Meteorologische Zeitschrift, Vol. 23, No. 5, 535–546 (published online December 10, 2014)


# Observations and numerical simulations of the train-induced air flow in a subway station

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(Manuscript received May 6, 2014; in revised form September 7, 2014; accepted September 10, 2014)

**Abstract**

This article presents observations and model simulations of wind and temperature in a subway station. The measurements are taken from an experiment with three ultrasonic anemometers at different levels in the underground facility. The available observations indicate a wind regime with a continuous background flow and train-induced ventilation with very effective air exchange between the platform level and the street level. Model simulations with a resolution of less than 1 m were performed with running trains in accordance with a regular timetable. The results demonstrate the applicability of the model to the complex underground geometry. Calculated time series of wind and temperature are very comparable to the observations. The findings of a parameter study indicate the necessity to record all details of train movements in order to define appropriate initial and boundary conditions for the model and to explain the observations correctly.

**Keywords:** Micro-scale simulation, field experiment, subway system, ventilation

## 1 Introduction

Subway transportation systems are key elements in the traffic planning of cities. Beside the large transport capacity, comfort, fast distribution of many people to their final destination and environmental friendliness are other arguments which indicate that the use of this underground system offers significant advantages.

However, the high concentration of people in the narrow spaces of subway facilities, such as stations, mezzanines, stairways or trains, involves the risk of uncomfortable or even dangerous situations. Since comfort and safety must be guaranteed, ventilation of the underground system is an absolute necessity during operating hours. Air pollutants emitted by the trains and the additional heat must be removed and replaced by fresh and uncontaminated air. Also, in the case of a disaster situation, such as a fire or terrorist attack with chemical and biological weapons, ventilation plays a very important role (Pflitsch et al., 2013; Hu et al., 2014).

The ventilation of a subway system can be managed in different ways. The most natural ventilation, even without train movement, is a background flow which is caused by the synoptic large scale pressure gradient modified by local features, such as urban heat islands. Such very persistent background currents in a tunnel system have been observed by Pflitsch (2001a, 2001b). A larger contribution must be attributed to the forced ventilation caused by moving trains. This piston effect and the corresponding piston wind are based on the pressure distribution when a subway train travels through a tunnel (Pan et al., 2013). In a tunnel with a limited section, the train pushes a pressure wave before it into the next station. This additional air mass will be discharged through the exits, removing the stale air from the station. The leaving train has the opposite effect, sucking fresh air from street level into the underground. The effectiveness and the order of magnitude of this piston ventilation effect have been estimated theoretically, for example by Wieghardt (1962) and Brown (1965). It is only when these two effects are not sufficient to guarantee an acceptable air quality that, additionally, air-conditioning systems need to be installed.

It is hard to capture the actual ventilation situation in a subway station due to the multitude of relevant factors. The complex interactions of the specific building features of the station with the superimposed weather conditions and the time dependent train movements makes it extremely difficult to get an overview of the detailed air exchange situation in an underground facility. Field experiments in real stations are the most valuable source of basic knowledge (Pflitsch, 2001b; Pflitsch et al., 2013; Straaten, 2014). However, due to the complex interactions mentioned above, general findings from these experiments which can be transferred to other locations are very limited.

Additional, very universal and powerful tools are CFD-models. Taking into careful account the restrictions and limitations of such models, they can be applied to arbitrary sites and situations. It is, therefore, not surprising that a number of studies have been published in the literature on train-induced air flow in subway stations (Jia et al., 2009; Pan et al., 2013; Byrne and Camelli, 2014), in tunnels (Shin and Park, 2003; Kim and Kim, 2007; Proverbio, 2009; Huang et al.,

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DOI 10.1127/metz/2014/0615 Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

2010, Huang et al., 2012; Yan et al., 2013) or for specific questions (Juraeva et al., 2013).

This paper presents the results of a field experiment in a subway station designed to complement the findings and results achieved so far. In addition, a numerical micro-scale model was used to simulate the air flow in a complex subway environment for a consecutive series of two-way train services. In a parameter study, the effects of train motion characteristics on the results are estimated.

## 2 Field experiment

In the event of a disaster in a subway station, fire and medical crews are trained to rescue people and to fight the causes. Appropriate means are necessary to prevent the propagation of smoke, hazardous materials and heat into the escape routes, so that persons who stay underground can reach the outside safely and emergency services can access the subway facilities. A special team of the Hannover fire brigade is testing the advantages and disadvantages of different options and techniques. A promising method is based on the application of extremely powerful fans to ventilate the contaminated areas (Franz, 2014).

In different field experiments in a subway station, the effects of up to four fans with an air exchange rate of more than 130,000 $m^3hr^{-1}$ running in different operating conditions should be quantified. These experiments are accompanied by meteorological observations (Straaten, 2014) in order to monitor the environmental conditions and to prove the ventilation effect. In order to guarantee the safety and comfort of the subway passengers, the experiments are performed after the regular train operating hours. However, wind observations were also recorded during the closing evening hours of the train service. These observations are used to characterize wind and air exchange between the subway station and the ambient environment outside.

The experiments took place in a subway station (Schlägerstrasse, Hannover) which is characterized by a relatively simple geometry. The station is approximately 100 m long over two floors with two tracks, separated by a row of pillars, with platforms nearly 4 m wide at each side. The different levels separate the service platform from the four exits to the street above. These exits are located in the prolongation of the track's orientation, while exit W is arranged perpendicular (Fig. 1). Train movement is from north to south on the western track while it is northbound on the eastern track.

Meteorological measurements have been performed in this station with different equipment. However, in this study, only the results of three 2D-**u**ltra**s**onic **a**nemometers USA (Thies, Göttingen) are used. Horizontal wind speed and wind direction as well as air temperature are observed with a frequency of 10 Hz. Measurement accuracy is $\pm 0.1\,ms^{-1}$ for wind speed, one degree for wind direction and $\pm 0.5$ K for temperature. USA-1 was located at the exit of the tunnel for southbound running trains at a height of 1.3 m above the platform and 1 m away from the platform edge. At this location, the characteristics of air movement caused by trains entering the station can be captured. The moving train pushes a significant volume of air into the station, which can escape only through the exits above. In order to quantify this train-induced ventilation, two ultrasonic anemometers are arranged at the exit S (USA-2) and at the exit W (USA-3). In the Figures the red colour is used for all results at site USA-1, blue for USA-2 and green for USA-3.

Exemplarily, the observations of the experiment on 28 February 2014 are used to describe the main features of train-induced air flow characteristics in the subway station. As demonstrated by Pflitsch (2001a), the air movement inside the subway facilities depends on the weather situation outside. In order to analyse the superimposed wind and the general weather situation, winds above the station as well as at the Meteorological Department of the University of Hannover (IMUK) are used. These observations underline the homogeneous conditions during the time of the selected period of the experiment. Wind direction was constant from the south and a 10 m wind speed is around $2.5\,ms^{-1}$ (Fig. 2). Parallel measurements at street level for 5 min periods at each hour confirm the stationary situation of the winds from the south and a 2 m wind speed of nearly $2\,ms^{-1}$. Assuming a logarithmic wind profile with a roughness length of 0.1 m, this wind speed matches to the 10 m observations at IMUK quite well. Temperatures at street level at this time of the day were around 6.5–7 °C.

