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Roof-level SF_6 tracer experiments in the city of Basel

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PREFACE

In 1998 COST action 715 started with the goal to better understand 'Meteorology applied to urban air pollution modelling'. Switzerland joined this action from its very beginning and soon a group of research institutions came together in order to discuss possible contributions to the goals of this COST action 715. The result was BUBBLE, the Basel UrBan Boundary Layer experiment that was originally designed and run by scientists from the Institute of Atmospheric and Climate Sciences ETH, the Institute of Meteorology, Climatology and Remote Sensing (University of Basel), the Institute of Air and Soil Pollution (EPFL), MeteoSwiss and the Observatory Neuchâtel. In the course of the planning and design process of BUBBLE, many research groups from all over the world (Canada, USA, Singapore, Australia, Germany, Bulgaria, Italy) joined in and the project became truly international. More information on BUBBLE can be found at its web site, http://www.unibas.ch/geo/mcr/Projects/ BUBBLE/.

At this stage of the project it was felt necessary to complement the very detailed and long-lasting observations of boundary layer characteristics in an urban area with data that directly correspond to the original addressee of COST 715, namely *urban air pollution*. Therefore collaboration was started with Risø National Laboratory (Denmark), scientists of which have long standing experience and expertise in the design and performance of tracer experiments. Also a research proposal was submitted to ETH for funding.

In this report now the authors present an overview on the tracer release experiments that resulted from all these efforts. The tracer experiments are probably unique with respect to the abundant meteorological information that is available for the area of Basel. Not only turbulence characteristics at the tracer release site are available as in many previous (also urban!) tracer experiments. Rather, several urban, suburban and rural reference turbulence sites with multiple levels are at hand, together with wind profiler, lidar, sodar and RASS observations throughout the entire urban boundary layer, and balloon soundings for certain periods. Also, the strategy of near-roof level release height and also sampling heights is different from most other urban tracer experiments where either high sources (only small influence of the urban surface on the dispersion process) or street level sources (results very specific for the street under consideration) were used. It is hoped that the present report helps scientists interested in urban dispersion processes to feed their models, test their concepts or otherwise sharpen their ideas in order to further improve our understanding on dispersion of atmospheric pollutants in urban areas.

Prof. A. Ohmura

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The success of the tracer experiment was, of course, largely dependent on the meteorological data available from the BUBBLE project. This was funded by the Swiss Ministry of Science and Education as COST 715 project (grant C00.0068). Additional funding from the international partner institutions through internal or explicitly BUBBLE-related projects came from The University of British Columbia (CA), The University of Western Ontario (CA), TU Dresden (Germany), The National University of Singapore, Indiana University (USA) and The University of Padova (I).

ABSTRACT

The Basel UrBan Boundary Layer Experiment (BUBBLE) was a major, long lasting and detailed experimental and modelling effort to better understand the meteorology in the urban boundary layer. Originating within the activities of COST715 (‘Meteorology Applied to Urban Air Pollution Problems’) the abundant near-surface and boundary layer instrumentation was complemented by a set-up of tracer gas samplers and a source, in order to directly and jointly use the meteorological and dispersion data for the development of our understanding in urban pollutant dispersion processes. In this report the tracer release experiments are described in detail, which were performed in the city of Basel, Switzerland in the framework of BUBBLE. The layout and operation of the source (near roof level) is discussed as well as the analysis procedure and calibration of the concentrations and the sampling positions and strategy. Also the available meteorological data are presented and their processing is discussed. Finally, each of the four experiments is presented separately and all the information is compiled in graphical and tabular form. With this, all the necessary information is available that potential modellers or other scientists interested in urban pollutant dispersion processes need for the further analysis or simulation of these releases.

ZUSAMMENFASSUNG

Das Basel UrBan Boundary Layer Experiment (BUBBLE) war ein bedeutendes und detailliertes Langzeitexperiment zur Untersuchung der städtischen planetaren Grenzschicht. Als Aktivität im Rahmen der COST-Aktion 715 ('Meteorology Applied to Urban Air Pollution Problems') war es durch zahlreiche bodennahe und Grenzschicht-Instrumente gekennzeichnet, die durch eine Anzahl von Tracer-Analysestationen sowie eine Tracerquelle ergänzt wurden, um so direkt die meteorologische und Turbulenzinformation zum besseren Verständnis von Austauschprozessen und Schadstoff-ausbreitung in der Stadt zu nutzen. Im vorliegenden Bericht werden die Tracer-Ausbreitungsexperimente detailliert beschrieben, die in der Stadt Basel, Schweiz, im Rahmen von BUBBLE durchgeführt wurden. Sowohl die Charakteristik und Operation der Quelle wie auch die Analysemethoden und Eichung der Tracerkonzentrationen, die Positionen der Sampler und die Beobachtunsstrategie werden vorgestellt und diskutiert. Zudem werden die verfügbaren meteorologischen Daten kurz dargestellt. Schliesslich wird jedes der vier durchgeführten Experimente separat diskutiert, und die relevante Information wird in graphischer und tabellarischer Form präsentiert. Damit ist alle notwendige Information vorhanden, um es potentiellen Schadstoff-Modellierern oder Personen, die an den Prozessen der Schadstoffausbreitung in städtischer Umgebung interessiert sind, zu ermöglichen, die BUBBLE-Tracerexperimente zu analysieren oder zu modellieren.

CONTENTS

1 INTRODUCTION

BUBBLE (Basel UrBan Boundary Layer Experiment) - an offspring of the COST action 715 - Meteorology applied to urban pollution problems - was an extensive meteorological measuring campaign carried out from mid 2001 to mid 2002 in the city of Basel, Switzerland (Rotach 2002, Rotach et al. 2002, Christen et al. 2002a,b). The aim was to observe by use of surface and remote sensing instruments the vertical structure of the atmospheric turbulence within the urban near-surface layer and street canyons as well as the flow field over the city and the rural surroundings.

As part of the overall BUBBLE effort, an Intensive Observation Period with additional instrumentation was carried out between June 15 and July 12 2002. This included a series of SF_6 tracer experiments that were performed with the aim to investigate the atmospheric dispersion process in the urban boundary layer. The tracer experiments were performed with a near roof-level source and the samplers were distributed close to roof level in a down-wind area stretching out to about 1.6km. Near roof level releases reflect, on the one hand, the typical situation in a city, where most of the pollutant sources are close to the ground (traffic, domestic heating). On the other hand, it can be shown that for those sources close to the ground it is most important to take into account the structure of the roughness sublayer when modelling urban scale dispersion (Rotach 2001). The rationale for these tracer experiments was therefore to prepare a data set to investigate this hypothesis in connection with detailed meteorological observations as available through BUBBLE. The part of Basel where the experiments were carried out is fairly homogenous in its city structure (Fig. 1). The mean building height in the area is 15.1m with a mean plan area density of 48%. It was the aim to perform the tracer experiments under ‘Clara Wind’ conditions, a thermally driven wind system that in the afternoon on cloud free summer days develops over Basel and is characterised by a persistent north-westerly direction of the wind. The meteorological conditions that favour the development of the north-westerly Clara Wind in the afternoon in Basel, creates in the morning a drainage flows from the nearby hills in the opposite direction.

During the campaign successful tracer experiments were carried out on 26 June, 4, 7 and 8 July 2002. On both 27 June and 5 July the meteorological conditions in the morning showed the indicators for the northwesterly Clara Wind to develop later in the day and the experimental procedure was started, but the Clara Wind did not develop and the experiments were finally cancelled late in the afternoon.

This report provides a description of the tracer experiments, illustrates the results and provides some background information of the meteorological conditions during the experiments. Preliminary results from the analysis of the tracer experiments can be found in Rotach et al. (2003) and Gryning et al. (2003). Concerning the meteorological data and BUBBLE in general, a detailed overview paper is planned (Rotach et al. 2004). Also, the project's web site contains detailed information on all the sites and observations (http://www.unibas.ch/ geo/mcr/Projects/BUBBLE/).

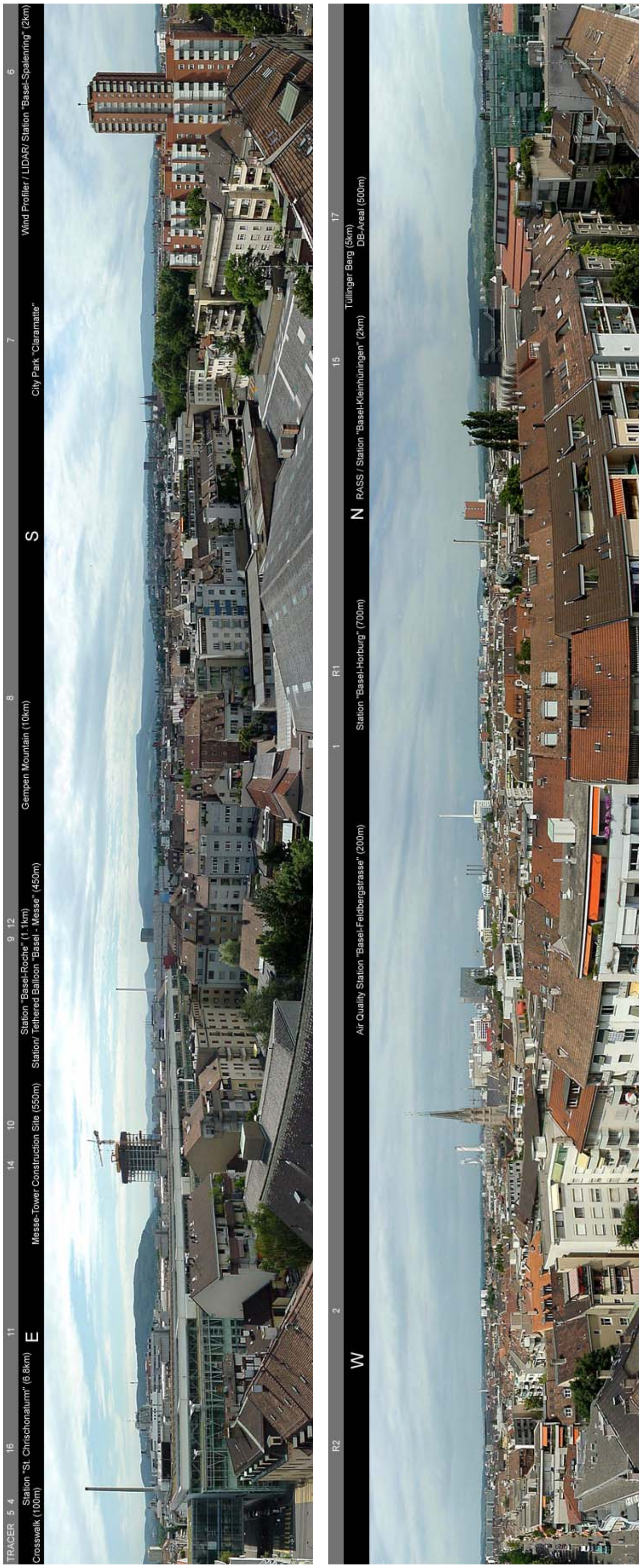


Figure 1
Composite 360° panorama of the experimental area taken from the measurement tower at "Sperrstrasse", position 3 in Figure 2. The numbers in the bar "tracer" refer to the direction of the sampler sites and the release points.

2 THE SF_6 TRACER TECHNIQUE

Details on the equipment and basic procedure for the tracer experiments can be found in Gryning (1981). The equipment has been used in many experimental campaigns and undergone numerous changes and improvements. Here we describe some of the general features of the tracer technique with emphasis on how the technique was adapted and used in this tracer campaign.

2.1 Experimental procedure

The experiments were carried out in an old part of Basel named “Kleinbasel”. The tracer was released into the roughness sublayer above the street canyons and sampling took place on the roof of the buildings. The tracer units (samplers) were typically positioned 1.5 metres above the roofs. At one position (Sperrstrasse, position 3 in Fig. 2) a tracer concentration profile was made within a street canyon. Prior to the experiments 12 roof level positions were selected (Tab. 1) and access during the experiments secured. Each position was assigned a person (operator) to operate the tracer-sampling unit during the experiments. In the choice of positions it was aimed at having two crosswind arcs and an along-wind series of tracer units, see Figure 2.

Table 2 shows a provisional timetable for the experiments and Table 3 gives some details on the release sites. The 12 sampling unit operators met at Sperrstrasse at 13:00 local summer time (=12:00 CET) before each of the experiments, where also the tracer units were brought from the laboratory. Approximately one hour before the envisaged start of tracer sampling (typically at 14:00 local summer time) the operators each took two tracer units, brought the units to their roof position and awaited communication on start of tracer sampling by walkie-talkie. After the experiment the units were collected by car and brought to laboratory at the University of Basel and usually analysed for content of tracer on the next day. It should be noted that when it was decided to start the procedure for an experiment at the morning meeting, the Clara Wind was not present, and often also not yet developed at 13:00 local summer time when the sampling units operators collected the tracer sampling units at Sperrstrasse and started to bring them to the positions on the roofs. The exact timing for start of sampling was decided based on the meteorological measurements at Sperrstrasse and at the release point - and then communicated to the operators of the sampling units by walkie-talkie.

During some of the experiments additional measuring positions were added due to unexpected behaviour of the wind direction. These positions were at ground level, Figure 2 and Table 1. On June 4 the release position was changed - position R2 on Figure 2

A tale on practical problems and curious incidents during the experiments can be found in Gryning (2003).

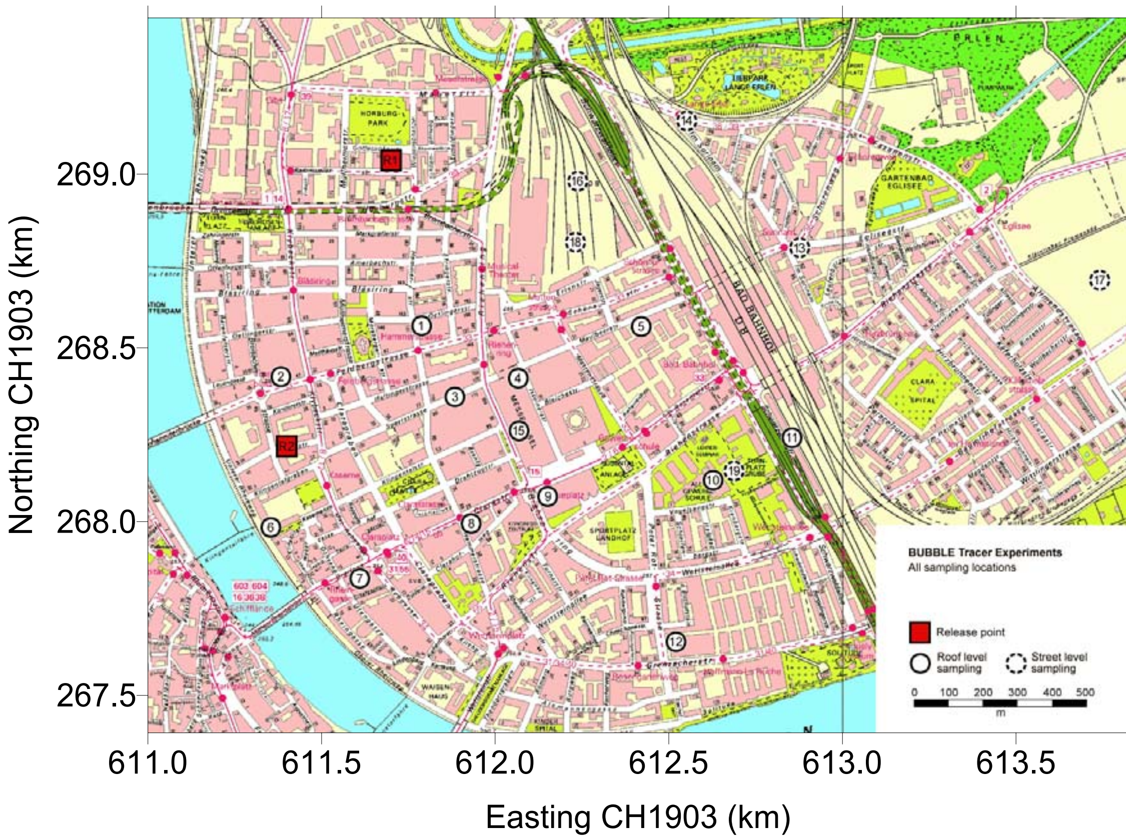


Figure 2 Map of the experimental area. The circles numbered 1 to 12 represent the original roof level layout of the tracer sampling positions. Circles numbered 13 to 19 are positions that were added during the experiments, these positions are at street level except for position 15. Sperrstrasse is position 3. The red squares show tracer release positions. R1 is the original position, R2 was added ad hoc and only used in one experiment [Base map (c) copyright GVA BS, 25.10.2002].

Table 1 [next page]

Description and morphometric data of the tracer sampling and release positions. Plan area density λ_P is defined as area covered by buildings per area, Frontal aspect ratio λ_F is defined as building front area at a given wind direction per area. The λ_F -values in the table represent a mean value over all wind directions. Complete aspect ratio λ_C is the total surface area (including walls, roofs and streets) per area (see Grimmond and Oke, 1999 for details). Vegetation is not included in the morphometric data. Data sources: 1m digital elevation model, 1m raster 3D-building model from the authorities of the city of Basel (3d-Stadtmodell BS, Bewilligung vom 16.7.2002, Auftrag Nr. TG022824, Grundbuch- und Vermessungsamt Basel-Stadt).

Site	Name	Location	Easting [m], CH 1903	Northing [m], CH 1903	Distance to R1 in m	Distance to R2 [m]	Height of ground level [m] above sea level	Height of roof [m] above sea level	Height of roof [m] above ground level	Height of sampler / release [m], above roof	Height of sampler / release [m], above ground level	Mean roof height z_H [m], inside a circle of 100m radius	Std. dev. of roof heights σ_{zH} [m], inside a circle of 100m radius	Plan area density λ_P inside a circle of 100m radius	Frontal aspect ratio λ_F inside a circle of 100m radius	Complete aspect ratio λ_C inside a circle of 100m radius
R1	*Parking Novartis Klybeck*	*flat roof*	*611692*	*269037*	*-*	*873*	*254.3*	*269.4*	*15.1*	*3.5*	*18.6*	*13.0*	*5.2*	*0.34*	*0.17*	*1.42*
R2	*Florastrasse*	*mobile platform*	*611400*	*268214*	*873*	*-*	*251.6*	*-*	*-*	*-*	*21.0*	*14.0*	*5.4*	*0.42*	*0.38*	*1.97*
1	*Oetlingerstrasse 170*	*flat roof*	*611780*	*268571*	*474*	*521*	*255.9*	*272.6*	*16.7*	*1.5*	*18.2*	*12.4*	*5.5*	*0.53*	*0.42*	*2.04*
2	*Feldbergstrasse 31*	*flat roof*	*611377*	*268408*	*703*	*-*	*253.4*	*271.7*	*18.3*	*1.5*	*19.8*	*11.0*	*5.4*	*0.48*	*0.39*	*1.93*
3a	*Tower "Basel-Sperrstrasse"*	*tower in street canyon*	*611890*	*268365*	*701*	*513*	*256.1*	*-*	*-*	*-*	*3.0*	*12.1*	*5.3*	*0.55*	*0.39*	*1.94*
3b	*Tower "Basel-Sperrstrasse"*	*tower in street canyon*	*611890*	*268365*	*701*	*513*	*256.1*	*-*	*-*	*-*	*10.0*	*12.1*	*5.3*	*0.55*	*0.39*	*1.94*
3c	*Tower "Basel-Sperrstrasse"*	*tower in street canyon*	*611890*	*268365*	*701*	*513*	*256.1*	*-*	*-*	*-*	*17.0*	*12.1*	*5.3*	*0.55*	*0.39*	*1.94*
4	*Messe Basel, Halle 1, NE*	*flat roof*	*612058*	*268417*	*720*	*689*	*256.5*	*278.9*	*22.4*	*1.5*	*23.9*	*17.7*	*5.4*	*0.65*	*0.30*	*1.76*
5	*FMI, Maulbeerstrasse 66*	*flat roof*	*612400*	*268551*	*859*	*1055*	*256.0*	*284.2*	*28.2*	*1.5*	*29.7*	*20.0*	*8.1*	*0.39*	*0.39*	*2.05*
6	*Klingentalschulhaus Kaserne*	*"castle style" roof*	*611350*	*267980*	*1111*	*-*	*250.4*	*274.9*	*24.4*	*1.5*	*25.9*	*14.3*	*6.0*	*0.22*	*0.20*	*1.48*
7	*Manor, Greifengasse 22*	*flat roof*	*611603*	*267838*	*1202*	*-*	*253.4*	*281.5*	*28.1*	*1.5*	*29.6*	*18.5*	*5.5*	*0.58*	*0.48*	*2.21*
8	*Clarastrasse 30*	*flat roof*	*611928*	*267994*	*1069*	*572*	*256.6*	*279.9*	*23.3*	*1.5*	*24.8*	*13.6*	*6.4*	*0.56*	*0.42*	*2.09*
9	*Parking Messe Basel*	*parking deck*	*612151*	*268091*	*1051*	*761*	*256.5*	*282.9*	*26.4*	*1.5*	*27.9*	*22.9*	*6.2*	*0.53*	*0.23*	*1.61*
10	*Schule f. Gestaltung, Bau G*	*flat roof*	*612641*	*268122*	*1318*	*1244*	*256.5*	*283.3*	*26.8*	*1.5*	*28.3*	*13.3*	*8.0*	*0.22*	*0.17*	*1.44*
11	*Parking DB*	*parking deck*	*612825*	*268259*	*1374*	*1426*	*258.9*	*269.9*	*10.2*	*1.5*	*11.7*	*7.7*	*3.4*	*0.18*	*0.08*	*1.18*
12	*Roche, Bau 74*	*flat roof*	*612503*	*267655*	*1602*	*1237*	*257.1*	*280.5*	*23.4*	*1.5*	*24.9*	*20.6*	*8.1*	*0.39*	*0.25*	*1.64*
13	*Schorenweg*	*ground level*	*612886*	*268795*	*1218*	*-*	*258.1*	*-*	*-*	*-*	*1.5*	*-*	*-*	*-*	*-*	*-*
14	*Bus Station "Lange Erlen"*	*ground level, sidewalk*	*612542*	*269155*	*858*	*-*	*256.4*	*-*	*-*	*-*	*1.5*	*-*	*-*	*-*	*-*	*-*
15	*Messe Basel, Halle 1, W*	*flat roof*	*612052*	*268272*	*-*	*655*	*256.5*	*278.9*	*22.4*	*1.5*	*23.9*	*19.2*	*5.2*	*0.68*	*0.26*	*1.65*
16	*DB-Areal, Erlkönig*	*ground level, track area*	*612180*	*269048*	*-*	*1142*	*255.6*	*-*	*-*	*-*	*1.5*	*8.1*	*2.6*	*0.06*	*0.04*	*1.09*
17	*Bäumlihof*	*ground level, grassland*	*613780*	*268700*	*-*	*2429*	*260.0*	*-*	*-*	*-*	*1.5*	*0.0*	*0.0*	*0.00*	*0.00*	*1.00*
18	*DB-Areal, South*	*ground level, parking lot*	*612216*	*268774*	*586*	*-*	*255.9*	*-*	*-*	*-*	*1.5*	*9.1*	*4.2*	*0.17*	*0.06*	*1.13*
19	*Schule f. Gestaltung, ground*	*ground level, park*	*612660*	*268143*	*1318*	*-*	*256.6*	*-*	*-*	*-*	*1.5*	*13.4*	*8.6*	*0.18*	*0.14*	*1.37*

Table 2 The provisional timetable for the experiments. Time indications are in local summer time (CET= local summer time -1).

BUBBLE Tracer Experiments
Experiment Time Table

Time	Activity	Who
Day before 18:00	Meeting at Spalenring: Decision for a possible release next day. *YES:* alert all sampler operators (AC). *NO:* nothing happens.	SEG, EK, MR, RV, AC
09:15	Meeting at Spalenring. Final decision to start an experiment. *YES:* confirm sampler operators (AC) and fix time for meeting at Sperrstrasse. *NO:* inform all sampler operators of cancellation. If sampler operators do not get a call until 10:00: Please contact us at 061 272 64 80 / 079 315 70 01	SEG, EK, MR, RV, AC
09:30	Start preparation of SF_6 units and bring them to Sperrstrasse.	SL, LC
~11:00	Move headquarter to Sperrstrasse.	SEG, AC, MR, EK
12:30	Earliest time to move to release point if weather permits.	SEG
13:00 or fixed time.	**Sampler operators meet at Sperrstrasse.**	All
13:00 or fixed time.	Distribution of samplers units, forms and walkie-talkies to sampler operators.	EK
13:00	Earliest time to start release of tracer at release point.	SEG
After 13:00	Fix times to start first and second samplers. **Then transfer of all samplers to measuring positions.**	All
14:00	**Earliest time to start first sampler unit.**	All
15:30	Earliest time to start second sampler unit.	All
17:00	Earliest time to stop experiment.	All
After stop	Bring the units to the street level (meeting point) and wait for pick up of sampler by car.	All, LC (Car)

2.2 *Tracer release*

The tracer SF_6 is a chemically inert and non-toxic gas that is available in cylinders, where it exists as a liquid with a gas pressure of about 20 bar at normal temperatures. The liquid cools when it evaporates. For the release rates that were used during these experiments the heat from the surrounding air to the liquid through the cylinder was abundant to maintain the evaporation. During the experiments the tracer was released via a pressure reduction valve mounted on the cylinder to either a flow meter or a mass flow controller and from then through a nylon pipe to the release point. The release rate was controlled differently in the experiments.

During the experiments on 26 June, 7 and 8 July the release was from the deck of a parking house. Figure 3 shows the release system. A constant release rate of the tracer was secured by observing a flow meter through which the tracer was led before it is released to the air through a pipe 3.8 metres above the building roof. The release of SF_6 was calculated from the time of release and the weight of the cylinder before and after each experiment. The accuracy of the release rate estimated in this way is a few per cent. In an experiment on 4 July the tracer was released form a cherry picker (mobile hydraulic platform), Figure 4. For logistic reasons the whole release equipment was placed in the basket. From the SF_6 cylinder in the basket the tracer was led through a mass flow controller and released at the top of a tripod with an extension pole 3 metres above the floor of the basket. The basket was 18 metres above the street, resulting in a total release height of 21 metres. For the mass flow controller the uncertainty in the flow rate is given by the manufacturer to be better than 1.5 per cent.

Because the novelty of tracer experiments in urban areas above the street canyons, the dilution of the tracer plume arising from filling the street canyons with tracer and tracer transport along the street canyons was largely unknown, and this gave rise to many considerations in the design of the experiment and the estimate for the release rate for the tracer. It was feared that the tracer concentrations would be small as compared to the background SF_6 concentration in the Basel area, but it was also feared that releasing an abundance of SF_6 would increase the general tracer level in the whole area thus making further experiments impossible for several days. Therefore several flow metres and two mass flow controllers were available for the tracer release, allowing tracer release rates in the range of 0.005 to $5 gs^{-1}$. In the first experiment a pre-calculated rate of $0.05 gs^{-1}$ was used, in the subsequent experiments it was based largely on the experience that was gained throughout the campaign.

Table 3. The tracer release sites.

Release position	Height of building roof (m)	Height above building roof (m)	Release height above ground	Tracer flow controlling device
Parking house	15.1	3.5	18.6	Flow meter
Cherry picker	–	–	21	Mass flow controller

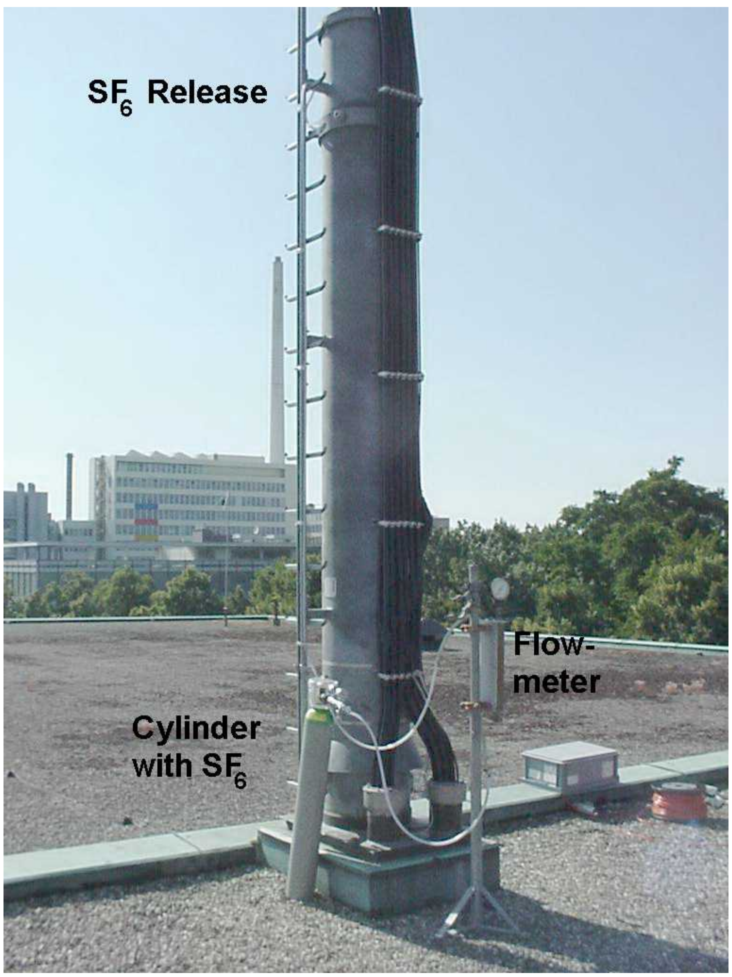


Figure 3 The tracer release system was used on the deck of the parking house.

