

# Estimating wind velocity standard deviation values in the inertial sublayer from observations in the roughness sublayer

Simona Falabino<sup>1,2</sup> · Silvia Trini Castelli<sup>1</sup>

Received: 27 July 2015 / Accepted: 9 May 2016 / Published online: 18 May 2016  
© Springer-Verlag Wien 2016

**Abstract** In air quality practice, observed data are often input to air pollution models to simulate the pollutants dispersion and to estimate their concentration. When the area of interest includes urban sites, observed data collected at urban or suburban stations can be available, and it can happen to use them for estimating surface layer parameters given in input to the models. In such case, roughness sublayer quantities may enter the parameterizations of the turbulence variables as if they were representative of the inertial sublayer, possibly leading to a not appropriate application of the Monin–Obukhov similarity theory. We investigate whether it is possible to derive suitable values of the wind velocity standard deviations for the inertial sublayer using the friction velocity and stability parameter observed in the roughness sublayer, inside a similarity-like analytical function. For this purpose, an analysis of sonic anemometer data sets collected in suburban and urban sites is proposed. The values derived through this approach are compared to actual observations in the inertial sublayer. The transferability of the empirical coefficients estimated for the similarity functions between different sites, characterized by similar or different morphologies, is also addressed. The derived functions proved to be a reasonable approximation of the actual data. This method was found to be feasible and generally reliable, and

can be a reference to keep using, in air pollution models, the similarity theory parameterizations when measurements are available only in the roughness sublayer.

## 1 Introduction

In air quality assessment, observations of atmospheric variables, typically wind speed, air temperature, friction velocity, Obukhov length, roughness, and displacement lengths, are often used as input and initial conditions in air pollution models. Depending on the available measurements, it can happen to use surface layer quantities and parameters that, in reality, are estimated from data collected at stations located in suburban or even urban areas. When dealing with urban areas, two sublayers in the surface layer are defined, the roughness sublayer (RSL), wherein the flow and turbulence are influenced by individual roughness elements, and the inertial sublayer (ISL), the remaining part of the surface layer above the RSL, where the influence of the individual roughness element is mixed up by turbulence. The Monin–Obukhov similarity theory (MOST hereafter) applies in the ISL, while, in principle, it does not hold in the RSL (Fisher et al. 2005; Foken 2006; Wilson 2008). Thus, using suburban or urban station measurements implies that values typical of the RSL are implicitly treated in the dispersion models as they were representative of the ISL. In this sense, they might be improperly used to estimate other needed variables for dispersion, such as the wind velocity standard deviations, on the basis of parameterizations derived from the MOST. In particular, the density and distribution of buildings and other obstacles can significantly perturb the turbulence structure (Rotach 1999; Feigenwinter et al. 1999; Fisher

---

Responsible Editor: C. Simmer.

✉ Silvia Trini Castelli  
S.TriniCastelli@isac.cnr.it

<sup>1</sup> Institute of Atmospheric Sciences and Climate, CNR-ISAC, Turin, Italy

<sup>2</sup> Department of General Physics, University of Torino, Turin, Italy

et al. 2005); thus, an incorrect use of turbulent quantities in atmospheric dispersion modeling may misdirect the simulations and related results. For simulations over domains including urban areas, the best approach would be to devise and use advanced dispersion models apt at dealing with built environments, parameterizing or numerically resolving the presence of obstacles. However, in application to air quality assessment, generally, simpler models are used, and the urban canopy is accounted for by means of roughness and morphological parameters.

A large number of works, and related scientific literature, have been dedicated to the investigation of the properties of the ISL and RSL and their scale parameters, both on the theoretical and experimental viewpoints. Among them, in more recent years and specifically in relation to the work proposed here, Luhar et al. (2006) addressed the problem of estimating urban meteorological variables from routinely rural measurements, motivated by the need of assessing dispersion in urban areas. One of the methods they considered was based on an analytical scheme, modeling a two-dimensional internal boundary layer by using MOST functions and rural variables as upwind inputs. The method was proved to be efficient in estimating the vertical wind velocity standard deviation of the modified flow over the urban surface when comparing the predictions to the observations. Princevac and Venkatram (2007) evaluated different methods to estimate surface layer parameters, friction velocity and Obukhov length, by fitting mean wind speed and temperature measurements, taken in urban sites, to MOST profiles, in stable conditions. Venkatram and Princevac (2008) extended the analysis to unstable conditions and even to the estimate of the turbulent velocities, using as input mean wind speeds, temperatures, and temperature fluctuations. While discussing and recognizing the limitations of applying MOST to measurements made in an urban site, these studies also were motivated by the need for meteorological inputs for dispersion modeling. The authors investigated whether MOST methods can provide an useful estimate of such quantities when the cited inputs are measured with a tower in urban areas. They found that also in urban sites, MOST provides both an adequate description of the velocity and temperature profiles in the surface layer, and adequate estimates of the friction velocity, of the Obukhov length and of the standard deviations of the turbulent velocities. In a following study, Qian et al. (2010) extended the analysis further, examining methods to improve the estimates of the friction velocity and turbulent velocities using formulations for the surface heat flux that include the stability parameter, given by the ratio between the height and the Obukhov length. They considered the applicability of such formulations in convective conditions and urban sites, and they proved that parameters required

to model dispersion in urban areas can be effectively estimated from measurements of wind speed and standard deviations of temperature fluctuations at one level.

