and $R^2 = 0.97$ at $x_{DST} = 864m$).
Figure 7.4: Lateral and vertical plume spreads $\sigma_y$ and $\sigma_z$ as parameterized by the Gaussian plume model. The wind tunnel data (with the fits given in Eqns. (7.7) and (7.8) indicated by the short dashed lines) is compared to the reference from Briggs (1973) for Pasquill turbulence types C ('slightly unstable') and D ('neutral').
Figure 7.5: Maximal $C^*$ estimated by the Gaussian fits to the lateral concentration profiles measured at $x_3 = 27$ m (1.8h). Dashed line indicates fit given in Eqn. (7.9).

\[
\sigma_y(x_{DST}) = 0.0556x_{DST} + 38.568 \tag{7.7}
\]

and

\[
\sigma_z(x_{DST}) = \frac{0.331x_{DST}}{\left(1 + 0.0197x_{DST}\right)^{0.5}}. \tag{7.8}
\]

It is remarked that the wind tunnel source is not an exact point source, but has a lateral and vertical extension of 6 m (full scale, 0.02 m at wind tunnel scale, see chapter 7.1 for source configuration) at $x_{DST} = 0$m. The virtual source location of an equivalent point source (i.e. producing the same far field mean concentration pattern) may by thought a bit more upstream, therefore the virtual point source distance may be assumed somewhat larger than $x_{DST}$. It does not appear plausible to estimate the virtual point source upstream displacement by setting $\sigma_y = 0$m in the above parameterization (7.7), the resulting displacement would be unreasonably large. The observation, that the lateral plume spreads at $x_{DST} = 384$m and 444m coincide roughly with Briggs' parameterization, might be taken as an indication for the smallness of the virtual point source upstream displacement. Nevertheless it is noted that the rate of lateral plume spread growth is clearly smaller than assumed in Briggs' formula at $x_{DST}$ greater than 384m. An extrapolation from $x_{DST} = 384$m towards the source shows that the initial rate of lateral plume spread
growth must have been much more accelerated than observed beyond \( x_{DST} = 384 \text{m} \).

The maximal concentrations \( C_{\text{max}}^* \) determined as the peak concentrations of the Gaussian fits to the lateral \( C^* \) profiles at \( x_3 = 27 \text{m} \) (1.8h) are shown in Fig. 7.5 with a corresponding parameterization in terms of \( x_{DST} \) being

\[
C_{\text{max}}^*(x_{DST}) = \frac{57.76}{x_{DST}^{1.39}}.
\]  

(7.9)

It is emphasized that these maximal concentrations refer to the lowest grid measurement level at \( x_3 = 27 \text{m} \) (1.8h), therefore slightly above the source height of \( x_3 - 21.3 \text{m} \) (1.5h). Given the estimated parameterizations (7.7), (7.8) and (7.9), the Gaussian plume model allows a full 3-dimensional parameterization of the concentration field. Horizontal cross sections of the thus parameterized concentration field at \( x_3 = 27 \text{m} \) (1.8h), \( x_3 = 45 \text{m} \) (3.1h) and \( x_3 = 69 \text{m} \) (4.7h) are compared to the wind tunnel measurements in Fig. 7.6.

It is of interest to link the observed dispersion pattern and in particular the estimated spread parameters to the turbulence characteristics. A prime candidate to facilitate such a linkage is the angular fluctuation of the wind vector. Fig. 6.11 on page 104 provides local profiles of \( \sigma_\theta \) and \( \sigma_e \), the standard deviations of lateral and vertical wind vector angular fluctuations respectively. Since in this study \( \sigma_\theta \) and \( \sigma_e \) are given and not varied, the functional relationships between those characteristics and the spread parameters \( \sigma_y \) and \( \sigma_z \) cannot be determined. Nevertheless a functional from suggested by Irwin (1979) can be tested which reads (as cited in Hanna et al. (1982, p. 31))

\[
\sigma_y = \sigma_\theta \frac{x_{DST}}{1 + 0.031x_{DST}^{0.46}}
\]  

(7.10)

for \( x_{DST} \leq 10^4 \text{m} \). According to Irwin (1979), it is implicit 'that the wind fluctuation [i.e. \( \sigma_\theta \)] are measured at the effective release height'. In the present scenario release height is close to roof level with a correspondingly large local \( \sigma_\theta \) which is not representative for the wind fluctuation over the whole vertical plume height (see Fig. 6.11, p. 104). Therefore, as a first approach, the appropriate \( \sigma_\theta \) for Irwin’s formula (7.10) is determined simply from a best fit of the formula to the measured \( \sigma_y \)'s. This fit is shown in Fig. 7.7 with the 'best fit \( \sigma_\theta \)' being 0.19 (in radian) (\( \approx 11^\circ \)). According to Fig. 6.11, this 'best fit \( \sigma_\theta \)' corresponds to the lateral angular fluctuations at roughly \( x_3 = 60 \text{m} \) (4.1h), it is about a factor of 2 smaller than \( \sigma_\theta \) close to roof level (approx. 0.35 radian \( \approx 20^\circ \)). Therefore, the originally proposed choice for \( \sigma_\theta \) would overestimate \( \sigma_y \) by a factor of about 2. Nevertheless, Irwin’s formula (7.10) reproduces the order of magnitude of the observed lateral plume spreads \( \sigma_y \) with a plausible value for \( \sigma_\theta \), i.e. the \( \sigma_\theta \) determined from a best fit is in the \( \sigma_y \) range observed within the vertical spread of the plume as measured by the \( \sigma_z \)'s. As in the
Figure 7.6: Concentrations $C^*$ measured in the wind tunnel compared to the Gaussian plume parameterisation given in the text ($R^2$ for lateral fits is typically 0.99, for vertical fits between 0.96 and 0.98, for details see appendix E).
case of Briggs' parameterization, the impression is that the increase of \( \sigma_y \) with increasing \( x_{DST} \) is somewhat overestimated. This may be due to the fact that with increasing height \( \sigma_\theta \) decreases. Since with increasing source distance the vertical spread of the plume increases, \( \sigma_y \) at greater \( x_{DST} \) should also be influenced by smaller \( \sigma_\theta \) than those \( \sigma_\theta \) at smaller \( x_{DST} \). If \( \sigma_\theta \) is modelled as a decreasing function of \( x_{DST} \), the overestimation of the rate of increase of \( \sigma_y \) with increasing source distance may be reduced. This dependency of relevant turbulent flow properties on the vertical spread of the plume (and therefore on \( x_{DST} \)) is also encountered in the following discussion of the effective advection velocity \( U_{1,eff} \) of the Gaussian plume.

It is instructive to estimate the effective advection velocity \( U_{1,eff} \) of the Gaussian plume which is assumed constant and homogeneous in the original parameterization scheme (see chapter 2.9, there the advection velocity is simply denoted by \( U_1 \) in Eqn. (2.33) on page 37). In the discussion above, the Gaussian plume model is used to parameterize \( C^* \) which includes according to its definition (7.1) the velocity scale \( U_{ref} \) measured at BSPR, \( x_3 = 31.8 \text{m} \) (2.2h). In terms of \( C^* \), the Gaussian parameterization is given by
\[
C^* = \frac{CU_{ref}L_{ref}^2}{Q} \\
= \frac{U_{ref}L_{ref}^2}{2\pi\sigma_y\sigma_zU_{1,eff}} \exp\left(-\frac{(x_2-x_{2,CNTR})^2}{2\sigma_y^2}\right) \cdot \left[\exp\left(-\frac{(x_3-h_{SRC})^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(x_3+h_{SRC})^2}{2\sigma_z^2}\right)\right]
\]
(7.11)

with \(x_{2,CNTR}\) being the \(x_2\) coordinate of the plume centerline which may be, as in the present case of a slightly deflected plume, a function of \(x_{DIST}\). Remembering the source height \(h_{SRC} = 21.3\text{m (1.5h)}\), \(C_{max}^*\), introduced above as the maximal concentration \(C^*\) at \(x_3 = 27\text{m (1.8h)}\) as estimated by the lateral Gaussian fits, is therefore given by the relation

\[
C_{max}^* = \frac{U_{ref}L_{ref}^2}{2\pi\sigma_y\sigma_zU_{1,eff}} \left[\exp\left(-\frac{(27m-21.3m)^2}{2\sigma_y^2}\right) + \exp\left(-\frac{(27m+21.3m)^2}{2\sigma_y^2}\right)\right]
\]
(7.12)

which can be used to estimate \(U_{1,eff}/U_{ref}\):

\[
\frac{U_{1,eff}}{U_{ref}} = \frac{L_{ref}^2}{2\pi\sigma_y\sigma_zC_{max}^*} \left[\exp\left(-\frac{(27m-21.3m)^2}{2\sigma_y^2}\right) + \exp\left(-\frac{(27m+21.3m)^2}{2\sigma_y^2}\right)\right]
\]
(7.13)

Using the above given parameterizations (7.7), (7.8) and (7.9) for \(\sigma_y(x_{DIST})\), \(\sigma_z(x_{DIST})\) and \(C_{max}^*(x_{DIST})\), the ratio \(U_{1,eff}/U_{ref}\) as a function of \(x_{DIST}\) can be calculated. Fig. 7.8 shows the result of this calculation. Two observations can be made:

- \(U_{1,eff}\) is roughly of the same magnitude as \(U_{ref}\) (±20%), which is plausible since \(U_{ref}\) is a RSL velocity scale and large parts of the dispersion process considered in this study take place in the RSL.
- \(U_{1,eff}/U_{ref}\) and therefore \(U_{1,eff}\) are not constant but increase with increasing source distance \(x_{DIST}\).