Fig. 3 shows the observations (due to the large amount of data only every twentieth value is used) at the three USAs for a period of 9 min after midnight. This is a time with regular operating trains but also with unscheduled movements. Caused by data failure observations at USA-1 are not available for the first 10 minutes. Times with entering and leaving trains are marked with arrows in the lower part, where colour indicates southbound (light and dark blue) or northbound (light and dark brown) movements. Up arrows represent trains entering the station and down arrows trains leaving the station. In the first 60 min trains arrived every 15 min and left the station after a short stop of about 20 s. Train movements are not exactly the same caused by the individual driving preferences of the train drivers. In the time after 60 min, the trains are transferred into the depot and do not stop (or stop only briefly) in the station.

Due also to the synoptic pressure gradient inside the tunnel system and in the station, a weak but permanent air flow from the south can be observed at site USA-1. This constant background wind will be significantly disturbed by train movements. Wind speed on the platform is increased sharply by each entry and exit. However, as also described by Pflitsch (2001b) or Juraeva et al. (2013), shortly after the passage the wind speed decreases exponentially and after a very short time the

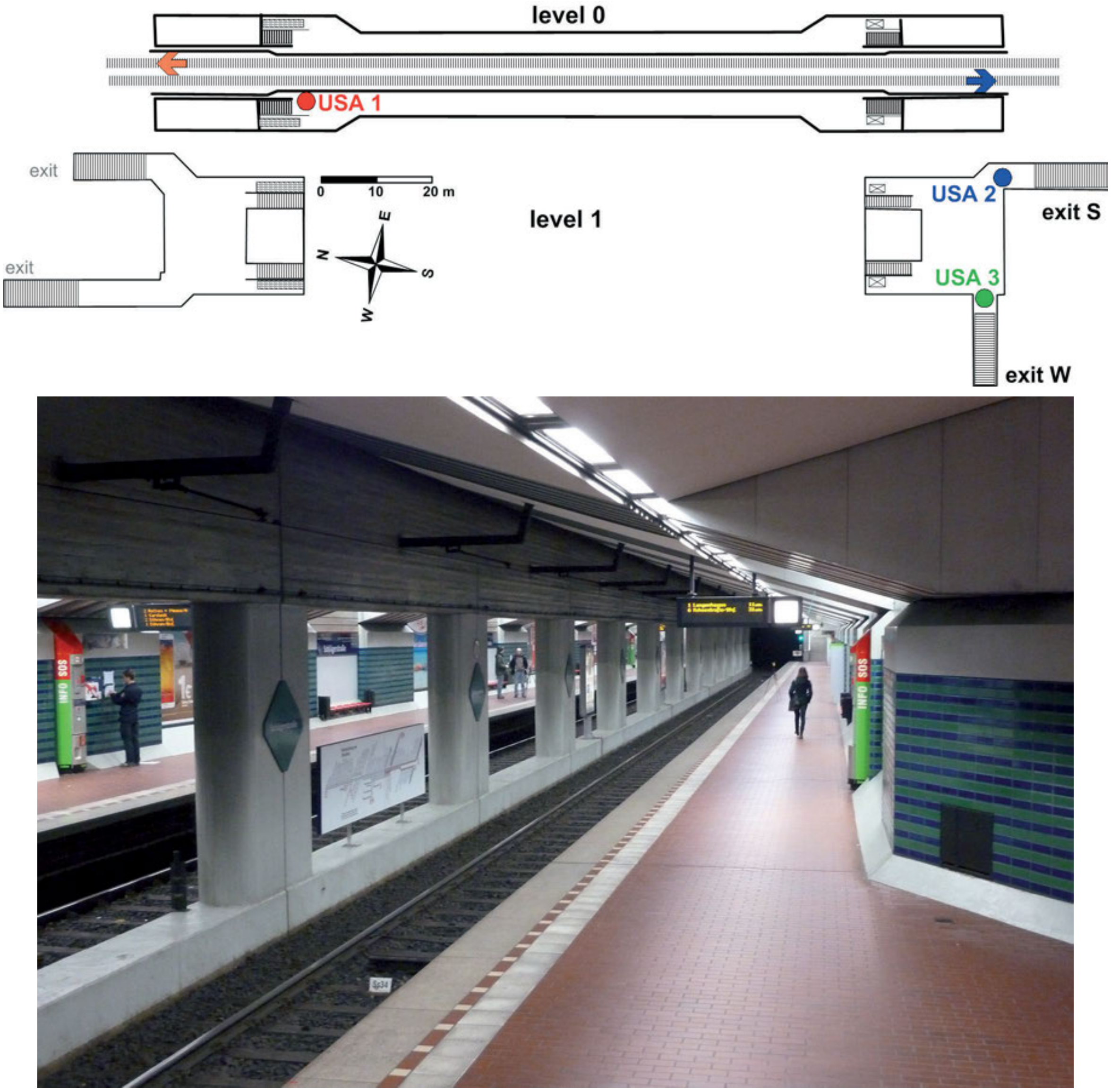


**Figure 1:** Plan of the Schlägerstrasse subway station and the location of the ultrasonic anemometers USA (above). View from north to south into the station (below).

background wind is re-established. This feature is also evident from the wind direction which is, in general, constant from the south. During the passage of the south-bound trains, the wind direction turns to the north because drag forces the ambient air to move in the same direction as the train. But again, the prevailing situation with a southerly flow in the tunnel system re-establishes very quickly.

Every train movement also affects the wind situation at exits S and W. While for the undisturbed situation the air flow is directed into the station, from the south and west, the wind is reversed after the train enters the station and air movement is then directed out of the exits. This regular ventilation feature occurs for every train movement, while in between the superimposed synoptic situation dominates.

Temperature at level 0 inside the station is much warmer at this time of the year than the air temperature at street level. Temperatures at level 1 near exits S and W are somewhere in between. Again, the air exchange between the two station levels is clearly recognizable for this meteorological variable as well. Temperature at level 0 (USA-1) is around 12–13 °C with an increase of 1–2 K during train movements, where even warmer air from inside the tunnel is advected into the station. However, temperatures at level 1, which are usually around 7 °C, increase up to 12 °C when the piston wind advects the level 0 air masses in the direction of the exits. These events take just a few moments before the prevailing situation re-establishes and cold air from the street level is sucked into the station, reducing the temperatures immediately. These complex, but regular and recurring situations for wind and temperature have been observed in a very similar manner, for example, by Pflitsch and Kleeberger (2000) or by Pflitsch (2001b) in subway stations in New York and Dortmund.