In the context of this line of research, here, we consider the option of using suburban or urban RSL parameters to provide turbulent variables that could be used in MOST formulations, which are applicable in the ISL above built and inhomogeneous areas. The goal is to investigate whether it is possible to derive values for the wind velocity standard deviations in the ISL using observed parameters that are collected in the RSL. The availability of an empirical formulation that provides the turbulent quantities using local roughness layer parameters, and that can be applicable in different cases, could be of interest for air pollution modeling. The intention here is to use the minimum information possible to derive turbulence variables, using only the friction velocity and the stability parameter estimated from the measured fluxes. When dealing with parameterizations in built and urban environment, similarity functions are expected to include morphological and roughness parameters. In previous studies (Trini Castelli et al. 2014a, b), we found that depending on the area of the urban structure considered around the measuring site, different values could be assigned to the morphological and roughness parameters. Thus, a certain arbitrariness is unavoidable when producing values that can be representative for very inhomogeneous and extended suburban and urban areas, as several experimental studies in the literature showed (see, for instance, Grimmond et al. 1998; Grimmond and Oke 1999), and their variability in space should be accounted for. To pursue our investigation and to verify the proposed approach, in this first analysis, we chose to use a simple and general expression for the wind velocity standard deviations, describing the functional relationship  $\frac{\sigma_i}{u_*} = f\left(\frac{z}{L}\right)$ , where  $i = u, v, w$  indicates the wind velocity components,  $u_*$  is the friction velocity,  $z$  is the height at which the measurement is taken, and  $L$  is the Obukhov length (Pahlow et al. 2001; Moraes et al. 2005; Trini Castelli et al. 2014a, b). Here, we use a relationship shaped on this type of formulation, which is based only on MOST parameters, to calculate ISL values based on experimental data collected inside the RSL at different sites, suburban and urban. In particular, such formulations include empirical coefficients that are generally estimated on the basis of observations collected in field experiments. An interesting and thorough discussion on the normalized standard deviations of velocity components in the ISL over two urban sites is presented in Fortuniak et al. (2013), providing empirical evidence that turbulence variables measured in the urban boundary layer can be described by local scaling and similarities within MOST. A problem related to the scaling in the similarity formulations is the self-correlation

between the dependent and independent variables, like in this case where both the wind velocity standard deviations and the stability parameter contain the friction velocity. Klipp and Mahrt (2004) examined the role of the self-correlation between the Obukhov length and the non-dimensional shear, having the friction velocity as common divisor, for stable conditions and for layers where MOST does not apply and relationships are determined by the local similarity theory. They constructed randomized actual data that no longer retain any physical connection between the fundamental variables, so that the average correlation becomes a measure of the self-correlation. They found self-correlations significantly larger than zero. At the same time, they recognize that self-correlation is difficult to avoid, to maintain simplicity in the scaling schemes, which use a limited number of fundamental variables. For such reason, this type of similarity formulations is being widely applied in dispersion models and boundary-layer parameterization.

To achieve our purpose, the main issues that need to be addressed are:

1. Whether it is reasonable to derive the wind velocity standard deviations in the inertial sublayer by a scaling on the roughness sublayer parameters;
2. Whether the empirical coefficients determining the wind velocity standard deviations can be transferred from one case to other similar cases, where parameters are only available at one level into the roughness sublayer;
3. Whether the formulations based on the empirical coefficients can be exported also in case of different types of sites.

This approach represents a first step to pursue our goal and a basis for a possible derivation of a formula for the profile of wind velocity standard deviations, accounting for the site geometry. Indeed, elaborating a similarity formulation that properly includes morphological and roughness parameters is a more advanced task, and it could be a development only after extensive analyses of several different observational data sets.

Here, two field experiments are considered: the UTP field campaign (Urban Turbulence Project, Ferrero et al. 2009; Trini Castelli et al. 2014a, b), in a suburban site, and the BUBBLE (Basel UrBan Boundary Layer Experiment, Rotach et al. 2004, 2005) field experiment, referring to observations collected both at a suburban and an urban station.

The data sets from the field experiments are presented in Sect. 2. In Sect. 3, we present the idea and methodology adopted to derive ISL wind velocity standard deviations from RSL parameters, and we assess their applicability for the different experiments. In Sect. 4, we verify whether the

calculated formulations can be exported to similar and different sites, quantifying the deviation from the actual observations. Conclusions are drawn in Sect. 5.

## 2 The reference data sets

### 2.1 The UTP field experiment

The UTP observational experiment (Mortarini et al. 2009, 2013; Trini Castelli et al. 2011, 2014a, b; Trini Castelli and Falabino 2013) was held in the city of Turin, located at the western edge of the Po Valley (Italy). The Alps, whose crest line is about 100 km distant, surround the city in the western, southern, and northern sectors, and a hill chain (maximum altitude of about 480 m above the city) characterizes the landscape in the eastern one.

The UTP meteorological station (45°1' latitude, 7°38.5' longitude) is located in an area in the southern outskirts of the town on grassy, flat terrain surrounded by buildings and plots of open field. The distance of tallest buildings (about 30 m high) from the mast is about 150 m in the north-northeast direction, while in the other directions, the closest buildings (from 4 to 18 m high) are at about 70–90 m distance. Therefore, the observation site is a rather typical suburban one, characterized by a complex geometry that is a mixture between green areas and urban structures. Three SOLENT ultrasonic anemometers, placed on a 25-m-high mast at the heights of 5, 9, and 25 m above the ground, were operated simultaneously and continuously for 15 months, besides some interruptions for maintenance, from January 18, 2007 to March 19, 2008. Wind- and temperature-observed data from the three anemometers were synchronized and stored at the rate of 20 Hz, and then, the full data record was originally elaborated into 1-h segments. A triple rotation (McMillen 1988) was applied for each hour, aligning the x-coordinate with the hourly mean streamwise wind direction, and then, each subset was detrended on the basis of a least-squares linear fit (Bendat and Piersol 2000). Stationarity and significance tests were applied to evaluate the confidence level of the observations. The final and full-period UTP data set is a sequence of 10,144 hourly-averaged data, but only the hourly averages in which at least 80 % of the data are valid are used. Since, in BUBBLE case (see next Sect. 2.3), we have available 10-min averaged data, to allow a valid comparison, in this work, the UTP data were calculated as 10-min averages, elaborating a new data set in the same way as above described for the 1-h set.

The UTP data set is characterized by a large number of low wind speeds, here considered as  $\bar{u} \leq 1.5 \text{ ms}^{-1}$  (Anfossi et al. 2005; Mortarini et al. 2013), that is 89, 82, and 54 %, respectively, at 5, 9, and 25-m height for the 10-min averaged set.

The stability conditions are estimated considering as ‘neutral’ those values for which  $\frac{z}{L} \rightarrow 0$ , where the limit is here taken as  $-0.01 < \frac{z}{L} < 0.01$ . The percentages are then:

Unstable cases,  $\frac{z}{L} < -0.01$ : 49, 48, and 59 % from ground up;

Stable cases,  $\frac{z}{L} > 0.01$ : 48, 44, and 32 % from ground up;

In Trini Castelli et al. 2014a, b morphological and roughness parameters in UTP site were calculated with different morphometric and meteorological approaches, thoroughly analyzing also their dependency on the wind velocity and urban structure. Based on the morphometric method, considering morphometric data in an area of 1.2 km radius around the measurement site, we estimated that the UTP site is characterized by a plan area parameter  $\lambda_p = 0.18$  and an average building height of  $z_H = 7$  m, which we use as the reference values in the present analysis.