This increase of \(U_{1,eff}\) is heuristically plausible given the observation that the plume’s spread constantly increases vertically with increasing source distance, therefore the wind field covered by the plume includes increasing wind speeds in greater heights. \(U_{1,eff}\) can be thought of as an aggregated measure of an effective advection velocity in the inhomogeneous wind field above the urban
Figure 7.8: Effective Gaussian plume advection velocity $U_{1, eff}$ in relation to $U_{ref}$ (straight line, Eqn. (7.13)). Dashed line indicates vertical average over the logarithmic wind profile from $x_3 = d_0 + z_0$ to $x_3 = 21.3m + \sigma_z(x_{DST})$ (see text).

model. One may try to link $U_{1, eff}$ quantitatively to the mean wind profile by calculating the average wind speed up to a given height. The result of such a calculation is included in Fig. 7.8: Based on the logarithmic wind profile (fit to the horizontally averaged mean wind profile as discussed in chapter 6.2) the average wind speed is calculated from $x_3 = d_0 + z_0 = 10.2m + 2.8m = 13.0m$ (0.9h) up to, somewhat arbitrarily, $x_3 = source$ height $+ \sigma_z(x_{DST})= 21.3m + \sigma_z(x_{DST})$ including increasingly larger wind speeds in greater heights due to increasing $\sigma_z(x_{DST})$ with increasing $x_{DST}$. Thereby contributions are neglected stemming (i) from deviations from the logarithmic wind profile close to roof level and (ii) from that part of the dispersion process taking place below roof level and in particular below $x_3 = 13m$ (0.9h). Including those contributions leads only to minor changes in the result (not shown). The thus calculated average wind speeds exceed the observed $U_{1, eff}$ with an apparent convergence at larger source distances. It is seen that the stated averaging procedure underestimates the increase rate of $U_{1, eff}$ with increasing source distance. This shortcoming might be dealt with by taking the upper height limit of wind speed averaging as $x_3 = 21.3m + \eta(x_{DST}) \cdot \sigma_z(x_{DST})$, thereby introducing the monotonously increasing correction function $\eta(x_{DST})$ smaller
than one to model the difference between the rates of increase of \( \sigma_z(x_{DST}) \) and \( U_{1,eff} \) respectively.

Despite the possibility to include an increasing \( U_{1,eff} \) in a physically somewhat plausible picture, the overall conclusion is that this finding constitutes a pecu-
liarity of the ‘uniform wind field Gaussian model’ used in the strongly sheared wind field close to a rough surface. The concentration field may still be parameter-
ized by a Gaussian model (thereby accepting the deviations in the vertical profiles close to roof level), but the parameter \( U_{1,eff} \) gets a more generalized interpretation than originally argued (and made plausible) in the derivation of the model. One remark regarding the practice to take the mean wind speed at the source location as \( U_{1,eff} \) (as mentioned e.g. in Beychok (1994, p. 99) and Hanna et al. (1982, p. 32)): For the dispersion scenario studied in this work, this approach would give \( U_{1,eff}/U_{ref} = U_{R1}/U_{ref} = 0.60m/s^{-1}/0.82m/s^{-1} = 0.73 \) (see section 7.1). From the results presented in Fig. 7.8 it follows, that \( C^\ast \) would be increasingly overestimated with increasing source distance, if the above introduced parameterizations \( \sigma_y(x_{DST}) \) and \( \sigma_z(x_{DST}) \) were inserted naively in the Gaussian parameterization scheme in combination with the mentioned constant \( U_{1,eff} \).

A final remark goes to the slight plume deflection which is obvious from the lateral concentration profiles (Fig. 7.3a, see also appendix E). This plume deflection has been incorporated in the above discussed Gaussian parameter-
ization (7.11), it is related to the urban model in Fig. 4.10 on page 63 where the locations of peak \( C^\ast \) as estimated from the Gaussian fits to the lateral \( C^\ast \) profiles are shown (small crosses). It is observed that the direction of deflection corresponds to the orientation of major street canyons. Therefore the orienta-
tion of street canyons appears to have an effect on the concentration pattern closely above roof level. Source artefacts possibly due to jets released from the source under a certain angle to the mean flow have been excluded (see section 7.1). The deflected plume and the approach flow direction (i.e. the positive \( x_1 \) direction along the wind tunnel axis) enclose an angle of roughly 4° whereas the relevant major street canyons and the approach flow direction intersect at an angle of, roughly estimated, 30°.

7.3 Travel times from the source to the field sampling stations

The tracer gas needs some time, the so-called travel time \( T \), to get from the release point R1 to any given sampling location. During the field tracer experi-
ment, concentration sampling started either 1 hour (June 26th and July 8th 2002) or 50 minutes (July 7th 2002) after the tracer release had started. In the
Figure 7.9: Examples of time series measured at the sampling stations S3a (top) and S1 (bottom) during the travel times study. The location S3a is located within the street canyon Basel-Sperrstrasse, 3m above street level, while S1 is 1.5m above local roof level at $x_3 = 18.6$m (1.3h). First (i.e. left) dashed line indicates the start of the gas release at R1, the second (i.e. right) dashed line indicates the onset of the concentration signal.

wind tunnel dispersion study the time between the opening of the source and the first detection of a concentration signal at the respective sampling stations was recorded. Typical concentration time series, as measured e.g. at sampling locations S1 and S3a, are shown in Fig. 7.9. To compare wind tunnel and field time scales, the non-dimensional travel time $T^*$ is used, defined by

$$T^* = \frac{U_{ref}}{L_{ref}} \cdot T$$

(7.14)

with $U_{ref}$ and $L_{ref}$ chosen as in the case of $C^*$, i.e. $U_{ref}$ equals the mean wind speed measured at BSPR, $x_3 = 31.8$m (2.2h), and $L_{ref}$ is taken to be the mean buildings height $h$. Five travel time measurements were made per sampling station. At location S8 the measured concentrations were at the lower end of the FFID detection range, therefore here the identification of the 'concentration signal onset' was somewhat influenced by subjective judgement. The measured non-dimensional travel times $T^*$ are plotted against the distance $R$ between the source and the sampling stations, which is made non-dimensional by dividing through the mean building height $h$ (Fig 7.10). A linear approximation (dashed line in Fig. 7.10) yields the 'rule of thumb'
It is interesting to compare this 'rule of thumb' to the finding in a wind tunnel dispersion study by Robins and Cheng (2003). Their study within modelled urban roughness focused on ground level tracer releases and ground level sampling stations within street canyons, distances between release point and receptor locations were roughly between 40m and 200m (full scale). Their travel times (denoted $T_{50}$ in their study) are found to be estimated by

$$T_{50} \approx 3.5 \frac{R}{U_h}$$  \hspace{1cm} (7.16) 

with $U_h$ being 'the wind speed just above roof level' (quote from Robins and Cheng (2003)). Obviously, due to the steep mean wind gradient just above roof level, the exact choice of a reference wind speed above roof level may alter the numerical factor in the travel time estimation, $U_{ref}$ measured at 2.2$h$ is clearly expected to be larger than 'the wind speed just above roof level'. This may explain the difference in the numerical factors in (7.15) and (7.16) of 4.5 and 3.5 respectively. Nevertheless the approximate numerical correspondence of the 'rule of thumb' derived in the present study and the estimation of Robins...
Based on the 'rule of thumb' (7.15) and taking the reference wind speed during the first sampling hour on each release day, the field travel times per sampling station and day are estimated in Tab. 7.1. The (in)accuracy of these estimations is given by the scatter of the data points around the 'rule of thumb' in Fig. 7.10. Given the waiting period between start of the tracer release and start of the tracer sampling in the field experiment, it is noted that the start of sampling roughly coincides with or is a bit later than the expected onset of the first concentration signal due to the tracer release.

### Table 7.1: Estimated field travel times per sampling station and tracer release day based on the 'rule of thumb' derived from the wind tunnel model. Accuracy is somewhat misleading, uncertainties apply as shown in Fig. 7.10. Distances R between release point R1 and sampling stations are calculated from wind tunnel model measures and deviate slightly from the measures given in the tracer report by Gryning et al. (2004) (see Tab. 4.3 on page 68).

<table>
<thead>
<tr>
<th>Station</th>
<th>R [m]</th>
<th>June 26th 2002</th>
<th>July 7th 2002</th>
<th>July 8th 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>472</td>
<td>25min</td>
<td>22min</td>
<td>18min</td>
</tr>
<tr>
<td>S3a</td>
<td>703</td>
<td>37min</td>
<td>33min</td>
<td>27min</td>
</tr>
<tr>
<td>S3b</td>
<td>703</td>
<td>37min</td>
<td>33min</td>
<td>27min</td>
</tr>
<tr>
<td>S3c</td>
<td>703</td>
<td>37min</td>
<td>33min</td>
<td>27min</td>
</tr>
<tr>
<td>S4</td>
<td>719</td>
<td>37min</td>
<td>34min</td>
<td>27min</td>
</tr>
<tr>
<td>S8</td>
<td>1067</td>
<td>56min</td>
<td>50min</td>
<td>41min</td>
</tr>
<tr>
<td>S9</td>
<td>1052</td>
<td>55min</td>
<td>49min</td>
<td>40min</td>
</tr>
</tbody>
</table>

and Cheng (2003) is noted.

7.4 Comparison to dispersion field data

During the intense observation period of the BUBBLE project field tracer experiments were conducted in Kleinbasel on four days (June 26th, July 4th, July 7th and July 8th 2002). On all of these days except July 4th the release location and the sampling locations were the same as those modelled in the wind tunnel with roughly the same approach flow direction as in the wind tunnel (an overview is given in Fig. 4.10 on page 63, additional field sampling locations were outside of the wind tunnel model area). A detailed description of the tracer field experiment is given by Gryning et. al (2004), all field data presented in the following is taken from their report.

During the field experiments the tracer gas (SF₆) was continuously released closely above roof level starting roughly one hour before the tracer sampling began. Total sampling time was three hours per day, mean concentrations and
June 26th 2002: Release time from 12:00 to 16:00

<table>
<thead>
<tr>
<th></th>
<th>13:00-</th>
<th>13:30-</th>
<th>14:00-</th>
<th>14:30-</th>
<th>15:00-</th>
<th>15:30-</th>
<th>16:00-</th>
<th>14:00-</th>
<th>16:00-</th>
</tr>
</thead>
<tbody>
<tr>
<td>U [m/s]</td>
<td>1.53</td>
<td>1.35</td>
<td>1.49</td>
<td>1.74</td>
<td>1.42</td>
<td>1.96</td>
<td>1.44</td>
<td>1.58</td>
<td></td>
</tr>
<tr>
<td>DD [°]</td>
<td>333</td>
<td>332</td>
<td>328</td>
<td>354</td>
<td>342</td>
<td>35</td>
<td>332</td>
<td>339</td>
<td></td>
</tr>
<tr>
<td>L [m]</td>
<td>-72.6</td>
<td>-13.2</td>
<td>-31.5</td>
<td>-9.3</td>
<td>-6.8</td>
<td>-92.7</td>
<td>-19.3</td>
<td>-20.9</td>
<td></td>
</tr>
</tbody>
</table>