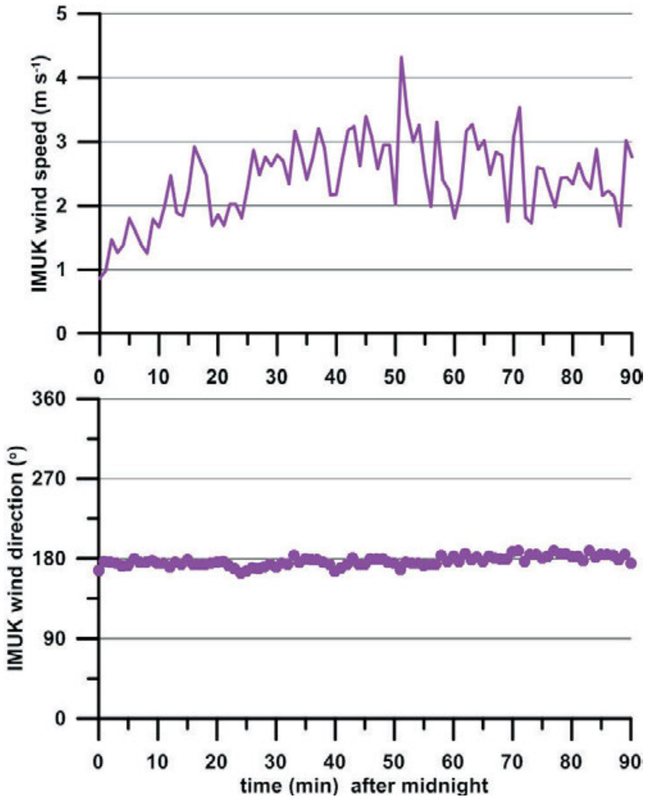


**Figure 2:** Observations of wind speed and wind direction on 28 February 2014 for the time after midnight.

The time series presented in Fig. 3 show very regular features for each train movement. Other details can be recognized more easily in an enlarged section (Fig. 4). The situation around $t = 20$ min is selected here, while wind and temperatures around $t = 35$ min are presented in Figs 10–12 for a comparison with the simulation results.

Wind speed is weak, but increases before the train enters the station. This increase ahead of the arrival is caused by the forced air flow in front of the moving train in the tunnel. As the train exits the tunnel, the air in front is pushed to the sides and to the top of the train. During the passage, platform wind increases again since the air is coupled with the train movement by drag forces. During the stop in the station, the wind speed returns to moderate and decreases exponentially after the departure. The arrival of the northbound moving train on the adjacent track has no effect on USA-1. However, when the train departs wind speed increases significantly for some moments before the background motion dominates again.

Wind direction at USA-1 is in accordance with the synoptic weather situation from the south. The southbound entering train pushed the air also to both sides resulting in easterly wind components on the near platform measuring site USA-1 (see also Fig. 9). In the following period, inertia will still maintain the direction of the train movement from the north until the train on the adjacent track leaves the station northbound. Then again easterly winds, and later westerly winds, can be observed at USA-1 as a result of the air flow around the running train before the calm motion from the south is re-established. The air flows at the exits S and W are strongly coupled with the train movements in the station. Immediately after the entry of a train the ventilation effect starts and winds are forced out of the exits. The reverse situation occurs after train departures.

This significant and sharp change in wind direction dominates the temporal behaviour of the temperature at the exits. The ventilation effect pushes the warm air from level 0 up to the exit level resulting in a temperature increase of up to 4 K in a very short time. However, a reverse in the wind direction after the exit of a train cools the air temperature by the same order of magnitude by suppressing warm air advection from level 0.

# 3 The numerical micro-scale model

## 3.1 Model equations

For simulations of mean wind and temperature, the micro-scale model ASMUS (**A**usbreitungs- und **S**trömungs**M**odell für **U**rbane **S**trukturen) is used (Gross, 2012a, 2014). This model has been applied to studies of the air flow around individual obstacles, such as buildings or wind power installations. It is now used for an underground situation with complex geometry and demanding boundary conditions.

The Navier–Stokes equations, the continuity equation and the first law of thermodynamics are used to calculate the mean wind $\bar{u}_i$ $(u, v, w)$ and potential temperature $\bar{\theta}$. In the coordinate system used, $u$ is the wind component orientated north–south, that is parallel to the tracks, and the $v$-component is the east–west direction.

The equations are Reynolds averaged and the resulting correlations of fluctuating quantities are parameterized by flux-gradient relationships.

$$\frac{d\bar{u}_i}{dt} = -\frac{1}{\bar{\rho}}\frac{\partial p^*}{\partial x_i} + g\frac{\theta^*}{\bar{\theta}}\delta_{i3} + \frac{\partial}{\partial x_k}\left[K_\mathrm{m}\left(\frac{\partial \bar{u}_i}{\partial x_k} + \frac{\partial \bar{u}_k}{\partial x_i}\right)\right] - \frac{1}{\bar{\rho}}\frac{\partial p_g}{\partial x_i} \tag{3.1}$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{3.2}$$

$$\frac{d\bar{\theta}}{dt} = \frac{\partial}{\partial x_k} K_\mathrm{h} \frac{\partial \bar{\theta}}{\partial x_k} \tag{3.3}$$

Beside the standard notation, $\bar{\rho}$ is the mean air density, $p^*$ and $\theta^*$ are air pressure disturbance and temperature disturbance and $\frac{\partial p_g}{\partial x_i}$ is the superimposed synoptic pressure gradient responsible for the background wind in the atmosphere as well as in the tunnel system. $K_\mathrm{m}$ and $K_\mathrm{h}$ are eddy diffusivities for momentum and heat respectively. In this study, no distinction is made between $K_\mathrm{m}$ and $K_\mathrm{h}$ and eddy diffusivity is calculated by