Due to the different averaging time interval, the distributions of the wind velocity standard deviations  $\sigma_i$  ( $i = u, v, w$ ) for the two data sets, 1-h and 10-min averages, show non-negligible differences (see Fig. 1). In particular, in the lower range of the horizontal components, there is a shift of the curve and of the peak of the distribution to lower values. This, of course, has effects on the calculation and analysis proposed, and it is an issue to be accounted for when generalizing and transferring the results to other cases. We cite that Princevac and Venkatram (2007) showed surface fluxes at heterogeneous and built sites being best estimated when using mean variables that are averaged over smaller intervals compared to the nominal time scale of 1 h.

## 2.2 The BUBBLE field experiment

BUBBLE (Christen and Vogt 2004; Rotach et al. 2004, 2005; Christen et al. 2007, 2009) is an extensive and well-

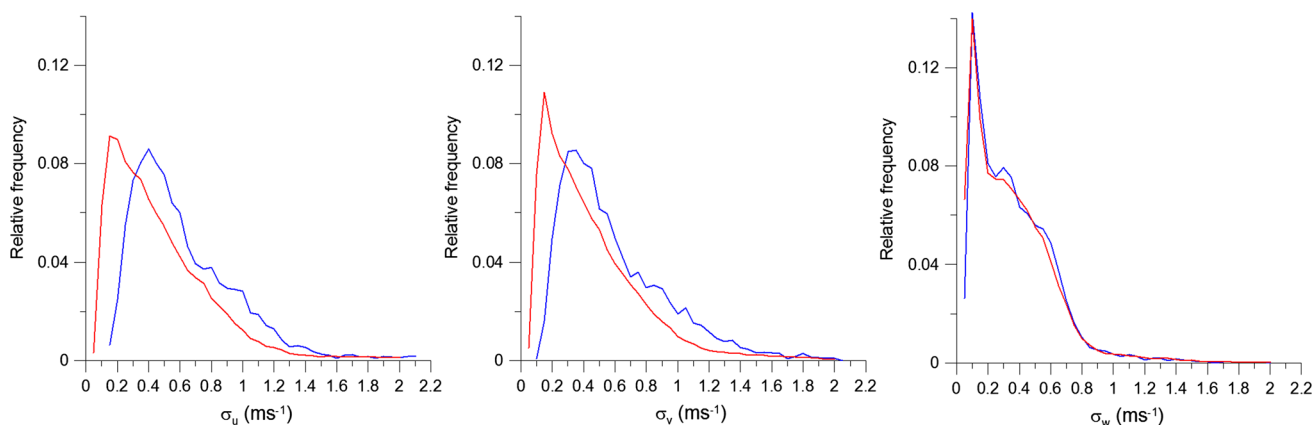
known field experiment carried out in the mid-size city of Basel (in Switzerland, about 200,000 inhabitants), surrounded by gentle but still complex topography.

In BUBBLE, a long-term observational network was established, supporting the permanent observations, to investigate the structure of the urban boundary layer. In this work, we consider the observations collected at two sites, an urban one (Basel-Sperrstrasse, Basel hereafter,  $47^\circ 33' 57''$  latitude and  $7^\circ 45' 49''$  longitude), where a 30-m tower was placed in a street canyon in a part of the city densely built-up, and a suburban site (Allschwil-Rämelstrasse, Allschwil hereafter,  $47^\circ 33' 19''$  latitude and  $7^\circ 33' 42''$  longitude), where instruments were placed on a hydraulic tower located in a vegetated suburban backyard surrounded by 2- or 3-storey residential single- and row-houses.

Basel station was operated for several months, from November 01, 2001 until July 15, 2002, while Allschwil station was operating only during the IOP, between June 4 and July 11, 2002. At the two towers, profiles of measured data were collected from 3D-ultrasonic anemometer-thermometers, respectively, at six levels (3.6, 11.3, 14.7, 17.9, 22.4, and 31.7 m height) for Basel and three levels (8.3, 12.1, and 15.8 m height) for Allschwil. Raw data were sampled quasi-synchronized at 20 Hz.

For our study, we have available 10-min averaged data in the global coordinate system, where  $u$  component points toward east,  $v$  component points toward north, and  $w$  component points upward.

The observed data were processed to align the x-coordinate with the 10-min mean streamwise wind direction; the final data sets are, respectively, indicated as BBU for Basel and BBS for Allschwil. A large number of low wind occurrences ( $\bar{u} \leq 1.5 \text{ ms}^{-1}$ ) were recorded, and unstable conditions were dominating, in particular, at the urban station, as indicated by the following percentages.



**Fig. 1** Distribution of the observed wind standard deviations at 25 m height for the UTP\_1 h set (blue line) and UTP set (red line):  $\sigma_u$  (left),  $\sigma_v$  (center), and  $\sigma_w$  (right)

Low wind data ( $\bar{u} \leq 1.5 \text{ ms}^{-1}$ ) :

- Allschwil: 85, 66, 53 % from ground up;
- Basel: 97, 93, 89, 74, 52, 30 % from ground up;

Unstable cases ( $\frac{z}{L} < -0.01$ ) :

- Allschwil: 64, 66, 69 % from ground up;
- Basel: 80, 89, 92, 91, 92, 88 % from ground up;

Stable cases ( $\frac{z}{L} > 0.01$ ) :

- Allschwil: 30, 29, 28 % from ground up;
- Basel : 12, 10, 6, 6, 6, 10 % from ground up

Regarding the morphological parameters, calculated considering morphometric data in a radius of 250 m around the measuring point, the suburban Allschwil site is characterized by a plan area parameter  $\lambda_p = 0.28$  and an average building height  $z_H = 7.5 \text{ m}$ , while for the urban Basel site, they are, respectively,  $\lambda_p = 0.54$  and  $z_H = 14.6 \text{ m}$  (Rotach et al. 2005).