Figure 4 The cherry picker during the tracer release at Florastrasse on 4 July 2002. The release is from the top of the extension that can be seen above the basket of the cherry picker.

2.3 Tracer sampling

Air sampling units, based on sampling of air in plastic bags, were used. Air is sucked in through an intake by a small diaphragm pump and led to one of three plastic bags that are inflated with a flow rate of about 300 ml/min. Magnetic valves regulate the inflation of the bags. The units inflate 3 bags in sequence, each having a sampling time of 30 min. A battery supplies the power to the unit. The units can be started by a radio signal, but this possibility was not used here because it was feared that the radio signal could not reach all units when positioned in an urban area. Instead the unit were started manually. The experiment consisted of 6 half-hour samples, which was achieved by operation two sampling units in sequence at each position. The units were placed 1.5 metres above the roof on a tripod as shown in Figure 5. A total number of 25 units were available for the experiments.

Figure 5 Tracer sampling units during tracer sampling. The two tracer sampling units are attached to a tripod 1.5 m above the roof. The sampling unit is placed at position 8 (see Fig. 2).

2.4 Tracer analysis.

All the air samples were brought to the laboratory at the University of Basel immediately after the experiment for analysis of content of the tracer. The analysis was performed by means of a pulsed electron capture detector gas chromatograph equipped with a molecular sieve column. The detection limit of the chromatograph is about 5 ngm^{-3} (≈1 ppt) of SF_6 with a linear range of the chromatograph up to about 6000 ngm^{-3} (≈1 ppb).

The gas chromatograph was calibrated by means of standards prepared at the National Environmental Research Institute in Denmark. As basis a commercial 1ppm standard supplied by Linde AG was used. This standard was further diluted into concentrations of 1013 ppt, 327 ppt, 101.3 ppt and 31.4 ppt (roughly corresponding to 6000, 1950, 605 and 187 ngm^{-3} of SF_6 but depending on air temperature and ambient pressure). The linearity of the response of the gas chromatograph is very good, as can be seen in Figure 6.

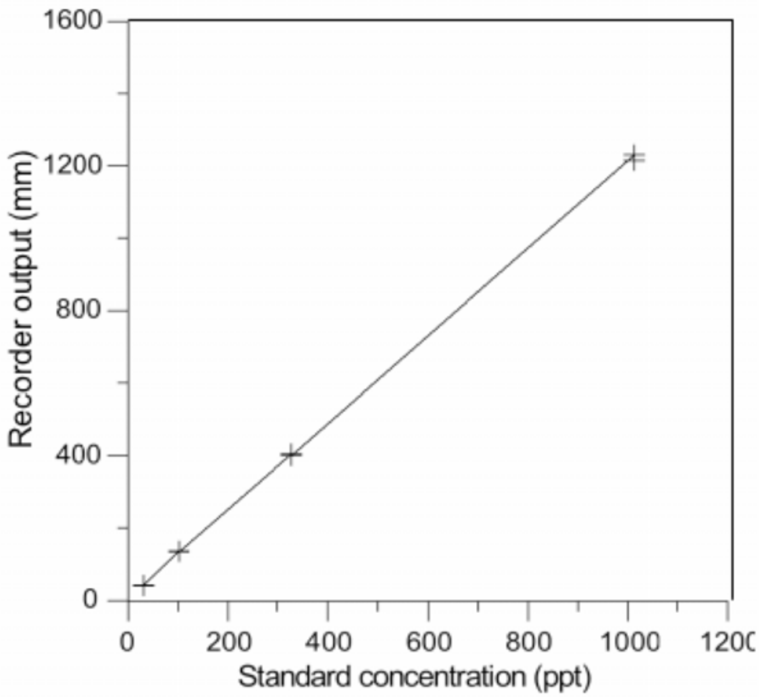


Figure 6 Height of the SF_6 peak from the output of the gas chromatograph plotted as function of the 4 calibration standard concentrations. The best linear fit through the origin is used to convert peak height to concentrations in units of ppt. It should be noted that each experiment is individually calibrated thus taking into account the slight changes in the performance of the gas chromatograph between the experiments.

In these tracer campaigns only the two lower standards were used for the calibration, because the measured tracer concentrations always were lower than 1000ngm^{-3}. These rather low concentrations also secured linearity of the gas chromatograph.

Examples of output from the chromatograph are shown in Figure 7. The left panel shows the background concentration of SF_6, the middle and right panels show typical tracer concentrations as measured during the experiments. The reproducibility of the output from the gas chromatograph is extremely good; in fact when a sample was reanalysed the results of the two samples usually were indiscernible from each other.

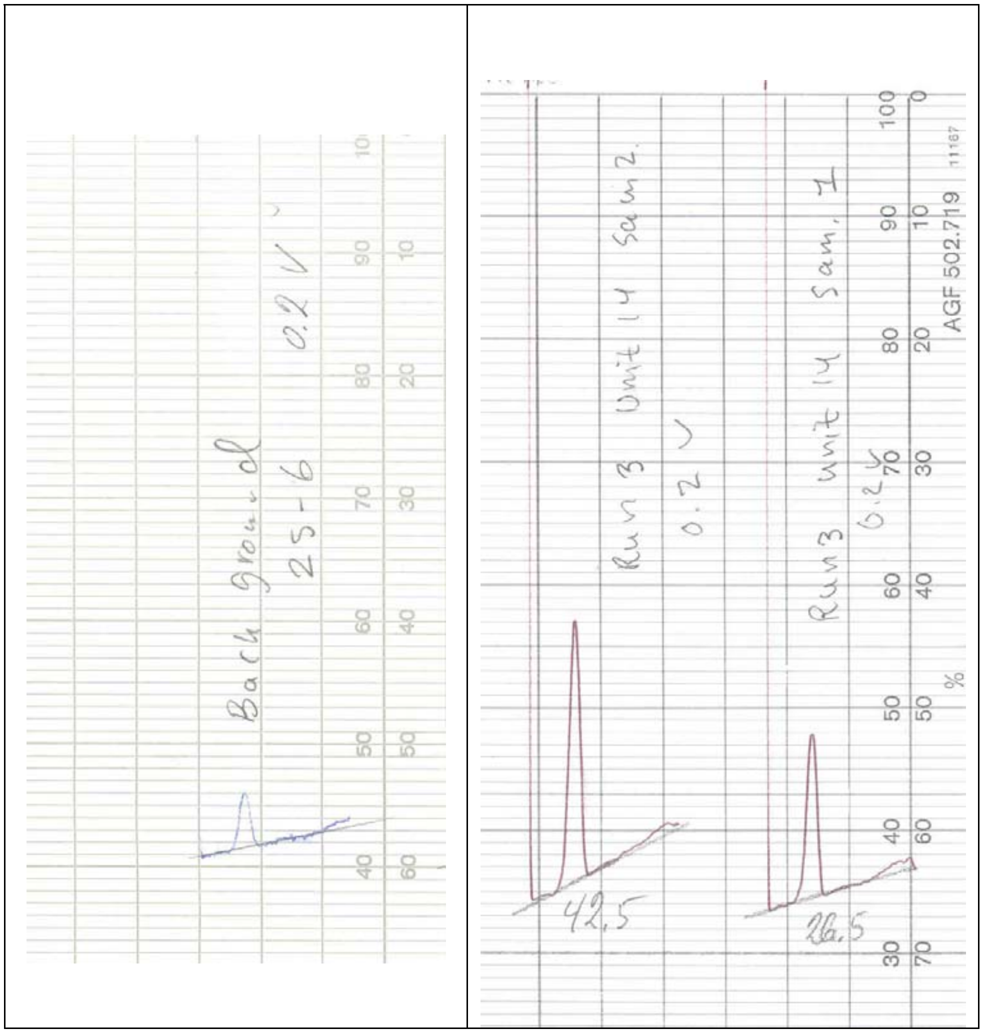


Figure 7 Examples of output from the gaschromotograph during the experiment. The SF_6 concentration is taken proportional to the peak height. The left panel shows the background concentration (33.6 ngm^{-3}); the left peak in the right panel represent a SF_6 concentration above background of 150.1 and the right panel of 81.5 ngm^{-3}.

During the analysis in the laboratory of the content of tracer in the bags, first the peak height is measured, then the background is subtracted and the output is converted to ppt by use of the best linear fit as shown in Figure 6. The concentrations are then converted to units of ngm^{-3} for later analysis and data interpretation. The conversion between ppt and ngm^{-3} is pressure and temperature dependent (Seinfeld 1986):

$$\chi\left[ngm^{-3}\right] = \frac{p\,M}{8.314 \cdot 10^{-2}\,T}\,\chi\left[ppt\right]$$

where $\chi\left[ngm^{-3}\right]$ and $\chi\left[ppt\right]$ are SF_6 tracer concentration in units of nano grams per cubic metre ngm^{-3} and parts per trillion ppt respectively, p is atmospheric pressure in hPa, T the air temperature in Kelvin, M the molar weight of SF_6 which is 146.05 $gmol^{-1}$, and $8.314 \cdot 10^{-2}$ a dimensional constant. For the conversion actual values of p and T measured at Sperrstrasse during each of the experiments were used.

2.5 Background concentration

Immediately before each of the experiments the background level of the tracer was measured (Table 4). It can be seen that in 3 of the 4 experiments the SF_6 background is about 30ngm^{-3}. The elevated background level on July 8 is believed to be caused by the SF_6 that was released during the tracer experiment the day before. This suggests that it took more than one day for the released tracer to be fully ventilated out of the Basel area. Lyck (1986) measured in the autumn of 1985 the SF_6 background to be 15-20 ngm^{-3} in a rural area near the Gösgen 20 km east of Aarau (Switzerland). The general level of the background in the city of Basel in 2002 thus is 1.5 to 2 times larger than in a rural part of Switzerland in 1985.

Table 4 Background level of SF_6 in Basel before each of the experiments.

Tracer experiment	**Background concentration of SF_6 [ngm^{-3}]**
26 June	33.6
4 July	32.2
7 July	34.0
8 July	53.2

3 DESCRIPTION OF THE EXPERIMENTS

This chapter provides an overall description of the 4 experiments. The distribution of the tracer over the experimental area is illustrated for the total 3-hour averaged tracer concentrations and the individual 6 half-hourly tracer measurements. Additionally are presented some of the meteorological parameters that control the spread of the tracer plume: the wind field over Basel, the mixing height based on lidar measurements, net radiation and turbulence measurements. The positions where meteorological measurements are performed are illustrated in Figure 8 and described in Table 5.

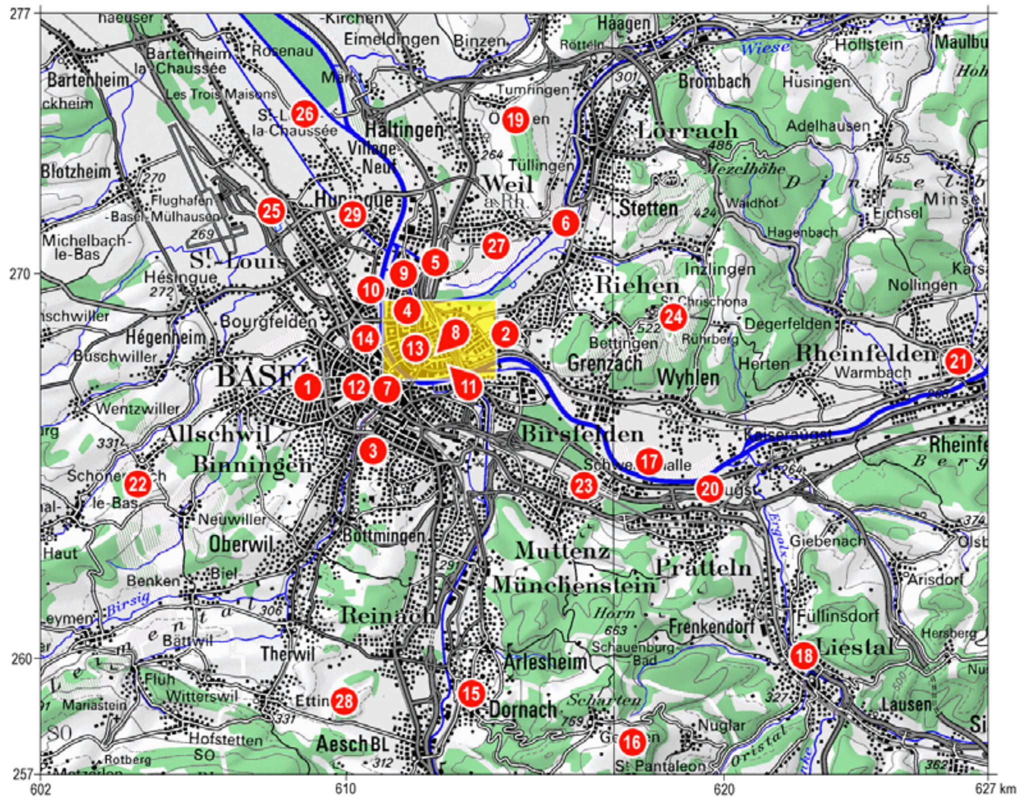


Figure 8 All sites with meteorological measurements during the BUBBLE-IOP in the large domain (20 x 25 km). The numbers refer to the sites description in Table 5. The yellow area indicates the small domain of the city part "Kleinbasel" where the tracer experiments were performed (2.5 x 2 km). Base Map: reproduction with authorization of the Swiss Federal Office of Topography, Wabern (BA024776).

Table 5 Wind measurement sites during the BUBBLE-IOP. The numbers in the rightmost columns indicate the total number of instruments installed at the sites for wind and turbulence measurements. WIN: Standard wind instrumentation (cup or propeller anemometers, wind vanes), TUR: High frequency ultrasonic anemometer measurements, RS: Remote sensing instrumentation.

	Code	*Site Name*	*Easting (m)*	*Northing (m)*	*Height*	*Measurement*	*Measurements*		
			CH 1903	*CH 1903*	*a.s.l. (m)*	*Height (1)*	*WI*	*TU*	*RS*
1	*ALLS*	*Allschwil -*	*609250*	*267180*	*277*	*15.8 m*		*3*	
2	*BBH*	*Basel - Baeumlihof*	*614130*	*268540*	*289*	*27.5 m*	*1*		
3	*BBIN*	*Basel - Binningen*	*610850*	*265620*	*316*	*17 m*	*2*		
4	*BHO*	*Basel - Horburg*	*611695*	*269040*	*254*	*18.4 m / 2.8 m*	*1*		
5	*BKL*	*Basel -*	*612465*	*270475*	*265*	*10 m*		*1*	*RASS*
6	*BLE*	*Basel - Lange Erlen*	*615835*	*271310*	*275*	*10 m*	*4*		
7	*BLE*	*Basel - Leonhard*	*611200*	*267055*	*273*	*41.5 m*	*1*		
8	*BME*	*Basel – Messe*	*612200*	*268070*	*258*	*26 m*		*1*	*Tether*
9	*BKL*	*Basel - Novartis*	*612000*	*270125*	*255*	*35 m*	*1*		
1	*BNS*	*Basel - Novartis St.*	*610840*	*269775*	*257*	*10 m*	*1*		
1	*BRO*	*Basel - Roche*	*612775*	*267748*	*255*	*45 m*	*1*		
1	*BSP*	*Basel – Spalenring*	*610360*	*267140*	*278*	*32.4 m / 15 m*	*5*	*6*	*Profile*
1	*BSP*	*Basel –*	*611890*	*268365*	*255*	*31.7 m / 20 m*	*12*	*8*	
1	*BSTJ*	*Basel - St. Johann*	*610750*	*268375*	*260*	*25 m*	*1*		
1	*DOR*	*Dornach*	*613080*	*258930*	*325*	*-*	*1*		
1	*GEM*	*Gempen*	*617640*	*257965*	*710*	*10 m*	*4*		
1	*GRN*	*Grenzach*	*617830*	*265130*	*265*	*28 m*	*1*	*1*	*SODA*
1	*LIES*	*Liestal -*	*621800*	*259950*	*320*	*25 m*	*1*		
1	*OET*	*Oetlingen*	*614770*	*274270*	*450*	*71 m*	*1*		
2	*PRA*	*Pratteln -*	*619625*	*264500*	*272*	*15 m*	*1*		
2	*RHF*	*Rheinfelden*	*626360*	*268045*	*285*	*10 m*	*1*		
2	*SBC*	*Schoenenbuch*	*604775*	*264325*	*400*	*10 m*	*1*		
2	*SHA*	*Schweizerhalle*	*616725*	*264550*	*270*	*40 m / 10 m*	*1*		
2	*CHR*	*St. Chrischonaturm*	*618700*	*269025*	*493*	*250 m (Tower)*	*1*		
2	*STLS*	*St. Louis*	*608100*	*271500*	*250*	*-*			*SODA*
2	*VLN*	*Village – Neuf*	*608940*	*274240*	*240*	*5 m*	*2*	*1*	
2	*WEIL*	*Weil am Rhein*	*614250*	*270905*	*250*	*10 m*	*1*		

(1) above ground / above roof level

3.1 Experiment on 26 June 2002

The experiment on 26 June 2002 was carried out with a tracer release of 0.0503gs^{-1} during the period 12:00-16:00 Central European Time (CET; GMT+1 hour) and with tracer sampling between 13:00-16:00 CET. The sky was clear during the experiment, as can be deduced from lidar measurements and net radiation (Figs. 12 and 13). Although the Clara Wind was established throughout the whole afternoon, the wind in the experimental area remained weak (1.6ms^{-1} at “Basel-Sperrstrasse”, 31m) and the wind direction at the release site was variable until 14:30 CET, when the direction became north-west. For the last part of the tracer release the conditions were with pronounced convection and the wind remained weak.

Note that the ‘friction velocity’ as given in Figure 13b, third panel and fourth panel respectively, simply reflects the observations at the respective level, i.e. $u_{*loc} = (\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$.

This definition does not take into account the direction of the momentum fluxes. In Section 4 it is shown how the profile information can be employed to derive a ‘characteristic velocity’ (which will be denoted $_*$).

Figures 9 and 10 illustrate the tracer concentrations. It can be seen that the plume spreads over the area with some structure. The wind field over the area is illustrated in Figure 11. It is seen to vary considerably both in time and space. From Figure 12 of the atmospheric backscatter observed by a Lidar at “Basel-Spalenring”, the mixing height was estimated to be 1.8 km. Taking the mixing height h from the lidar measurements (see Tab. 6), the kinematic heat flux $\left(\overline{w'T'}\right)$ and air temperature T from the measurements at Sperrstrasse, the convective velocity $w_* = \left((g/T)\overline{w'T'}\,h\right)^{1/3}$ can be estimated to 2.3 ms^{-1}.

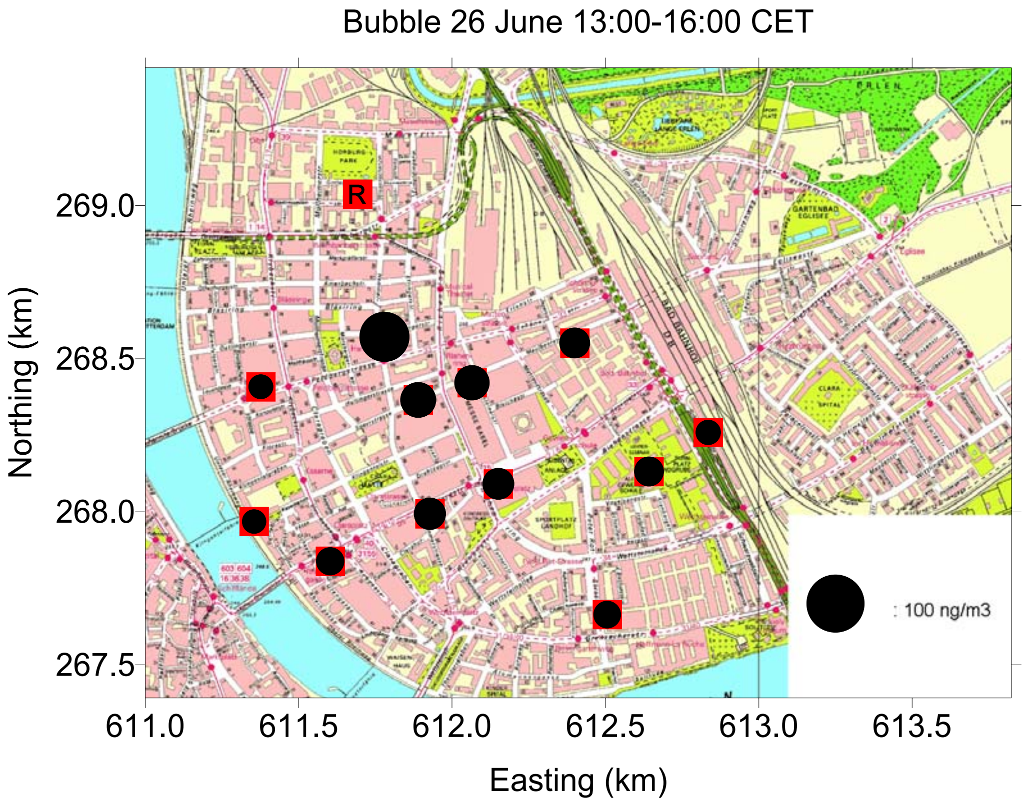


Figure 9 The tracer concentrations averaged over the period for the experiment on 26 June 2002, 13:00-16:00 CET. The release point is marked with R in a red square, at the tracer sampling positions the measured concentration is indicated with the area of the filled circle. For comparison a filled circle representing 100 ngm^{-3} is shown in the white box. Base map (c) copyright GVA BS, 25.10.2002.

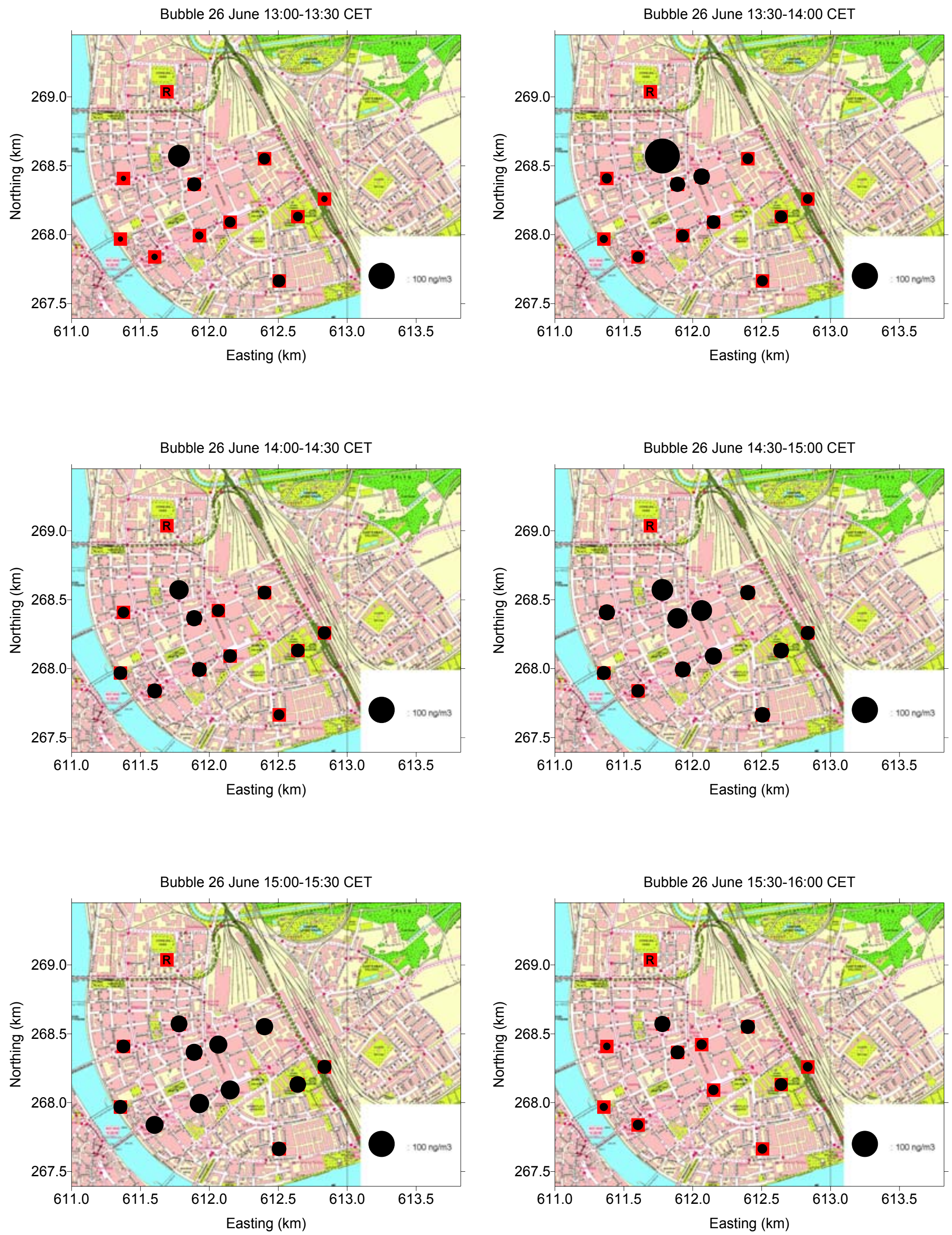


Figure 10 Illustration of the half-hourly averaged tracer concentrations for the experiment on 26 June 2002. For further details see the legend for Fig. 9. Base map (c) copyright GVA BS, 25.10.2002.

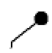
Figure 11 Following pages:

Meteorological information for June 26 2002 during the tracer release. Each page shows the information for one hour as indicated on top of the plot for the detailed wind field.

Top panels: Profiles of horizontal wind speed, wind direction and potential temperature between 270 m (~Surface) and 1200 m a.s.l. measured by the remote sensing instrumentation: RASS at "Basel-Kleinhüningen" (5, urban), 1280MHz Wind profiler at "Basel-Spalenring" (12, urban), SODAR at "Grenzach" (17, rural) and the tower measurements from the 250m TV tower at "St. Chrischona" (24).

Lower panels: Wind fields over the whole BUBBLE-Domain (upper map) and a subset of the city part where the tracer experiments took place (lower map). The surface measurements are performed at meteorological masts and represent usually the conditions between 10 and 30 metres above the ground level (for exact heights and numbers refer to Table 5). The release points are drawn with red colour. The wind barbs indicate wind speed and direction with the following convention (example: wind from SW):

Wind speed < 1 m/s

 *Short bar: 1 m/s*

 *Long bar: 2 m/s*

All times are indicated in CET and mark the end of a half hourly averaged period.

a) 12.00 – 13.00

b) 13.00 – 14.00

c) 14.00 – 15.00

d) 15.00 – 16.00

Base maps (inner domain): reproduction with authorization of the Swiss Federal Office of Topography, Wabern (BA024776).