$$K_\mathrm{m} = 0.4\ell_g\sqrt{E} \tag{3.4}$$

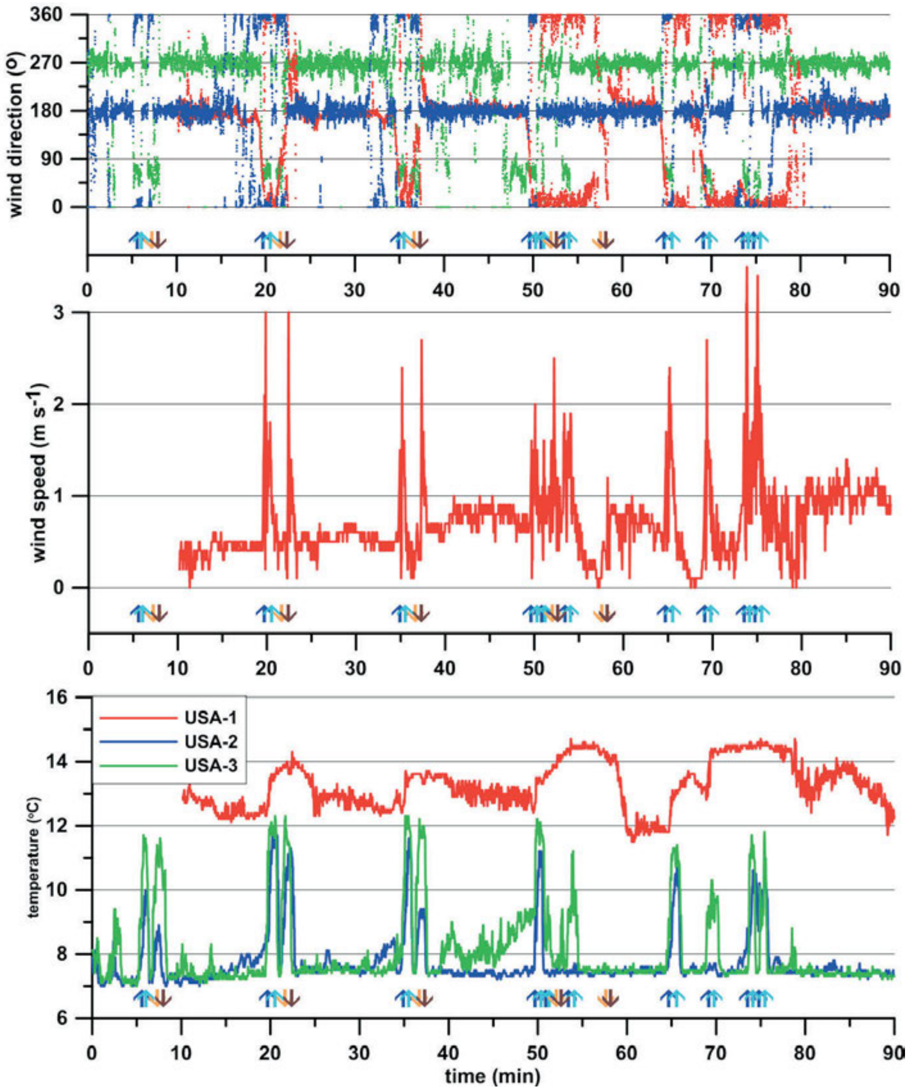


**Figure 3:** Observed time series of wind direction, wind speed and temperature at USA-sites in the Schlägerstrasse subway station on 28 February 2014 (only every twentieth value is shown). → arrival southbound, → departure southbound, → arrival northbound, → departure northbound.

with mixing length $\ell_g$ and turbulence kinetic energy $E$. While $\ell_g$ is related to the grid increments in the three directions $\Delta x, \Delta y, \Delta z$

$$\ell_g = \sqrt[3]{\Delta x \cdot \Delta y \cdot \Delta z} \tag{3.5}$$

turbulence kinetic energy is calculated using

$$\frac{dE}{dt} = \frac{\partial}{\partial x_k} K_\mathrm{m} \frac{\partial E}{\partial x_k} + K_\mathrm{m} \left( \frac{\partial \bar{u}_i}{\partial x_k} + \frac{\partial \bar{u}_k}{\partial x_i} \right) \frac{\partial \bar{u}_i}{\partial x_k} - K_\mathrm{h} \frac{g}{\bar{\theta}} \frac{\partial \bar{\theta}}{\partial x_i} \delta_{i3} - \frac{E^{3/2}}{\ell_g} \tag{3.6}$$

Obstacles are introduced in the model by a porosity concept (Gross, 2014), where buildings and walls are represented by impermeable grid volumes with porosity $P = 0$, while $P = 1$ is valid else. The moving train runs with a prescribed train speed, covering different grid points at each time step. $P = 0$ with vanishing velocity and zero turbulence kinetic energy are assumed.

The set of model equations is solved on a numerically staggered grid where all scalar quantities are arranged in the centre of the grid volume, while velocity components are defined at the corresponding side walls. The pressure disturbance $p^*$ is calculated by solving a three-dimensional discrete Poisson equation directly by Gaussian elimination in the vertical and fast Fourier transforms in the horizontal directions. A grid resolution of $\Delta x = \Delta y = 1$ m is used in horizontal directions and in the vertical $\Delta z = 0.5$ m is adopted.

The boundary conditions for the velocity components at all indoor building surfaces are zero and turbulence kinetic energy is proportional to the local friction velocity squared. The friction velocity is calculated assuming a logarithmic wind profile between the surface and the closest grid value in the atmosphere, with stability functions according to Dyer (1974). At the open lateral boundaries with $P = 1$, no-flux conditions for all variables are used.

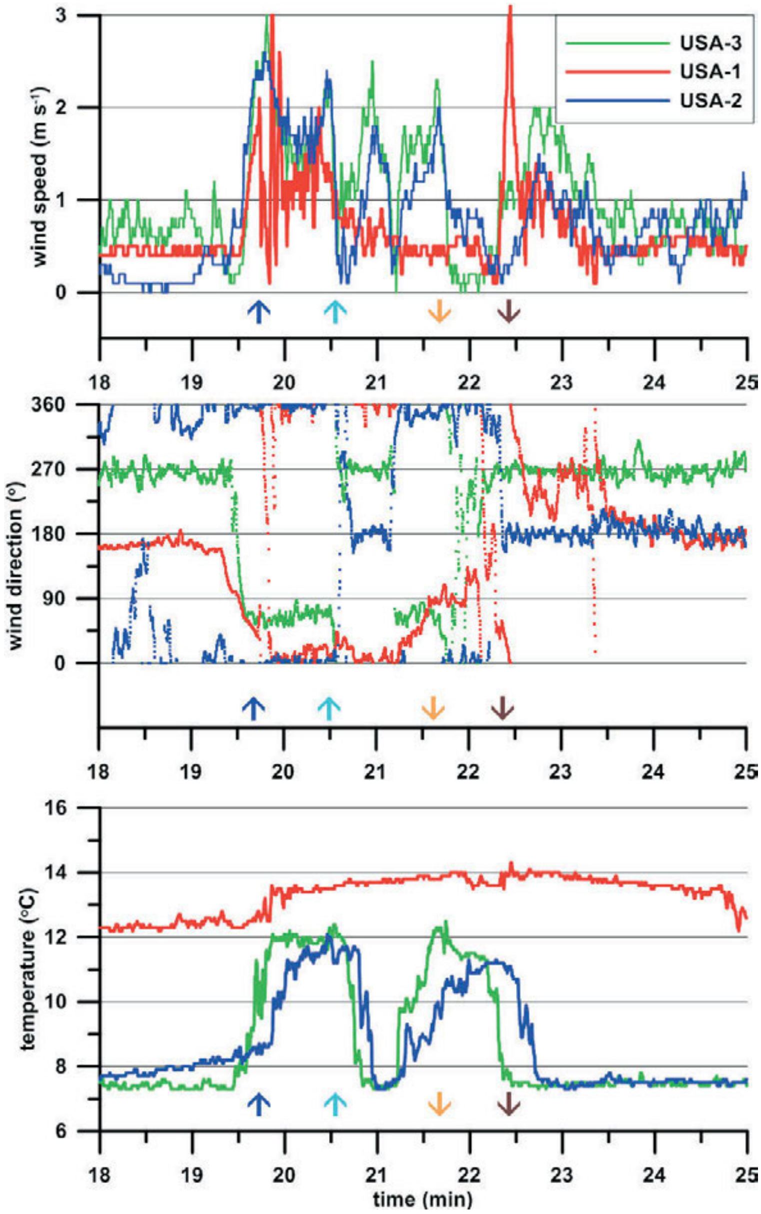


**Figure 4:** Detailed presentation of the observed time series of wind direction, wind speed and temperature at USA-sites in the Schlägerstrasse subway station on 28 February 2014.

## 3.2 Input parameters – station

With a horizontal grid resolution of 1 m not all the details of Schlägerstrasse Station can be considered in the numerical simulation. However, the characteristic features of this underground facility are well represented. Vertical and horizontal cross sections of the model station are given in Fig. 5.