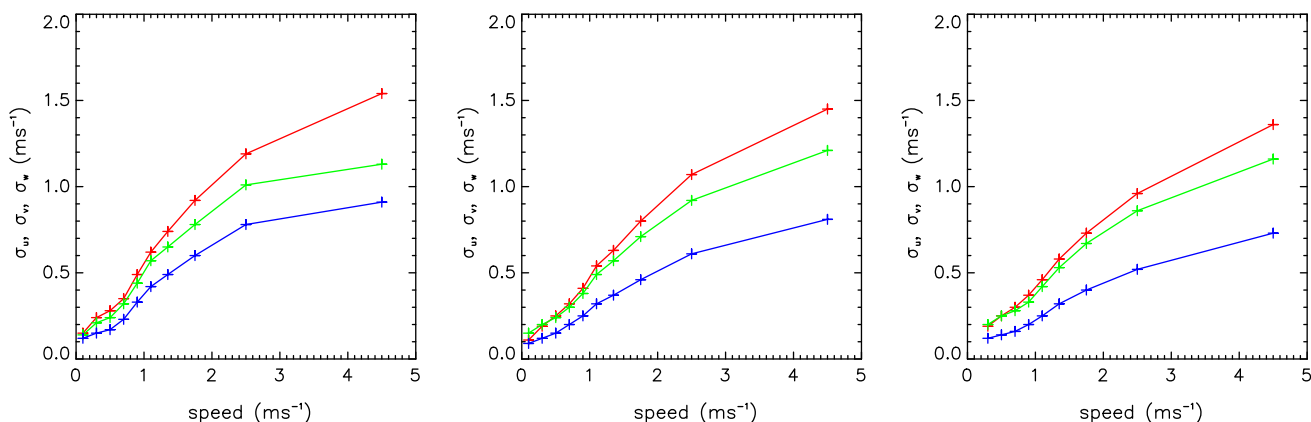
### 2.3 Comments on the low-wind conditions

With reference to the particular low wind conditions, characterizing all sites considered here, in Trini Castelli and Falabino (2013), we found that in the UTP case, the curves of the two horizontal components of the wind velocity standard deviations, determined as functions of wind speed classes, overlap for wind speeds smaller than about  $1.5 \text{ s}^{-1}$ . They start differentiating for higher wind speeds. This implies that in low wind conditions, there is not anymore a well-defined wind direction. We repeated the analysis for the BUBBLE case, calculating the mean wind velocity standard deviations for ten wind speed classes (Figs. 2, 3). We notice that in the suburban site (Fig. 2), an analogous result is obtained at all levels: the

two horizontal components are very similar up to a speed of  $1$  or  $1.5 \text{ ms}^{-1}$ , and they start differentiating for higher values. At the urban site (Fig. 3), at the lower levels,  $3.6$  and  $11.3 \text{ m}$ , laying inside the street canyon, the two horizontal components are separated for any wind speed value. The along-wind component  $\sigma_u$  for low wind speed, less than  $1 \text{ ms}^{-1}$ , takes values analogous to the suburban case. The crosswind component  $\sigma_v$ , instead, has the same behavior and values of the vertical one  $\sigma_w$ , with the two curves superposing. This clearly reveals the effect of the street canyon, where the walls of the buildings act as boundaries for the development of turbulent vortices, for which the crosswind width and height get a similar scale. At and above the height of the buildings, gradually, the two horizontal components approach, and again, they take practically the same value below  $1.5 \text{ ms}^{-1}$  wind speed. We recall that this type of condition typically originates from the phenomenon of meandering, which, inside the street canyon, finds its containment due to the presence of the building walls. Therefore, also BUBBLE observations confirm that a well-defined wind direction cannot be identified in low wind conditions.