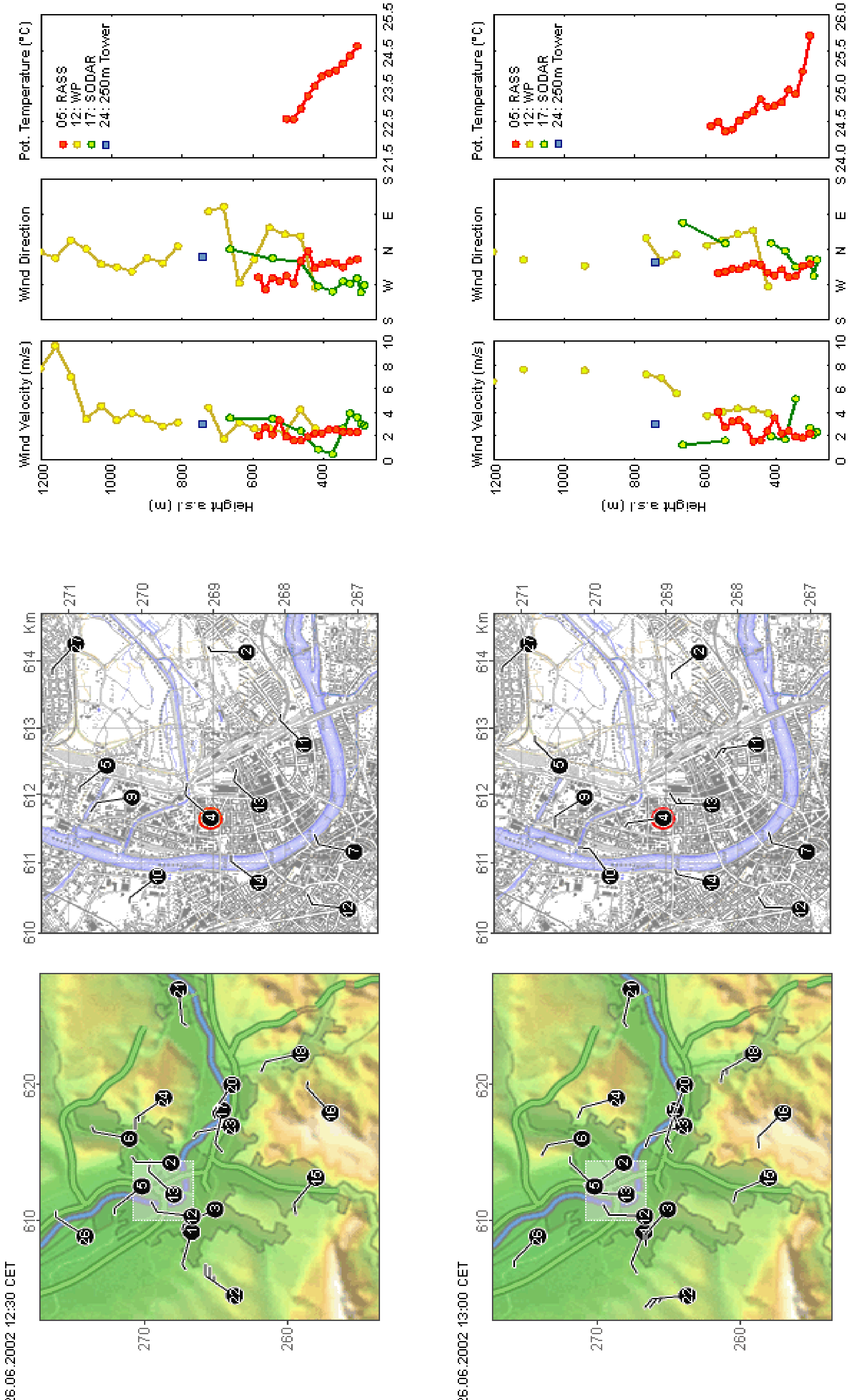


Figure 11a 12.00 – 13.00

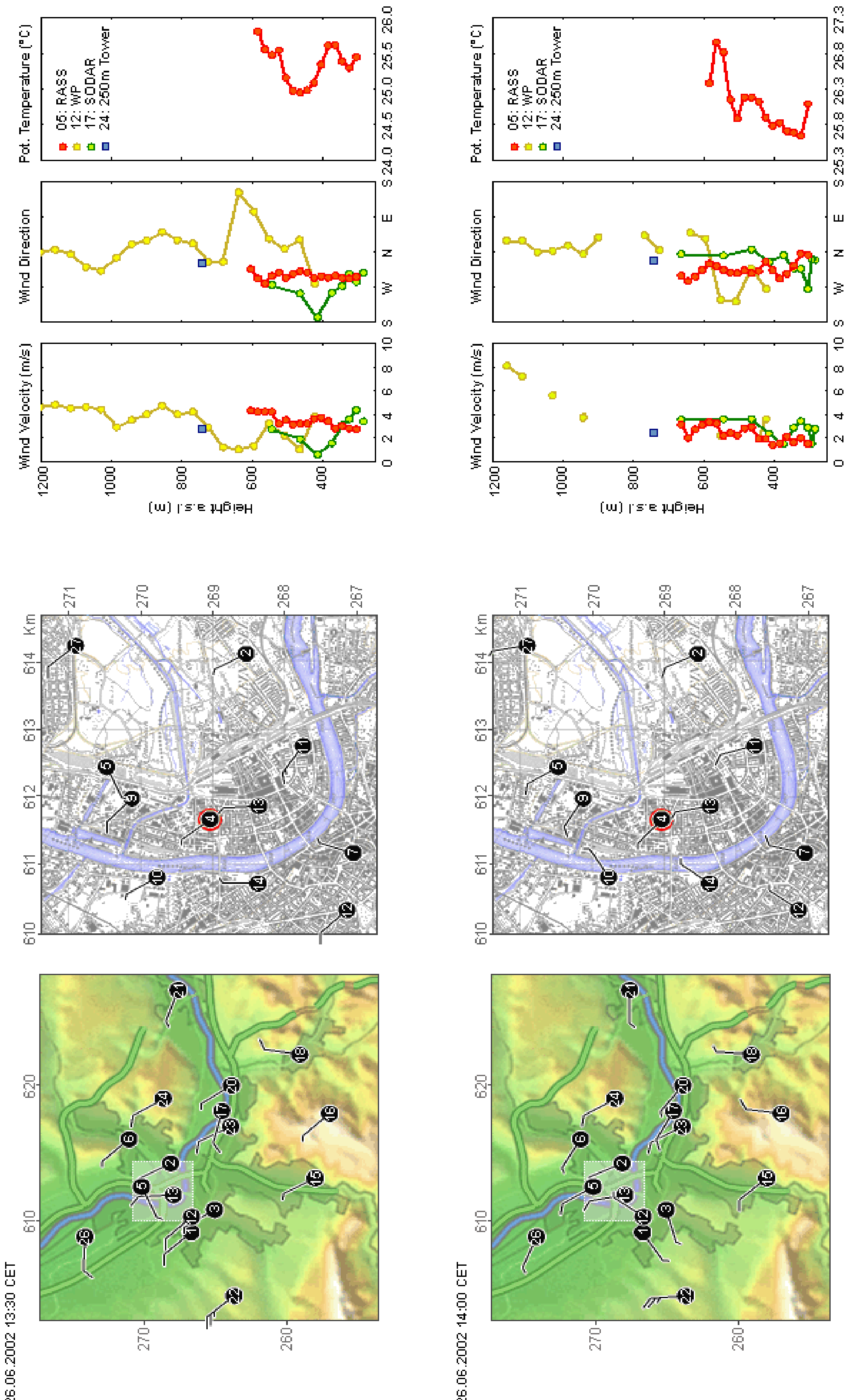


Figure 11b 13.00 – 14.00

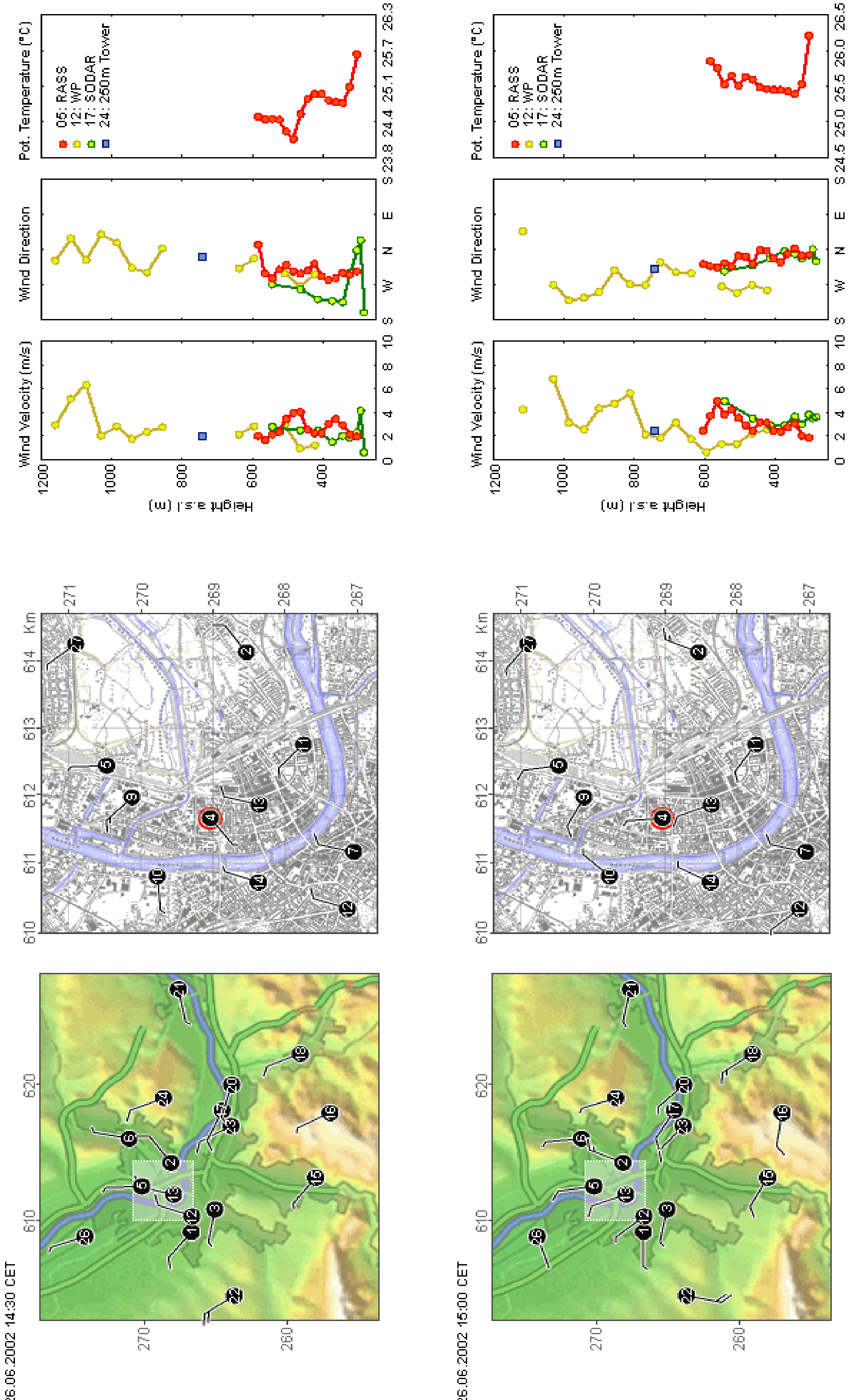


Figure 11c 14.00 – 15.00

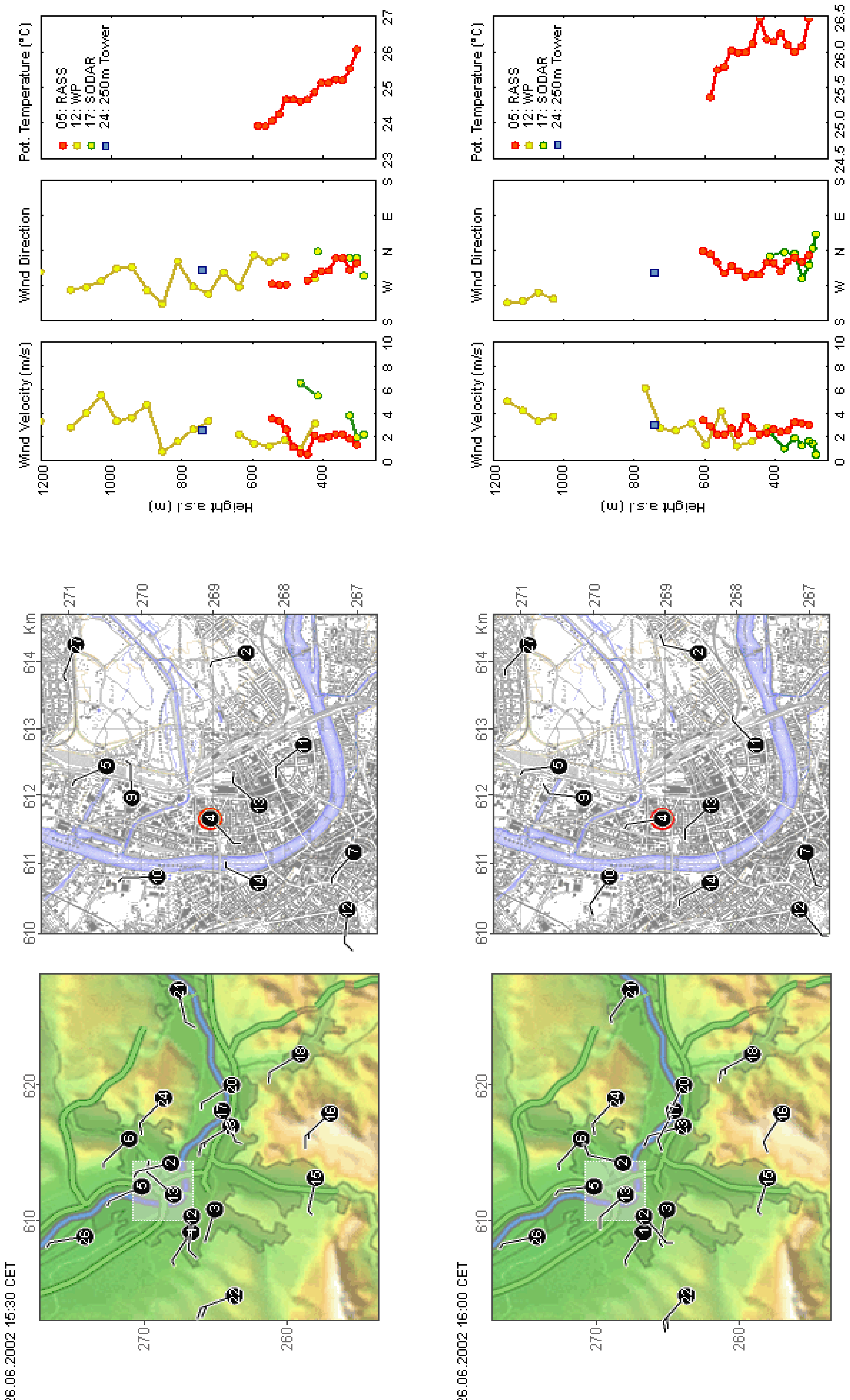


Figure 11d 15.00 – 16.00

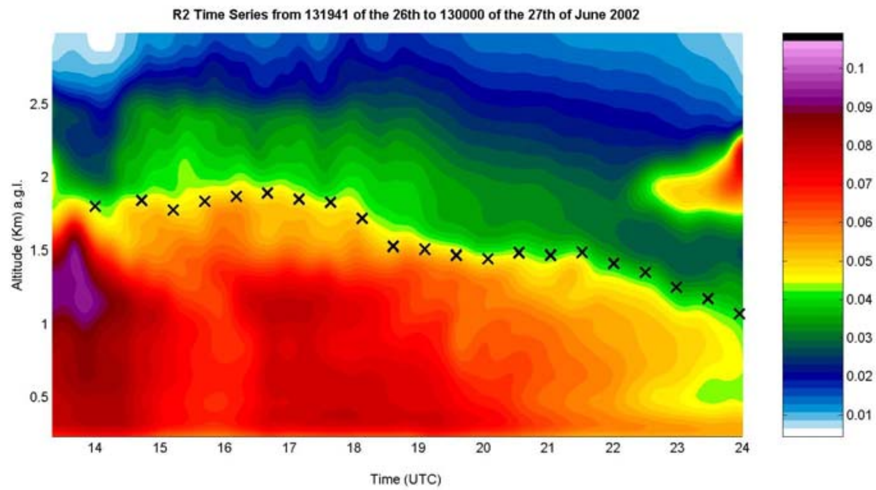


Figure 12 Lidar scans of the backscatter (colour code) from the atmosphere on 26 June 2002. The measurements are performed at "Basel-Spalenring" about 2 km southwest of the experimental area. The mixing height as determined from the derivative of the range-corrected signal is indicated by crosses. Note that the time in this figure – different from the rest of this report – is in UTC, rather than CET (=UTC+1). Tracer sampling was from 12:00 to 15:00 UTC.

Figure 13 following pages.

a) Standard meteorological parameters on June 26, 2002 from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Basel – Horburg (4, urban, release point R1), Allschwil-Rämelstrasse (1, suburban) and Village-Neuf (26, rural). The grey shaded period indicates the 3 hours of tracer sampling. Air pressure (upper most panel) is not converted to sea level. All times are indicated in CET.

b) The upper two plots illustrate net radiation and sensible heat flux from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Allschwil-Rämelstrasse (1, suburban), Grenzach (17, rural), Village-Neuf (26, rural). Sensible heat fluxes are calculated based on 30-min block averages. The third plot shows 30 min values of local Reynolds stress u_{*loc} (taking also lateral stress into account) and Monin-Obukov stability- (z-d)/L (unstable range only). Both time series are from the top measurement at Basel-Sperrstrasse (31.7m). The last row of plots shows vertical profiles of mean horizontal wind speed (blue profiles) at Basel-Sperrstrasse for each of the 30 min. sampling blocks of the experiment. Red profiles are local u_{*loc}. Both, wind speed and u_{*loc} were sampled by 6 ultrasonic anemometers on the tower. The mean height of the buildings in the whole tracer area is indicated by the grey shaded background (15.1m). All times are indicated in CET.

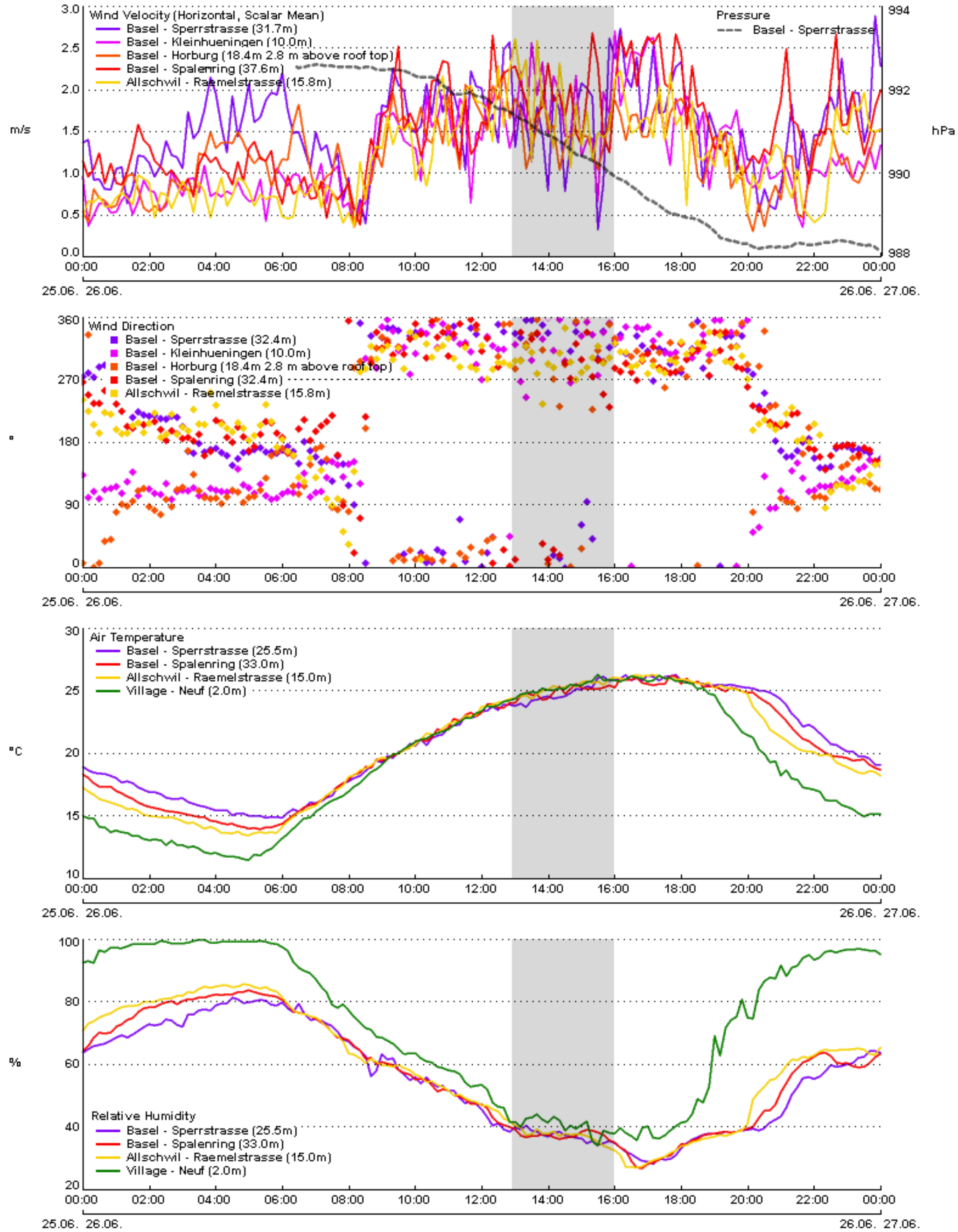

Wind Velocity (Horizontal, Scalar Mean)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Pressure
Basel - Sperrstrasse
m/s
hPa
Wind Direction
Basel - Sperrstrasse (32.4m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (32.4m)
Allschwil - Raemelstrasse (15.8m)
Air Temperature
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
°C
Relative Humidity
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
%
25.06. 26.06.
26.06. 27.06.

Figure 13a

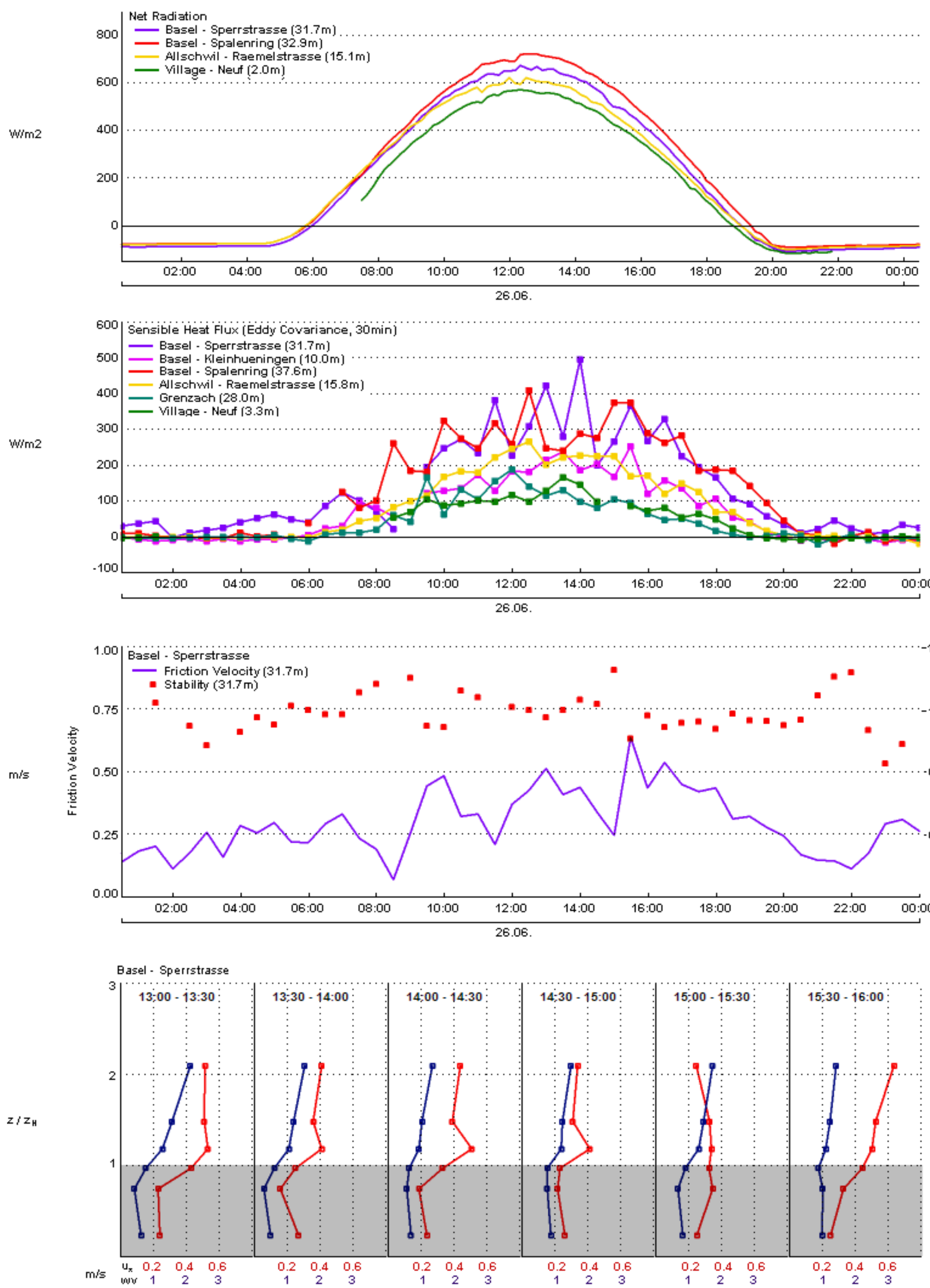

Net Radiation
Basel - Sperrstrasse (31.7m)
Basel - Spalenring (32.9m)
Allschwil - Raemelstrasse (15.1m)
Village - Neuf (2.0m)
W/m2
26.06.
Sensible Heat Flux (Eddy Covariance, 30min)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Grenzach (28.0m)
Village - Neuf (3.3m)
W/m2
26.06.
Basel - Sperrstrasse
Friction Velocity (31.7m)
Stability (31.7m)
Friction Velocity
m/s
Stability - (z-d) / L
26.06.
Basel - Sperrstrasse
13:00 - 13:30
13:30 - 14:00
14:00 - 14:30
14:30 - 15:00
15:00 - 15:30
15:30 - 16:00
z / zH
m/s

Figure 13b

3.2 Experiment on 4 July 2002

The experiment on 4 July was different in the sense that the usual release position was abandoned because the Clara Wind did not develop. The flow remained westerly throughout the afternoon. A cherry picker (lift) was borrowed from another BUBBLE experimental team and brought to Florastrasse (Figs. 2 and 4) to be used for the tracer release. It was placed in a blue parking zone. Tracer release was at 21m (z/h=1.4) from a pipe mounted on a tripod with a 3-meter extension that was placed in the cherry picker's basket 18m above the ground. The release was from 14:40 to 18:00 CET with sampling between 15:00 and 18:00 CET. Figures 14 and 15 illustrate the measured tracer concentrations. A mass flow controller controlled the release rate of 0.0499 gs^{-1} (corresponding to 500 ml/min). As illustrated in Figures 16 and 18 the wind direction was westerly and around 3.2 ms^{-1} at Basel-Sperrstrasse, 31m. The day was cloudy (Figs. 17 and 18). Taking the mixing height h from the lidar measurements (see Tab. 8), the kinematic heat flux $\left(\overline{w'T'}\right)$ and air temperature T from the measurements at Sperrstrasse, the convective velocity w_* can be estimated to 1.8 ms^{-1}.

Note that the 'friction velocity' as given in Figure 18b, third panel and fourth panel respectively, simply reflects the observations at the respective level, i.e.

$u_{*loc} = (\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$.

This definition does not take into account the direction of the momentum fluxes. In Section 4 it is shown how the profile information can be employed to derive a 'characteristic velocity' (which will be denoted $_*$).