The main body of the station consists of a 100 m long cave with stairs and elevators on both ends to reach the upper levels. The two tracks are located in the central part with two side platforms, one each for the trains in both directions. The station ends on both sides in 100 m long tunnel openings. The tracks lie 1 m deeper than the platforms in the station to allow passengers easy access. As a structural requirement, the two tracks are separated by a row of columns. Stairways and escalators on both ends of the platforms allow passengers to proceed towards the exits. The next level, level 1, is configured as a mezzanine which allows passengers to enter from multiple entrances and proceed to the correct platform without having to cross the street before entering. Passengers can use four exits at street level to directly access the outside from the subway station.

With the grid resolution used here the station is represented in the model by 300 × 46 x 30 grid points.

## 3.3 Input parameters – train

The train is represented by a moving solid body where, for all grid points covered at different times by this body, $P = 0$ is adopted, while before and after the passage $P = 1$ is used. In accordance with the subway trains operating regularly (e.g. type TW2500) and considering

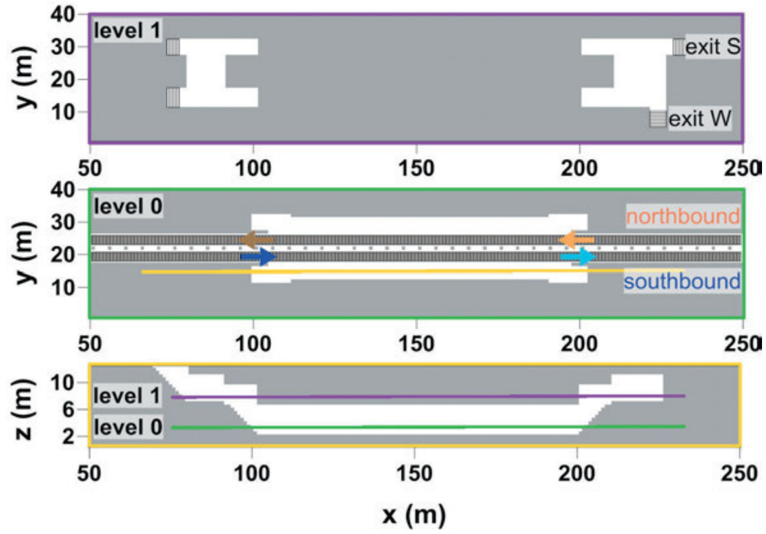


**Figure 5:** Grid representation of the Schlägerstrasse Station in horizontal and vertical cross sections. Different coloured arrows represent entry and exit of the trains northbound and southbound.

the grid resolution, the train cars are defined as being 20 m long, 3 m wide and 4 m high. Usually, two coupled cars of this type run during the regular operating hours of the Hannover rapid transit system.

Beside the dimensions, a timetable as well as the driving characteristics of a train must be specified. For train speed on the running line, a value of 50 $kmh^{-1}$ is used here (Fig. 6). Before entering the station the train is slowed down inside the tunnel and stops in the middle of the platform. To make sure that all passengers have time to stand up and alight while the train is standing or to board and sit down safely before departure, a stop of 20 s is fixed. Thereafter, the train accelerates rapidly while entering the exit tunnel.

The train schedule and the train movements can be freely prescribed in the model. According to the observations at the time of the experiment, southbound and northbound running trains are well separated in time, so they do not enter the station together. A regular sequence, as shown in Fig. 6, is adopted here and, in total, the effects of train movements on the air flow in the station are studied for a series of four pairs of trains entering the station.

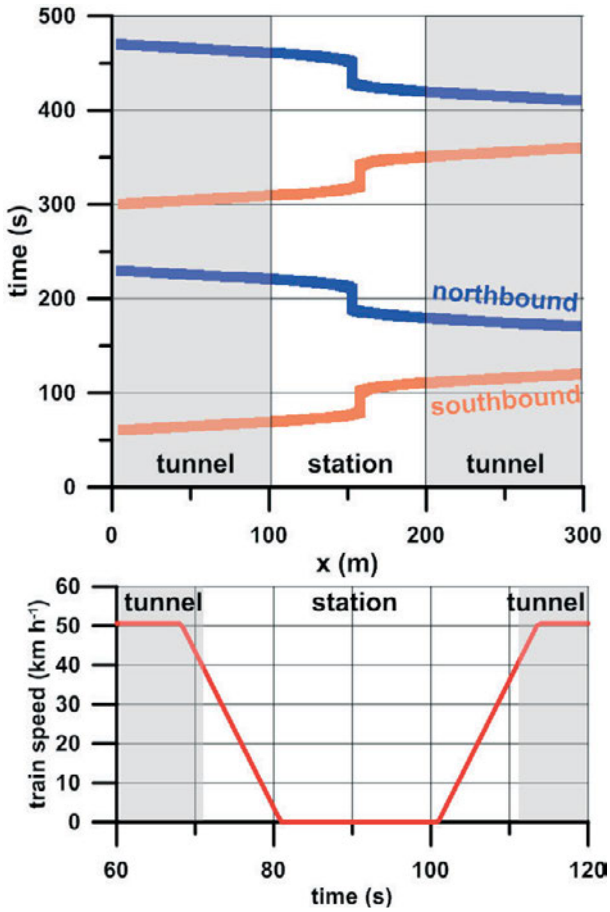


**Figure 6:** Time variation of train speed for one cycle (below) and train schedule (above).

## 3.4 Input parameters – meteorology

The meteorological conditions adopted here are associated with a weak air flow from the south. In order to maintain this motion throughout the simulation period in the station, a corresponding pressure gradient has to be specified in the tunnel system as well as in the atmosphere. Based on the results of a one-dimensional boundary layer model for the atmosphere (e.g. Gross, 2012b) and for a turbulent flow between two parallel plates, the wind speed at 2 m above ground and a representative mean wind speed in an idealized tunnel are calculated. In Fig. 7, the results are given for a variation of the superimposed pressure gradient. A pressure gradient of $\frac{\partial p_g}{\partial x} = 0,5 \cdot 10^{-3}\,Nm^{-3}$ represents the situation on 28 February 2014 quite well, with a subway wind of approximately 0.5 $ms^{-1}$ and a near surface wind in the atmosphere of 2 $ms^{-1}$; therefore this value was adopted here.

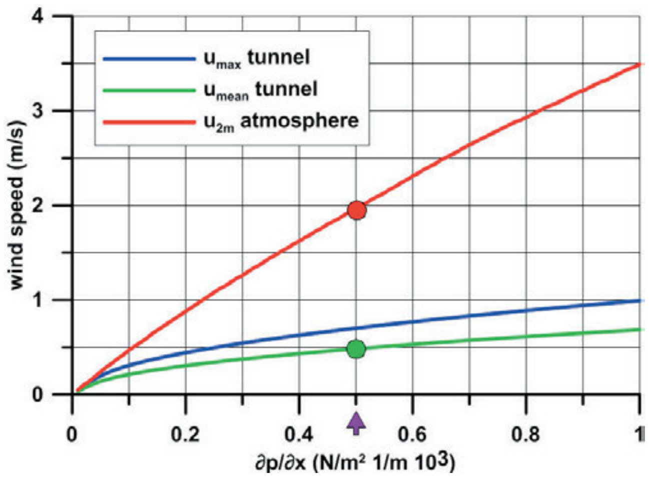


**Figure 7:** Calculated mean wind speed in a tunnel and in the near surface atmosphere (2 m above ground) depending on pressure gradient.