July 7th 2002: Release time from 13:10 to 17:00

<table>
<thead>
<tr>
<th></th>
<th>14:00-</th>
<th>14:30-</th>
<th>15:00-</th>
<th>15:30-</th>
<th>16:00-</th>
<th>16:30-</th>
<th>17:00-</th>
<th>15:00-</th>
<th>17:00-</th>
</tr>
</thead>
<tbody>
<tr>
<td>U [m/s]</td>
<td>1.75</td>
<td>1.45</td>
<td>1.64</td>
<td>2.00</td>
<td>2.56</td>
<td>2.50</td>
<td>1.60</td>
<td>1.98</td>
<td></td>
</tr>
<tr>
<td>DD [°]</td>
<td>289</td>
<td>349</td>
<td>287</td>
<td>315</td>
<td>343</td>
<td>305</td>
<td>319</td>
<td>322</td>
<td></td>
</tr>
<tr>
<td>L [m]</td>
<td>-13.1</td>
<td>-11.4</td>
<td>-11.6</td>
<td>-25.3</td>
<td>-42.5</td>
<td>-32.1</td>
<td>-12.4</td>
<td>-12.3</td>
<td></td>
</tr>
</tbody>
</table>

July 8th 2002: Release time from 14:00 to 18:00

<table>
<thead>
<tr>
<th></th>
<th>15:00-</th>
<th>15:30-</th>
<th>16:00-</th>
<th>16:30-</th>
<th>17:00-</th>
<th>17:30-</th>
<th>18:00-</th>
<th>16:00-</th>
<th>18:00-</th>
</tr>
</thead>
<tbody>
<tr>
<td>U [m/s]</td>
<td>1.69</td>
<td>2.24</td>
<td>3.24</td>
<td>2.77</td>
<td>2.15</td>
<td>2.60</td>
<td>1.97</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td>DD [°]</td>
<td>33</td>
<td>321</td>
<td>303</td>
<td>306</td>
<td>295</td>
<td>284</td>
<td>357</td>
<td>323</td>
<td></td>
</tr>
<tr>
<td>L [m]</td>
<td>-2.6</td>
<td>-8.9</td>
<td>-77.7</td>
<td>-169.4</td>
<td>-101.6</td>
<td>-36.3</td>
<td>-5.6</td>
<td>-35.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: Overview over the meteorological conditions on the three field tracer experiment days relevant for comparison to the wind tunnel measurements. Half hour mean values during the sampling periods are given together with the averages over the first sampling hour and the complete 3-hours sampling period per day. Wind speeds and wind directions were measured at $x_3 = 31.8m \ (2.2h)$ at the field measurement tower BSPR, the Monin-Obukhov length L is calculated from estimated ISL values (data from Gryning et al. (2004)).

Meteorological conditions during the experiments are available as half hour averages. Wind direction and reference wind speed $U_{ref}$ to calculate $C^*$ were measured at the measurement tower Basel-Sperrstrasse at the top level, $x_3 = 31.7m \ (2.2h)$. A summary of the meteorological conditions is given in Tab. 7.2.

Given the narrow shape of the wind tunnel plume (see Fig. 7.6) it is evident that variations of the wind direction may have a substantial impact on the $C^*$ distribution. One may argue that fluctuations of the half-hourly averaged wind directions in the field are more due to turbulent fluctuations and less to diurnal instationarity of boundary conditions. To check this argument for plausibility, a 3-minutes wind tunnel velocity time series ($u_1$ and $u_2$ component) measured
at the location BSPR, $x_3 = 31.8m$ (2.2h), has been subdivided into smaller time periods equivalent to 0.5h field time. (Equivalent time periods are determined based on the $t^*$ concept introduced in section 7.3. Equating the $t^*$'s of the wind tunnel and the field setting gives a relation between the respective dimensional time periods.) The equivalent wind tunnel time is calculated to be 3.6s, based on the mean wind speed during the three tracer release days $U_{field}$ (BSPR, $x_3 = 31.8m$ (2.2h)) = $(1.58m/s + 1.98m/s + 2.45m/s)/3 = 2.00m/s$ (see Tab. 7.2) and the mean wind tunnel wind speed of $U_{WT}$ (BSPR, $x_3 = 31.8m$ (2.2h)) = 3.32m/s during the 3-minutes measurement. Therefore the wind tunnel time series allows 49 ($= 180/3.6$) estimations of the half-hourly averaged wind direction in the field under stationary boundary conditions. Fig. 7.11a shows the wind direction fluctuations in the field during the tracer release experiments, while Fig. 7.11b gives the 49 wind tunnel estimates under stationary boundary conditions. Two observations can be made:

- The wind direction fluctuations under stationary wind tunnel boundary conditions are significantly smaller than those recorded during the tracer release experiments.

- The wind directions under stationary wind tunnel boundary conditions correspond well to the approach flow direction DD = 330°. Therefore no distorting influence of neighbouring buildings on the wind direction is observed at the measurement level $x_3 = 31.8m$ (2.2h). Since the buildings in the immediate neighbourhood of the location BSPR have heights of a bit less than 1h, no influence has been expected anyway.

Given this analysis, it appears plausible to attribute the wind direction variations in the field during the tracer release experiments mainly to instationary boundary conditions and not to turbulent fluctuations.

In the wind tunnel five concentration time series à 3 minutes were measured per field sampling location (stations S1, S3a, S3b, S3c, S4, S8, S9). The source was opened shortly after the start of each concentration measurement. Based on the reference wind speeds, wind tunnel time periods are determined equivalent to the timing of the release and sampling in the field (along the lines of the $t^*$ concept introduced in Eqn. (7.14)). This approach is exemplified by taking, e.g., one of the wind tunnel concentration time series at station S9 (run #5) and comparing it to the field data from July 7th 2002: On this day the reference wind speed in the field during the 3-hours sampling period was $U_{ref,field} = 1.98m/s$, while the reference wind speed in the wind tunnel during the 3-minutes time series was $U_{ref,WT} = 0.80m/s$. Field sampling started 50 minutes after the start of the tracer release with six 30-minutes sampling periods. Based on the reference wind speeds and the geometric model scale factor of 1/300, the equivalent wind tunnel periods are 24.8s (corresponding
Figure 7.11: (a) Wind direction fluctuations during the field experiment as given in Tab. 7.2. Dashed lines indicate the wind direction modeled in the wind tunnel, DD = 330°, straight lines give 3-hourly averaged wind directions during the sampling periods. (b) Wind direction fluctuations in the wind tunnel at location BSPR, $x_3 = 31.8$m (2.2h), as determined from a 3-minutes velocity time series ($u_1$ and $u_2$ measured simultaneously). The time series is subdivided into 49 periods each equivalent to 0.5h field time as described in the text, each data point gives the respectively averaged wind direction. Dashed line corresponds to approach flow direction DD = 330°.
Figure 7.12: Concentration time series measured in the wind tunnel at sampling location S9 (run #5). Dashed vertical line at $t_{WT} = 11.0s$ indicates opening of the source, step function gives mean concentrations averaged over the time periods equivalent to the six sampling periods of half an hour in the field on July $7^{th}$ 2002, smooth line represents running concentration average starting with the onset of the concentration signal at $t_{WT} = 26.6s$.

to 50 minutes field time) and 14.9s (corresponding to 30 minutes field time). Therefore six wind tunnel mean concentrations are determined from the wind tunnel time series starting 24.8s after source opening with a subsequent averaging time of 14.9s respectively. This procedure is shown in Fig. 7.12. To convert the dimensional field concentrations to non-dimensional $C^*$'s, the half-hourly averaged reference wind speeds in the field during the respective sampling periods are used (see Tab. 7.2). In the wind tunnel velocity time series were measured simultaneously with the concentration time series. Accordingly, the reference wind speeds in the wind tunnel are determined equivalently to the field scenario by averaging over the respective time periods of 14.9s. This procedure is applied to all five concentration time series measured in the wind tunnel at all locations. To compare the field data from the other two field experiment days (June $26^{th}$ and July $8^{th}$ 2002), the same procedure is applied to the wind tunnel time series with somewhat different time scales since on these days the respective reference wind speeds were different (1.58m/s and 2.45m/s) and sampling started 60 minutes after start of the tracer release.

The thus calculated $C^*$'s from field and wind tunnel measurements are shown
Figure 7.13: Field concentrations (filled symbols) compared to wind tunnel concentrations (open symbols) at location S1 as described in the text. Sampling period numbering is chronologically, i.e. '1' corresponds to the first half hour sampling period on each field experiment day etc., included is the data from June 26th (triangles), July 7th (squares) and July 8th (diamonds) 2002. Dashed horizontal line gives long term mean concentration at S1 as estimated from a 15 minutes wind tunnel time series.

per sampling location in Figs. 7.13 to 7.19. Each diagram shows the estimates stemming from the five wind tunnel time series per location employing three sets of time scales to each series corresponding to the varying meteorological conditions on the three field experiment days. Thereby fifteen sets of estimations are obtained for the six successive periods of half an hour field time. From Figs. 7.13 to 7.19 two observations can be made:

- The wind tunnel data clearly overestimates the field data. Somewhat overlapping field and wind tunnel data points are only observed for location S1 and S8, but still with on average clearly larger wind tunnel C*'s. The gap between field and wind tunnel data is largest for locations S4 and S9.

- The scatter of the half-hourly averaged C*'s (field time scale) around the long-term mean, as modelled in the wind tunnel, is significant. The long-term mean is estimated from 15-minutes wind tunnel time series per location with continuous release, i.e. the source was open for the complete time period and not opened just after the start of the time
Figure 7.14: Field concentrations compared to wind tunnel concentrations at location S3a. Symbols as in Fig. 7.13.

Figure 7.15: Field concentrations compared to wind tunnel concentrations at location S3b. Symbols as in Fig. 7.13.
**Figure 7.16:** Field concentrations compared to wind tunnel concentrations at location S3c. Symbols as in Fig. 7.13.

**Figure 7.17:** Field concentrations compared to wind tunnel concentrations at location S4. Symbols as in Fig. 7.13.
Figure 7.18: Field concentrations compared to wind tunnel concentrations at location S8. Symbols as in Fig. 7.13.

Figure 7.19: Field concentrations compared to wind tunnel concentrations at location S9. Symbols as in Fig. 7.13.
period as in the analysis above. The origin of this scatter is related to the temporal characteristics of concentration fluctuations as exemplified in Fig. 7.12.