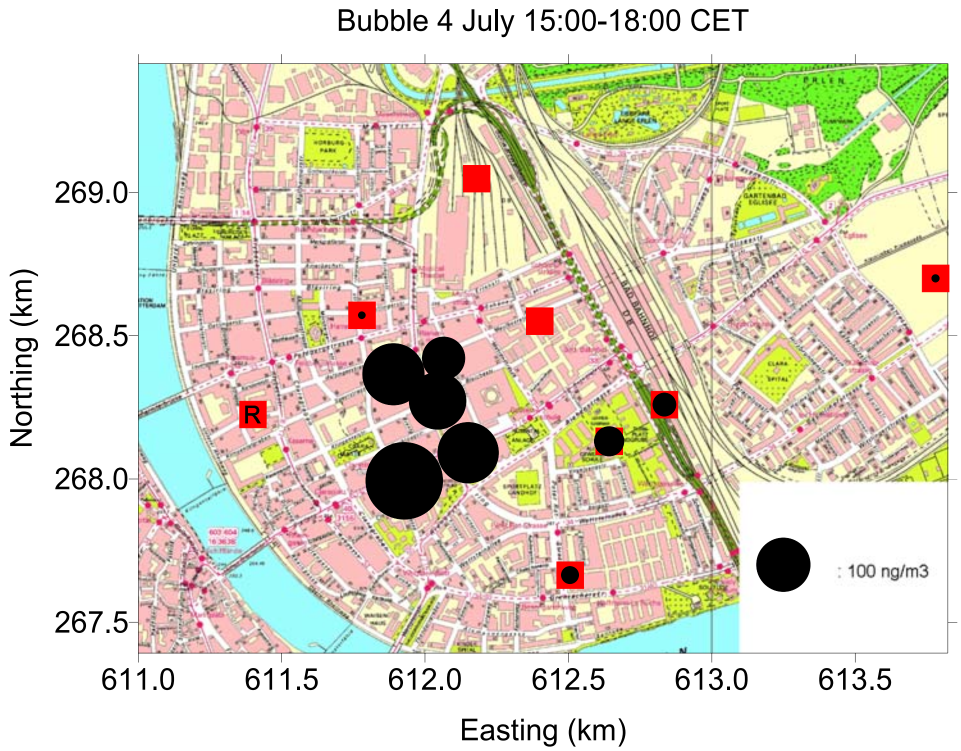


Figure 14 The tracer concentrations averaged over the period for the experiment on 4 July 2002, 15:00-18:00 CET. The release point is marked with R in a red square, at the tracer sampling positions the measured concentration is indicated with the area of the filled circle. For comparison a filled circle representing 100 ngm^{-3} is shown in the white box. Base map (c) copyright GVA BS, 25.10.2002.

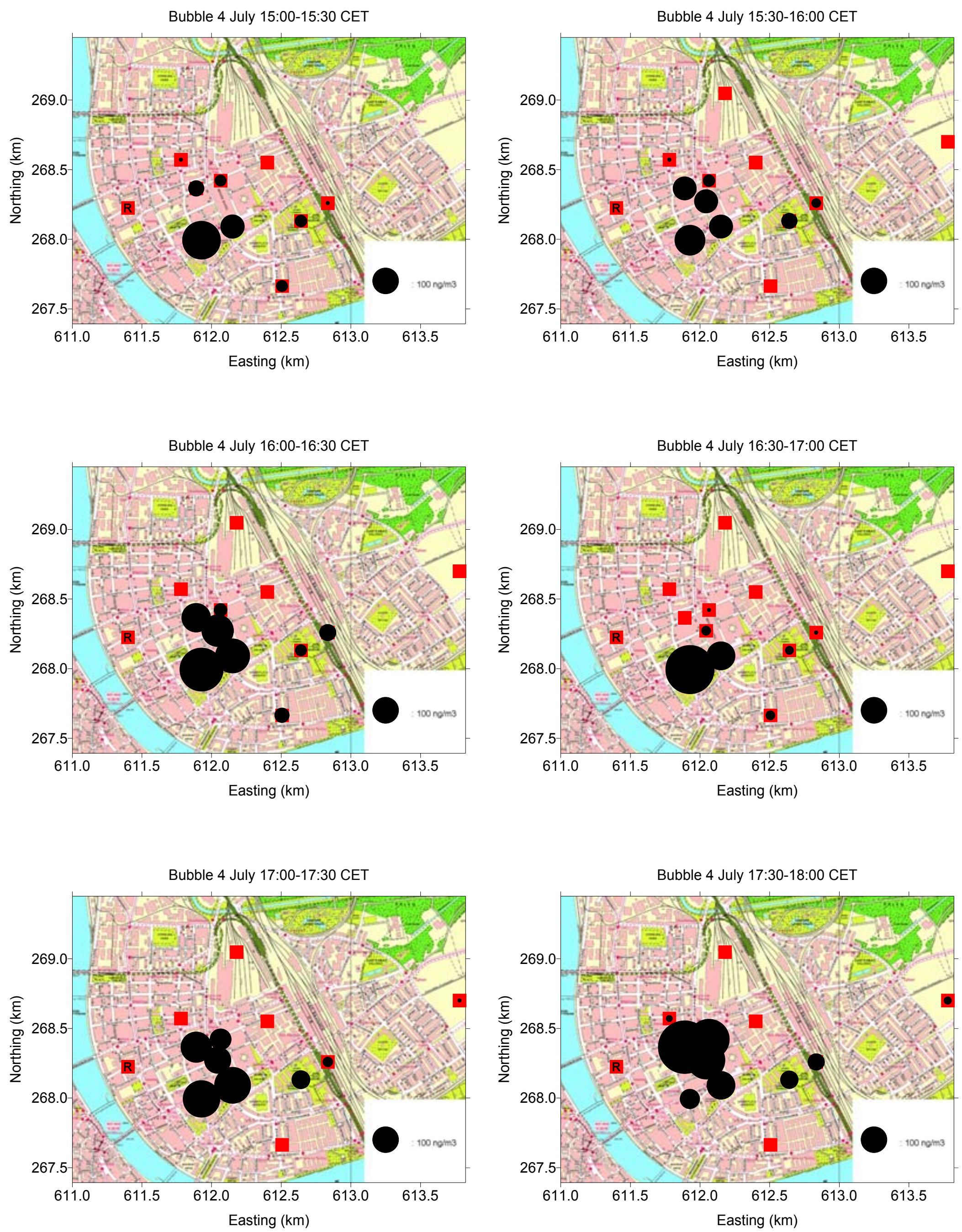


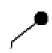
Figure 15 Illustration of the half-hourly averaged tracer concentrations for the experiment on 4 July 2002. Further details in the caption for Figure 14. Base map (c) copyright GVA BS, 25.10.2002.

Figure 16 Following pages:

Meteorological information for July 4 2002 during the tracer release. Each page shows the information for one hour as indicated on top of the plot for the detailed wind field.

Top panels: Profiles of horizontal wind speed, wind direction and potential temperature between 270 m (~Surface) and 1200 m a.s.l. measured by the remote sensing instrumentation: RASS at “Basel-Kleinhüningen” (5, urban), 1280MHz Wind profiler at “Basel-Spalenring” (12, urban), SODAR at “Grenzach” (17, rural) and the tower measurements from the 250m TV tower at “St. Chrischona” (24).

Lower panels: Wind fields over the whole BUBBLE-Domain (upper map) and a subset of the city part where the tracer experiments took place (lower map). The surface measurements are performed at meteorological masts and represent usually the conditions between 10 and 30 metres above the ground level (for exact heights and numbers refer to Table 5). The release points are drawn with red colour. The wind barbs indicate wind speed and direction with the following convention (example: wind from SW):

Wind speed < 1 m/s  *Short bar: 1 m/s*  *Long bar: 2 m/s*

All times are indicated in CET and mark the end of a half hourly averaged period.

a) 14.00 – 15.00

b) 15.00 – 16.00

c) 16.00 – 17.00

d) 17.00 – 18.00

Base maps (inner domain): reproduction with authorization of the Swiss Federal Office of Topography, Wabern (BA024776).

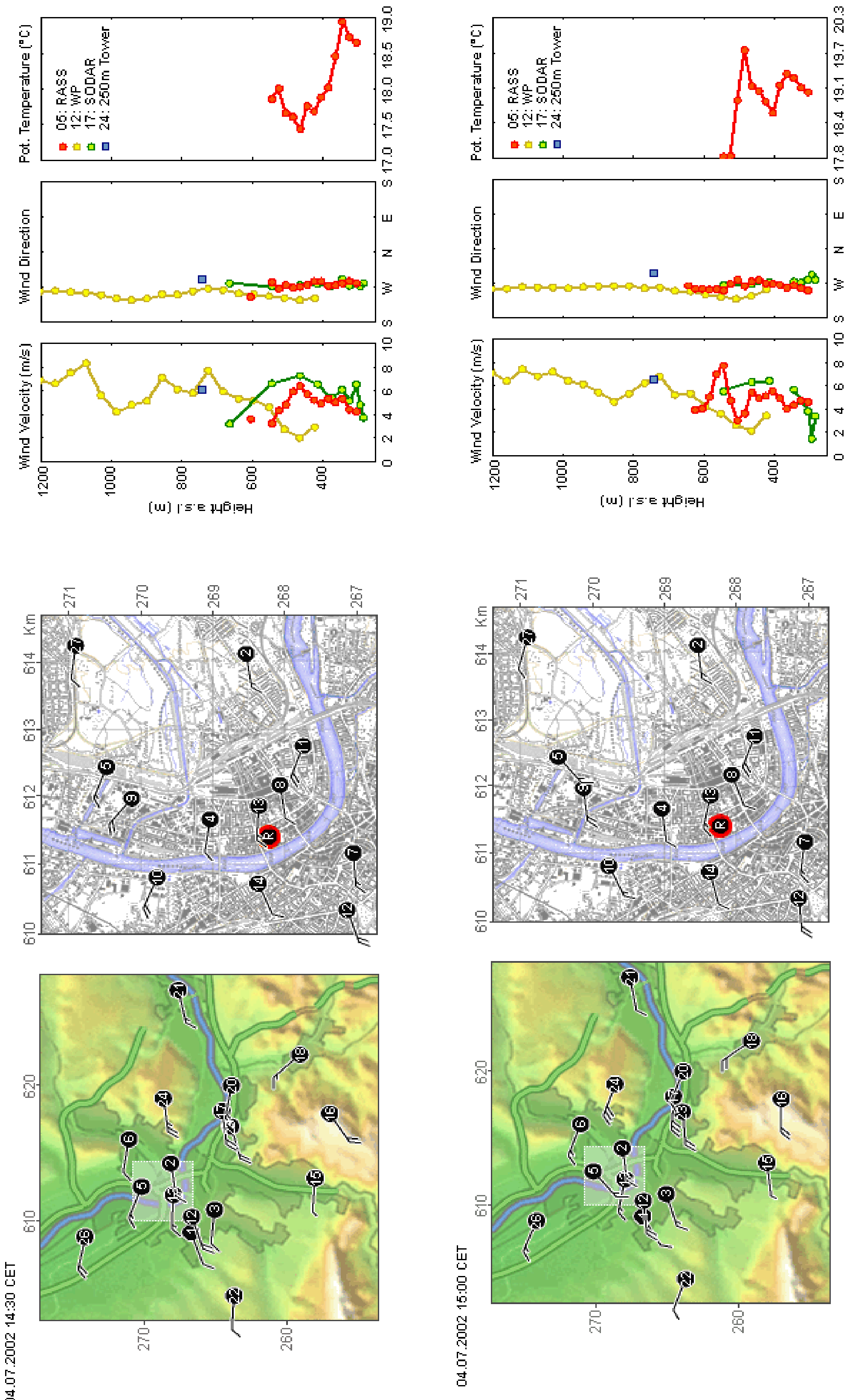


Figure 16a 14.00-15.00

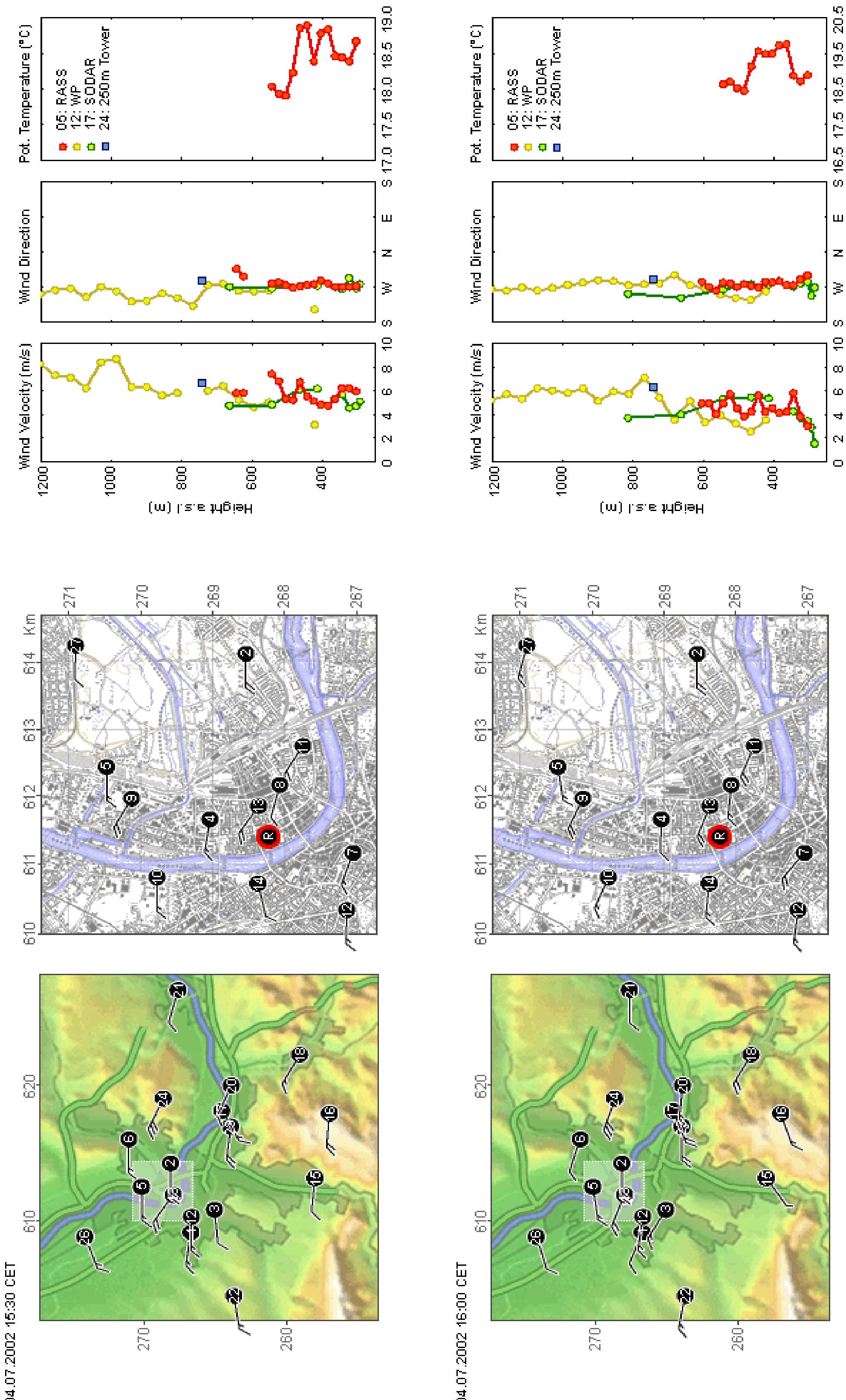


Figure 16b 15.00 – 16.00

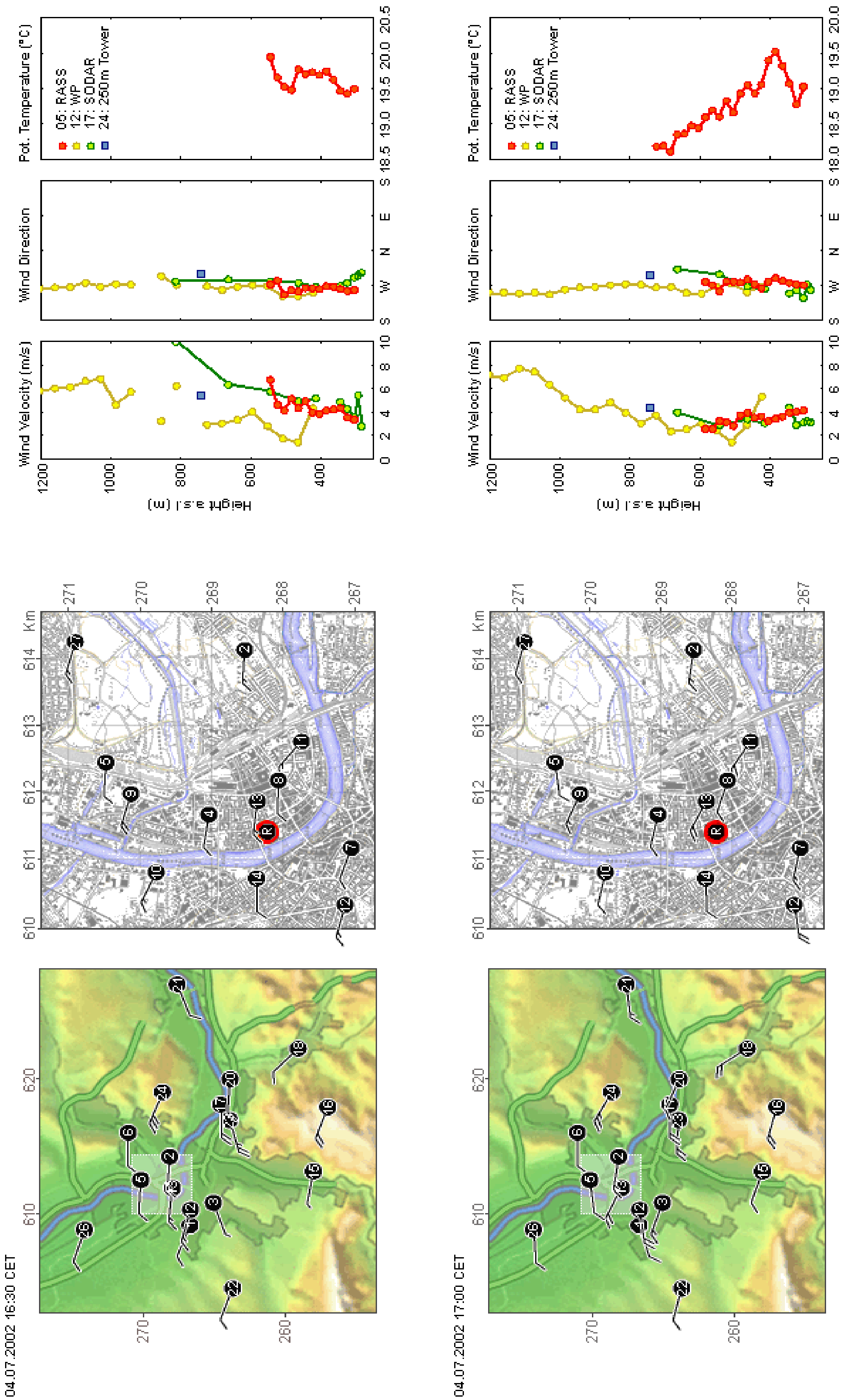


Figure 16c 16.00 –17.00

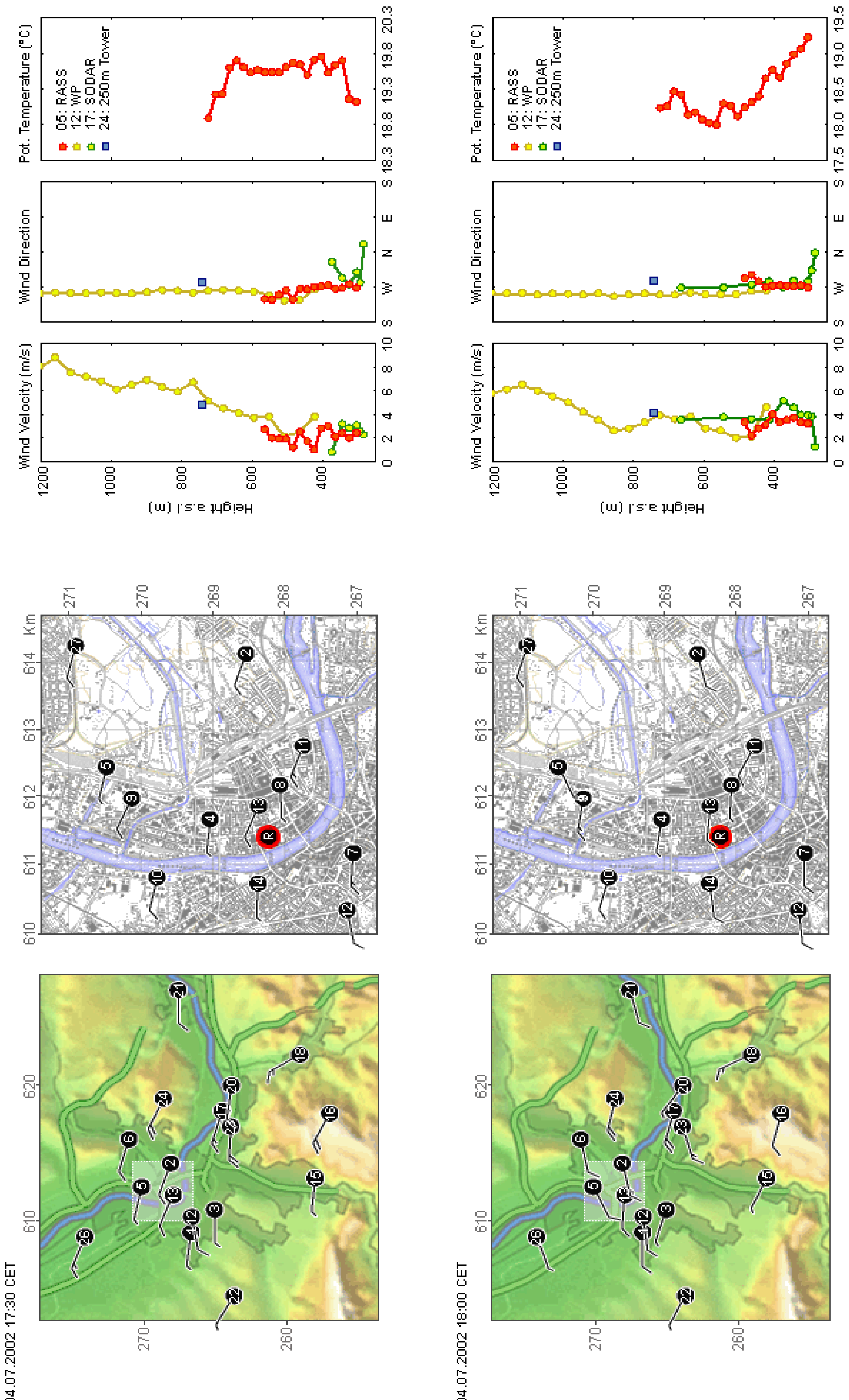


Figure 16d 17.00-18.00

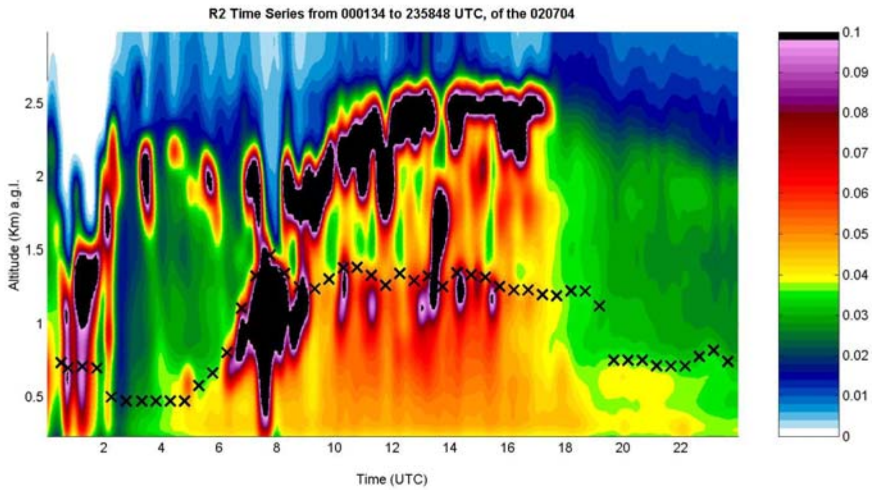
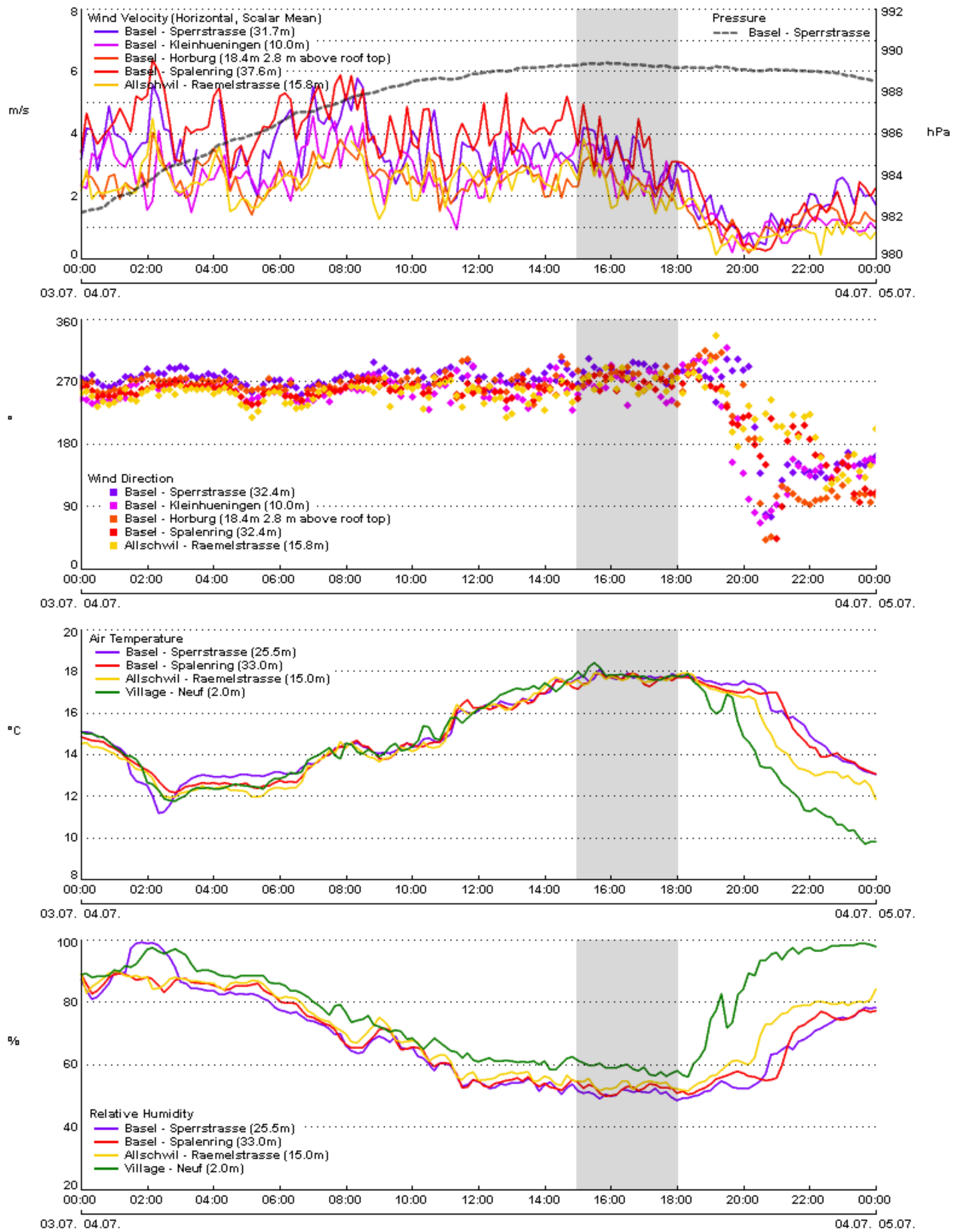


Figure 17 Lidar scans of the backscatter (color code) from the atmosphere on 4 July 2002. Tracer sampling was from 14:00 to 17:00 UTC.

Figure 18 Following pages

a) Standard meteorological parameters on July 4, 2002 from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Basel – Horburg (4, urban, release point R1), Allschwil-Rämelstrasse (1, suburban) and Village-Neuf (26, rural). The grey shaded period indicates the 3 hours of tracer sampling. Air pressure (upper most panel) is not converted to sea level. All times are indicated in CET.

b) The upper two plots illustrate net radiation and sensible heat flux from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Allschwil-Rämelstrasse (1, suburban), Grenzach (17, rural), Village-Neuf (26, rural). Sensible heat fluxes are calculated based on 30-min block averages. The third plot shows 30 min values of local Reynolds stress u_{*loc} (taking also lateral stress into account) and Monin-Obukov stability- (z-d)/L (unstable range only). Both time series are from the top measurement at Basel-Sperrstrasse (31.7m). The last row of plots shows vertical profiles of mean horizontal wind speed (blue profiles) at Basel-Sperrstrasse for each of the 30 min. sampling blocks of the experiment. Red profiles are local u_{*loc}. Both, wind speed and u_{*loc} were sampled by 6 ultrasonic anemometers on the tower. The mean height of the buildings in the whole tracer area is indicated by the grey shaded background (15.1m). All times are indicated in CET.