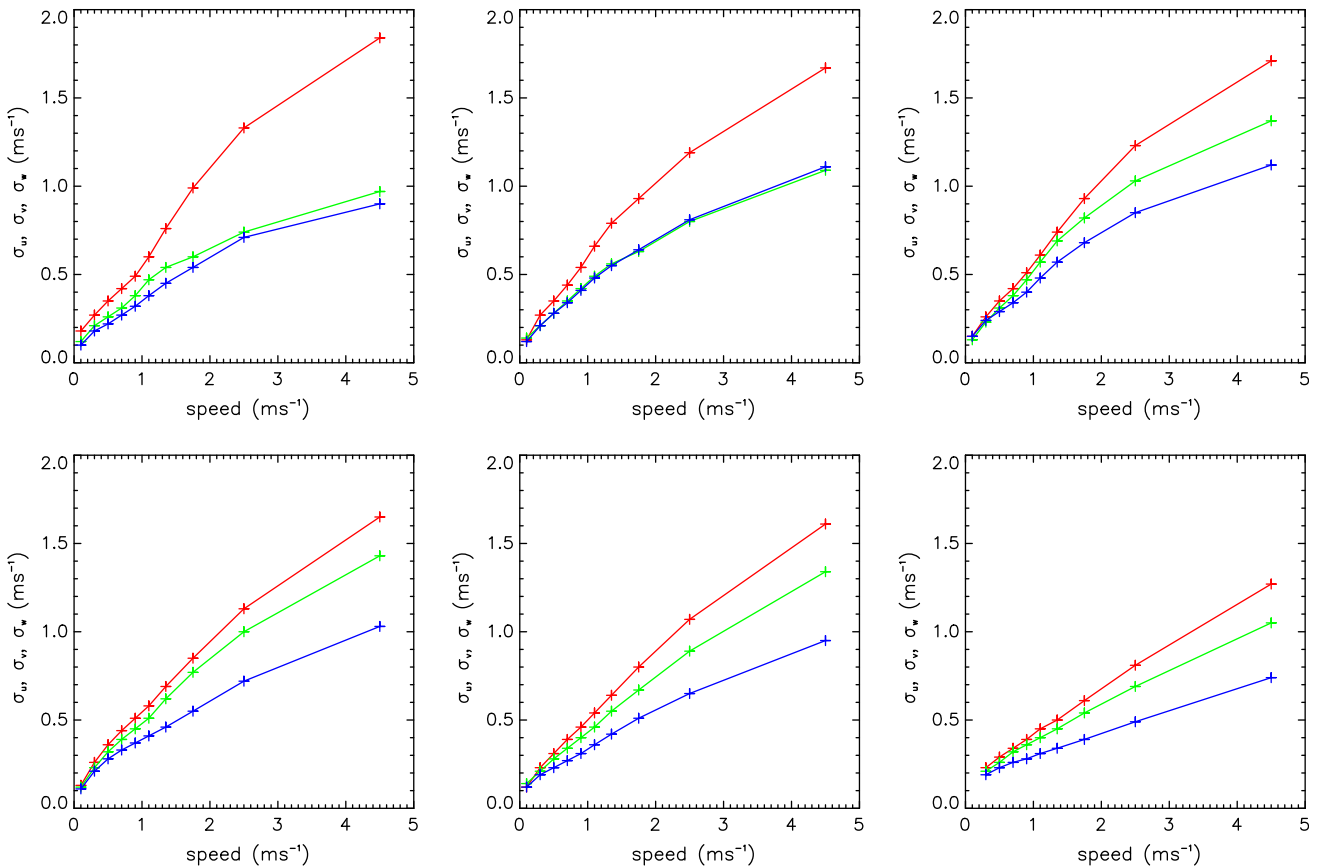
### 3 The methodology

In the frame of the UTP and BUBBLE experiments, we have observed data from sonic anemometers available at different vertical heights, both in the RSL and in the ISL. Having a vertical profile of data allows deriving the values at higher heights in the ISL from parameters measured in the RSL, miming standard conditions where measurements are available only at one height, and comparing them with the actual observations. This approach, in principle, will be valid for the specific geometry and roughness characteristics of the site considered.



**Fig. 2** BUBBLE data set, Allschwil site. Wind velocity standard deviations as functions of wind speed classes:  $\sigma_u$  red line,  $\sigma_v$  green line,  $\sigma_w$  blue line, at  $8.3 \text{ m}$  (left),  $12.1 \text{ m}$  (center), and  $15.8 \text{ m}$  (right) height





**Fig. 3** As in Fig. 2 but for Basel site, at 3.6 m (top left), 11.3 m (top center), 14.7 m (top right), 17.9 m (bottom left), 22.4 m (bottom center), and 31.7 m (bottom right) height

A general formulation for the wind velocity standard deviations  $\sigma_i$  in the homogeneous surface layer or in the inertial sublayer, following MOST, is:

$$\frac{\sigma_i}{u_*} = a_i \left( 1 + b_i \left| \frac{z}{L} \right| \right)^{c_i} \tag{1}$$

with  $i = u, v, w$  and where, again,  $u_*$  is the friction velocity,  $z$  is the measurement height,  $L$  is the Obukhov length,  $a_i, b_i$  and  $c_i$  are empirical coefficients.

We cite that Rotach (1999) found that MOST can be applied in the higher part of RSL when using ‘local’ scaling variables, which means friction velocity and Obukhov length computed from shear stress and heat fluxes measured at the local height. This local similarity was investigated also in our previous works for the UTP site, assessing the dependency of the surface layer variables on the height.

Here, we consider a different approach, not applying a local scaling but estimating the values of the empirical coefficients  $a_i, b_i$ , and  $c_i$  that may be used to derive an ISL value for the standard deviations,  $\sigma_{i\_ISL}$ , from the available observed data in the RSL. The formula in Eq. (1) is valid for the ISL. Here, we use a ‘hybrid’ formulation that

resembles it, but where the RSL parameters are included and we empirically, through the best fit, estimate the values of the  $a_i, b_i$ , and  $c_i$  coefficients that can ‘correct’ the computation of the standard deviations for applying it in the ISL, as follows:

$$\sigma_{i\_ISL} = a_i u_{*RSL} \left( 1 + b_i \left| \frac{z}{L} \right|_{RSL} \right)^{c_i} \tag{2}$$

where  $u_{*RSL}, |z/L|_{RSL}$  are the friction velocity and the stability parameter calculated from measured data in the RSL, which are typically collected at station heights within the average building height  $z_H$ . The stability parameter is calculated estimating the heat flux from the measured sonic temperatures, at the same level as for the friction velocity. The correction for deriving the standard deviation in the ISL from RSL parameters is thus embedded in the values of the coefficients.

In the following, we estimate the ISL standard deviations from the RSL values in UTP and BUBBLE cases. Then, we investigate the applicability and transferability of this approach in other cases and try to address the issues anticipated in the introduction.

**Table 1** Empirical coefficients estimated from the best fit at the ISL level (Eq. 2) for the standard deviations of the wind velocity fluctuations for the different data sets

	$a_u$	$a_v$	$a_w$	Stratification	$b_u$	$b_v$	$b_w$
UTP	$2.55 \pm 0.78$	$2.16 \pm 0.79$	$1.65 \pm 0.53$	Unstable	-0.99	-1.45	-1.74
				Stable	2.06	2.81	1.24
BBS	$2.43 \pm 0.40$	$1.97 \pm 0.40$	$1.31 \pm 0.17$	Unstable	-0.61	-2.60	-1.30
				Stable	2.30	4.60	1.70
BBU	$2.93 \pm 0.74$	$2.30 \pm 0.71$	$1.75 \pm 0.44$	Unstable	0.13	-0.12	-0.19
				Stable	2.97	2.84	3.40

### 3.1 Estimation of the wind velocity standard deviations in the ISL from RSL parameters

To derive the wind velocity standard deviations in the ISL from a scaling of RSL parameters, firstly, we applied a best-fit procedure for obtaining the empirical coefficients in Eq. (2). The function was fitted to the data for each averaging period using the Levenberg–Marquardt least-squares method.

In the literature, the height of the RSL has been defined as about twice the average building height  $z_H$  (Rotach 2001) or even more, up to  $3-5z_H$  (see, for instance, Roth 2000). The  $2z_H$  RSL height can be of reference for typical European cities like Turin and Basel (Fisher et al. 2006), thus, we choose it as the criterion to identify which measured data are inside the RSL or in the ISL, above the suburban and urban sites considered.

In UTP experiment, the highest observational level, 25 m, was found to be in the ISL (Trini Castelli et al. 2014a, b), while the two lower ones, 5 and 9 m, are in the RSL and equidistant from the average building height  $z_H = 7$  m.

We thus decided to use values at both the two RSL-levels, to determine the unknown coefficients,  $a_i$ ,  $b_i$ , and  $c_i$  for calculating a  $\sigma_{i\_ISL}$  value in the ISL. As similarly done in a former work (Trini Castelli and Falabino 2013), we estimated the coefficients performing the fit procedure on the  $\sigma_{i\_ISL}$  values measured at  $z_{ISL} = 25$  m using the RSL parameters  $u_*$ ,  $|z/L|$  collected at 5 and 9 m in Eq. (2).