Two aspects, present in the field scenario and not modelled in the wind tunnel, might be discussed as contributors to the larger wind tunnel concentrations: Instationarity of the mean wind direction and influence of thermal effects. The effect of 'street canyon filling', taking place on time scales affecting the measurements during the first sampling periods and removing concentration from above roof level downwards into the street canyons until equilibrium is reached, is not considered to be relevant for the observed deviations due to the modelling approach of choosing only time equivalent concentration mean values from the wind tunnel data. This filling effect is observed only at the most distant locations S8 and S9 (see e.g. the somewhat reduced values of \( C^* \) at S8 during sampling period 1 in Fig. 7.18 and the increasing moving average at S9 in Fig. 7.12). Nevertheless, as stated, due to the modelling approach this should not contribute to a systematic overestimation of the field data by the wind tunnel data. From Figs. 7.13 to 7.19 it is also seen that the effect of 'street canyon filling' does not appear to have a strong impact on the wind tunnel \( C^* \)'s since the short term averages fluctuate well around the long term mean and do not stay significantly below it (except maybe during the first one or two sampling periods at location S8).

With regard to instationary mean wind directions during the field experiment, Fig. 7.11 implies that potential effects should be least on June 26\(^{th}\) 2002. Nevertheless, no improved correspondence of the wind tunnel data to the field data is observed if the analysis is restricted to this day. The increased direction fluctuations on July 7\(^{th}\) may lead to an increased lateral spread of the plume with subsequently lower mean concentrations in the narrow peak region observed under stationary conditions. The trend to more westerly winds observed on July 8\(^{th}\) may have the largest impact at those locations with peak mean concentrations or large lateral mean concentration gradients. Inspection of Fig. 4.10 (p.63, with the line of crosses indicating the plume centerline) reveals that locations S4 and S9 are close to the plume centerline with correspondingly near-peak mean concentration values, while locations S1, S3a, S3b and S3c are located at the flanks of the Gaussian-shaped lateral mean concentration profiles with correspondingly large lateral gradients. Given these sampling locations, the stated wind direction trend to more westerly winds on July 8\(^{th}\) 2002 may therefore lead to lower field concentrations in comparison to the wind tunnel findings. The improved correspondence of field to wind tunnel data at location S8 coincides with comparatively small lateral gradients further away from the plume centerline.

The persuasiveness of the above, rather qualitative discussion of "effects in
principle" is somewhat questionable due to the observation that the wind tunnel data clearly overestimates the field data even during the first three sampling periods on June 26th 2002 where the wind direction in the field was essentially the same as the wind direction modelled in the wind tunnel (Fig. 7.11). Additionally, the above given arguments concerning the effect of the wind direction trend on July 8th would lead to the expectation, that the field $C^*$'s on this day are somewhat smaller than the field $C^*$'s on June 26th. A convincing confirmation of this expectation cannot be found in the field data. Therefore wind direction fluctuations are not seen as the main cause for the systematically larger wind tunnel concentrations.

Turning to the effects of thermal turbulence on dispersion it is noted that during the field tracer experiments (very) unstable stratification appears to have prevailed. If the height level $x_3 = 31.7$ m (2.2h) is considered, the stability parameter $\zeta = (x_3 - d_0)/L$ is calculated to -1.03, -1.75 and -0.61 on the respective days (see Tab. 7.2) (see also the stability characterizations as 'strong convective' in Rotach et al. (2004), Tabs. 2 and 3 in their publication). Taking $\zeta$ as an estimation of the Richardson number, it is interesting to quote Pasquill (1974, p. 302) who comments on the result of the dispersion field study in Leicester (1937-9):

'...; furthermore, the effect of stability on vertical mixing near the ground is known to be more clearly related to the Richardson number, rather than lapse rate alone and this means that in unstable conditions any tendency for a reduction of wind speed to produce higher concentrations would be opposed by an increase in effective instability.'

The observation in the Leicester field data was 'that in the most unstable conditions the variation [of concentration] with wind speed was of little practical consequence.' (Pasquill (1974, p. 302)). Therefore it appears not unreasonable to expect larger $C^*$'s in the wind tunnel (neutral conditions) than during the BUBBLE field experiment (strong instability). To arrive at a quantitative estimate of this effect, resort is taken to the urban Gaussian plume parameterizations from Briggs (1973) which are based on the dispersion field experiment in St. Louis (according to Hanna et al. (1982, p. 30)). Briggs (1973) proposed different parameterizations for neutral and for moderately/extremely unstable conditions. Given the setup of the present study, focus is on the plume centreline, on source distances $x_{DST}$ between 400m and 900m and on the height range between the ground and, say, $x_3 = 30$ m (2.1h). Evaluating Briggs' formulas as given in Hanna et al. (1982) reveals that from Pasquill stability class D (neutral) to class A-B (moderately/extremely unstable) the predicted concentrations are decreased by a factor 4 to 5 at the designated locations.
Inspection of Figs. 7.13 to 7.19 reveals that a factor of this order of magnitude would give a clearly better correspondence between field and wind tunnel data at locations S1 and S8. At locations S3a, S3b and S3c wind tunnel and field concentrations differ by a factor of about 10, while at the locations S4 and S9 close to the wind tunnel plume centreline the concentrations differ by a factor of 10 to 100. The effects of instability with regard to decreasing the plume centreline concentrations appear to be significant. Of course, far away from the plume centreline the concentrations under unstable conditions might be expected to be increased in comparison to those under neutral conditions. In this regard it is interesting to observe that at the location most far away from the wind tunnel plume centreline, location S8, the effect of concentration reduction due to instability seems to be least.

7.5 Conclusions

Over urban roughness the horizontal mean concentration pattern above \( x_3 = 27 \text{m} \) (1.8h) of a passive, conservative and non-buoyant tracer, released from a point source closely above roof level at \( x_3 = 21.3 \text{m} \) (1.5h) under neutral conditions, is very well described by a Gaussian plume parameterization at source distances between \( x_{DST} = 384 \text{m} \) (26.3h) and 864m (59.2h). The vertical mean concentration pattern is less well described by the Gaussian parameterization with the deviations being in the height range close to roof level. Here the actual decrease of measured mean concentrations appears to be less rapid with increasing height than assumed by the Gaussian model. Additionally, the following observations are made:

- The lateral plume spreads \( \sigma_y \) at \( x_{DST} = 384 \text{m} \) and 444m are in accordance with Briggs' urban plume parameterization (Briggs (1973)), but in the studied scenario his formula is found to overestimate the rate of lateral plume spread growth. Therefore at greater source distances the observed lateral plume spreads are consistently smaller than predicted by Briggs' formula.

- The vertical plume spreads \( \sigma_z \) are found to be consistently smaller than predicted by Briggs' vertical urban plume spread formula at all source distances. Again, Briggs' formula appears to overestimate the rate of vertical spread growth. The overestimation of lateral and vertical plume spread leads to an underestimation of mean concentrations in the region around the plume centreline. Interestingly Olesen (1995) finds the underestimation of concentrations to be a common shortcoming of the dispersion models he evaluated (the evaluation presented by him was...
conducted in the context of a workshop on operational short-range atmospheric dispersion models for environmental impact assessment in Europe (November 1994)).

- The observed decrease of the mean concentration maxima with source distance at \( x_3 = 27\) m (1.8h) leads to the conclusion of an increase of the effective advection wind speed with increasing source distance \( x_{DST} \) in the Gaussian parameterization scheme. In the presence of a strong wind shear field above urban roof level the mean wind speed as an input parameter to this parameterization scheme should not be taken constant, but instead should be modelled as a function of source distance \( x_{DST} \). The magnitude of the observed effective advection wind speeds is comparable to the typical wind speed above roof level which was measured at \( x_3 = 31.8\) m (2.2h). Taking the mean wind speed at the tracer release point as a constant input parameter for the Gaussian parameterization would lead to an increasing mean concentration overestimation with increasing source distance.

Irwin (1979) relates the lateral plume spread \( \sigma_y \) to the standard deviation \( \sigma_\theta \) of lateral angular wind direction fluctuations. To give a somewhat plausible representation of the observed plume spread by Irwin's relation \( \sigma_\theta \) should not be taken as measured (or estimated) at the source location, but should be chosen to be representative for the height range covered by the plume. In the present study, the best fit of Irwin's formula to the measured lateral plume spreads was obtained for \( \sigma_\theta \) measured at about \( x_3 = 60\) m (4.1h). Again it is observed that \( \sigma_\theta \) should better be modelled as a function of source distance since increasingly greater height levels with reduced \( \sigma_\theta \)'s get involved in plume dispersion. Irwin's formula with constant \( \sigma_\theta \) leads to an overestimation of the rate of lateral plume spread growth.

Summarizing, in the investigated dispersion scenario within the urban RSL the Gaussian plume parameterization relying on a constant advection wind speed \( U_1 \) or a constant lateral wind fluctuation measure \( \sigma_\theta \) clearly suffers from certain deficiencies as given above. Taking those parameters as functions of source distance \( x_{DST} \) (and thereby treating them as tuning parameters) obviously improves the parameterization, while e.g. the Gaussian vertical mean concentration distribution close to roof level still deviates from the profiles measured in this study. This latter observation is in agreement with the reviewing remarks made by Gryning et al. (1987).

The field concentrations measured in Kleinbasel under strongly unstable conditions are clearly smaller than those measured in the wind tunnel under neutral conditions. This difference should plausibly be attributed to the different stability regime. Briggs' urban formulas estimate this effect to account for a factor of up to 4 or 5 in the mean concentration values, i.e. according to his formulas
concentrations near the plume centreline under strongly unstable conditions are expected to be only 20% to 25% of those concentrations measured under neutral conditions. A factor of this size would close part of the gap between the present field and wind tunnel data at two measurement locations, concentrations at other locations differ by a factor of up to 10 to 100. In addition to the different stability regime the instationary field wind directions might have also enhanced the lateral plume spread in the field. Corresponding effects are supposed to be strongest for those stations near the wind tunnel plume centreline (stations S4 and S9). There the wind tunnel concentrations are particularly large in comparison to the field measurements.
Seite Leer / Blank leaf
Chapter 8

Summary

This wind tunnel study has investigated thoroughly the urban turbulence structure above roof level within the urban surface layer. The turbulence characteristics have been analysed both in terms of horizontal averages and in terms of local profiles. The relevancy of the wind tunnel model results for the full scale urban scenario is established by observing a very good reproduction of local field turbulence characteristics. This observation refers to the roughness sublayer as well as to the inertial sublayer.

As expected and known from previous studies, the roughness sublayer, estimated to reach up to 3.3h, is characterized by a large horizontal variability of turbulence characteristics as e.g. the mean wind speed $U_1$, turbulent velocities $\sigma_i$, or the Reynolds fluxes $u'_i u'_3$. This horizontal variability is distinctively larger above realistic urban roughness (as modelled in this study) than above idealized roughness used in other wind tunnel studies (e.g. Raupach (1981), Cheng and Castro (2002a)). As one consequence, the vertical divergence of dispersive stresses close to roof level are found to be larger than the vertical divergence of horizontally averaged Reynolds fluxes. If observations in plant canopies made by Böhm et al. (2000) are also taken into consideration, it does not appear plausible to neglect contributions of dispersive stresses to the overall momentum balance in the height range around roof level. Regrettably, systematic horizontal measurements were made only down to 1.8h. Lower heights were not included due to experimental difficulties (as they are painfully bemoaned by other wind tunnel studies as well).