Wind Velocity (Horizontal, Scalar Mean)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Pressure
Basel - Sperrstrasse
m/s
hPa
Wind Direction
Basel - Sperrstrasse (32.4m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (32.4m)
Allschwil - Raemelstrasse (15.8m)
Air Temperature
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
°C
Relative Humidity
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
%
03.07. 04.07.
04.07. 05.07.

Figure 18a

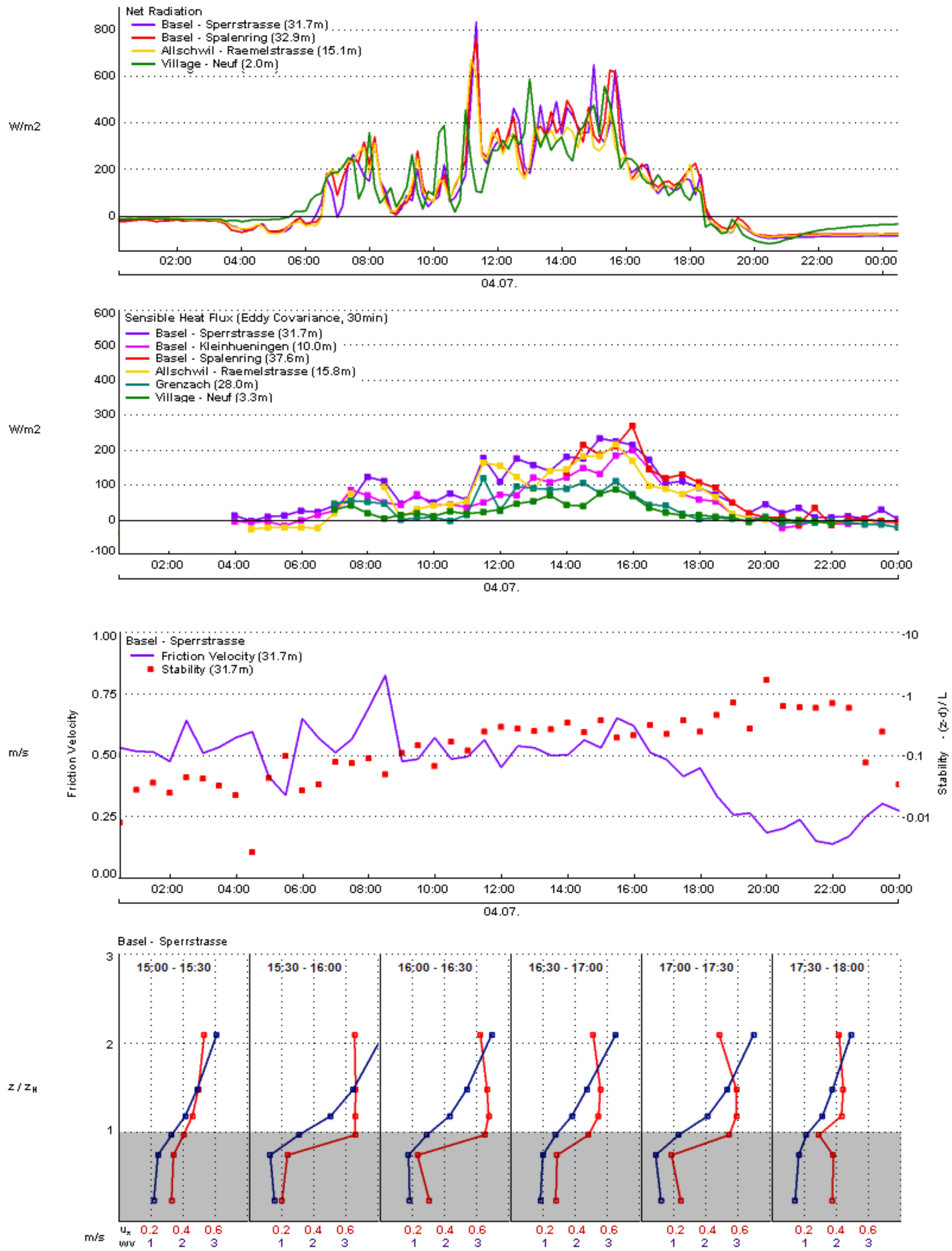

Net Radiation
Basel - Sperrstrasse (31.7m)
Basel - Spalenring (32.9m)
Allschwil - Raemelstrasse (15.1m)
Village - Neuf (2.0m)
W/m2
04.07.
Sensible Heat Flux (Eddy Covariance, 30min)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Grenzach (28.0m)
Village - Neuf (3.3m)
W/m2
04.07.
Basel - Sperrstrasse
Friction Velocity (31.7m)
Stability (31.7m)
Friction Velocity
m/s
Stability - (z-d) / L
04.07.
Basel - Sperrstrasse
15:00 - 15:30
15:30 - 16:00
16:00 - 16:30
16:30 - 17:00
17:00 - 17:30
17:30 - 18:00
z / zH
m/s
u*
wv

Figure 18b

3.3 *Experiment on 7 July 2002*

The experiment on 7 July was performed with a tracer release of 0.3008gs^{-1} between 13:10 and 17:00 CET with tracer sampling 14:00-17:00 CET. It was a partly cloudy day (Figs. 22 and 23). Although the conditions were favourable for the development of a Clara Wind situation, the wind remained somewhat westerly (Fig. 21) and the tracer plume only partly covered the tracer unit sampling set-up until about 13 CET when the wind direction turned slightly towards north-west as it is typical for the Clara Wind (Fig. 21 and 23). Mixing height can be seen on Figure 22 to be approximately 1.9 km. Taking the heat flux and air temperature from the measurements at Sperrstrasse (Tab. 10) then w_* becomes 2.25 ms^{-1}.

Note that the 'friction velocity' as given in Figure 23b, third panel and fourth panel respectively, simply reflects the observations at the respective level, i.e.

$$u_{*loc} = (\overline{u'w'}^{2} + \overline{v'w'}^{2})^{1/4}.$$

This definition does not take into account the direction of the momentum fluxes. In Section 4 it is shown how the profile information can be employed to derive a 'characteristic velocity' (which will be denoted $_*$).

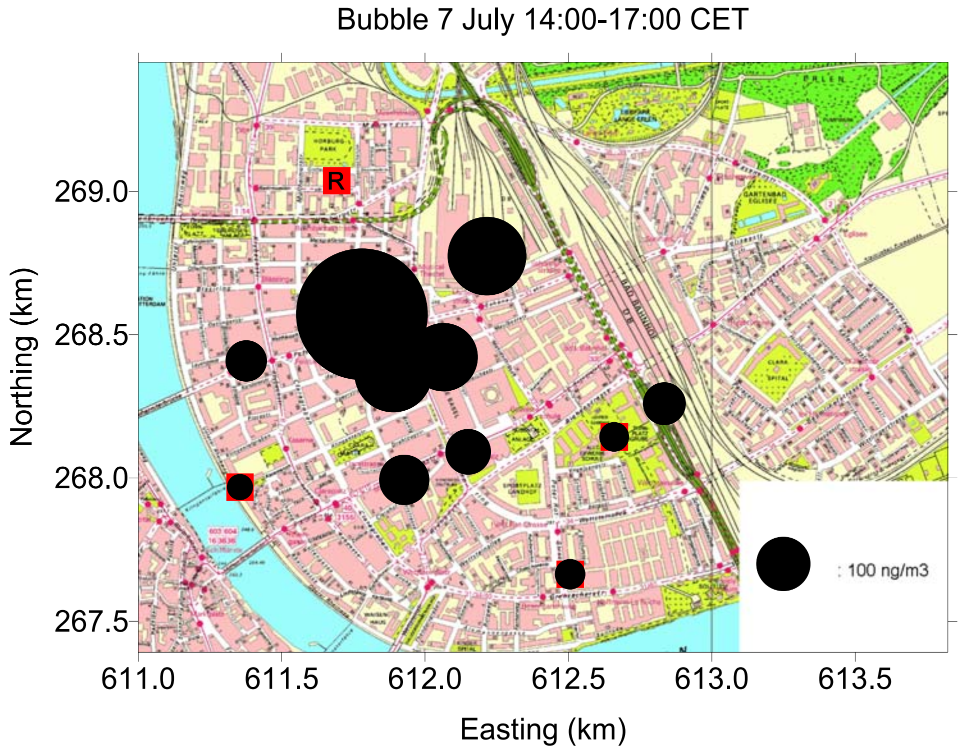


Figure 19 The tracer concentrations averaged over the period for the experiment on 7 July 2002, 14:00-17:00 CET. The release point is marked with R in a red square, at the tracer sampling positions the measured concentration is indicated with the area of the filled circle. For comparison a filled circle representing 100 ngm^{-3} is shown in the white box. Base map (c) copyright GVA BS, 25.10.2002.

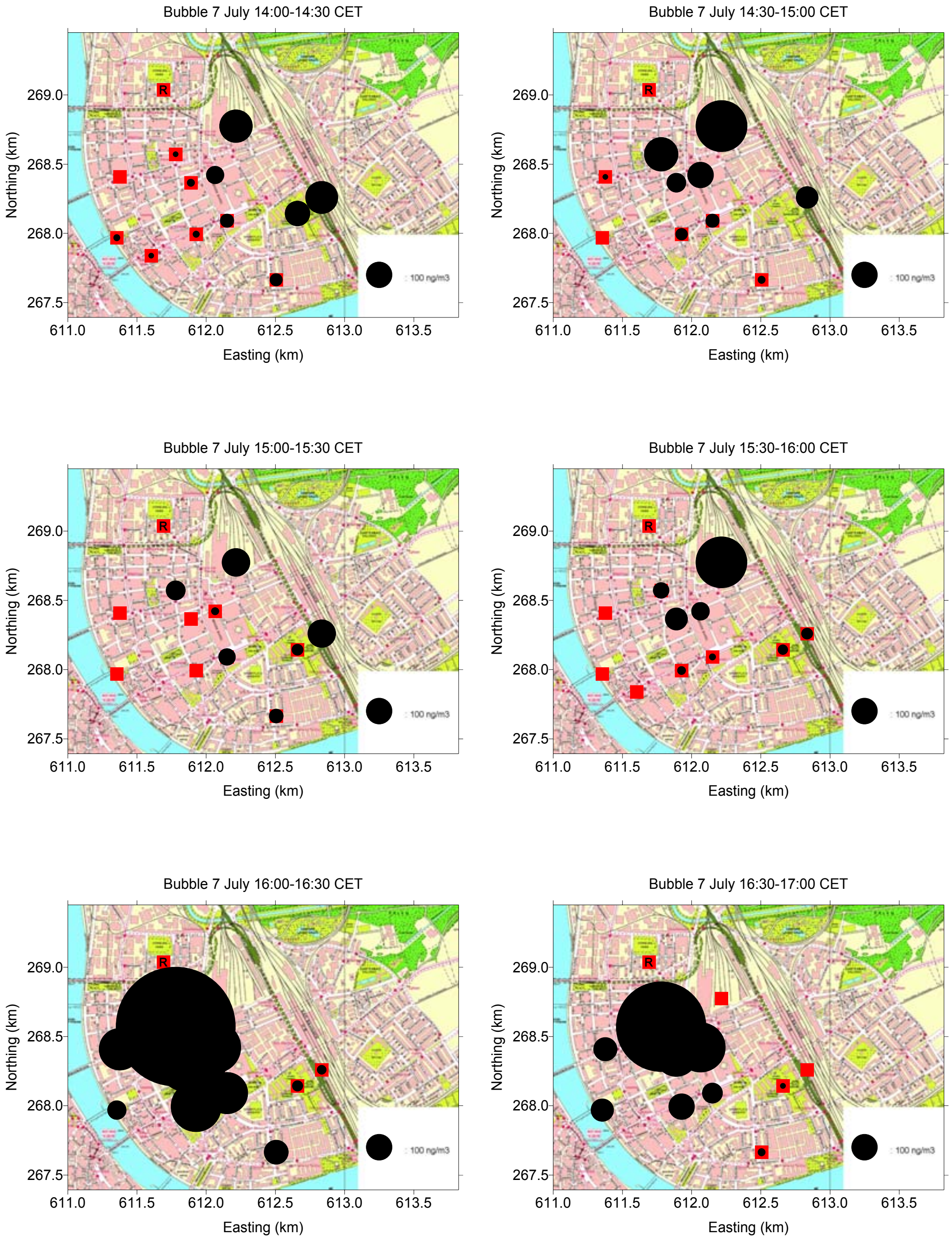


Figure 20 Illustration of the half-hourly averaged tracer concentrations for the experiment on 7 July 2002. Further details in the legend for Figure 19. Base map (c) copyright GVA BS, 25.10.2002.

Figure 21 Following pages:

Meteorological information for July 7 2002 during the tracer release. Each page shows the information for one hour as indicated on top of the plot for the detailed wind field.

Top panels: Profiles of horizontal wind speed, wind direction and potential temperature between 270 m (~Surface) and 1200 m a.s.l. measured by the remote sensing instrumentation: RASS at “Basel-Kleinhüningen” (5, urban), 1280MHz Wind profiler at “Basel-Spalenring” (12, urban), SODAR at “Grenzach” (17, rural) and the tower measurements from the 250m TV tower at “St. Chrischona” (24).

Lower panels: Wind fields over the whole BUBBLE-Domain (upper map) and a subset of the city part where the tracer experiments took place (lower map). The surface measurements are performed at meteorological masts and represent usually the conditions between 10 and 30 metres above the ground level (for exact heights and numbers refer to Table 5). The release points are drawn with red colour. The wind barbs indicate wind speed and direction with the following convention (example: wind from SW):

Wind speed < 1 m/s *Short bar: 1 m/s* *Long bar: 2 m/s*

All times are indicated in CET and mark the end of a half hourly averaged period.

a) 13.00 – 14.00

b) 14.00 – 15.00

c) 15.00 – 16.00

d) 16.00 – 17.00

Base maps (inner domain): reproduction with authorization of the Swiss Federal Office of Topography, Wabern (BA024776).

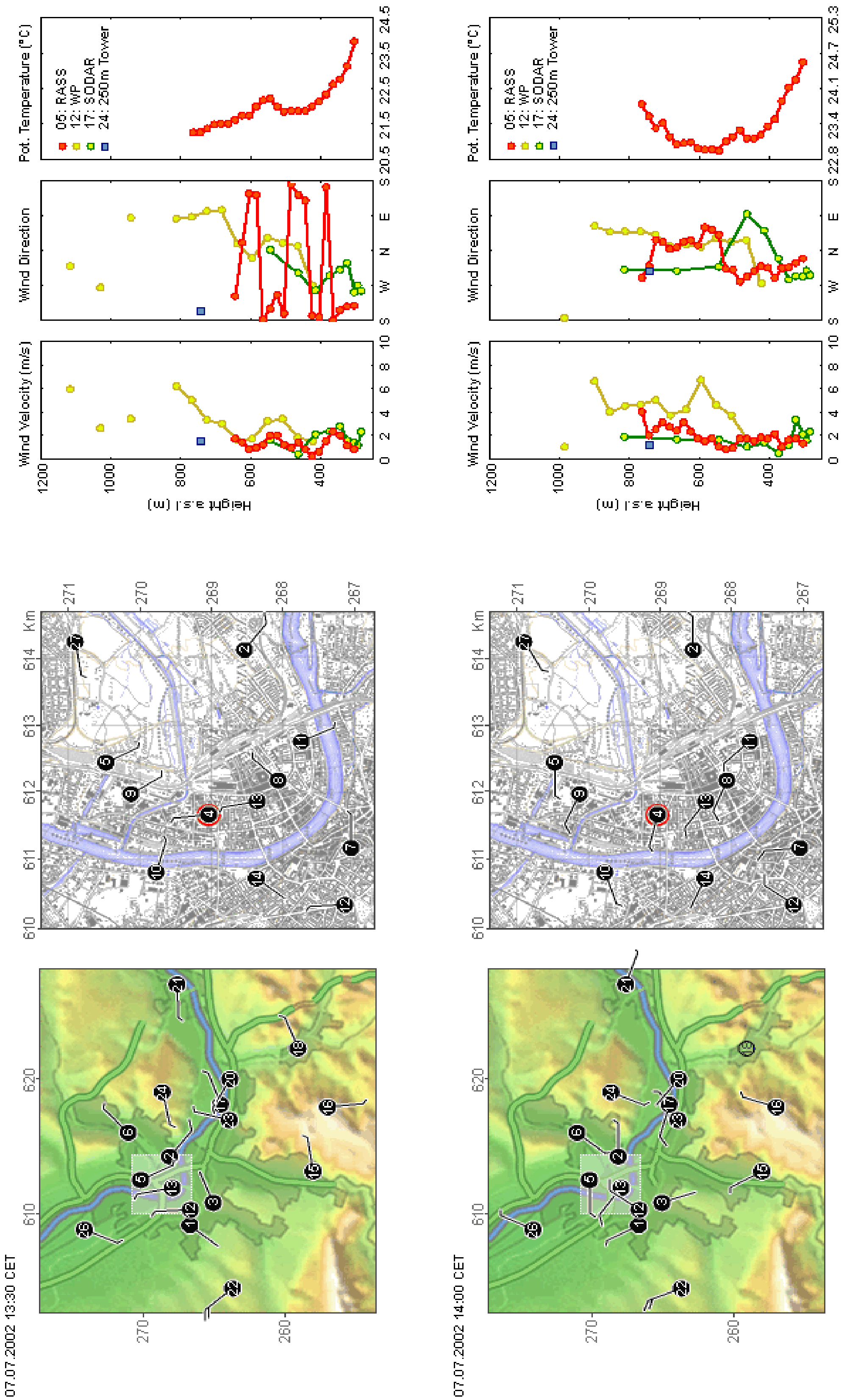


Figure 21a 13.00 – 14.00

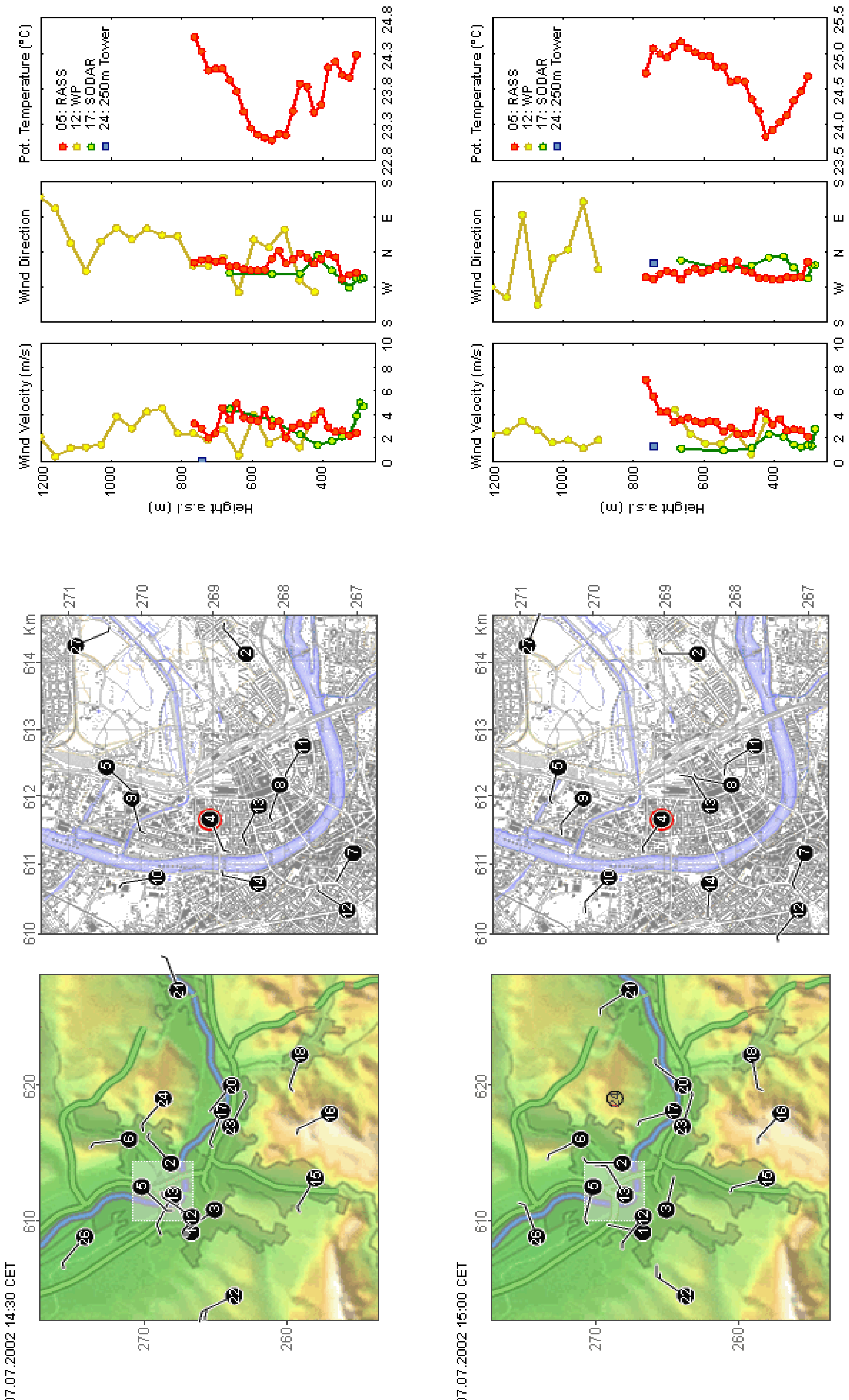


Figure 21b 14.00 – 15.00

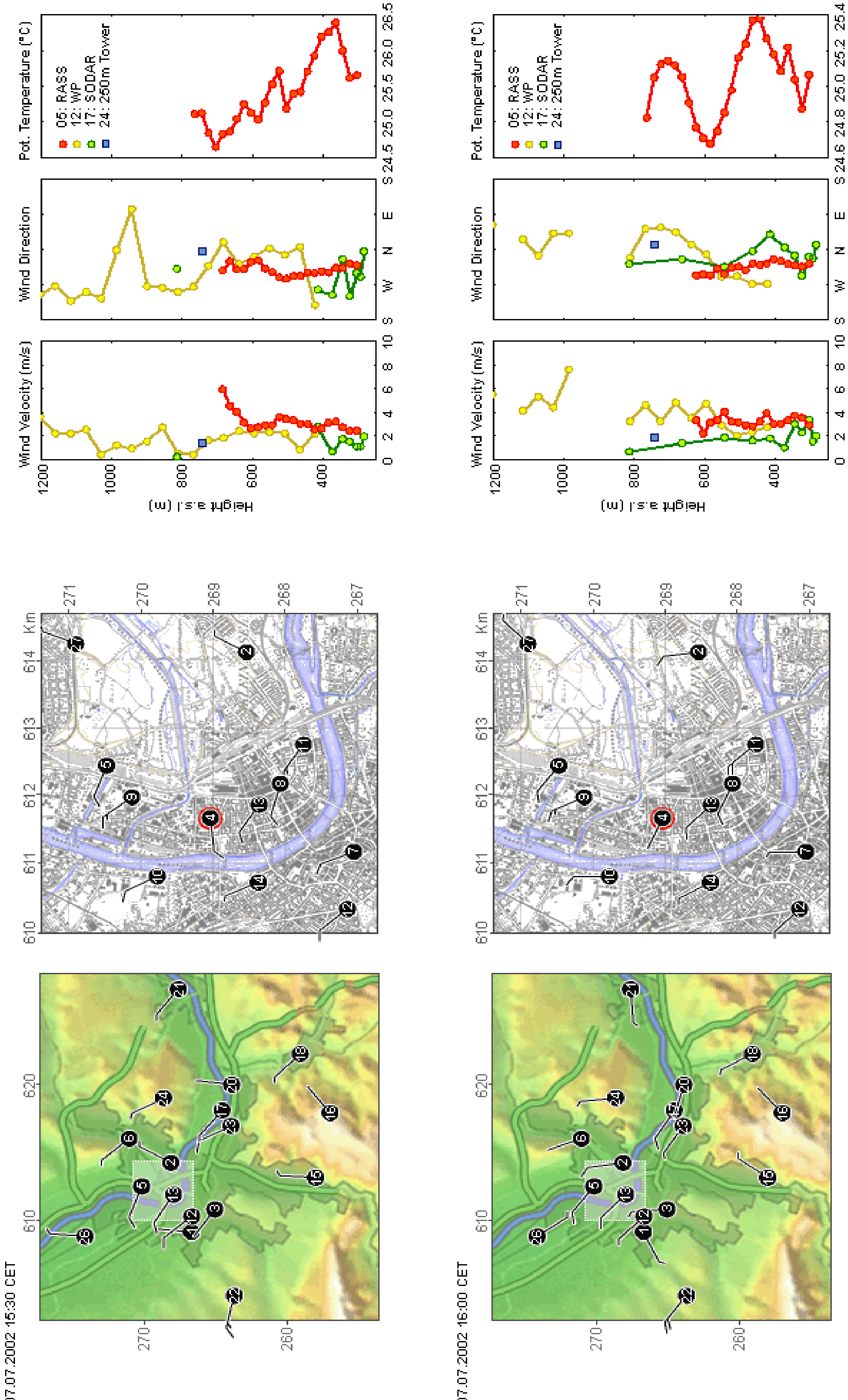


Figure 21c 15.00 – 16.00

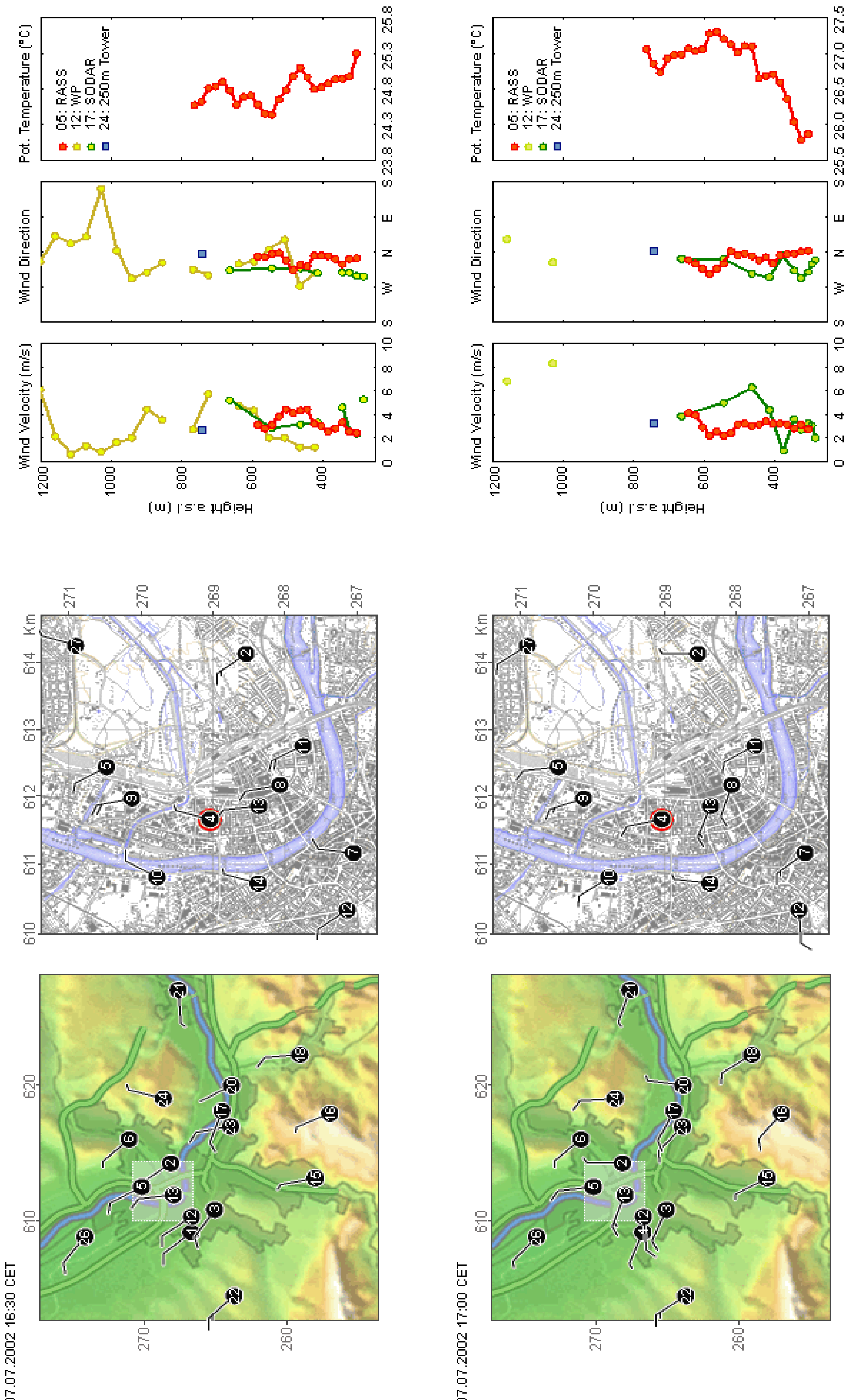


Figure 21d 16.00 – 17.00

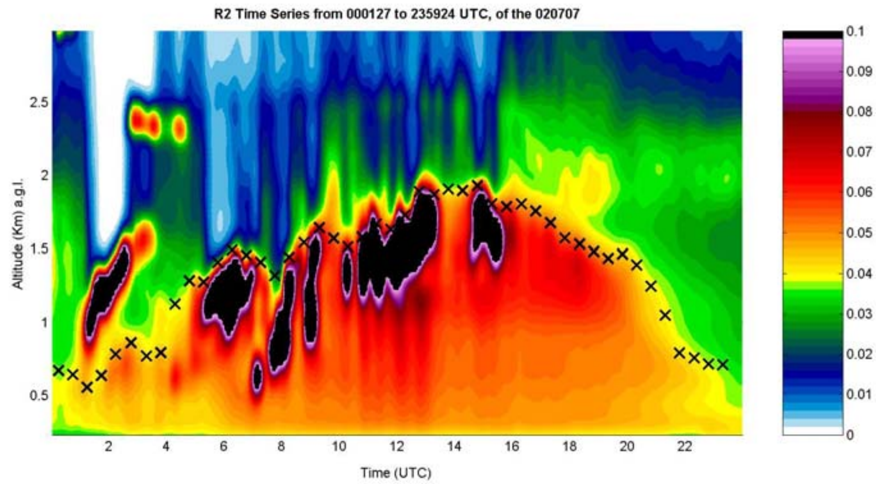


Figure 22 Lidar scans of the backscatter from the atmosphere on 7 July 2002. Tracer sampling was from 13:00 to 16:00 UTC.