The temperature distribution in the subway facilities are adopted according to the observations with $T = 14\,°C$ inside the tunnel, $T = 12\,°C$ at the platform level, $T = 7\,°C$ at the mezzanine and $T = 7\,°C$ at street level.

## 4 Results

Numerical simulations with the micro-scale model have been performed for time periods including a number of trains passing the station. The actual schedule of the train movements was approximated in the model only in an idealized form. The model equations are integrated forward in time with a time step $\Delta t$ satisfying the CFL criterion. Because of the high wind speeds during the train passages and the small grid resolution, $\Delta t$ is often smaller than 0.05 s. Against this background, great effort would be necessary to simulate the observed time period of 60–90 min. However, the observations show that, in between the train movements, the background basic state re-establishes very quickly and only small changes in the meteorological variables are evident. Therefore, in the simulations, the time in between the services is reduced while train movements in the station are adopted according to the regular schedule. This results in a total simulation time of 1200 s with four entries and exits northbound as well as southbound.

### 4.1 Platform level 0 results

The simulated series for wind at location USA-1 at level 0 is given in Fig. 8. The coloured arrows in the lower panel indicate the arrival and departure of trains from the two different directions. A positive along-track $u$-wind component means an air flow from north to south, and a positive $v$-component a cross wind from west to east. Without train movements, air flow in the station is dominated by the superimposed pressure driven wind from the south. USA-1 is located close to the partition wall which separates the tunnel exit and the stairways to level 1. The wind from the south is diverted into these openings resulting in a westerly ($v$-) component at this site. This background situation is significantly disturbed near USA-1 when trains enter or leave the station, especially through the northern tunnel. Platform wind speeds achieve values of more than $3\,ms^{-1}$ within a short time, but die down almost as rapidly as they had developed. Overall, the time series show a very regular picture which is dominated by the train movements.

The large cross-wind component results from the air flow around the head of the moving train when leaving the tunnel. While inside the tunnel the direction of the piston wind is fixed by the orientation of the bordering walls, the air is discharged in all directions when entering the station. This wind modification is presented in Fig. 9 by streamlines at 1 m above the platform. The location of the train at the specific times is given by the blue box, while grey areas indicate the station walls and the columns in between the two tracks.

During arrival, the general wind direction is from the south, while in the area of influence of the moving train, northerly winds are dominant. Near the head of the train the wind is also deflected to the sides, resulting in the large cross-wind components, as depicted in Fig. 8. Some seconds later, shortly before the train stops in the middle of the platform, the wind modifications are more pronounced, including the small scale vortices behind the individual columns.

The simulated results can be used for a rough comparison with the observations at site USA-1. Due to the multitude of uncertainties concerning the grid representations of the station and the train and the details of train movement, a perfect one-to-one matching cannot be expected. However, the general picture of the complex interactions between the moving train and the surrounding atmosphere should be captured by the model. In Fig. 10, observed and simulated time series of the along-track wind component for a time slot of a complete southbound/northbound service is shown. The model is able to capture the essential features with an increase ahead of the arrival (piston wind) and a following decrease. During the passage of the train, wind speed increases drastically with a slow, exponential decline afterwards. The characteristic time scale for an exponential decay to half of the maximum value is in the order of 10 s. This characteristic picture was observed and simulated by other authors as well (e.g. Jia et al., 2009; Juraeva et al., 2013). The entry into the station of the northbound running train has only a little effect at site USA-1, in the observations as well as in the simulation. When leaving the station and entering the north tunnel, the accelerating train also affects the surrounding air and this also results in a distinct increase in wind speed on the opposite platform. However, the simulated increase is not as pronounced as the observations show. This difference could be caused for two reasons. First, the uncertain-

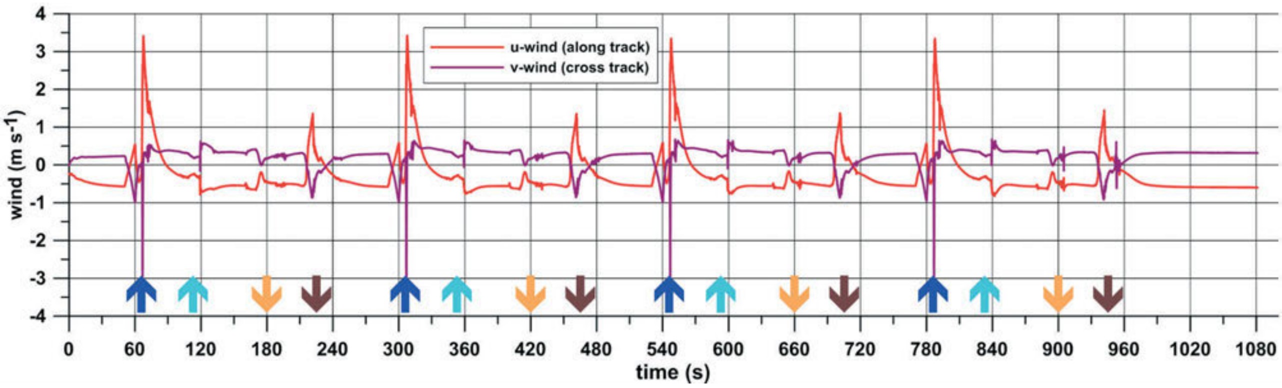


**Figure 8:** Simulated time series of along-track wind component and cross component at location USA-1.

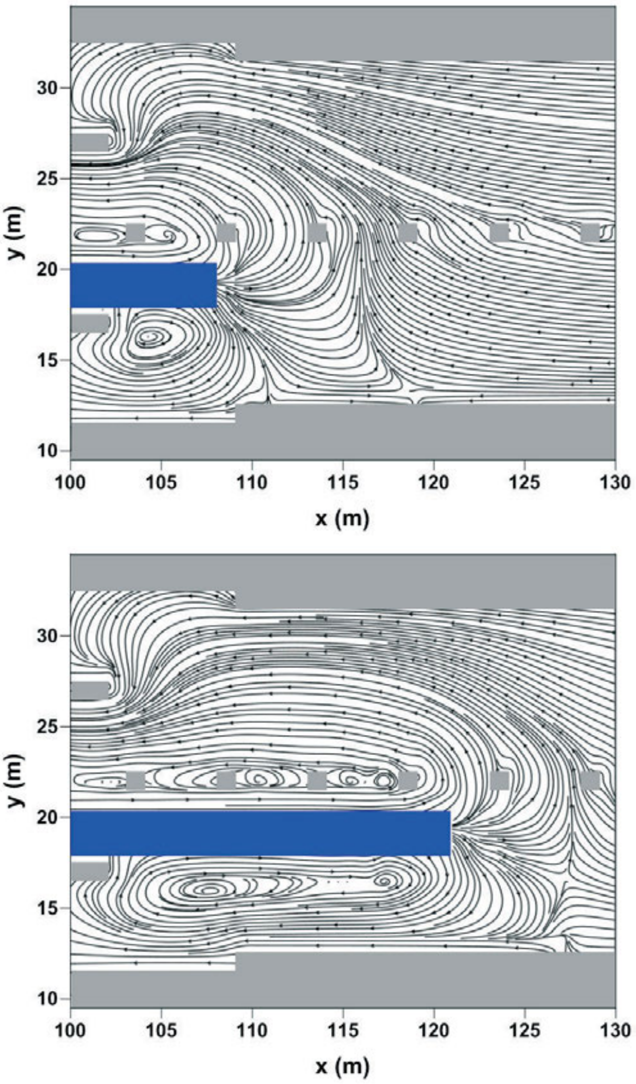


**Figure 9:** Simulated streamlines during the arrival of a train at $t$ = 307.0 s (above) and $t$ = 308.5 s (below). The train is indicated by blue boxes, the station building by grey boxes.