The coefficients were estimated considering data for which observations are available at all levels. Although the exponent  $c_i = 0.33$  is predicted by the theory only for an unstable surface layer, similar values were found even in stable conditions in Trini Castelli and Falabino (2013). Thus, as a reasonable approximation, here, we assign the fixed value  $c_i = 0.33$ , then we estimated  $a_i$  as analogously done in Trini Castelli and Falabino (2013) from the neutral data, and finally calculated  $b_i$  with the fit procedure on the observed data at 25 m. The  $a_i$  coefficients correspond to the neutral values of  $\frac{\sigma_i}{u_*}$ , that is when  $\frac{z}{L} \rightarrow 0$ , here defined as the range  $-0.01 < \frac{z}{L} \leq 0.01$ . The fitting procedure for the  $b_i$  coefficient is repeated a hundred times, varying the initial

value of the parameter. The value estimated for  $b_i$  that is associated to the minimum RMSE is then considered.

The fit procedure was applied both for the two separate data sets at 5 and 9 m and including all normalized values at the two levels together in a unique data set. The values of the empirical coefficients for the unstable and stable stratifications including all 10-min averaged data and considering them at 5 and 9 m together to derive the 25-m values, are reported in Table 1. When calculating the empirical coefficients separately from the 5 and 9-m roughness layer parameters, we found that  $a_i$  values are smaller for the 9-m set than for the 5-m one. We verified that the  $a_i$  values in Table 1 are in between them, slightly less than the average between the pairs  $a_i(5\text{ m})$  and  $a_i(9\text{ m})$ . The final values used can thus be considered representative of the intermediate 7-m height.

We note that the values of the analytical  $a_i$  coefficients depend on the averaging time used for processing the observations (see for a discussion Vickers and Mahrt 2003; Mahrt 2010; Luhar 2012), since different distributions characterize not only the standard deviations (Fig. 1) but also the other variables. However, the values of the other empirical coefficients, derived through the best-fit procedure, contribute to make the final empirical functions to be effectively representative of the data sets. This implies that the single coefficients may be characterized by a degree of arbitrariness, thus the set of empirical coefficients has to be considered as a whole for their use. It also indicates that proper sets of coefficients need to be chosen depending on the application considered, its space and time scales and the spatial and temporal resolutions in the model simulations.

In BUBBLE cases, to be congruent with the approach adopted for UTP set and to consider observations well inside the RSL, we selected as RSL values those collected at the height that is the closest to the average building height,  $z_H$ . Using the  $2z_H$  height for the RSL limit, as ISL reference values, we considered those measured at the highest tower levels, which in both cases are a bit higher than  $2z_H$ , thus respecting the chosen criterion. For the suburban data set BBS, we identified as ISL level the one at 15.8 m height, and as RSL parameters, those collected at

8.3 m ( $z_H = 7.5$  m); for the urban data set BBU, the ISL level is at 31.7 m, and the RSL parameters are those available at 14.7 m ( $z_H = 14.6$  m).

The empirical coefficients  $a_i$  and  $b_i$  are reported in Table 1, and were thus calculated fitting in formula (2) the  $\sigma_{i\_ISL}$  measured at  $z_{ISL} = 15.8$  m for BBS and  $z_{ISL} = 31.7$  m for BBU and using the parameters  $u_{*RSL}, |z/L|_{RSL}$  measured at 8.3 and 14.7 m for BBS and BBU, respectively.

We calculated the empirical coefficients also using the roughness parameters from all other BBS (12.1 m) and BBU (3.6, 11.3, 17.9, 22.4 m) levels, fitting the standard deviation function to the ISL observations. As in UTP case, it is confirmed that the  $a_i$  values decrease with increasing height, independently of the complexity of the urban structure, thus due to a proportional increase of the local friction velocity with height.

In Table 1, we report also the standard deviations estimated for the analytical coefficients  $a_i$  to provide a quantification of their related uncertainty. They, as it can be expected, are generally higher than what we found in previous works but for the empirical coefficients calculated locally at the considered height (best agreement at 9 m for UTP 1-h averages set:  $\pm 0.63, \pm 0.78, \text{ and } \pm 0.20$ , respectively, for  $u, v, \text{ and } w$ ) and in the corresponding literature (respectively,  $\pm 0.25, \pm 0.25, \pm 0.26$  in Roth 2000, for  $z/z_H > 0.7$ , as in our cases). We also note that using RSL parameters at higher levels, closer to the ISL height, reduces the error.

We made some tests calculating the empirical coefficients using subsets of data, like 50 or 25 % of the observations. We found that the analytical coefficients  $a_i$  may vary by an order of  $10^{-2}$ , largely within their related standard deviation (Table 1), while the  $b_i$  coefficients adjust on the basis of the fit procedure. This modest variation does not lead to a change in the overall agreement between estimates and observations, supporting the feasibility of the empirical approach.

Summarizing, the cases considered here for the discussion, and reported in Table 1, are identified as:

UTP: UTP experiment, suburban site, best fit of the  $\sigma_{i\_ISL}$  values at 25 m using roughness layer parameters at 5 and 9 m; BBS: BUBBLE experiment, Allschwil suburban site, best fit of the  $\sigma_{i\_ISL}$  values at 15.8 m using roughness layer parameters at 8.3 m; BBU: BUBBLE experiment, Basel urban site, best fit of the  $\sigma_{i\_ISL}$  values at 31.7 m using roughness layer parameters at 14.7 m.

It is not straightforward to infer which among the characteristics of the sites, morphological or meteorological, can determine the values of the empirical coefficients. From Table 1, we notice a trend to increase for the  $a_i$  coefficients for increasing geometrical complexity. In fact,

at the Turin UTP site, rather high buildings are mixed up with small obstacles, so the  $z_H$  is a bit lower than in Allschwil, but the suburban structure is more complex. The variability of the  $b_i$  coefficients, which are those derived by the fit of the data while the  $a_i$  coefficients are derived analytically, could be related to the specific characteristic of the site, in particular, to the stability conditions, and cannot be easily interpreted. This was already discussed in Trini Castelli and Falabino (2013), since it was not possible to derive an analytical regular function for the analogous coefficients in that study.