Figure 23 Following pages

a) Standard meteorological parameters on July 7, 2002 from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Basel – Horburg (4, urban, release point R1), Allschwil-Rämelstrasse (1, suburban) and Village-Neuf (26, rural). The grey shaded period indicates the 3 hours of tracer sampling. Air pressure (upper most panel) is not converted to sea level. All times are indicated in CET.

b) The upper two plots illustrate net radiation and sensible heat flux from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Allschwil-Rämelstrasse (1, suburban), Grenzach (17, rural), Village-Neuf (26, rural). Sensible heat fluxes are calculated based on 30-min block averages. The third plot shows 30 min values of local Reynolds stress u_{*loc} (taking also lateral stress into account) and Monin-Obukov stability- (z-d)/L (unstable range only). Both time series are from the top measurement at Basel-Sperrstrasse (31.7m). The last row of plots shows vertical profiles of mean horizontal wind speed (blue profiles) at Basel-Sperrstrasse for each of the 30 min. sampling blocks of the experiment. Red profiles are local u_{*loc}. Both, wind speed and u_{*loc} were sampled by 6 ultrasonic anemometers on the tower. The mean height of the buildings in the whole tracer area is indicated by the grey shaded background (15.1m). All times are indicated in CET.

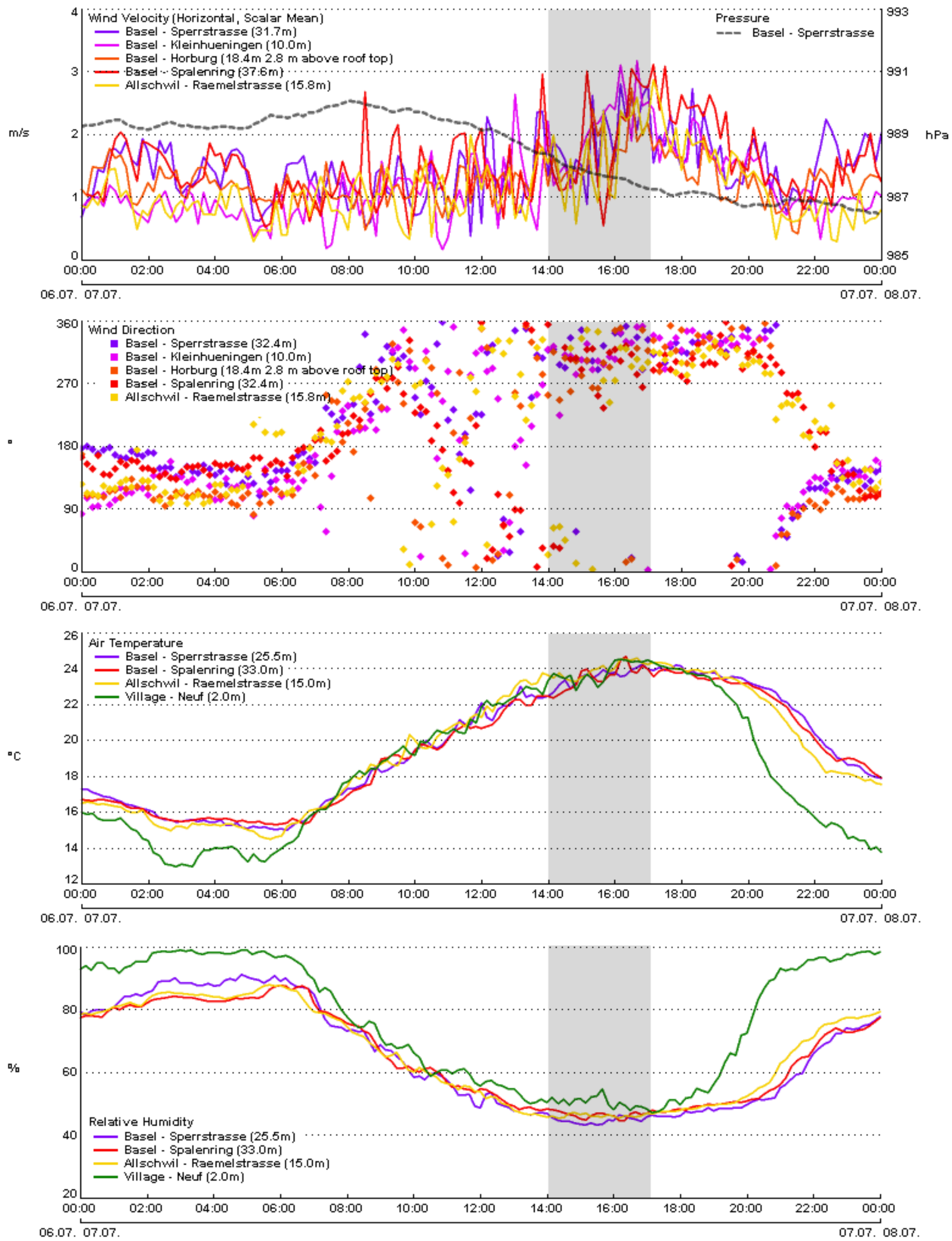

Wind Velocity (Horizontal, Scalar Mean)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Pressure
Basel - Sperrstrasse
m/s
hPa
Wind Direction
Basel - Sperrstrasse (32.4m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (32.4m)
Allschwil - Raemelstrasse (15.8m)
°
Air Temperature
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
°C
Relative Humidity
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
%
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00
06.07. 07.07.
07.07. 08.07.

Figure 23a

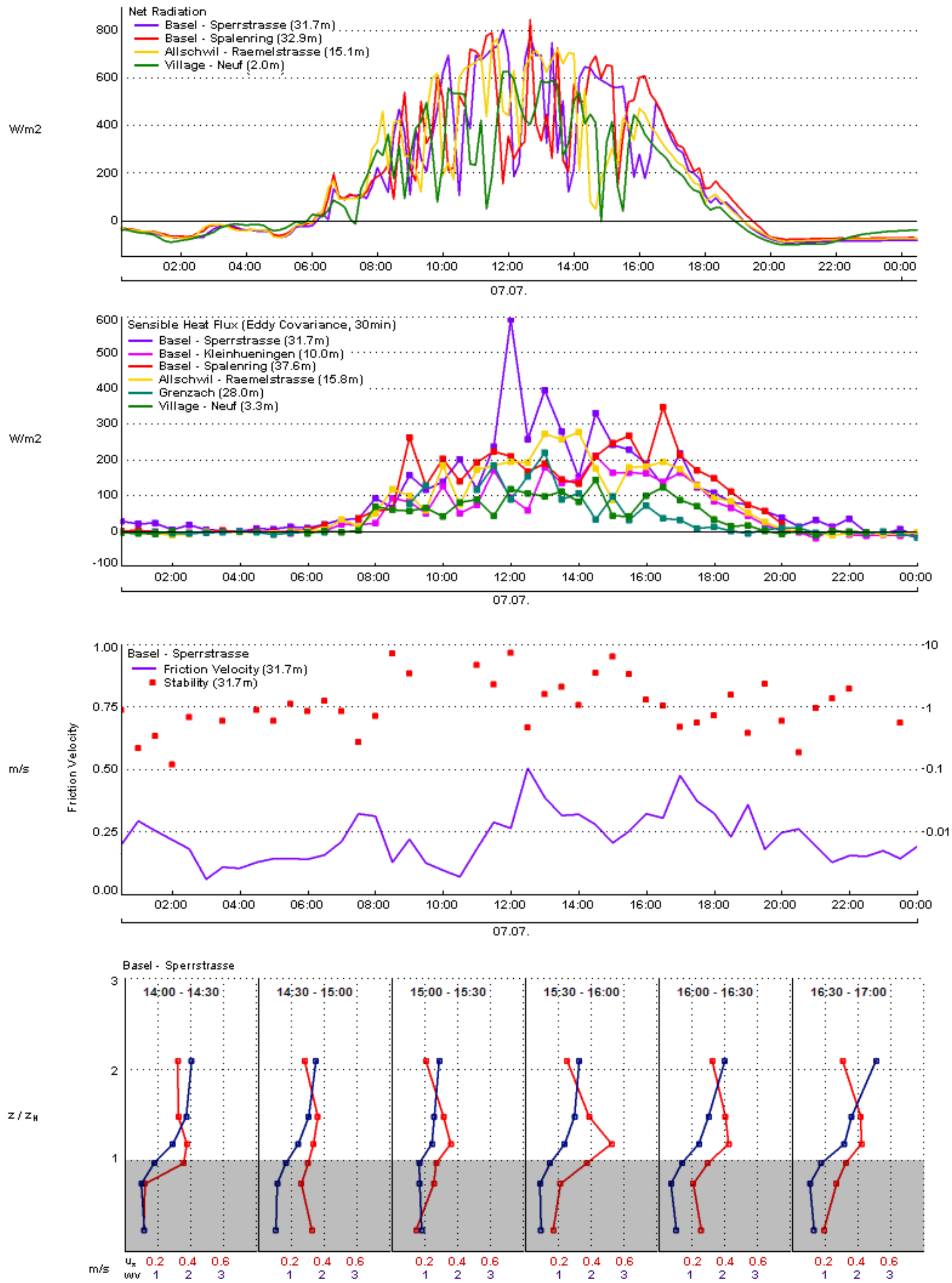

Net Radiation
Basel - Sperrstrasse (31.7m)
Basel - Spalenring (32.9m)
Allschwil - Raemelstrasse (15.1m)
Village - Neuf (2.0m)
W/m2
07.07.
Sensible Heat Flux (Eddy Covariance, 30min)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Grenzach (28.0m)
Village - Neuf (3.3m)
W/m2
07.07.
Basel - Sperrstrasse
Friction Velocity (31.7m)
Stability (31.7m)
m/s
Friction Velocity
Stability - (z-d) / L
07.07.
Basel - Sperrstrasse
14:00 - 14:30
14:30 - 15:00
15:00 - 15:30
15:30 - 16:00
16:00 - 16:30
16:30 - 17:00
z / zH
m/s

Figure 23b

3.4 Experiment on 8 July 2002

The experiment on 8 July was performed with a tracer release rate of 0.1319gs^{-1} between 14:00 -18:00 CET with tracer sampling 15:00-18:00 CET (Figs. 24-25). It was a clear day except for a few clouds around 15 CET (Fig. 28). The conditions were thus favourable for the development of a Clara Wind, which also developed but became westerly (Fig. 28) during the last part of the experiment. Mixing height can be seen on Figure 27 to be around 1.3 km. Taking the heat flux and air temperature from the measurements at Sperrstrasse (Tab. 12) then w_* becomes 1.86 ms^{-1}.

Note that the ‘friction velocity’ as given in Figure 28b, third panel and fourth panel respectively, simply reflects the observations at the respective level, i.e.

$$u_{*loc} = (\overline{u'w'}^{2} + \overline{v'w'}^{2})^{1/4} .$$

This definition does not take into account the direction of the momentum fluxes. In Section 4 it is shown how the profile information can be employed to derive a ‘characteristic velocity’ (which will be denoted $_*$).

Bubble8 July 15:00-18:00 CET

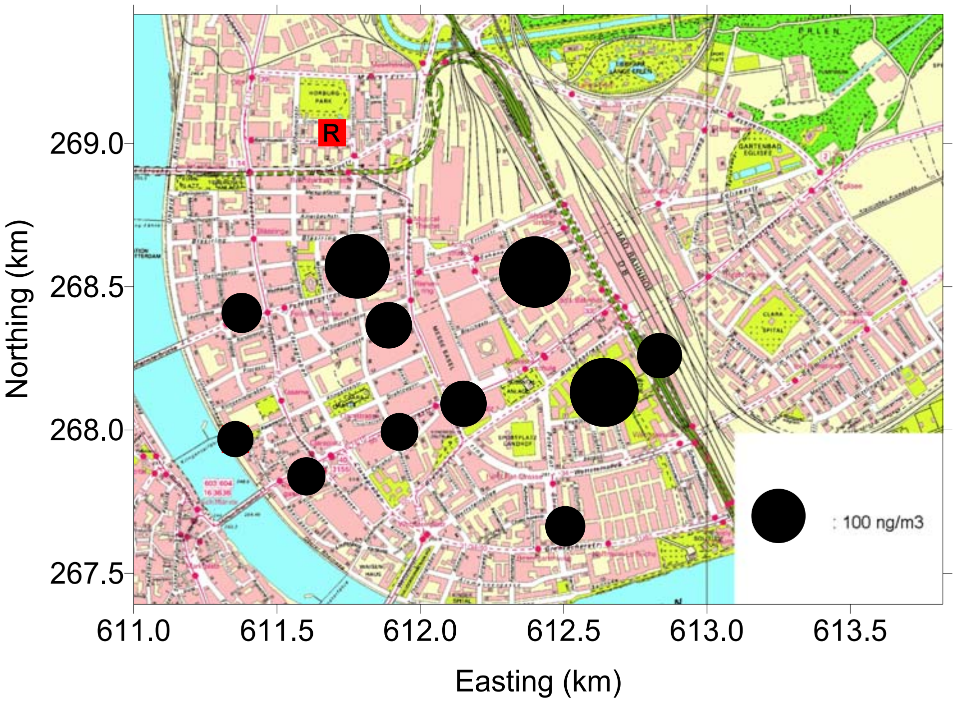


Figure 24 The tracer concentrations averaged over the period for the experiment on 8 July 2002, 15-18 CET. The release point is marked with R in a red square, at the tracer sampling positions the measured concentration is indicated with the area of the filled circle. For comparison a filled circle representing 100 ngm^{-3} is shown in the white box. Base map (c) copyright GVA BS, 25.10.2002.

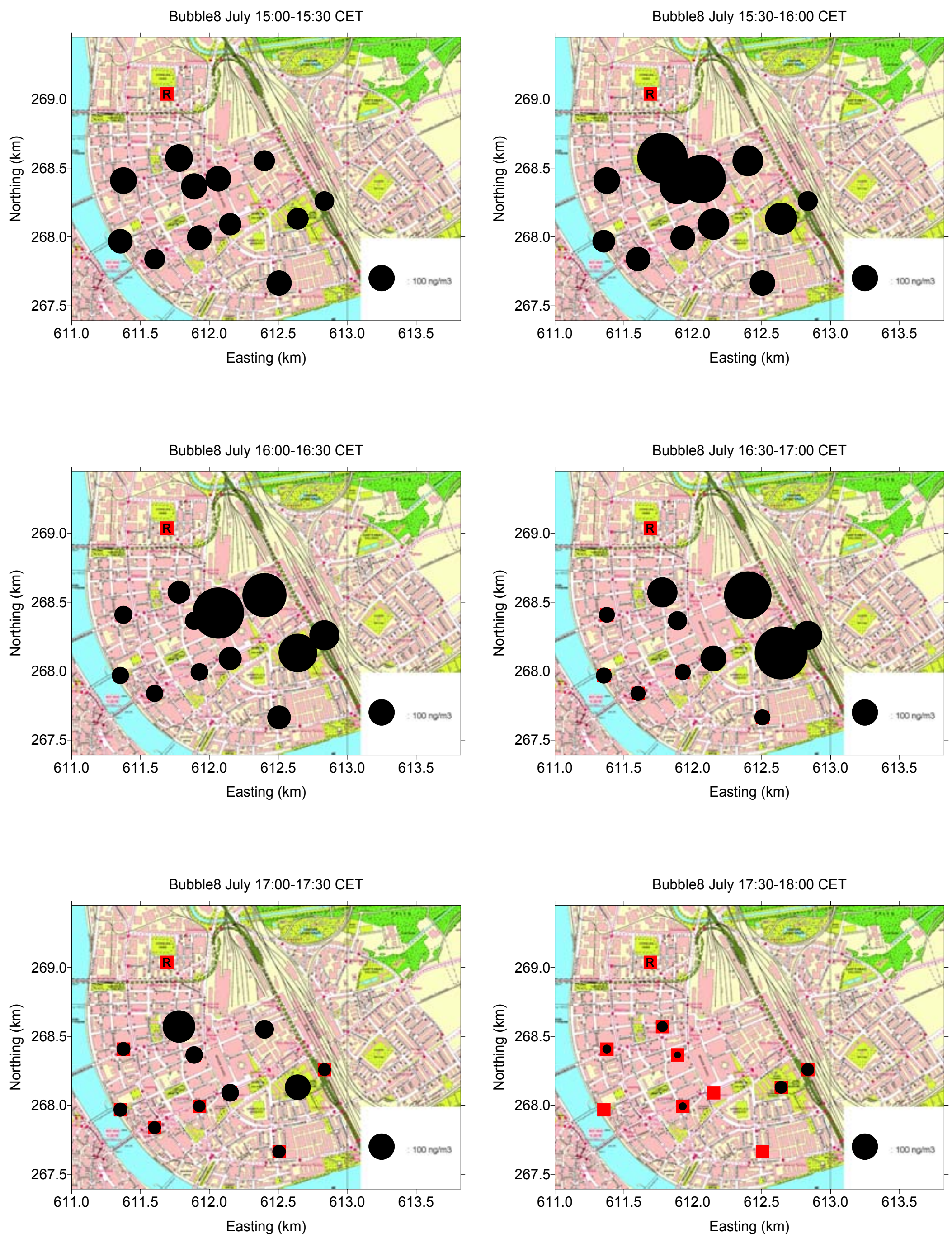


Figure 25 Illustration of the half-hourly averaged tracer concentrations for the experiment on 8 July 2002. Further details in the legend for Figure 24. Base map (c) copyright GVA BS, 25.10.2002.

Figure 26 Following pages:

Meteorological information for July 8 2002 during the tracer release. Each page shows the information for one hour as indicated on top of the plot for the detailed wind field.

Top panels: Profiles of horizontal wind speed, wind direction and potential temperature between 270 m (~Surface) and 1200 m a.s.l. measured by the remote sensing instrumentation: RASS at “Basel-Kleinhüningen” (5, urban), 1280MHz Wind profiler at “Basel-Spalenring” (12, urban), SODAR at “Grenzach” (17, rural) and the tower measurements from the 250m TV tower at “St. Chrischona” (24).

Lower panels: Wind fields over the whole BUBBLE-Domain (upper map) and a subset of the city part where the tracer experiments took place (lower map). The surface measurements are performed at meteorological masts and represent usually the conditions between 10 and 30 metres above the ground level (for exact heights and numbers refer to Table 5). The release points are drawn with red colour. The wind barbs indicate wind speed and direction with the following convention (example: wind from SW):

Wind speed < 1 m/s *Short bar: 1 m/s* *Long bar: 2 m/s*

All times are indicated in CET and mark the end of a half hourly averaged period.

a) 14.00 – 15.00

b) 15.00 – 16.00

c) 16.00 – 17.00

d) 17.00 – 18.00

Base maps (inner domain): reproduction with authorization of the Swiss Federal Office of Topography, Wabern (BA024776).