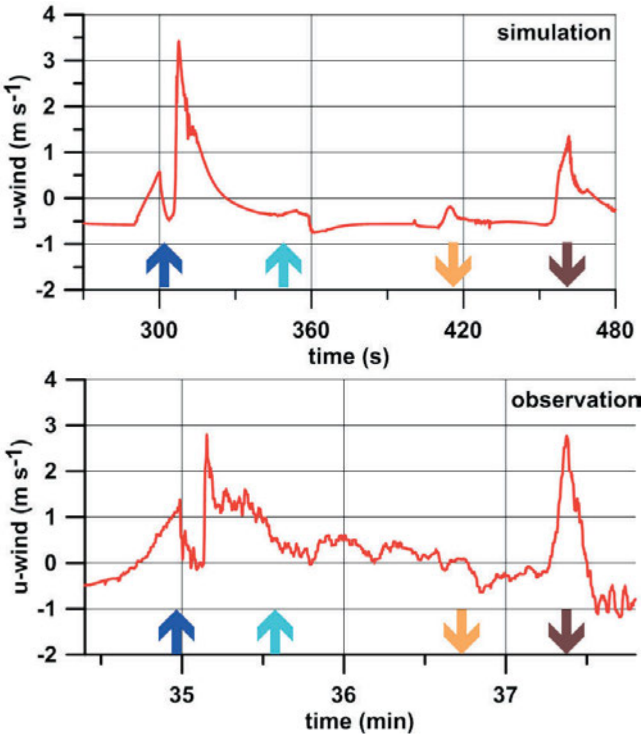


**Figure 10:** Simulated and observed along-track wind components for one service northbound and one southbound at site USA-1.

ties in prescribing the movement of the individual trains in detail in the simulations and secondly in a faster re-establishment of the background flow in the model.

## 4.2 Exit level 1 results

Beside air-conditioning systems, moving trains can induce a very effective air exchange between the tunnel space and the ambient environment at street level by the piston wind caused pressure gradient change (e.g. Huang et al., 2012). The arriving train pushes an additional volume of air into the station which can escape only through the other tunnel, not occupied by trains, or through the exits at upper levels. This exit ventilation was also measured by ultrasonic anemometers at exits S and W. The observations demonstrate clearly the direct interaction of train movement and air flow at the exits. Shortly before the arrival or after the departure of trains at platform level, wind direction at the exit level changes completely (Fig. 11). Well before the arrival, wind in the

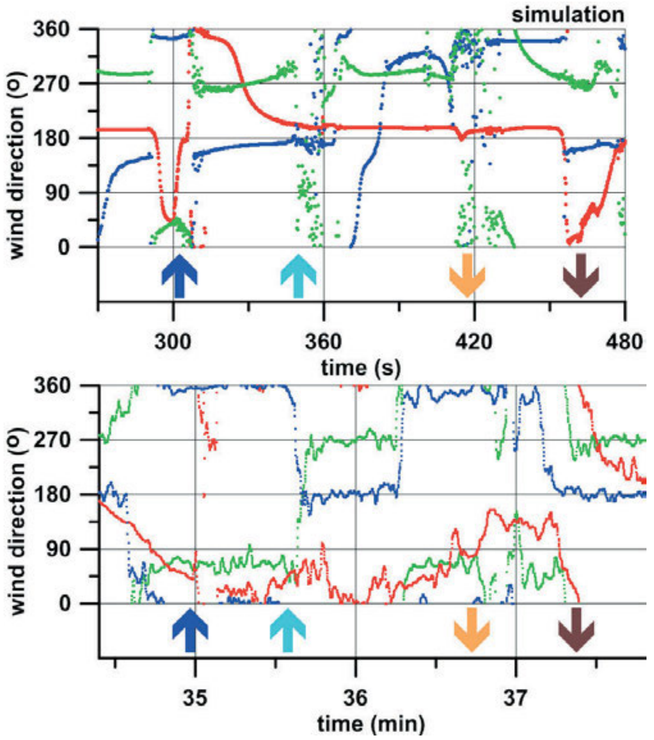


**Figure 11:** Simulated and observed wind directions for one service northbound and one southbound at site USA-1 (red), USA-2 (blue) und USA-3 (green).

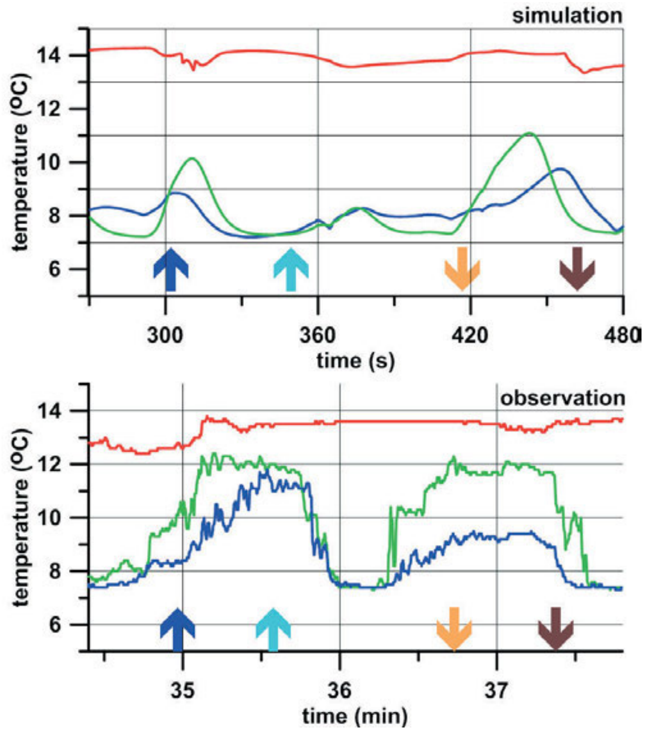


**Figure 12:** Simulated and observed temperatures for one service northbound and one southbound at site USA-1 (red), USA-2 (blue) und USA-3 (green).

simulation as well as in the observation is from outside into the station, but during the entry of the train the air flow at the exits is directed out.