Horizontally averaged Reynolds fluxes stay constant throughout the inertial sublayer, estimated to reach up to 5.5h, and within the roughness sublayer down to at least 1.8h. This is an important contribution to any discussion about a 'typical' Reynolds flux profile within the roughness sublayer. Those discussions seem to have started with the field observation of (locally) decreasing Reynolds fluxes with decreasing height (Rotach (1993a)) and were
continued recently by Kastner-Klein and Rotach (2004) with a proposed parameterization scheme based on a peak in the Reynolds flux profile. In the urban setting investigated in this study, a peak in the horizontally averaged Reynolds fluxes has not been observed down to 1.8h. In contrast to the horizontally averaged profile, local profiles show significant variations ranging from a large peak covering the whole roughness sublayer to decreasing Reynolds fluxes with decreasing height. Therefore it appears to be highly risky to draw conclusions about horizontal averages from local measurements, in particular if the observed variations of up to 50% of local Reynolds fluxes around the horizontal average within the roughness sublayer are taken into account. Here the pursued wind tunnel modelling approach showed its strength to provide new insights not available from the field data alone.

The domination of sweeps is not found to be a characterizing property of the whole roughness sublayer, in contrast to statements made by Raupach (1981). Only below 2.3h sweeps start to dominate the vertical momentum transport, above that height ejections are found to make larger contributions. About at the same height range the vertical turbulent TKE flux changes its sign from an upward flux at greater heights to a downward flux close to roof level. Therefore the above roof level part of the roughness sublayer is itself subdivided into the height range close to roof level, where sweeps dominate and the vertical turbulent TKE flux transports TKE downwards into the street canyons, and the height range above, where ejections become dominant and the vertical turbulent TKE flux points upwards.

Throughout the inertial sublayer and even within the roughness sublayer at least down to 1.8h the horizontally averaged mean wind profile is logarithmic. The friction velocity estimated from the profile fit is clearly some 20% larger than the friction velocity inferred from the constant horizontally averaged Reynolds fluxes in the inertial sublayer. This has also been observed by other wind tunnel studies (e.g. Kastner-Klein and Rotach (2004)). An analysis of the TKE budget within the inertial sublayer reveals that vertical turbulent TKE fluxes make a non-negligible contribution, therefore a local equilibrium of TKE production and dissipation is not obtained. The most plausible explanation appears to be that the turbulent flow within the inertial sublayer is not completely adapted to the urban roughness. Based on the minimum of vertical turbulent TKE flux contributions to the TKE budget the height of flow adaptation is estimated to be between 2.7h and 3.4h. Given that the measurements were made about 1.6km (equivalent to 110h) downstream of the model inflow edge and that the approach flow was modelled according to realistic atmospheric turbulence conditions taken from field measurements, it is not assumed that this imperfect flow adaptation is due to model artefacts but might be a common feature of urban surface layer flows with insufficient, but nevertheless frequently prevailing urban fetches. Interestingly, the observation
of a logarithmic wind profile and vertically constant Reynolds stresses is not sufficient to identify a completely adapted inertial sublayer, but the possible difference between the respectively estimated friction velocities might contain information about the state of local energetic equilibrium. The study by Cheng and Castro (2002a) provides further interesting aspects to the discussion about which estimate should be taken to represent the 'true' friction velocity. The present study did not measure the surface drag, therefore this question has to remain open. Needless to say that the practice to estimate Reynolds fluxes from logarithmic wind profile fits or vice versa is particularly error-prone in the urban context.

The dispersion study analysing the mean concentration field of a passive tracer ($C_2H_6$) released from a source closely above roof level (1.5h) and sampled at downstream source distances from 384m to 864m revealed that the horizontal distribution is very well represented by a Gaussian parameterization, while the vertical distributions closely above roof level show a less rapid decrease of mean concentrations with increasing height than predicted by a Gaussian distribution. In the vertical dimension the deviations of an urban inhomogeneous wind field from the homogeneous wind field assumed by the Gaussian model are particularly obvious. This shortcoming of the Gaussian model in the presence of strong wind shear has also been remarked in other studies (see e.g. Gryning et al. (1987)). Additionally it must be said that a somewhat satisfactory representation of the concentration data by a Gaussian parameterization is only achieved by allowing the advection wind speed, assumed to be constant in the original Gaussian model, to become a function of source distance. I.e., the advection wind speed itself must be parameterized as an increasing function with increasing downstream source distance. Even if a physically somewhat plausible explanation can be given in terms of increasing 'advection-relevant' wind speeds in greater heights with increasing vertical plume width at greater source distances, the overall impression of exploiting the advection wind speed as a tuning parameter (and not as sound physical modelling parameter) is apparent.

When the measured concentration field in the wind tunnel is compared to the urban Gaussian parameterization scheme proposed by Briggs (1973), it is found that the actually measured plume is more confined around the plume centreline, i.e. the lateral and vertical spread parameters $\sigma_y$ and $\sigma_z$ are observed to be clearly smaller as well as less rapid increasing than assumed by Briggs' formulas. This would lead to an underestimation of mean concentrations in the region around the plume centreline by Briggs' parameterization. The underprediction of concentrations appears to be a shortcoming shown by other dispersion models as well (see e.g. Olesen (1995) for a model evaluation).

Comparing the wind tunnel concentration data to the field tracer experiment conducted in the corresponding full scale urban setting of Kleinbasel, it is found...
that the wind tunnel concentrations are clearly larger than the field concentrations. Depending on the measurement location, the difference ranges from a factor of 4 or 5 to a factor between 10 and 100. This is most readily explained by the fact that the wind tunnel experiment was made under neutral conditions while in the field the stability regime was strongly unstable. Therefore the two data sets cannot be directly compared. Only the conclusion can be made that different stability regimes can account for factors in mean concentrations of the mentioned size.

A final thought goes to the generality of the insights obtained in this study and in particular to their applicability to other urban scenarios. It is a non-trivial task to describe the roughness geometry of an urban landscape efficiently. Typically roughness classes are defined according to certain morphometric characteristics ($h$, $\lambda_P$, $\lambda_F$, etc.) supplemented by verbal descriptions and photographic illustrations (see e.g. Grimmond and Oke (1999) and the therein cited studies). The assumption inherent in those urban classification schemes and based on emerging empirical evidence is that the roughness variation within each roughness class is small enough to allow meaningful statements about distinct aerodynamic flow properties for each roughness class. The point to remember is that those classifications are not derived from a watertight turbulence theory but stem from reviews of empirical findings and plausibility arguments. Therefore there is always the risk that future work will necessitate adaptations of the existing schemes (well, it might be a risk for the practitioner, but a chance for new insights for the scientist). This foreplay sets the right stage for the statement that essential findings of this study are expected to be applicable to other urban scenarios belonging to the surface shape category 'tall and high density' as defined by Grimmond and Oke (1999) (see their work, in particular their Tables 6 and 7, for a detailed characterization). These essential findings assumingly applicable to other urban scenarios include

- the height range of the RSL and the existence of a constant flux layer above with a well-defined logarithmic wind profile,
- the constancy of horizontally averaged Reynolds fluxes even within the upper part of the RSL,
- the turbulence characteristics within the RSL (as e.g. local variability of Reynolds flux profiles, contributions of sweeps and ejections, role of dispersive stresses, etc.),
- and the dispersion characteristics for the studied dispersion scenario.

Also the estimated height of flow adaptation agrees roughly with commonly quoted estimates which supports its general validity. Given the commonly prevailing urban fetches of homogeneous roughness typically restricted to at most
several kilometres as in the case of Basel, it appears plausible that qualitative characteristics within the modelled ISL are also applicable to other urban scenarios, as e.g. the difference between $u_{*\text{log}}$ and $u_{*\text{flux}}$ and the contributions of vertical turbulent TKE flux. But the exact extend of ISL turbulence adaptation to the urban surface depends of course on the given fetch, therefore care has to be taken when some of the present results characteristic for incomplete flow adaptation in the upper heights of the ISL are applied to other scenarios (e.g. the quantitative difference of 20% between $u_{*\text{log}}$ and $u_{*\text{flux}}$ may vary).
Seite Leer / Blank leaf
Appendix A: Spires and roughness elements

Roughness elements were installed on the wind tunnel floor upstream of the urban model area to model the near-ground turbulence within the approach flow (see Fig. 4.2 on page 51). Narrow and wide roughness elements with the same height of 40mm were used alternating, the widths being 40mm and 80mm. To model the turbulence at greater heights, vortex generators ('spires') were mounted at the inflow edge of the wind tunnel (using the nomenclature of the Hamburg wind tunnel group, the spires are of type 'V2500' with footers of type '16'). They are shown in Fig. A.1 including the distances between them. The measures of the roughness elements configuration are given in Fig. A.2.

Figure A.1: Arrangement of vortex generators ('spires') at the inflow edge of the wind tunnel (spires type 'V2500', footers type '16').
Figure A.2: Configuration of roughness elements on the wind tunnel floor, the total number of rows was 18.
Appendix B: Measurement accuracy and reproducibility

In the first part of this appendix the accuracy of individual measurements of turbulence parameters is discussed as well as the reproducibility of the whole turbulence model. The latter subject is of importance since between the turbulence measurement campaign and the dispersion measurement campaign the wind tunnel was used for another project including a complete reconfiguration of the wind tunnel settings (a different roughness model, a different approach flow configuration, a different ceiling adjustment). In the second part the accuracy of the concentration measurements is discussed.

Turbulence measurement accuracy

The overwhelming part of the turbulence measurements was done during the first measurement campaign including measurements at about 1,385 different locations above and within the urban model. In the second campaign mainly reproducibility checks were made and only a few extra measurement locations were added. Generally, turbulence measurement conditions were less favourable during the second campaign due to unfavourable seeding particles and laser light quality resulting in significantly reduced LDA data rates (i.e. instantaneous velocity measurements per second). Since the presentation of turbulence results is almost exclusively based on data from the first campaign, in the following the focus is on this first campaign.

The acquisition time per location was set to either three minutes or 100,000 velocity samples whatever was reached first. The sample size per location was almost always between 50,000 and 100,000 samples with an average of close to 90,000 samples per location. The acquisition frequencies were roughly between 400Hz and 900Hz with an average of close to 600Hz.