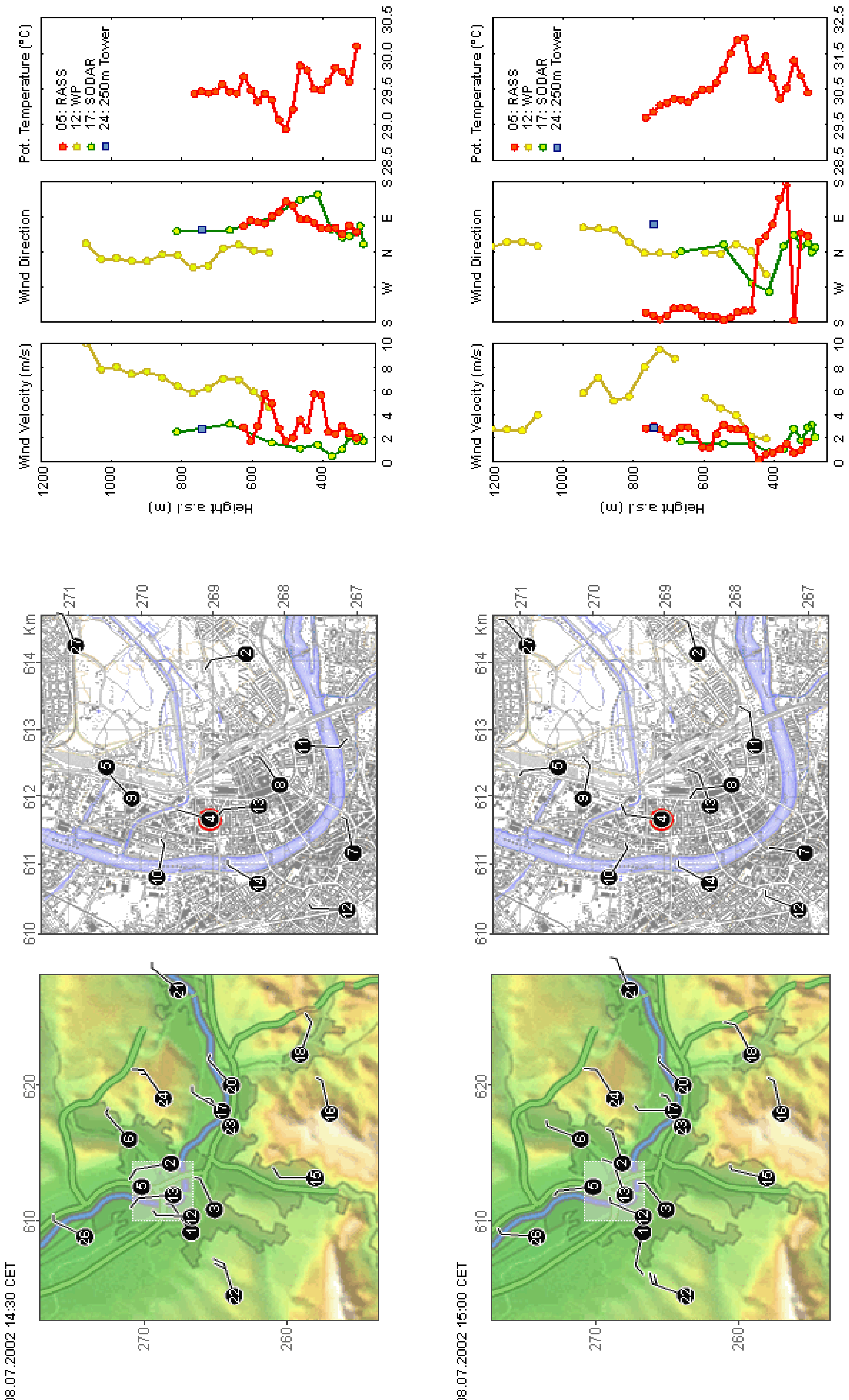


Figure 26a 14.00 – 15.00

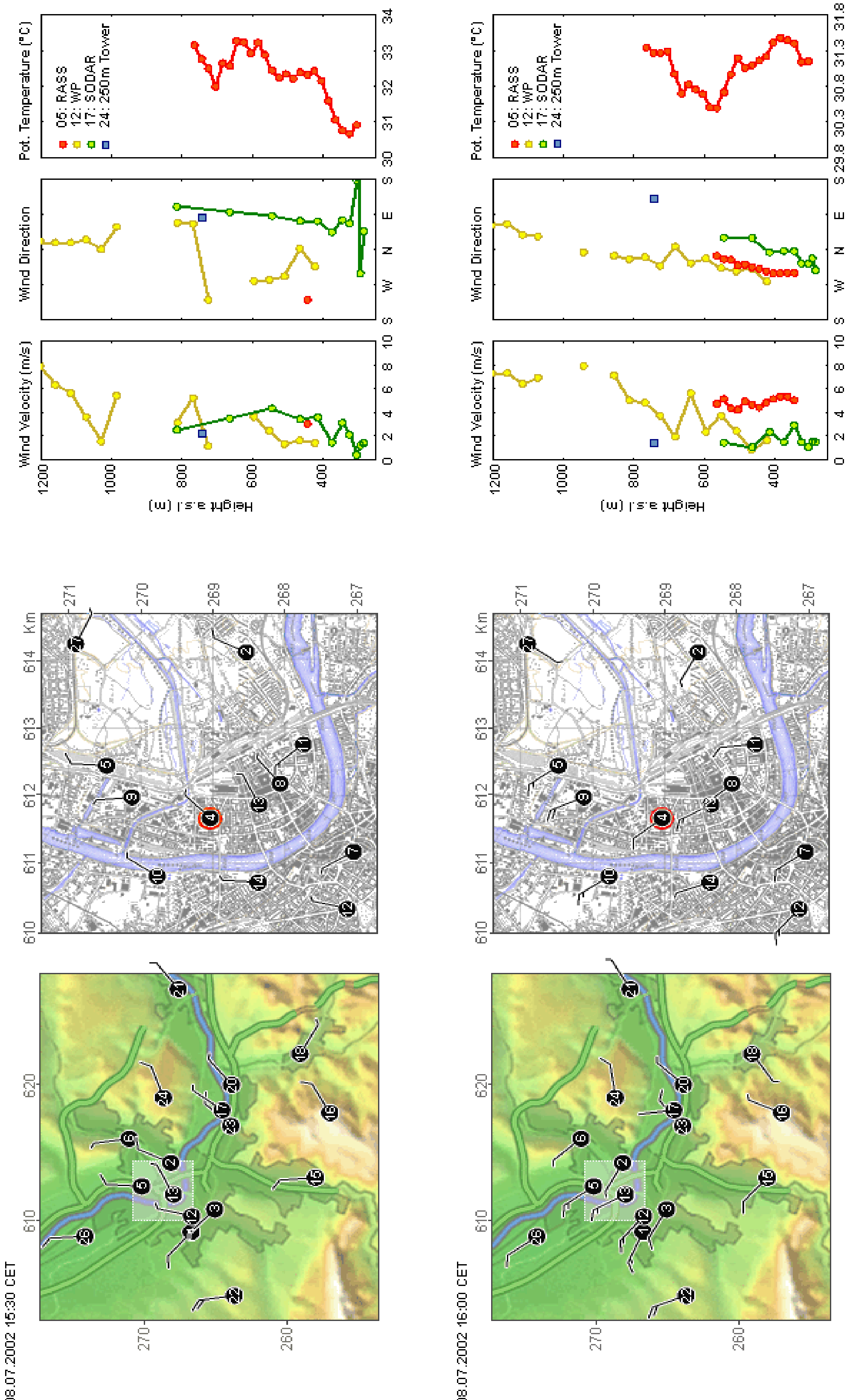


Figure 26b 15.00 – 16.00

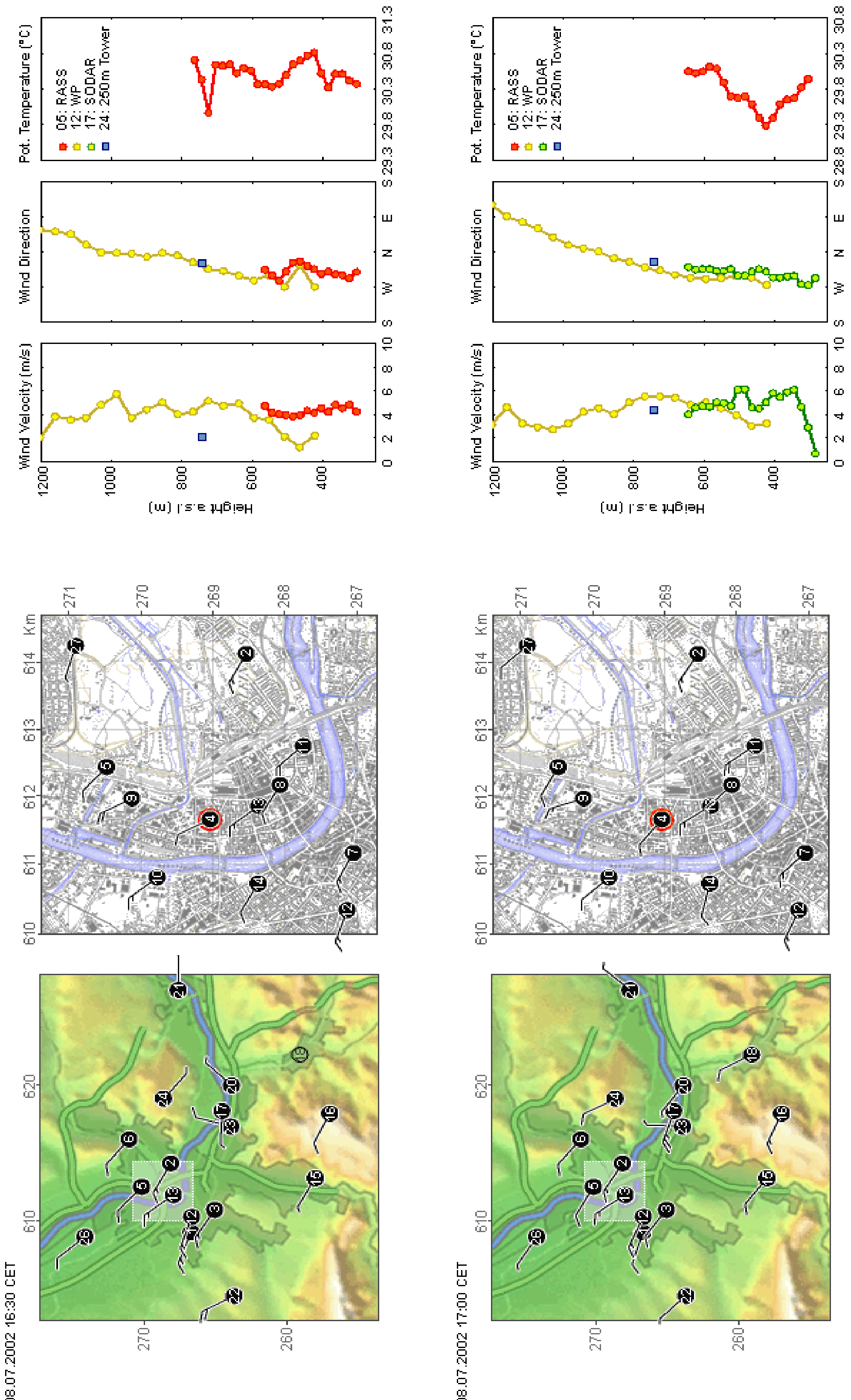


Figure 26c 16.00 – 17.00

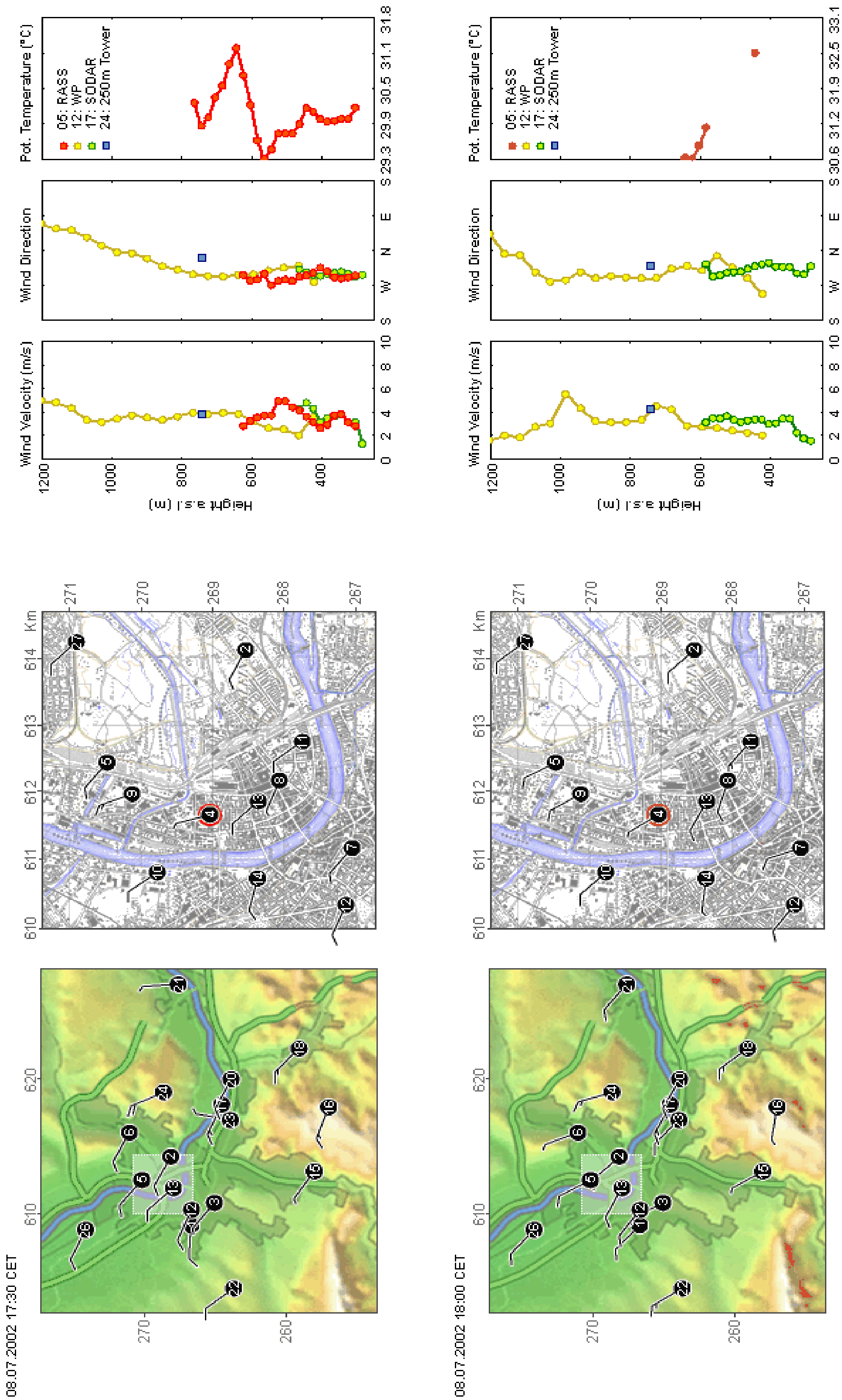


Figure 26d 17.00 – 18.00

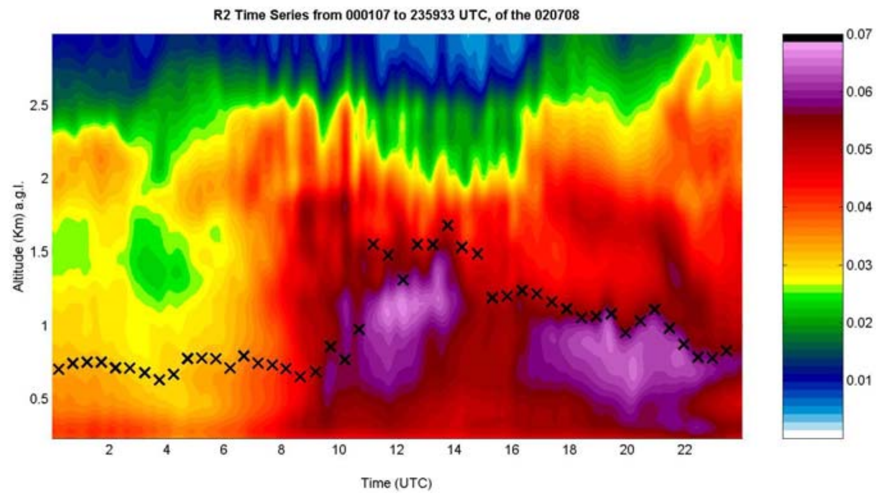


Figure 27 Lidar scans of the backscatter (colour code) from the atmosphere on 8 July 2002. Tracer sampling was from 14:00 to 17:00 UTC.

Figure 28 Following pages

a) Standard meteorological parameters on July 8, 2002 from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Basel – Horburg (4, urban, release point R1), Allschwil-Rämelstrasse (1, suburban) and Village-Neuf (26, rural). The grey shaded period indicates the 3 hours of tracer sampling. Air pressure (upper most panel) is not converted to sea level. All times are indicated in CET.

b) The upper two plots illustrate net radiation and sensible heat flux from selected stations: Basel- Sperrstrasse (13; urban), Basel-Kleinhüningen (5, industrial track area), Basel-Spalenring (12, urban), Allschwil-Rämelstrasse (1, suburban), Grenzach (17, rural), Village-Neuf (26, rural). Sensible heat fluxes are calculated based on 30-min block averages. The third plot shows 30 min values of local Reynolds stress u_{*loc} (taking also lateral stress into account) and Monin-Obukov stability- (z-d)/L (unstable range only). Both time series are from the top measurement at Basel-Sperrstrasse (31.7m). The last row of plots shows vertical profiles of mean horizontal wind speed (blue profiles) at Basel-Sperrstrasse for each of the 30 min. sampling blocks of the experiment. Red profiles are local u_{*loc}. Both, wind speed and u_{*loc} were sampled by 6 ultrasonic anemometers on the tower. The mean height of the buildings in the whole tracer area is indicated by the grey shaded background (15.1m). All times are indicated in CET.

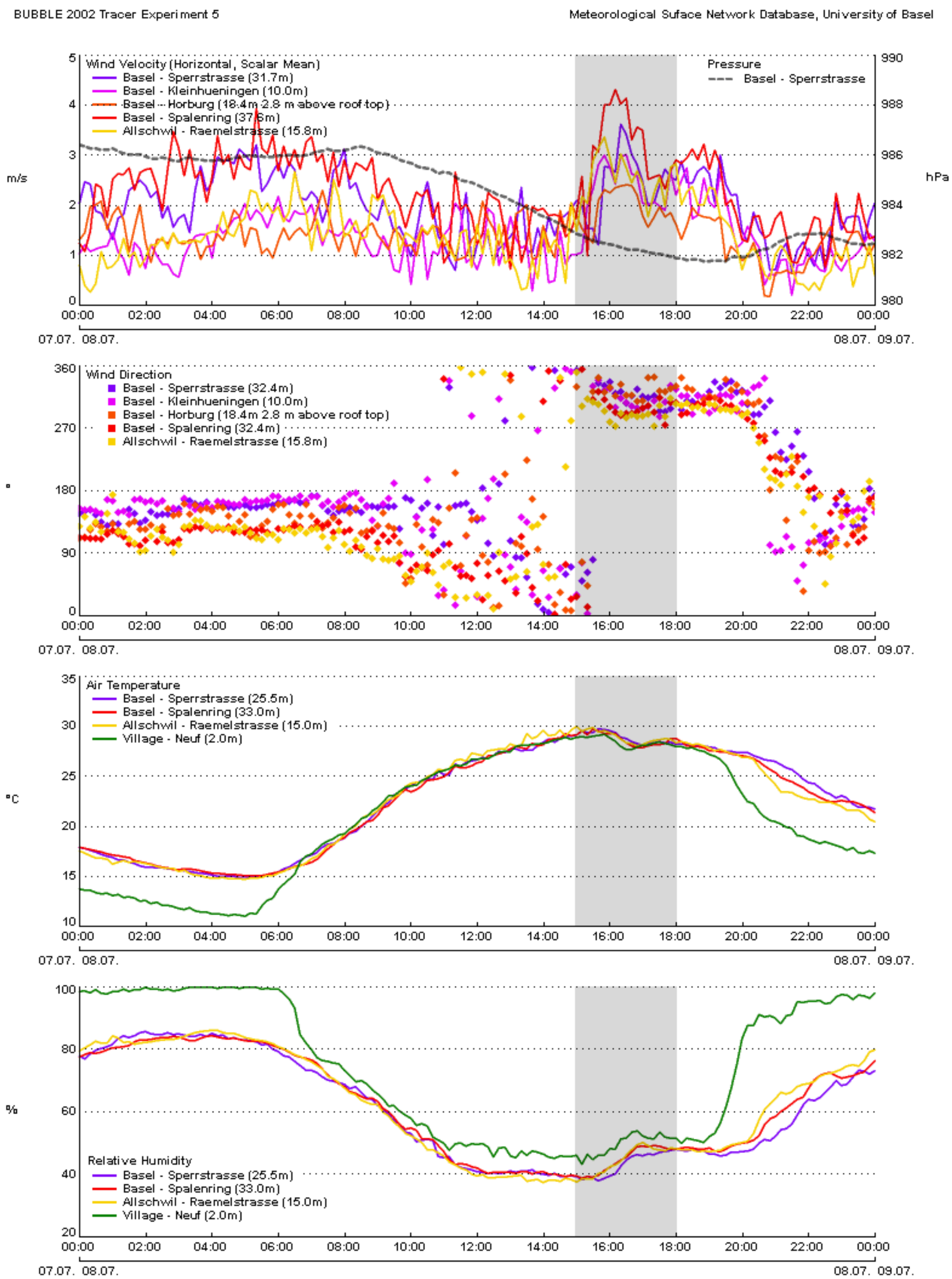

BUBBLE 2002 Tracer Experiment 5
Meteorological Suface Network Database, University of Basel
Wind Velocity (Horizontal, Scalar Mean)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Pressure
Basel - Sperrstrasse
m/s
hPa
Wind Direction
Basel - Sperrstrasse (32.4m)
Basel - Kleinhueningen (10.0m)
Basel - Horburg (18.4m 2.8 m above roof top)
Basel - Spalenring (32.4m)
Allschwil - Raemelstrasse (15.8m)
Air Temperature
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
°C
Relative Humidity
Basel - Sperrstrasse (25.5m)
Basel - Spalenring (33.0m)
Allschwil - Raemelstrasse (15.0m)
Village - Neuf (2.0m)
%
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00
07.07. 08.07.
08.07. 09.07.

Figure 28a

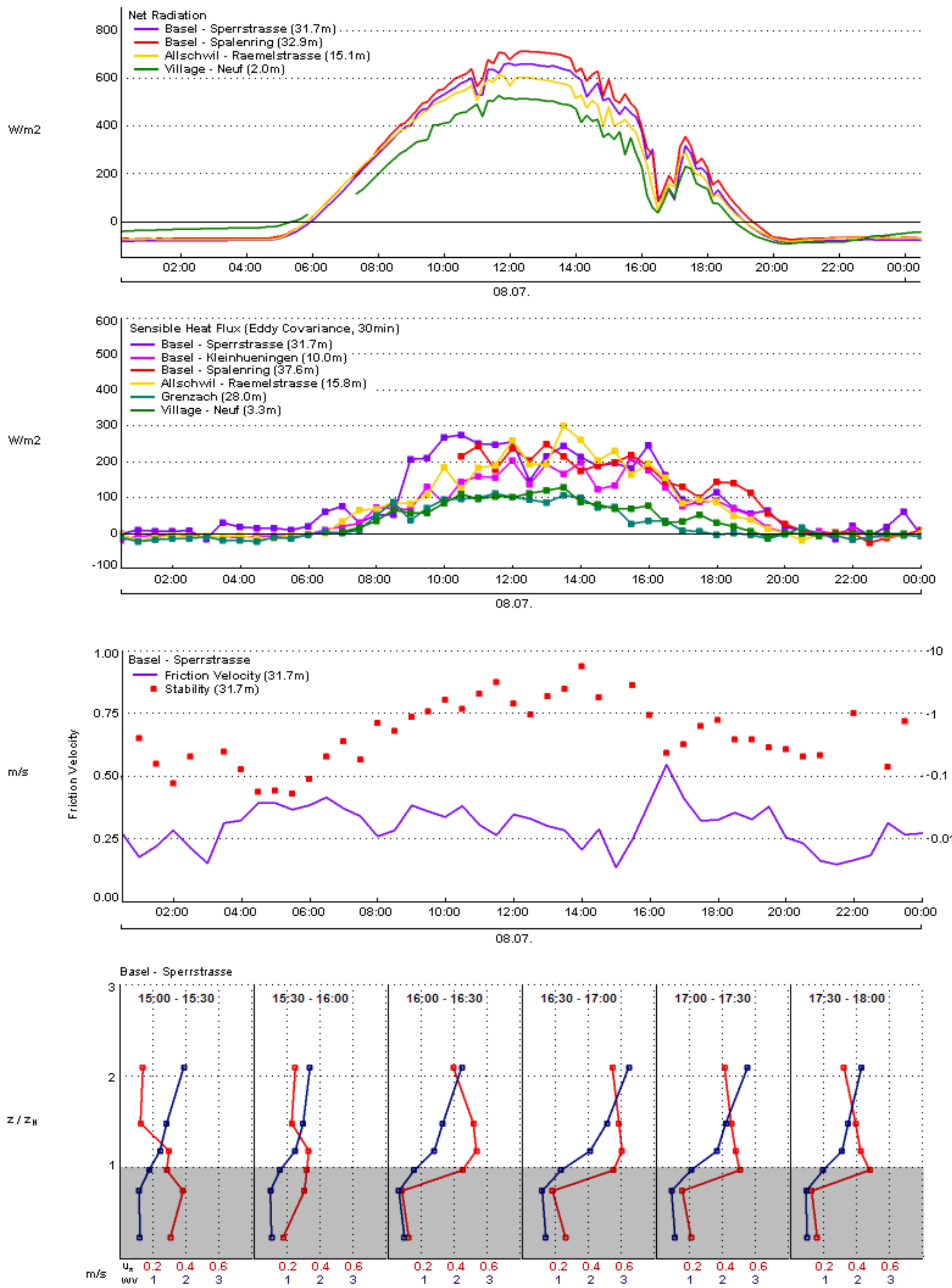

Net Radiation
Basel - Sperrstrasse (31.7m)
Basel - Spalenring (32.9m)
Allschwil - Raemelstrasse (15.1m)
Village - Neuf (2.0m)
W/m2
08.07.
Sensible Heat Flux (Eddy Covariance, 30min)
Basel - Sperrstrasse (31.7m)
Basel - Kleinhueningen (10.0m)
Basel - Spalenring (37.6m)
Allschwil - Raemelstrasse (15.8m)
Grenzach (28.0m)
Village - Neuf (3.3m)
W/m2
08.07.
Basel - Sperrstrasse
Friction Velocity (31.7m)
Stability (31.7m)
m/s
Friction Velocity
Stability - (z-d) / L
08.07.
Basel - Sperrstrasse
15:00 - 15:30
15:30 - 16:00
16:00 - 16:30
16:30 - 17:00
17:00 - 17:30
17:30 - 18:00
z / z_H
m/s

Figure 28b

4 TRACER DATA AND METEOROLOGICAL PARAMETERS

4.1 Turbulence data

From the observational network we use turbulence data from the site closest to the tracer release area, i.e. Sperrstrasse (position 3 in Fig. 2). There, Reynolds stress was measured at 6 levels on a tower, namely at 3.6m, 11.3 m, 14.7 m, 17.9 m, 22.4 m and 31.7 m above ground. The mean building-related information for that site (average building height in circles of various radii around the site) can be obtained from Table 1 (site 3). The local building height, h_l, amounts to 15.1m thus revealing that the turbulence observations ranged up to about 2.1 times h_l.

The data employed here are usually statistics averaged over 30 minutes. Due to the obvious difficulty to define any sort of 'streamline' coordinates within and closely above an urban street canyon, we use the simplest possible approach, viz.

- Rotation of the coordinate system into the mean wind direction, so that (x,y,z) and the corresponding components of the wind vector (u,v,w) correspond to the along-wind, lateral and vertical directions, respectively.
- In the vertical direction, in particular, no attempt is made in order to 'make the average w component to zero'. Mean vertical flow into and out of the canyon is therefore possible.
- No 'detrending' is applied for this relatively short averaging interval.

From this procedure the Reynolds stress components are obtained, and they are used in the next section to derive a reference velocity, as well as the velocity variances that are summarized in Tables 6, 8, 10 and 12.

Usually, in boundary layer flows a reference or scaling velocity is defined from the surface Reynolds stress components

$$u_* = (\overline{u'w'}_o^2 + \overline{v'w'}_o^2)^{1/4},$$

where the subscript 'o' refers to the surface value. Over complicated, rough surfaces like in urban environments various observations have shown that $\overline{u'w'}$ in particular exhibits a distinct profile with a maximum somewhere above roof level and values going towards zero in the vicinity of the zero plane displacement height (e.g., Rotach 2001). The directional shear component, on the other hand is often found to be negligibly small. Rotach (2001) argues that the Reynolds stress component at the height of its maximum actually reflects the drag that the flow aloft 'sees' from the bulk of the surface, and hence a reference velocity may be defined according to

$$_{*} = (-\overline{u'w'}_{\max})^{1/2}$$

in order to avoid confusion with the traditional definition of the friction velocity (some of us like the idea that the traditional symbol for the friction velocity be given a 'roof' [or hat] in an urban environment). Kastner-Klein and Rotach (2004) have noted that individual profiles of $\overline{u'w'}$ (as measured over, say, an averaging interval of 30 minutes) may exhibit distinct peaks that reflect very local flow characteristics and are not desired in the 'ensemble average' sense, in which information on $_{*}$ is often required. They have therefore devised a parameterisation for the Reynolds stress profile, which eliminates highly local characteristics in this profile. This parameterisation is also useful in describing single realizations (as a observed profile over a certain averaging interval) as in the present case. Details on its characteristics and reasoning can be found in Kastner-Klein and Rotach (2004)

From the BUBBLE observational network we use the five higher levels, i.e. these above the local zero place displacement height. For each averaging interval the observations of $\overline{u'w'}$ are fitted to a curve of the general form

$$\overline{u'w'}(z) = a\hat{z}^2 \exp\left\{-b\hat{z}\right\}$$

where $\hat{z} = z - d$ is a relative height and d is the zero plane displacement height for shear stress (see Kastner-Klein and Rotach (2004) for details). Thus, from the fit one obtains optimal values for the parameters a, b and d. These are then related to the physical variables of interest as follows:

The height of maximum (magnitude) Reynolds stress, z_m:

$$z_m = 2/b - d$$

The maximum Reynolds stress, $\overline{u'w'}_{\max}$

$$\overline{u'w'}_{\max} = \overline{u'w'}(z_m) = a(2/b)^2 \exp\left\{-2\right\}$$

Finally, the 'friction velocity' or reference velocity can be deduced:

$$_{*} = \sqrt{-\overline{u'w'}_{\max}}$$

Figure 29 shows a typical example of observed $\overline{u'w'}$ at Sperrstrasse, together with the fitted profile, which yields $_{*}$=0.422ms^{-1} and z_m=25.4m for that particular case.

Much less is known concerning the sensible heat fluxes over urban areas than is the case for the momentum fluxes. A typical series of (kinematic) heat flux profiles is shown in Figure 30. Often, a maximum heat flux is observed slightly above roof level (17.9m). Higher up the heat flux remains approximately constant while a steep gradient is observed around roof level and a minimum is obtained below. Based on the averaged profile as shown in Figure 30 and with the goal of obtaining a relatively robust estimate, the ‘surface heat flux’ is obtained from averaging the observations of the two uppermost level, i.e. at 22.4m and 31.7m, respectively.

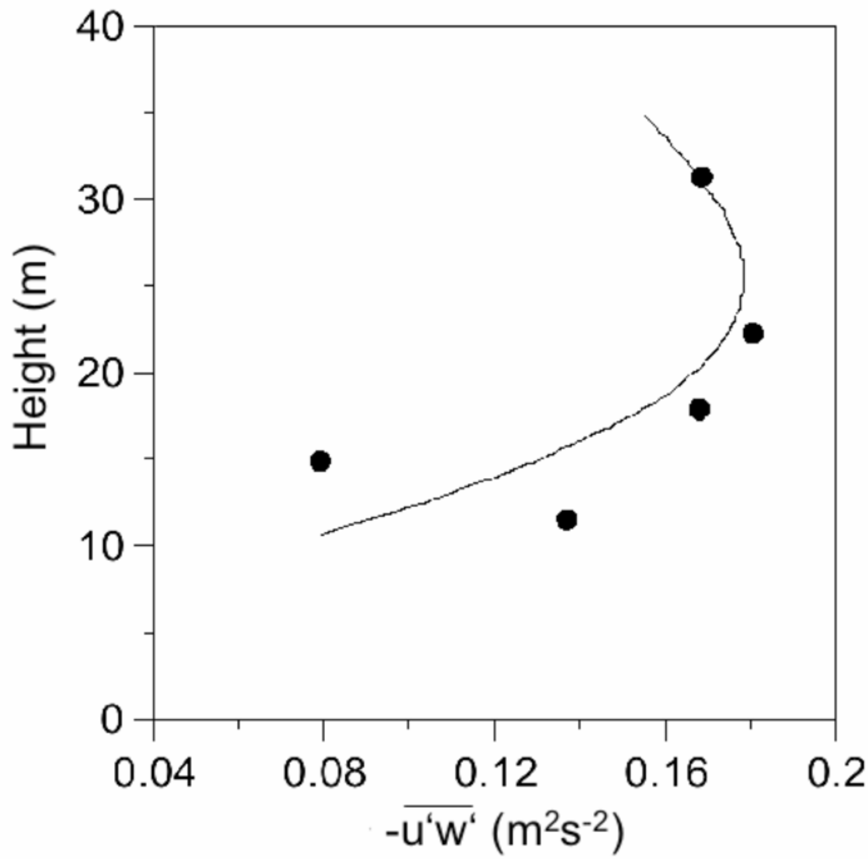


Figure 29 Profile of observed (filled circles) and fitted (full line) Reynolds stress component $-\overline{u'w'}$ at Sperrstrasse (position 3) from the tracer experiment on 4 July 2002, 17:30 to 18:00 CET.

4.2 The mixed-layer height

Mixed layer height is obtained from continuous Lidar observations at the site ‘Spalenring’, about 2 km southwest of the tracer area. The lidar is a single-wavelength backscatter-depolarisation instrument and has been built at the Observatory of Neuchâtel. The operational wavelength is 532nm (2nd harmonic of the Nd:YAG laser). The backscatter signal is measured separately in two polarisations, where one is parallel to the polarisation of the transmitted laser beam (referred to as 'p' polarisation) and the other is perpendicular to it (referred to as 's' polarisation).

As a standard algorithm to retrieve the mixed-layer height (or more precisely the aerosol mixed layer height) from the Lidar signal, the derivative of the backscatter signal profile was used. Figure 31 shows the range-corrected lidar signal (polarisation 'p') from 13:00 UTC on 26 June 2002 until 13:00 UTC on 27 June 2002 (similar to Figs. 12, 17, 22 and 27 for the tracer experiments). The horizontal axis shows the time of measurements and the vertical axis the altitude. The range-corrected lidar signal is presented by colour code in relative units. The time resolution is 6 min and the altitude resolution is 40 m. This 'time-height' cross–section presents a very complicated development with a 'step-wise' aerosol-mixed layer on which we also see 'superimposed' aerosol accumulation layers. Nevertheless, we recognise in this diurnal cycle the various development stages of the mixed-layer such as growing, descend and residual layer formation during the night. An interesting feature is the formation of a detached aerosol layer during the night at the altitude of the (previous) daytime mixed-layer top.