Such characteristic changes in wind direction for each train movement are obvious in the simulated and observed time series. While the main features are well reproduced by the model, there is a significant difference during the time when the train stops to allow passengers to enter and exit. In the simulation, the superimposed wind conditions from the south are re-established much faster than has been observed. In all probability, this difference is caused by the boundary conditions at the exits, where street level wind is prescribed from the south.

By the ventilation effect there is an advection of air between the platform level and the exit level, but also an exchange of air mass characteristics, such as temperature. During the experiment, the lower level was much warmer than the ambient air outside. The ventilation induced circulation transports air of different temperatures between the two station levels depending on train movement. This significantly determines the time behaviour of this meteorological variable as shown in Fig. 12. While on platform level 0 the temperature change is typically about 1 K, at the exits the order of magnitude is up to 4 K within a short time. The simulated duration of the warming and cooling events is shorter than observed which is caused by the faster re-establishment of the ambient wind regime as explained above. Although the air and temperature exchange between the two levels is very regular, much more complex interactions must be effective which can be assumed by analysing the observed time series (Fig. 3). Sharp temperature increases occur as well as a continuous rise (e.g. $t = 15$ min, $t = 45$ min), parallel warming events on both exits appear (e.g. $t = 20$ min, $t = 65$ min) as well as individual failures (e.g. $t = 54$ min, $t = 70$ min). Due to the low complexity of the subway station with only two narrow platform levels the air exchange between the station and the ambient atmosphere at street level is mainly caused by train movement and piston wind. However, in multi-level stations which extend deep into the underground chimney effects through staircases and escalators become more important for ventilation (Pflitsch et al., 2013)

## 4.3 Parameter variations

Observations show very regular features for the interactions of train movements and meteorological variables, but not exactly the same picture. In order to estimate the importance of individual factors and the expected bandwidth, a parameter study for a small number of selected variables was performed. For comparison, the effect of a parameter variation on the maximum outflow at the two exits S and W was used. During the period of the field experiment, maximum outflow at both exits was about 2 $ms^{-1}$. In the numerical simulation with the standard setting, only half of this value was calculated (Fig. 13). However, by changing individual parameters

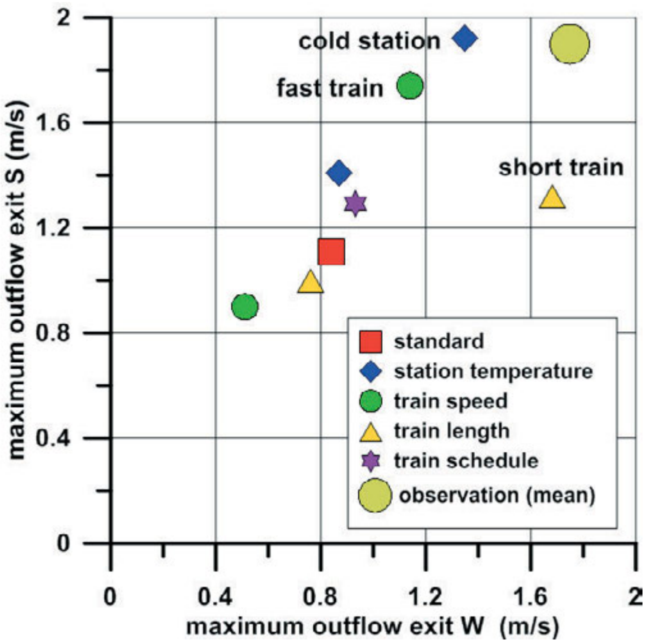


**Figure 13:** Maximum outflow at the exits S and W for different parameters

within a plausible range, the outflow through the exits might be significantly modified. The results of the parameter study can be summarized as follows:

- Assuming a cooler station atmosphere results in a significant increase in maximum outflow, whereby a 2 K cooling has a larger effect than a 1 K temperature reduction. The reason for this modification is an increased hydrostatic pressure gradient caused by the larger temperature difference between the station and the outside with the consequence of stronger winds.
- With a faster train (70 $kmh^{-1}$), the piston wind is stronger and pushes more air into the station which must be discharged through the exits. For the same reason, a slower train (30 $kmh^{-1}$) reduces the maximum outflow.
- A two-coach system 40 m long was used as the standard train. While an extension to three wagons has nearly no effect, with a reduction to only one coach a relevant increase in ventilation through the exits was simulated. The explanation probably lies in the fact that the short train during its stop in the station is far away from the tunnel exit and the air inside the tunnel, accelerated by the arriving train, can flow unhindered into the station. For the same situation, a longer train is closer to the tunnel exit and partly blocks the outflow.
- When the train is running through the station without a stop, only a small effect on maximum outflow is calculated.

This parameter study for a small selection of variables clearly shows the remarkable effects on some aspects of the air flow situation in a subway station. It emphasizes the fact that, during field experiments, a wide variety of information must be recorded in order to understand and interpret the observations correctly.

## 5 Conclusions

In this paper, observations of a field experiment for air flow in a subway station are presented together with the results of a three-dimensional micro-scale model.

The observations confirm the findings of earlier studies that a persistent background current develops in the tunnel system depending on the superimposed pressure gradient. During the operating hours, this background flow is masked by the large wind speeds caused by running trains. However, during intervals between train services or during the night with no train movements, the undisturbed situation re-establishes very quickly.

The entry and exit of trains in the station is associated with a distinct piston effect which is responsible for effective ventilation of the subway facilities. The observations show a coherent pattern with a change in wind direction at the exits to the street level for all train movements in the station. Furthermore, the importance of the ventilation effect on temperature exchange between the different levels of the station was demonstrated. Although the interactions between train movements and the various meteorological variables are usually very regular and repeat themselves with small variations, unexpected events with a very different picture appear as well in between. It can therefore be concluded, that beside the meteorological measurements, other information like train speed, train morphology or train schedule must be recorded with high accuracy during a field experiment in order to understand and explain the observations in a correct manner.

In addition, a three-dimensional micro-scale model was used to study the airflow and temperature distribution in the complex building environment of a subway station. This model, verified against various wind tunnel experiments, has been used so far for calculating wind distribution in the atmospheric urban boundary layer. It is extended now for simulations in the near future of the underground with the best conditions for a full coupling of the wind regimes below and above the surface.

The model was applied to a situation comparable to the field experiment in order to use the observations to estimate the closeness of the numerical results to reality. Simulated winds at platform level are very comparable to the observations for the times with train movements but also for the persistent background current in between and after services. The piston effect and the complete time series for the wind are calculated in the right order of magnitude within the period of two train movements in opposite directions. Also, a distinct ventilation effect at the exits to the street level, caused by the entry and exit of trains in the subway station, has been calculated and especially demonstrated by a significant simulated temperature change. However, the order of magnitude of this air exchange depends strongly on the definition of the initial conditions as well as on train characteristics. In summary, one can conclude, that the micro-scale model used here is applicable for the calculation of wind and temperature distribution in complex subway facilities. In the near future, it is planned to couple the underground with the atmosphere above and to use such a coupled model for simulations of air pollution problems and disaster situations.

## Acknowledgements

The author would like to thank R. Günther and A. Straaten, Department of Meteorology and Climatology, University of Hannover for providing the ultrasonic wind data. We acknowledge support by Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of Leibniz Universität Hannover.

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