Three sources of measurement inaccuracy were (i) slight variations of the wind tunnel operating speed during and between the 3-minutes acquisition periods,
(ii) inherent inaccuracies of the LDA measurements and (iii) statistical scatter
due to limited sample size. Variations of the 'free stream' wind tunnel speed
(variations of roughly 0.1m/s to 0.2m/s at an average 'free stream' velocity of
about 8.5m/s) were dealt with by measuring the average 'free stream' velocity
for each 3-minutes acquisition period with the Prandtl tube installed above
the first half of the test section well-removed from the wind tunnel boundary
walls. Wind tunnel fluctuations were then somewhat mitigated by scaling each
3-minutes velocity statistics to a common reference 'free stream' velocity set
to 8.5m/s (corresponding roughly to the overall mean 'free stream' velocity
for the first campaign). To convert the measured pressure differences at the
Prandtl tube to 'free stream' velocities, the ambient pressure, temperature and
humidity was taken at least twice a day in the wind tunnel hall.

To estimate the remaining inaccuracy after adjustment for wind tunnel fluctu¬
atations, ten successive 3-minutes velocity measurements (\(u_1\) and \(u_3\)) were made
at two height levels \(x_3 = 19.5m\) (1.3h) and \(x_3 = 204m\) (14.0h)) respectively
above the urban model. Therefore, formally, a sample of ten 3-minutes es¬
timates of the turbulence statistics were acquired at each of the two height
levels. The relative accuracy (standard deviation divided by mean value over
the ten samples) was found to be about

- 1% for the mean wind speed \(U_1\)
- 2% for the turbulent velocities \(\sigma_1\) and \(\sigma_3\)
- 5% for the Reynolds fluxes \(u'_1 u'_3\)

The observed uncertainty in the mean wind speed LDA measurements corre¬
sponds roughly to the experience of the Hamburg wind tunnel group, which
has experienced uncertainties in the range of \(< 0.05m/s\).

The above stated uncertainties do not incorporate the fluctuating ambient
conditions which enter the velocity measurements due to the scaling by the
'free stream' velocity measured by the Prandtl tube. To estimate the effects
of those ambient variations, the approach was as follows: At 444 of the 1.385
locations velocity measurements were made at least twice, at 102 locations
more than twice due to intersecting profiles and/or repeated measurements.
Those multiple measurements were distributed over the whole first campaign
(about two months) covering various ambient conditions and were therefore
used collectively to estimate the uncertainties. For each multiple measurement
point the respective empirical standard deviation was determined and an av¬
erage standard deviation over all multiple measurement points was calculated
per turbulence statistics. The resulting estimated absolute uncertainties are,
corresponding to the standard measurement settings (i.e. a wind tunnel free
stream velocity of 8.5m/s and velocity time series of 3 minutes),
• 0.08m/s for the mean wind speed $U_1$
• 0.02m/s for the turbulent velocities $\sigma_1$
• 0.01m/s for the turbulent velocities $\sigma_1$
• 0.01m$^2$/s$^2$ for the Reynolds fluxes $\overline{u_1'u_3'}$

and correspond roughly to or are slightly larger than the above stated relative uncertainties. Therefore these absolute ranges of scatter are taken as appropriate estimates of the corresponding turbulence measurement uncertainties.

A remark goes to the measurement of the spectra. During the measurement of the time series the laser probe mounted on the traverse system visibly vibrated and arose the question of possible effects on the spectra. This was checked by comparing spectra taken at the same location measured once without further support and once with further support for the probe to suppress the vibrations. No difference was observed, neither in the spectra nor in the turbulent velocities. Nevertheless, careful inspection in particular of the $u_1$ spectra taken at $x_3 = 31.8m$ (2.2h), 72m (4.9h) and 108m (7.4h) reveals a dubious spike in each spectrum roughly at $n = 0.25, 0.49$ and 0.65 respectively. This corresponds in all case to a frequency between about 11.4Hz and 11.5Hz and suggests the interpretation as either the eigenfrequency of the traverse system or electrical signal disturbances by interactions with other measurement devices which were used at the same time by other experiments in the wind tunnel laboratory. Whatever the origin may be, the spikes are considered to be artefacts. Nevertheless, the spectral shapes and their overall physically sensible interpretation (in the sense of an atmospheric turbulence model) is not affected.

**Turbulence model reproducibility**

During the six-month-break between the first and second measurement campaign the wind tunnel settings were completely 'reshuffled' for other project studies, therefore it was a worthwhile exercise at the beginning of the second campaign to check the reproducibility of the turbulence model which was thoroughly analysed in the course of the first campaign.

The ten vertical profiles and the topmost of the five horizontal profiles were remeasured. Figs. B.1 to B.5 compare the horizontally averaged turbulence portraits of the two campaigns. The overall reproducibility is found to be very good, though the following qualifications have to be made:

(i) The vertical turbulent velocity $\sigma_3$ is systematically increased by about 3% in the second campaign which is also observed for the vertical mean
Figure B.1: Horizontally averaged mean wind over the ten vertical profiles as measured during the first campaign (filled symbols) and second campaign (empty symbols).

Figure B.2: Horizontally averaged Reynolds fluxes $u'_1 u'_3$ as measured during the first campaign (filled symbols) and during the second campaign (empty symbols).
Figure B.3: Horizontally averaged turbulent velocities $\sigma_1$ (diamonds) and $\sigma_3$ (triangles) as measured during the first campaign (filled symbols) and second campaign (empty symbols).

Figure B.4: Horizontally averaged Skew $u_1$ (diamonds) and Skew $u_3$ (triangles) as measured during the first campaign (filled symbols) and during the second campaign (empty symbols).
wind speeds $U_3$ (not shown) although the latter are rather small (a few centimetres per second downward up to $x_3 = 50m$ (3.4h)). This might be either due to variations in the ceiling height from the first to the second campaign (the ceiling was newly-adjusted for the second campaign) or due to a slight misalignment of the laser probe. In case of a slight probe misalignment the comparison to the field data suggests a misalignment in the second campaign, not in the first campaign. Due to its potentially unfavourable effects on the axial pressure gradients, no further 'playing around' with the ceiling height was undertaken. The overall profile shape of $\sigma_3$ is not altered, the reproduction of Skew $u_3$, Flat $u_3$ and $u'_1u'_3$ appears to be consistent (with the qualifications made in (ii)).

(ii) From roughly $x_3 = 120m$ (8.2h) upwards Skew $u_1$ and Flat $u_1$ show clear variations. This might be interpreted as another indication of slight variations in the overall wind tunnel configuration. Nevertheless, this height range is clearly above the model domain, so no further actions were taken.

(iii) During the second campaign Flat $u_3$, horizontally averaged over the topmost of the five horizontal profiles at $x_3 = 69m$ (4.7h), is observed to be more consistent with the horizontal averages over the ten vertical
profiles. In the first campaign a somewhat unreasonable difference was observed at this height level. Since the horizontal averages over the ten vertical profiles collapse well, the value for Flat $u_3$ at $x_3 = 69m$ ($4.7h$) estimated during the second campaign is considered more plausible. The estimation from the first campaign is seen as an outlier which could not be further explained.

These qualifications are not considered to spoil the overall very good reproducibility of the turbulence model, sufficient to combine the turbulence results of the first campaign with the dispersion results of the second campaign.

**Concentration measurement accuracy**

The observable of interest is $C^*$ as defined in Eqn. (7.1) on page 153. In addition to $L_{ref}$ it is based on the measurement of the following quantities:

- The mean concentration $C$ which is measured as the FFID concentration downstream of the source minus the SFID background concentration upstream of the source. Averaging time for $C$ is three minutes. The SFID and FFID signals are calibrated twice or thrice per day.

- The velocity $U_{ref}$ which is measured by the 'free stream' velocity $U_{WT}$ at the Prandtl tube times a constant factor to get the mean wind speed at the location BSPR at $x_3 = 31.8m$ ($2.2h$). The constant factor is estimated during the turbulence measurements, its applicability assumes Reynolds number similarity and in particular constancy of $U_1$(BSPR, $x_3 = 31.8m$ ($2.2h$))/$U_{WT}$. Measurement of the ambient temperature and pressure enter the calculation of the flow velocity at the Prandtl tube.

- The source strength $Q$ which is set at the mass flow controller which has been calibrated once before the dispersion study. Ambient temperature and pressure are measured twice or thrice per day to determine the volume flow rate.

Instead of determining the influence of the individual measurement uncertainties the statistics of $C^*$ itself have been estimated. Two different estimations were done.

For the first estimation a convenient measurement location about 684m downstream of the source close to the plume centerline at $x_3 = 34.8m$ ($2.4h$) has been chosen somewhat arbitrarily. $C^*$ has been measured for varying $U_{ref}$
Figure B.6: $C^*$ measured at different reference wind speeds, source strengths and source configurations as described in the text. Straight line corresponds to the overall mean value, dashed line demarcates the overall standard deviation of 0.0006.

(from 0.82m/s to 3.60m/s), varying source strength $Q$ (150l/h and 200l/h) and varying source geometry (designs CYL, STS and LTS). The averaging time for the two lowest velocities was 5 minutes, for all other velocities $C$ was averaged over 2 minutes. During these daylong measurements the SFID and FFID have been recalibrated twice and the ambient conditions have been determined twice. The resulting $C^*$ statistics are shown in Fig. B.6. The overall standard deviation of $C^*$ is estimated to be 0.0006.

For the second estimation of $C^*$ uncertainty the lowest grid of concentration measurement points ($x_3 = 27m (1.8h)$) has been measured twice on two different days meaning different ambient conditions and experimental setups in terms of SFID/FFID calibration. One grid measurement was done with the LTS, the other with the STS. The source strength was kept constant at 200l/h, $U_{ref}$ was always about 0.82m/s and averaging time per point was 3 minutes. Two $C^*$ measurements are therefore available for each of the 132 locations (= 9 x 15 - 3, since three locations were skipped during the LTS measurements). It is found that the two $C^*$ measurements per point scatter on average 0.00035 around their respective mean. The clearly reduced scatter in comparison to the first estimation approach is attributed to the smaller number of varied parameters.

200
It is remarked that both estimation approaches give scatters which are consistent with each other with respect to their magnitude. The first estimation provides a better coverage of varied parameters, therefore the uncertainty is estimated to be 0.0006 for all $C^*$ measurements. The scatter bars in the respective $C^*$ plots are based on this estimation.
Appendix C: Fit of the logarithmic wind profile

In the following (and throughout this work) the software used for curve fitting and parameter estimation was TableCurve\textsuperscript{TM} 2D, version 4, from AISN Software Inc..