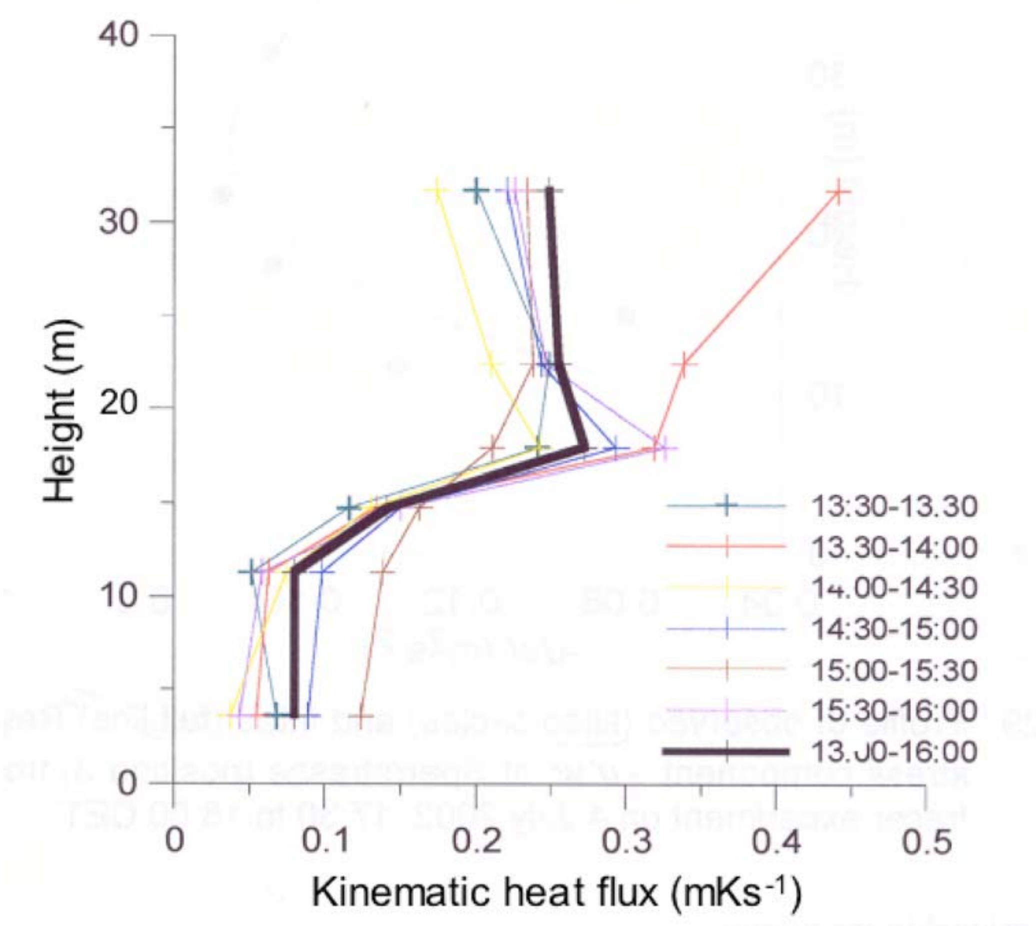


Figure 30 Profiles of $\overline{w'T'}$ at Sperrstrasse (position 3) from the tracer experiment on 26 June 2002, 13:00 to 16:00 CET.

The line marked by 'x' (i.e.,. the aerosol mixed layer top) is determined from the following conditions: height of

- the largest (in absolute values) local minimum of the lidar signal log-derivative
- that is the closest to the surface
- under the restriction of continuity in time.

The altitudes marked by 'x' are determined with a 30 min resolution. Figure 32 shows three selected individual lidar profiles and Figure 33 the corresponding derivatives (all profiles during the period presented in Fig. 31). From Figure 33 we may observe that for certain times more than one local minimum is present (e.g., the middle panel in Fig. 33). In this case the last of the three conditions above (continuity of the determined mixed layer height) becomes crucial.

Figure 34 finally presents the 'time-height' cross-section of the log-derivative (i.e., the gradient of the logarithm) of the range-corrected signal for the same period as in Figure 31. Again, the diagnosed mixed-layer heights are marked ‘x’.

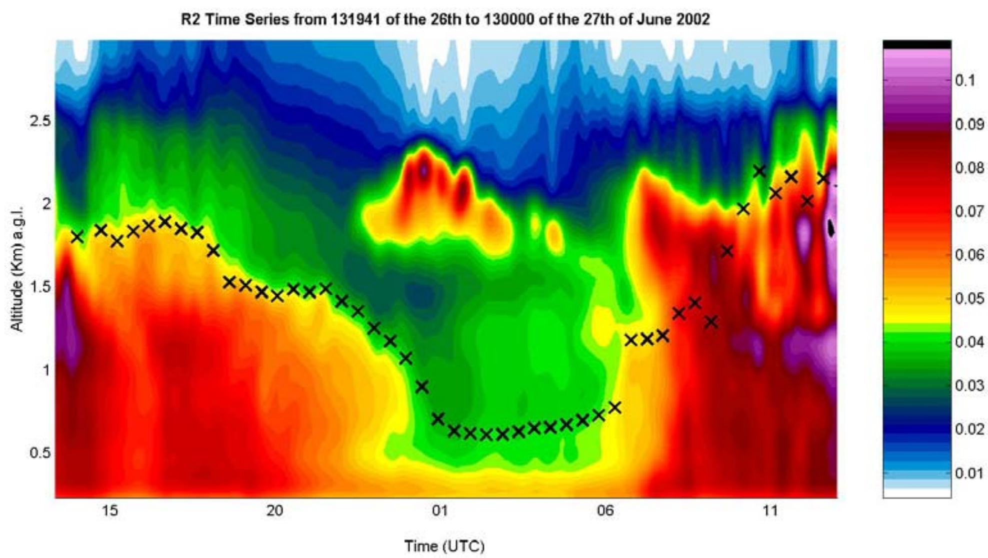


Figure 31 Time-height cross-section of the range-corrected lidar signal (colour code) from 13:00 UTC on 26 June 2002 until 13:00 UTC on 27 June 2002.

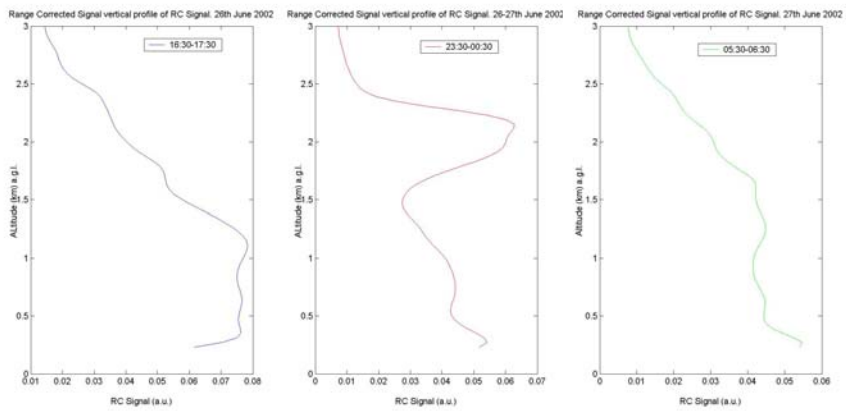


Figure 32 Selected individual vertical profiles of the range-corrected lidar signal on June 26/27 2002: 17:30-18:30 (left), 01:30-02:30 (middle), 06:30-07:30 (right). Note that times in the inlets are in UTC, while in the caption in CET.

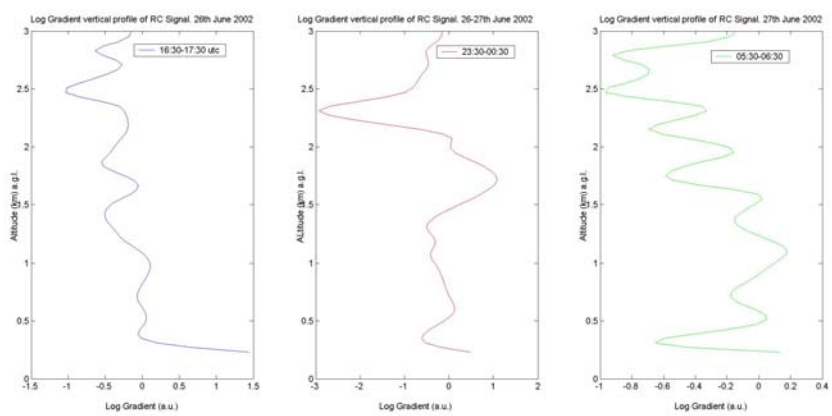


Figure 33 As Figure 32 but for the log derivative of the range-corrected lidar signal.

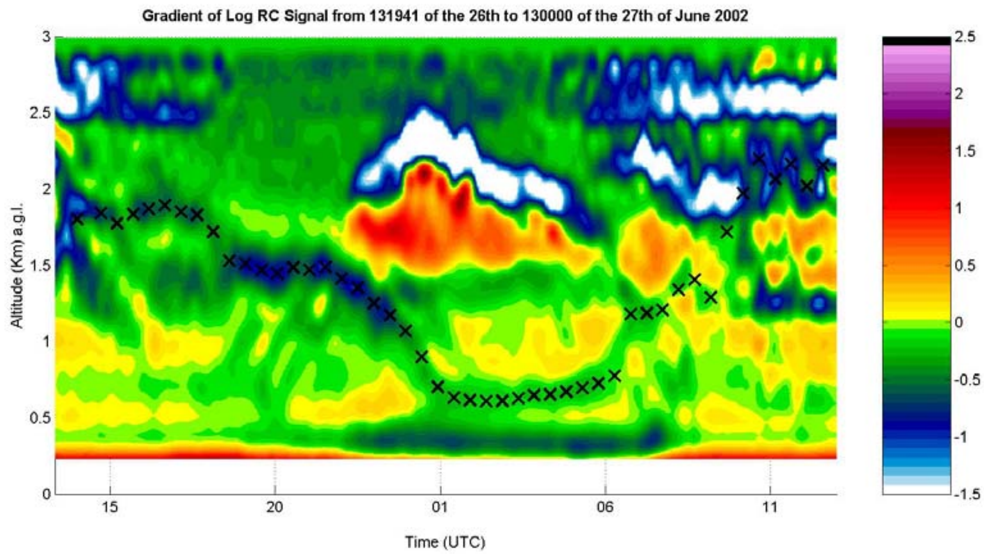


Figure 34 Time-height cross-section of log-derivative of the range-corrected lidar signal (clour code) from 13:00 UTC on 26 June 2002 to 13:00 UTC on 27 June 2002.

4.3 The mean wind

Many different observational systems are available for mean wind information in connection with the BUBBLE tracer experiments. For the near-surface wind speed information we use the sonic anemometer data from the tower at 'Sperrstrasse' (levels 17.9 m and 22.4 m have been selected).

For upper level wind the closest instrument (RASS at site 'Kleinhünigen, approximately 2.2 km from the Sperrstrasse site) has been selected. Also, good data coverage was obtained from these measurements. Wind speed observations as input in dispersion models (if necessary) are given at 40, 100, 200 and 300 m above ground level.

4.4 Tables of tracer data and meteorological parameters

In this section the tracer and meteorological data from the four experiments are listed. Note that for the meteorological parameters the average values given for the entire period of an experiment or for 1-hour periods do not necessarily correspond to a simple average over the 6 or 2 thirty-minute values, respectively. For example, the average reference velocity, $_{*}$, is determined by averaging the observed Reynolds stress components and then applying the procedure outlined in Section 4.1. Similarly, the one-hour averages for the velocity variances (i.e., standard deviations) are based on an analysis of the Reynolds stress tensor with an averaging time of 60 min and the values for the entire period are based on averaging the three hourly means. For wind speed measurements -99.00 is the error code. If one or two

10-min. averages are not available, the remaining are used and labelled as 30min. averages.

Table 6 Meteorological data for experiment #1, 26 June 2002. Time indications in CET. IS stands for inertial sublayer value.

Parameter	**z [m a.g.l.]**	**13:00-13:30**	**13:30-14:00**	**14:00-14:30**	**14:30-15:00**	**15:00-15:30**	**15:30-16:00**	**13:00-14:00**	**14:00-15:00**	**15:00-16:00**	**13:00-16:00**
$\hat{u}_*$ [ms^{-1}]	z_m	0.559	0.407	0.429	0.305	0.300	0.656	0.427	0.314	0.467	0.410
z_m [m]		23.5	24.0	21.5	20.8	20.5	42.2	22.0	20.5	24.1	21.7
w_* [ms^{-1}]	IS	2.230	2.679	2.111	2.253	2.260	2.252	2.475	2.184	2.257	2.312
z_i [m]		-	-	-	1753	1888	1842	-	1753	1865	1809
$\overline{w'T'}$ [Kms^{-1}]	IS	0.225	0.391	0.191	0.233	0.236	0.233	0.308	0.212	0.235	0.252
θ [K]	31.2	298.8	299.4	299.1	299.8	300.3	300.8	299.1	299. 5	300.6	299.7
L [m]	IS	-72.6	-13.2	-31.5	-9.3	-8.8	-92.7	-19.3	-11.1	-33.2	-20.9
WD [°]	31.7	333	332	328	354	342	35	332	344	333	339
σ_w [ms^{-1}]	17.9	0.618	0.538	0.641	0.514	0.578	0.562	0.595	0.547	0.575	0.573
σ_w [ms^{-1}]	31.7	0.764	0.628	0.767	0.663	0.646	0.720	0.707	0.654	0.675	0.679
σ_v [ms^{-1}]	17.9	1.065	1.005	0.998	1.090	1.346	0.853	1.011	1.238	1.167	1.143
σ_v [ms^{-1}]	31.7	1.294	1.204	1.197	1.311	1.596	1.141	1.206	1.460	1.545	1.411
σ_u [ms^{-1}]	17.9	1.010	0.930	1.012	0.811	0.885	0.954	0.967	0.857	0.951	0.925
σ_u [ms^{-1}]	31.7	1.343	1.218	1.331	0.930	1.065	1.249	1.273	1.013	1.196	1.165
u [ms^{-1}]	17.9	1.06	0.94	1.22	1.34	1.13	1.34	1.00	1.28	1.24	1.17
u [ms^{-1}]	31.7	1.53	1.35	1.49	1.74	1.42	1.96	1.44	1.62	1.69	1.58
u [ms^{-1}]	40	2.87	1.97	1.83	1.79	1.62	2.57	2.42	1.81	2.10	1.30
u [ms^{-1}]	100	2.86	2.46	3.30	2.50	2.50	2.50	2.67	2.90	2.50	2.69
u [ms^{-1}]	200	2.53	3.23	3.16	2.43	1.60	2.57	2.88	2.80	2.09	2.59
u [ms^{-1}]	300	3.46	3.37	2.10	4.80	2.09	2.16	3.42	3.45	2.13	3.00

Table 7 The measured half-hourly averaged tracer concentrations from the experiment on 26 June 2002. Concentrations are given as "observed minus background" (Table 4). Time indications are in CET.

Site	13:00-13:30 ngm^{-3}	13.30-14:00 ngm^{-3}	14:00-14:30 ngm^{-3}	14.30-15:00 ngm^{-3}	15:00-15.30 ngm^{-3}	15:30-16:00 ngm^{-3}
1	69.1	177.5	54.2	67.3	41.1	37.4
2	3.7	14.9	18.7	37.4	26.2	7.5
3c-17m	28.0	33.6	37.4	59.8	41.1	28.0
4	-	39.2	22.4	61.7	46.7	14.9
5	18.7	16.8	26.2	33.6	43.0	29.9
6	3.7	9.3	26.2	28.0	28.0	9.3
7	5.6	16.8	31.8	24.3	46.7	14.9
8	9.3	20.6	31.8	37.4	54.2	-
9	16.8	26.2	26.2	43.0	52.3	14.9
10	13.1	20.6	26.2	35.5	39.2	22.4
11	5.6	13.1	24.3	28.0	28.0	13.1
12	22.4	16.8	16.8	35.5	29.9	13.1
3a-2m	20.6	31.8	39.2	54.2	33.6	24.3
3b-10m	24.3	20.6	37.4	59.8	33.6	28.0
Release from Parking house. Release from 12:00 to 16:00. Release rate: 0.0503 $gSF_6\ s^{-1}$						

Table 8. Meteorological data for experiment #2, 4 July 2002. Time indications in CET. IS stands for inertial sublayer value.

Parameter	**z [m a.g.l.]**	**15:00-15:30**	**15:30-16:00**	**16:00-16:30**	**16:30-17:00**	**17:00-17:30**	**17:30-18:00**	**15:00-16:00**	**16:00-17:00**	**17:00-18:00**	**15:00-18:00**
$\hat{u}_*$ [ms^{-1}]	z_m	0.531	0.687	0.679	0.548	0.582	0.422	0.608	0.620	0.508	0.596
z_m [m]		31.6	24.3	23.8	24.2	21.6	25.4	26.1	23.6	22.3	24.0
w_* [ms^{-1}]	IS	2.074	2.130	1.785	1.680	1.590	1.472	2.102	1.734	1.533	1.813
z_i [m]		1348	1334	1317	1254	1230	1230	1341	1286	1230	1286
$\overline{w'T'}$ [Kms^{-1}]	IS	0.197	0.216	0.129	0.113	0.098	0.077	0.207	0.121	0.087	0.138
θ [K]	31.2	292.5	292.6	292.5	292.3	292.7	292.6	292.6	292.4	292.7	292.5
L [m]	IS	-56.7	-111.9	-180.8	-108.5	-149.9	-72.7	-81.1	-147.1	-111.8	-114.1
WD [°]	31.7	278	273	265	283	272	261	276	274	267	272
σ_w [ms^{-1}]	17.9	0.679	0.815	0.742	0.657	0.683	0.573	0.781	0.672	0.567	0.673
σ_w [ms^{-1}]	31.7	0.760	0.826	0.725	0.644	0.637	0.604	0.778	0.641	0.586	0.668
σ_v [ms^{-1}]	17.9	1.213	1.178	1.080	1.007	0.979	1.201	1.146	1.081	1.114	1.113
σ_v [ms^{-1}]	31.7	1.413	1.291	1.085	0.981	0.975	1.173	1.200	1.132	1.100	1.144
σ_u [ms^{-1}]	17.9	1.028	1.222	1.197	0.958	1.047	0.811	1.216	1.003	0.804	1.008
σ_u [ms^{-1}]	31.7	1.203	1.446	1.365	1.225	1.135	0.939	1.446	1.177	0.984	1.202
u [ms^{-1}]	17.9	2.53	2.18	1.92	2.07	1.55	1.66	2.36	2.00	1.61	1.99
u [ms^{-1}]	31.7	4.16	3.48	2.27	3.50	2.47	2.75	3.82	2.89	2.61	3.11
u [ms^{-1}]	40	4.87	3.93	2.66	4.00	2.77	3.06	4.40	3.53	2.92	3.62
u [ms^{-1}]	100	5.50	4.36	3.43	4.80	3.16	3.16	4.93	4.12	3.16	4.07
u [ms^{-1}]	200	6.16	5.49	5.07	4.27	2.80	2.83	5.83	4.27	2.82	4.44
u [ms^{-1}]	300	7.30	6.06	3.40	2.50	3.33	-99	6.68	2.95	3.33	4.32

Table 9 The measured half-hourly averaged tracer concentrations from the experiment on 4 July 2002. Concentrations are given as "observed minus background" (Table 4). The time indications are in CET.

site	15:00-15:30 ngm^{-3}	15:30-16:00 ngm^{-3}	16:00-16:30 ngm^{-3}	16:30-17:00 ngm^{-3}	17:00-17:30 ngm^{-3}	17:30-18:00 ngm^{-3}
1	2.1	2.1	0.0	0.0	0.0	6.4
3c-17m	36.4	80.4	123.3	0.0	139.3	409.5
4	19.3	21.4	25.7	2.1	66.5	242.2
5	0.0	0.0	0.0	0.0	0.0	0.0
8	214.4	135.1	274.4	345.1	199.4	57.9
9	83.6	81.5	173.6	117.9	192.9	115.8
10	21.4	36.4	19.3	10.7	49.3	47.2
11	2.1	12.9	40.7	2.1	15.0	40.7
12	19.3	0.0	32.2	12.9	0.0	0.0
15	-	81.5	150.1	12.9	105.0	212.2
16	-	0.0	0.0	0.0	0.0	0.0
17	-	0.0	0.0	0.0	2.1	8.6
3a-2m	0.0	137.2	143.6	12.9	186.5	530.6
3b-10m	10.7	160.8	117.9	0.0	182.2	605.6

Release from Florastrasse.

Release from 14:40 to 18:00.

Release rate: 0.0499 $gSF_6\ s^{-1}$

Table 10 Meteorological data for experiment #3, 7 July 2002. Time indications in CET. IS stands for inertial sublayer value.

Parameter	**z [m a.g.l.]**	**14:00-14:30**	**14:30-15:00**	**15:00-15:30**	**15:30-16:00**	**16:00-16:30**	**16:30-17:00**	**14:00-15:00**	**15:00-16:00**	**16:00-17:00**	**14:00-17:00**
$\hat{u}_*$ [ms^{-1}]	z_m	0.350	0.300	0.317	0.386	0.410	0.426	0.327	0.359	0.419	0.311
z_m [m]		20.6	17.5	20.1	19.6	21.1	20.5	19.0	19.8	20.8	19.9
w_* [ms^{-1}]	IS	2.485	2.246	2.351	2.223	1.943	2.208	2.373	2.289	2.084	2.253
z_i [m]		1870	1908	1897	1931	1806	1788	1889	1914	1797	1867
$\overline{w'T'}$ [Kms^{-1}]	IS	0.249	0.180	0.208	0.173	0.124	0.183	0.215	0.191	0.153	0.186
θ [K]	31.2	297.7	297.8	298.4	298.5	298.5	298.9	297.8	298.5	298.7	298.3
L [m]	IS	-13.1	-11.4	-11.6	-25.3	-42.5	-32.1	-12.4	-18.5	-36.5	-12.3
WD [°]	31.7	289	349	287	315	343	305	319	301	324	322
σ_w [ms^{-1}]	17.9	0.490	0.528	0.463	0.590	0.542	0.525	0.497	0.567	0.588	0.511
σ_w [ms^{-1}]	31.7	0.525	0.634	0.619	0.612	0.600	0.559	0.630	0.621	0.602	0.618
σ_v [ms^{-1}]	17.9	0.666	0.804	1.039	0.746	0.784	1.015	1.001	0.796	1.263	1.020
σ_v [ms^{-1}]	31.7	0.679	0.873	1.238	0.829	0.979	1.103	1.187	1.064	1.649	1.300
σ_u [ms^{-1}]	17.9	0.821	0.689	0.766	1.197	0.865	0.802	0.886	1.025	0.925	0.945
σ_u [ms^{-1}]	31.7	0.844	0.630	0.892	1.427	1.122	1.049	0.971	1.245	1.147	1.121
u [ms^{-1}]	17.9	1.21	1.24	1.20	1.22	1.59	1.62	1.23	1.21	1.61	1.35
u [ms^{-1}]	31.7	1.75	1.45	1.64	2.00	2.56	2.50	1.60	1.82	2.53	1.98
u [ms^{-1}]	40	1.33	1.86	2.23	2.67	3.06	3.10	1.60	2.45	3.08	2.38
u [ms^{-1}]	100	1.83	2.63	2.57	3.06	3.40	3.23	2.23	2.82	3.31	2.79
u [ms^{-1}]	200	2.36	2.26	2.33	3.26	3.97	3.47	2.31	2.80	3.72	2.94
u [ms^{-1}]	300	2.07	3.10	3.29	3.50	3.46	2.60	2.58	3.39	3.03	3.00

Table 11 The measured half-hourly averaged tracer concentrations from the experiment on 7 July 2002. Concentrations are given as "observed minus background" (Table 4). The time indications are in CET.

site	14:00-14:30 ngm^{-3}	14:30-15:00 ngm^{-3}	15:00-15:30 ngm^{-3}	15:30-16:00 ngm^{-3}	16:00-16:30 ngm^{-3}	16:30-17:00 ngm^{-3}
1	4.3	170.3	55.3	38.3	2096.3	1191.8
2	0.0	4.3	0.0	0.0	258.6	83.0
3c-17m	8.5	55.3	0.0	74.5	843.9	269.2
4	46.8	100.0	8.5	48.9	391.6	363.9
6	6.4	0.0	0.0	0.0	53.2	76.6
7	4.3	-	-	0.0	-	-
8	6.4	21.3	0.0	10.6	374.6	100.0
9	27.7	27.7	42.6	6.4	257.5	61.7
11	155.4	72.4	114.9	19.2	12.8	0.0
12	23.4	8.5	29.8	-	87.3	8.5
18	161.7	389.5	117.1	387.3	-	0.0
19	93.6	-	19.2	14.9	17.0	4.3
3a- 3m	8.5	51.1	4.3	93.6	662.9	253.3
3b-10m	12.8	44.7	4.3	36.2	843.9	279.9
Release from Parking house. Release from 13:10 to 17:00. Release rate: 0.3008 gSF_6 s^{-1}						

Table 12. Meteorological data for experiment #4, 8 July 2002. Time indications in CET. IS stands for inertial sublayer value.

Parameter	z [m a.g.l.]	15:00-15:30	15:30-16:00	16:00-16:30	16:30-17:00	17:00-17:30	17:30-18:00	15:00-16:00	16:00-17:00	17:00-18:00	15:00-18:00
$\hat{u}_*$ [ms^{-1}]	z_m	0.175	0.303	0.532	0.601	0.504	0.425	0.244	0.568	0.467	0.411
z_m [m]		15.0	18.5	21.0	23.1	20.4	19.6	17.5	21.9	19.9	20.4
w_* [ms^{-1}]	IS	1.983	2.265	1.793	1.568	1.576	1.860	2.135	1.688	1.731	1.859
z_i [m]		1534	1488	1190	1202	1241	1218	1511	1196	1230	1312
$\overline{w'T'}$ [Kms^{-1}]	IS	0.158	0.242	0.150	0.099	0.097	0.163	0.200	0.125	0.130	0.152
θ [K]	31.2	304.1	304.5	303.8	303.1	303.0	303.1	304.3	303.5	303.1	303.6
L [m]	IS	-2.6	-8.9	-77.7	-169.4	-101.6	-36.3	-5.6	-113.8	-60.4	-35.4
WD [°]	31.7	33	321	303	306	295	284	357	305	289	323
σ_w [ms^{-1}]	17.9	0.564	0.509	0.598	0.633	0.565	0.494	0.557	0.601	0.495	0.555
σ_w [ms^{-1}]	31.7	0.677	0.647	0.694	0.653	0.557	0.517	0.675	0.608	0.540	0.608
σ_v [ms^{-1}]	17.9	1.033	0.823	0.810	0.846	0.701	0.666	1.187	0.775	0.731	0.898
σ_v [ms^{-1}]	31.7	1.315	1.235	0.898	1.090	1.001	1.041	1.586	1.047	1.020	1.218
σ_u [ms^{-1}]	17.9	0.940	0.881	1.014	0.999	0.875	0.838	0.877	0.960	0.864	0.900
σ_u [ms^{-1}]	31.7	1.138	0.914	1.417	1.181	0.865	0.781	1.182	1.061	0.893	1.045
u [ms^{-1}]	17.9	1.29	1.38	2.05	1.83	1.57	1.64	1.34	1.94	1.60	1.63
u [ms^{-1}]	31.7	1.69	2.24	3.24	2.77	2.15	2.60	1.97	3.00	2.38	2.45
u [ms^{-1}]	40	0.95	-99.00	4.09	3.69	2.39	3.45	0.95	3.89	2.92	2.59
u [ms^{-1}]	100	2.20	5.30	4.66	7.95	3.77	4.19	3.75	6.30	3.98	4.68
u [ms^{-1}]	200	2.55	3.43	4.03	-99.00	4.26	3.90	2.99	4.03	4.08	3.70
u [ms^{-1}]	300	2.36	-99.00	4.50	4.69	3.59	3.65	2.36	4.59	3.62	3.52

Table 13 The measured half-hourly averaged tracer concentrations from the experiment on 8 July 2002. Concentrations are given as "observed minus background" (Table 4). The time indications are in LST.

site	15:00-15:3 ngm^{-3}	15:30-16:00 $ngm^{-3}s$	16:00-16:30 ngm^{-3}	16.30-17:00 ngm^{-3}	17:00-17:30 ngm^{-3}	17:30-18:0 ngm^{-3}
1	111.7	372.4	74.5	133.0	154.3	17.0
2	104.3	104.3	46.8	36.2	27.7	10.6
3c-17m	100.0	185.1	48.9	53.2	44.7	6.4
4	95.8	342.6	387.3	-	-	-
5	63.8	138.3	285.2	332.0	51.1	-
6	87.3	74.5	42.6	36.2	27.7	0.0
7	61.7	87.3	42.6	31.9	23.4	-
8	89.4	89.4	44.7	36.2	21.3	8.5
9	72.4	144.7	76.6	97.9	44.7	0.0
10	68.1	151.1	217.1	410.7	95.8	23.4
11	55.3	57.5	131.9	123.4	23.4	23.4
12	93.6	93.6	80.9	36.2	25.5	0.0
3a-3m	89.4	159.6	46.8	69.2	42.6	8.5
3b-10m	100.0	155.4	53.2	42.6	31.9	12.8

Release from Parking house.

Release from 14:00 to 18:00.

Release rate: 0.1319gSF_6 s^{-1}

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