### 3.2 Analysis of the results

We address, in a qualitative and quantitative way, whether the proposed approach is reasonable, responding to the questions:

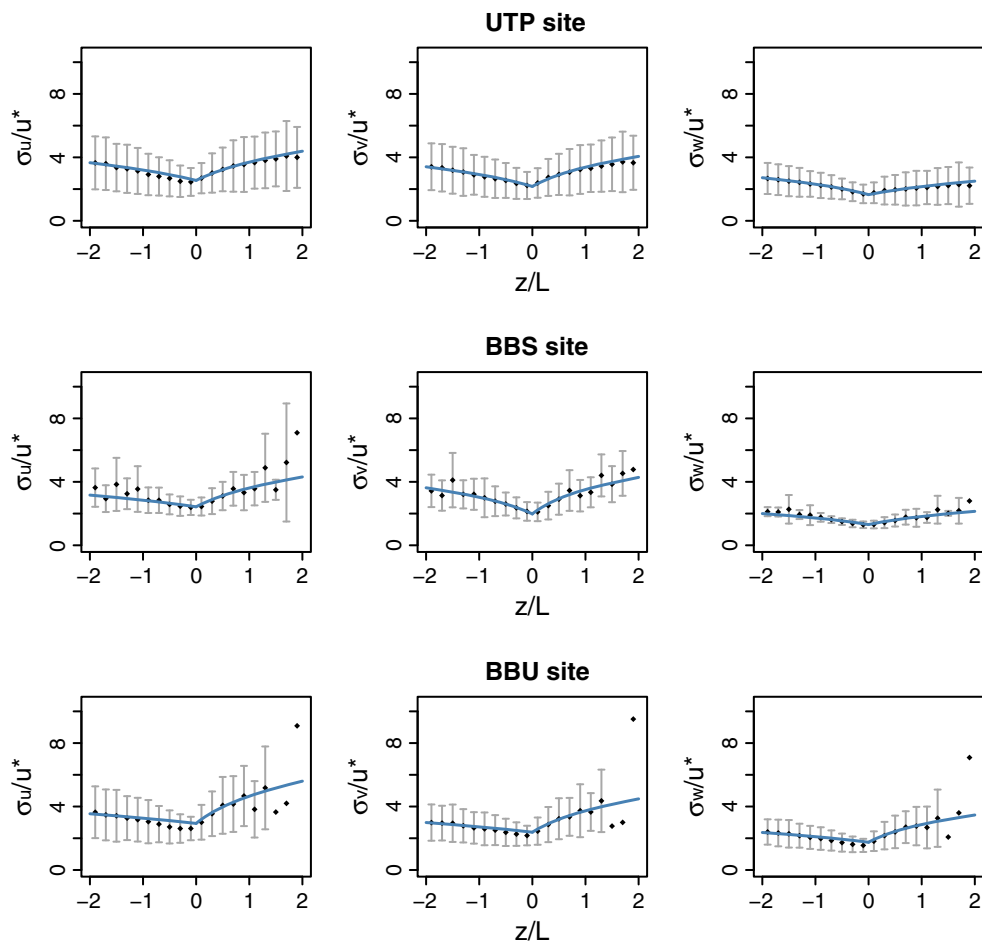
- Are the standard deviations derived in the inertial sublayer by a scaling on the roughness sublayer parameters reasonable?
- Can this approach be used also in the densely urban structure?

The agreement between the actual observations and the ISL wind velocity standard deviations derived from RSL parameters is discussed, as a first step, comparing their stability-dependent functions and considering their ratio.

Using the empirical coefficients estimated with the best fit described in Sect. 3.1, we recalculated the 10-min averaged ISL wind velocity standard deviations from Eq. (2) for UTP ( $\sigma_{i\_25}$ ) and BUBBLE ( $\sigma_{i\_15.8}$  for Allschwil and  $\sigma_{i\_31.7}$  for Basel) data sets from the corresponding RSL values, then compared them with the actual observations.

In Fig. 4, the curves of the functions formulated in Eq. (2) for all normalized wind velocity standard deviation components, in UTP, BBS, and BBU cases, are plotted together with the observed data, as functions of the stability parameter  $z/L$  classes, for the full range of typical intervals used in the literature when evaluating similarity functions, that is  $-2 < \frac{z}{L} \leq 2$ . Data have been split and averaged over 20 stability classes, each of width 0.2. The error bars are estimated as the standard deviations of the data in each stability class and represent the variability of observations in that class. If the number of data in the class is less than 5, the experimental value is considered not statistically significant, and to highlight this aspect, the variability bars are not shown in the plot. We note that the bars are generally rather large, because inside the classes, there is no distinction among, for instance, different wind directions and the morphological characteristics related to them, thus such variability can be expected. A thorough analysis of these





**Fig. 4** Wind velocity standard deviations: longitudinal (*left*), cross-flow (*center*) and vertical (*right*), normalized ISL-observed data (*diamonds*) and the RSL-derived function (*solid line*) for UTP (*top*), BBS (*center*), and BBU (*bottom*) sets

aspects was presented in Trini Castelli et al. (2014a, b). This feature is particularly noticeable when the data averaging time is larger, as shown in our previous works for the 1-h averaged data set. For UTP case, the behavior of the function is smoother, and the variability in the class reduces for the 10-min averaged data with respect to the 1-h averages (not shown).

The functions well represent the observations for all components, the main differences occurring for  $|z/L| > 1$ . In all cases, the agreement between the values derived in the ISL and the actual observations looks good for the classes where the number of data is statistically significant. The variability inside the classes is, however, rather large. We recall that data for the BBS set cover only five weeks, so less variability can be expected for the Allschwil site. The standard deviation of the mean of the class, of course, results rather small because of the generally large number of observations in the classes, and varies between orders of  $10^{-3}$  to  $10^{-1}$ . Therefore, the deviation of the fitting curve from the observed values in the plots provides a direct

estimate of the quality of the agreement. A quantitative estimation of the agreement is given for the standard statistics in Table 2.

We computed the ratio of the standard deviations derived from the RSL parameters over the observed values at the ISL height as functions of  $z/L$  classes,  $\sigma_{u\_p}/\sigma_{u\_o}$ ,  $\sigma_{v\_p}/\sigma_{v\_o}$ , and  $\sigma_{w\_p}/\sigma_{w\_o}$  where ‘p’ stands for ‘predicted’ and ‘o’ for ‘observed’.