Estimating the parameters of the logarithmic wind profile

In the following the detailed estimation approach is described for the logarithmic profile parameters (see Eqn. (2.19) on page 30) of the horizontally averaged mean wind profile.

Firstly, the ISL height range is estimated from the vertically constant part of the horizontally averaged $-u'_{1}w_{3}$ profile. Though one could argue about the inclusion of one or two more height levels it is argued retrospectively that this should not be a major source of uncertainty in the parameter estimation since in the present case the 'very good fit height range' of the logarithmic law clearly exceeds whatever plausible ISL height range might be chosen. The ISL height is estimated to be from $x_{3} = 48$ m (3.3h) to 81 m (5.5h).

Secondly, the parameters to be estimated are selected. Since the ISL height range is well above mean building height and the effect of the zero plane displacement $d_{0}$ is most significant only close to this mean building height the friction velocity $u_{*}$ and the roughness length $z_{0}$ are estimated while setting $d_{0}$ to a fixed value. A wide range covering the physically plausible values of $d_{0}$ seems to be from 0.5h to h: Garrat (1994, p.86) gives $d_{0}/h=2/3$ as a rule of thumb for naturally vegetated surfaces with an increasing ratio for more densely covered surfaces, the 'reasonable zones or envelopes' of Grimmond and Oke (1999) cover the range $d_{0}/h\geq0.5$ for the Kleinbasel plan aspect ratio $\lambda_{P} \approx 0.54$. A naive expectation could be that by trying different values the
correct value for $d_0$ should show up as giving the best fit to the wind profile in the ISL height range (i.e. $R^2$ should be maximised). The result of such a systematic variation of $d_0$ based on 17 different values is presented in Tab. C.1. $R^2$ varies only in the third decimal place and does not show an optimal fit peak. Based on further arguments provided in the case study below, the observed variations of $R^2$ are not a sensible selection criterion. Calculating the average and scatter over the 17 different values for $d_0$ one arrives at $u_{\log} = 0.65 \text{m/s} \pm 0.05 \text{m/s}$ and $z_0 = 2.7 \text{m} \pm 0.8 \text{m}$.

Thirdly, to do a bit better than just 'averaging over uncertainty', the review given by Grimmond and Oke (1999) is consulted to identify 'physically plausible' values. For the ratio $d_0/h$ they give the recommendations 0.5 for low-, 0.6 for medium- and 0.7 for high-density urban areas (p.1279). Consulting further their density classification (Tab. 6 in their publication) the present case is classified as 'high-density' which also agrees with a visual comparison of the Kleinbasel roughness with the pictorial classifications given by Grimmond and Oke (Fig. 8 in their publication). Since no contradictory indications are found in the present data (and, of course, it is not known any better) the estimated

<table>
<thead>
<tr>
<th>$d_0$ [m] (fixed)</th>
<th>$u_{\log}$ [m/s]</th>
<th>$z_0$ [m]</th>
<th>$d_0/h$</th>
<th>$z_0/h$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>0.70</td>
<td>3.5</td>
<td>0.48</td>
<td>0.24</td>
<td>0.998</td>
</tr>
<tr>
<td>7.5</td>
<td>0.70</td>
<td>3.4</td>
<td>0.51</td>
<td>0.23</td>
<td>0.998</td>
</tr>
<tr>
<td>8.0</td>
<td>0.69</td>
<td>3.3</td>
<td>0.55</td>
<td>0.22</td>
<td>0.998</td>
</tr>
<tr>
<td>8.5</td>
<td>0.68</td>
<td>3.2</td>
<td>0.58</td>
<td>0.22</td>
<td>0.998</td>
</tr>
<tr>
<td>9.0</td>
<td>0.68</td>
<td>3.0</td>
<td>0.62</td>
<td>0.21</td>
<td>0.998</td>
</tr>
<tr>
<td>9.5</td>
<td>0.67</td>
<td>2.9</td>
<td>0.65</td>
<td>0.20</td>
<td>0.998</td>
</tr>
<tr>
<td>10.0</td>
<td>0.66</td>
<td>2.8</td>
<td>0.68</td>
<td>0.19</td>
<td>0.998</td>
</tr>
<tr>
<td>10.2</td>
<td>0.66</td>
<td>2.8</td>
<td>0.70</td>
<td>0.19</td>
<td>0.998</td>
</tr>
<tr>
<td>10.5</td>
<td>0.66</td>
<td>2.7</td>
<td>0.72</td>
<td>0.19</td>
<td>0.998</td>
</tr>
<tr>
<td>11.0</td>
<td>0.65</td>
<td>2.6</td>
<td>0.75</td>
<td>0.18</td>
<td>0.997</td>
</tr>
<tr>
<td>11.5</td>
<td>0.64</td>
<td>2.5</td>
<td>0.79</td>
<td>0.17</td>
<td>0.997</td>
</tr>
<tr>
<td>12.0</td>
<td>0.64</td>
<td>2.4</td>
<td>0.82</td>
<td>0.16</td>
<td>0.997</td>
</tr>
<tr>
<td>12.5</td>
<td>0.63</td>
<td>2.3</td>
<td>0.86</td>
<td>0.16</td>
<td>0.997</td>
</tr>
<tr>
<td>13.0</td>
<td>0.62</td>
<td>2.2</td>
<td>0.89</td>
<td>0.15</td>
<td>0.997</td>
</tr>
<tr>
<td>13.5</td>
<td>0.62</td>
<td>2.1</td>
<td>0.92</td>
<td>0.15</td>
<td>0.997</td>
</tr>
<tr>
<td>14.0</td>
<td>0.61</td>
<td>2.0</td>
<td>0.96</td>
<td>0.14</td>
<td>0.997</td>
</tr>
<tr>
<td>14.5</td>
<td>0.60</td>
<td>1.9</td>
<td>0.99</td>
<td>0.13</td>
<td>0.997</td>
</tr>
</tbody>
</table>

| mean             | 0.65             | 2.7      |        |        |      |
| std. dev.        | 0.05             | 0.8      |        |        |      |

Table C.1: Estimated parameters $u_{\log}$ and $z_0$ for given $d_0$ obtained from fits of the logarithmic profile to the horizontally averaged mean wind profile between $x_3 = 48\text{m}$ (3.3h) and 81m (5.5h).
parameters belonging to \( d_0/h = 0.7 \)

\[
\begin{align*}
  u_{\text{log}} &= 0.66m/s \pm 0.05m/s \\
  z_0 &= 2.8m \pm 0.8m \\
  d_0 &= 10.2m
\end{align*}
\]

are taken as the 'best' estimations with the error given by the above documented estimation scatter.

**Effect of measurement accuracy on estimations of \( u_{\text{log}} \) and \( z_0 \)**

In the last section, the uncertainty in \( u_{\text{log}} \) and \( z_0 \) is simply due to the uncertainty in \( d_0 \). The uncertainty in the velocity measurements per height level should also have an impact. To get an impression of this impact a corresponding simulation is done as follows. Assuming that the 'true' ISL height range is from \( x_3 = 48m \) (3.3h) to 81m (5.5h) and the 'true' parameters are as estimated above (i.e. \( u_{\text{log}} = 0.66m/s, z_0 = 2.8m \) and \( d_0 = 10.2m \)), a random sample of 50 profiles is generated in the ISL height range at the same height levels as they are available for the horizontally averaged mean wind profiles analysed above (i.e. at \( x_3 = 48m, 51m, 57m, 63m, 69m, 75m, 81m \)). For each profile velocity measurements at the given height levels are simulated by taking the 'true' wind speed according to the assumed 'true' logarithmic wind profile and adding a normally distributed measurement error with a standard deviation of 0.08m/s (see appendix B). Thereby 50 profile measurements with the stated accuracy are generated. Assuming further that the 'true' \( d_0 = 10.2m \) is known, 50 estimations of \( u_{\text{log}} \) and \( z_0 \) are obtained from the profile sample with a \( R^2 \) for each fit. The resulting distributions are shown in Fig. C.1 and summarized by mean and standard deviation as

\[
\begin{align*}
  u_{\text{log}} &= 0.67m/s \pm 0.06m/s \\
  z_0 &= 2.9m \pm 0.7m \\
  R^2 &= 0.97 \pm 0.02.
\end{align*}
\]

This quantifies the impact of the velocity measurement inaccuracy on the parameter estimation accuracy. In particular, the quality of fit \( R^2 \) should not be expected to be larger than 0.97 on average. The analysis in the last section was based on the horizontally averaged mean wind profile with assumingly reduced uncertainties per height level. Therefore a somewhat higher \( R^2 \) does not appear to be implausible.
Logarithmic vs. power profile in the urban surface layer

Although the fit of the logarithmic profile to the horizontally averaged wind tunnel data has been made just in the estimated ISL height range between (and including) $x_3 = 48\text{m} \ (3.3\text{h})$ and $81\text{m} \ (5.5\text{h})$, it is observed that the fit parameterizes the data very well down to $x_3 = 24\text{m} \ (1.6\text{h})$. The power law wind profile given by

$$\frac{U_1(x_3)}{U_{1,\text{ref}}} = \left(\frac{x_3 - d_0}{x_{3,\text{ref}} - d_0}\right)^\alpha$$

might be compared to this excellent 'logarithmic performance'. Therefore the power law with reference heights $x_{3,\text{ref}}$ between (and including) $x_3 = 48\text{m} \ (3.3\text{h})$ and $81\text{m} \ (5.5\text{h})$ is fitted to the wind tunnel data in the same estimated ISL height range as the logarithmic profile. It is found that the variation of the fit with $x_{3,\text{ref}}$ is very small. Fig. C.2 shows the comparison of the profiles for $x_{3,\text{ref}} = 81\text{m} \ (5.5\text{h})$ and $\alpha = 0.35$. Apparently both profiles describe the wind tunnel data equally well in the estimated ISL height range. Below this height range the logarithmic profile shape is more appropriate, above this height range the power law seems to be more capable to represent the data.
Figure C.2: Comparison of the power law and the logarithmic profile fit to the horizontally averaged mean wind profile measured in the wind tunnel. The fit was done only in the indicated estimated ISL height range, lower dashed line gives mean building height. Parameters for the power law are $x_{3,\text{ref}} = 81 \text{m (5.5h)}$ and $\alpha = 0.35$. In both cases $d_0$ was set to 10.2m ($0.7h$).
Seite Leer / Blank leaf
APPENDIX D: Local Reynolds flux and mean wind profiles

The local parameters given in Tab. 6.1 on page 94 are derived from the local Reynolds flux profiles and the local mean wind profiles at the ten vertical profile locations. These local profiles are given in Figs. D.1 to D.4. The locally estimated parameters $z_0$, $u_{+\text{local flux}}$ and $u_{+\text{local log}}$ indicated in the diagrams correspond to those summarized in Tab. 6.1 on page 94.
Figure D.1: Local Reynolds flux profiles at the locations H, M, Q, P, R and T. The two upper dashed lines give the subjectively estimated local constant flux height range as an estimate for the local ISL height range, vertical dashed line gives average flux with this height range. $u_{-local \log}$ is calculated from this average flux. Lowest horizontal dashed line gives mean building height $h = 14.6$ m.
Figure D.2: Local Reynolds flux profiles at the locations S, high, low and BSPR with symbols as in Fig. D.1.
Figure D.3: Local mean wind profiles at the locations H, M, Q, P, R and T with the respective locally estimated parameters of the logarithmic profiles (straight lines). The two upper dashed lines give the local ISL height range estimated from the local constant flux height range (see Fig. D.1). Lowest horizontal dashed line gives mean building height $h = 14.6\text{m}$. 
Figure D.4: Local mean wind profiles at the locations S, high, low and BSPR with symbols as in Fig. D.3.
APPENDIX E: Concentration profiles

The lateral and vertical spread parameters $\sigma_y$ and $\sigma_z$ of the dispersion process are derived from the lateral and vertical profiles of $C^*$ given in Fig. E.1 to E.4. The lateral profiles were measured at $x_3 = 27m (1.8h)$, vertical profiles were measured at the estimated peak locations of the corresponding lateral profiles.
Figure E.1: Lateral profiles of $C^*$ at the source distances $x_{DST}$ from 384m to 684m with the indicated lateral spreads $\sigma_y$. Profiles were measured at $x_3 = 27m$ (1.8h).
Figure E.2: Lateral profiles of $C^*$ at the source distances $x_{DST}$ from 744m to 864m with the indicated lateral spreads $\sigma_y$. Profiles were measured at $x_3 = 27m$ (1.8h).
Figure E.3: Vertical profiles of $C^*$ measured at the lateral peak locations at the source distances $x_{DST}$ from 384m to 684m with the indicated vertical spreads $\sigma_z$. 

218
Figure E.4: Vertical profiles of $C^*$ measured at the lateral peak locations at the source distances $x_{DST}$ from 744m to 864m with the indicated vertical spreads $\sigma_z$. 

$x_{DST} = 744\text{m}$
$\sigma_z = 60\text{m}$
$R^2 = 0.971$

$x_{DST} = 804\text{m}$
$\sigma_z = 65\text{m}$
$R^2 = 0.963$ 

$x_{DST} = 864\text{m}$
$\sigma_z = 64\text{m}$
$R^2 = 0.972$
Seite Leer / Blank leaf
APPENDIX F: Concentration and source strength conversions

The following may appear dispensable for everyone who is used to convert from volume measures to mass measures and back again. Those may skip this appendix completely. Others may benefit or be confused completely. The purpose of the following is mainly for the author to lay down his understanding for later reference.

The most intuitive unit to measure gas concentrations is probably mass density \([\text{mass/volume}]\) since it corresponds nicely to the picture of gas molecules with definite masses located in a certain volume at a given time. The mass density of a given amount of gas depends on the ambient temperature and pressure which leads to certain inconveniences for concentration calibrations as explained in the following.

In this study SFID/FFID calibrations are conducted with reference concentrations provided by calibration gases (which are quite expensive). As soon as the calibration gas is released to be detected by the not yet calibrated SFID/FFID probes its mass density adapts to the ambient conditions (temperature and pressure), therefore the reference mass density varies from day to day and even within the same day. To circumvent the inconvenience to recalculate the reference mass densities once, twice or even thrice every day, another concentration unit is used which measures the concentration in units of the density of the non-diluted gas. I.e. the non-diluted gas, ethane in this case, has a certain mass density depending on the given ambient conditions and any diluted gas concentration can be expressed in relation to the non-diluted density, e.g. a relative concentration of 0.1 simply means one tenth of the non-diluted ethane density. Obviously this measure of concentration is always smaller than one, more concentration than in the state of non-dilution (under the given ambient conditions) is not possible. But more important, this relative concentration measure is also independent of the ambient conditions. E.g. increasing the pressure leads to an increased mass density of a given gas sample, but the reference mass density of the non-diluted same gas under the same increased pressure also increases, therefore the relative concentration
stays constant. The unit used in this study for the relative concentrations is 'volume parts per million' (ppm), i.e. relative concentrations are measured in multiples of 0.000001. Therefore a concentration of one million ppm corresponds to pure non-diluted ethane which corresponds in turn to the respective mass density of ethane under the given ambient conditions. The advantage of this practice is that the calibration signals of the SFID/FFID correspond directly to the reference concentrations given in ppm by the calibration gas provider without further transformation on the basis of daily and intra-daily changing ambient conditions. The subsequent SFID/FFID concentration signals are recorded in ppm.

Unfortunately the necessity to include the ambient conditions in the conduction of the dispersion experiment cannot be completely circumvented. The reason is that the source strength is regulated by a mass flow controller, its throughput is given in normal litres per hour which is essentially the same as mass per time. To calculate C*, both source strength and concentration should preferably be given either as mass flow and mass density or as volume flow and relative concentration (mixing the units implies a cumbersome fiddling around with the always changing mass density of ethane depending on the ambient conditions). Since the SFID/FFID signals are calibrated to relative concentrations, it is decided to measure the source strength as a volume flow (this is merely a matter of taste, it is equally possible to transform the relative concentrations to mass densities). The ambient conditions are continuously documented during the dispersion experiment. Given a certain desired source strength in liters per hour, the ambient conditions are used to calculate backwards the corresponding normal liters per hour which have to be set at the mass flow controller. Therefore the price for a convenient SFID/FFID calibration is paid by a less convenient source strength regulation. Since the measurement software is adapted to this procedure, this price is not too high.

Given the source strength in liters per hour (l/h) and the concentrations in ppm, C* is calculated as follows (with \( \rho_{C_2H_6} \) being the mass density of (non-diluted) ethane in \([kg/m^3]\) depending on the ambient conditions):

\[
C^* = U_{ref} \cdot L_{ref}^2 \cdot \frac{C[kg/m^3]}{Q[kg/s]} \\
= U_{ref} \cdot L_{ref}^2 \cdot \frac{C[kg/m^3]}{3600 Q[kg/h]} \\
= U_{ref} \cdot L_{ref}^2 \cdot \frac{10^{-6} \cdot C[ppm] \cdot \rho_{C_2H_6}}{3600 Q[m^3/h] \cdot \rho_{C_2H_6}} \\
= U_{ref} \cdot L_{ref}^2 \cdot \frac{10^{-6} \cdot C[ppm]}{3600} \cdot 10^{-3} \cdot Q[l/h]
\]
\[ = U_{ref} \cdot L_{ref}^2 \cdot 3.6 \cdot \frac{C[ppm]}{Q[l/h]} \]

with \( U_{ref} \) in [m/s] and \( L_{ref} \) in [m].
Bibliography


[23] ESDU guideline 85020, 1985: 'Characteristics of atmospheric turbulence near the ground, part II: Single point data for strong winds (neutral atmosphere)'


227


228


[57] Pascheke, F., 2000: 'Analyse zeitlich hochaufgelöster Windmessungen in einer städtischen Grenzschicht und Reproduktion wesentlicher Turbulenzeigenschaften im Grenzschichtwindkanal', diploma thesis at the Meteorological Institute, University of Hamburg


230


[82] Schatzmann, M., 2001: 'Turbulenz und Grenzschicht', lecture script, Meteorological Institute of the University of Hamburg


[87] Snyder, W.H., 1972: 'Similarity criteria for the application of fluid models to the study of air pollution meteorology', Boundary-Layer Meteorology, 3, pp. 113-134


231


Curriculum vitae

1973 Born in Hamburg, Germany
1979 - 1983 Elementary school Hoisbüttel
1983 - 1992 Gymnasium Buckhorn
1992 - 1993 Military service
1993 - 1995 Undergraduate studies of physics, University of Hamburg
1995 - 1996 ERASMUS student at the Imperial College, London (UK)
   International Diploma of the Imperial College in 'Quantum Fields
   & Fundamental Forces' (postgraduate course in physics)
1996 - 1998 Diploma studies of physics, University of Hamburg
   Title of diploma thesis: 'Application of Universal Dynamics to the
   Iteratively Smoothing Unigrid and Cell Growth and Analysis of a
   new Two-Grid-Algorithm'
1999 - 2001 IT consultant at Accenture GmbH, Germany
2002 - 2005 PhD studies of turbulence physics, ETH Zurich (CH)
   Title of PhD thesis: 'Wind tunnel modelling of turbulence and
   dispersion above tall and highly dense urban roughness'
Conference contributions


B. Feddersen, B. Leitl, M. Schatzmann, 2005: 'Wind tunnel modelling of urban turbulence and dispersion over the City of Basel (Switzerland) within the BUBBLE project', Proceedings of the 5th International Conference on Urban Air Quality, 29-31 March 2005, Valencia, Spain
Acknowledgements

This work would not have been possible without the excellent experimental equipment of the Hamburg wind tunnel group. I thank Prof. Michael Schatzmann for giving me the opportunity to work at the Meteorological Institute in Hamburg and acknowledge his encouraging and continuous support for this work. The Hamburg wind tunnel group and in particular Bernd Leitl introduced me to the experimental techniques of wind tunnel modelling, their experience guided my first steps in the wind tunnel. A big thank you for that.

After some confusion in the beginning about the official ETH supervisor of this work, Prof. Hans Richner agreed to take that role. I thank him for that. Mathias Rotach provided very helpful feedback on this work which benefited the interpretation of my results. This is even more acknowledged since the spatial distance between Hamburg and Zurich made direct communication not always easy. Prof. Ulrike Lohmann gave helpful comments on the first draft version of this work which enhanced the readability and comprehensibility of the final version. I also would like to thank Andreas Christen and Roland Vogt for the provision of field data and some interesting discussions. Student workers Anke Beyer, Elham Emami and Dennis Brüning helped with the construction and installation of the wind tunnel model. Their support is also greatly acknowledged as well as the support of the librarians at the Institute in Hamburg who helped me in my search for some ‘difficult to get’ papers.

The first months of this work were characterized by an extensive documentation of building structure. The technical drawing experience of my sister Christina were a great source of help for me during this admittedly very dull piece of work.

Finally, I thank my parents for their support during all the years of my academic education.