For the UTP case, with the subset including the 5 and 9-m data together when available at both levels, the ratios vary between 0.9 and 1.2, with a tendency to overpredict in unstable and stable ranges and an underprediction approaching the neutral values. The median values of the ratios, calculated for the full set of  $z/L$  classes, are 1.02, 1.02, and 1.08 for  $u$ ,  $v$ , and  $w$  components, respectively. When the ratios are computed separately for the 5 and 9-m sets, they mostly vary between 0.9 and 1.1, and the agreement improves when using the higher 9-m RSL parameters, showing a sensitivity to the measurement

**Table 2** Statistics of the ISL wind velocity standard deviations calculated from RSL parameters with Eq. (2) and empirical coefficients from Table 1, compared to the actual ISL observations

Case	Observed mean	Predicted mean	CORR	RMSE	FB	FA2
<b>UTP</b>						
$\sigma_u$	0.48	0.51	0.91	0.17	-0.08	0.92
$\sigma_v$	0.43	0.45	0.88	0.16	-0.05	0.91
$\sigma_w$	0.33	0.34	0.92	0.11	-0.03	0.90
<b>BBS</b>						
$\sigma_u$	0.73	0.75	0.92	0.15	-0.04	0.99
$\sigma_v$	0.66	0.67	0.89	0.15	-0.02	0.98
$\sigma_w$	0.40	0.42	0.95	0.07	-0.04	1.00
<b>BBU</b>						
$\sigma_u$	0.80	0.90	0.81	0.29	-0.11	0.93
$\sigma_v$	0.68	0.74	0.81	0.24	-0.08	0.94
$\sigma_w$	0.49	0.55	0.81	0.17	-0.12	0.96

height. For both sets, the vertical standard deviation tends to be underpredicted, while the predicted horizontal components are higher than the observed in the unstable range and mostly lower in the stable range. The median values are, respectively, 0.97, 0.97, 0.98 for the 5-m set and 1, 0.99, 0.98 for the 9-m set. For the BBS case, the ratios mostly vary between 1 and 1.1, besides some points for classes of  $z/L > 1$ , where, however, the number of data is not significant (see also Fig. 4). The agreement is slightly better for conditions of stronger instability,  $z/L < -1$ , and the median values are, respectively, 1.07, 1.09, and 1.06. For the BBU case, all standard deviations tend to be overpredicted, and the ratios vary between 1 and 1.3, with medians 1.19, 1.17, and 1.16.

To quantify the results, in Table 2, we report the statistics calculated for the different data sets, UTP, BBS, and BBU. The metrics that were calculated are: correlation coefficient (CORR), root mean squared error (RMSE), fractional bias (FB), and factor of two (FA2), as follows:

$$CORR = \frac{\sum_i [(\varphi_{oi} - \bar{\varphi}_o)(\varphi_{pi} - \bar{\varphi}_p)]}{\left[\sum_i (\varphi_{oi} - \bar{\varphi}_o)^2\right]^{1/2} \left[\sum_i (\varphi_{pi} - \bar{\varphi}_p)^2\right]^{1/2}} \quad (3)$$

$$RMSE = \left[\frac{1}{N} \sum_i (\varphi_{oi} - \varphi_{pi})^2\right]^{1/2} \quad (4)$$

$$FB = 2 \frac{\bar{\varphi}_o - \bar{\varphi}_p}{\bar{\varphi}_o + \bar{\varphi}_p} \quad (5)$$

$$FA2 = \text{fraction of data that satisfy the condition } 0.5 \leq \frac{\varphi_{pi}}{\varphi_{oi}} \leq 2.0 \quad (6)$$

where  $\varphi$  represents a generic variable, and again, subscripts ‘o’ and ‘p’ stand for ‘observed’ and ‘predicted’, respectively.

The error indices, RMSE and FB, are relatively small, and the FA2 shows a good agreement between the observed ISL data and the values derived by RSL

measurements. The quality of the results are similar both in the suburban and urban sites. The methodology applied to the urban site gives a somewhat worse performance when looking at the predicted mean, CORR, and RMSE, but the FA2 is comparable to other cases. The results show not only that the turbulence in the RSL is well correlated with the turbulence in the ISL, but also that the RSL-scaled wind standard deviations may provide reasonable estimates of the actual ISL values, also when applied to complex geometries.

### 4 Verification

Not always there is the possibility to estimate the local empirical coefficients used to calculate the wind velocity standard deviations in formulae like Eq. (2). In particular, when using atmospheric dispersion models for wide areas, it is generally not possible to estimate the varying coefficients, accounting for the heterogeneity of the domain considered. For this reason, we investigate and discuss the possibility to adopt the coefficients estimated in one case for calculating the ISL standard deviations in other cases where only RSL data are available. We may expect that the transferability of the results may work well for similar conditions, like sites characterized by analogous morphometric parameters or subjected to the same atmospheric conditions, but they may have a limited application in very different cases. Regarding the data sets used here, a common feature is the high percentage of low wind conditions, while the morphological characteristics vary from suburban to densely urban, as in BUBBLE set.

#### 4.1 From UTP to BBS and viceversa

UTP and BUBBLE-Allschwil sites have similar morphological characteristics, given their  $\lambda_p$  and  $z_H$  values, so in

this context, the transferability of the empirical coefficients can be expected to be efficient.

We considered the following cases:

1. UTP-to-BBS.

The ISL wind velocity standard deviation values in BUBBLE-Allschwil site are calculated by Eq. (2) using the local RSL parameters at 8.3 m from BBS data set and the empirical coefficients estimated for UTP set (Sect. 3.1). Then, they are compared with the BBS observations collected at 15.8 m, which we consider as representative of the ISL values.

2. BBS-to-UTP5m and BBS-to-UTP9m.

The ISL wind velocity standard deviation values in UTP site are calculated using the RSL parameters separately from 5-m (BBS-to-UTP5m) and 9-m (BBS-to-UTP9m) UTP data set and the empirical coefficients estimated for BBS set (Sect. 3.2). Then, they are compared with the UTP observations collected at 25 m, which were found to be inside the ISL.

In Fig. 5, we report the comparison between the functions, derived transferring the empirical coefficients from one site to the other, and the actual wind velocity standard deviation observed data. Since we consider the normalized values, only one derived function is given for both BBS-to-UTP5m and BBS-to-UTP9m cases, because it depends only on the BBS coefficients and the  $|z/L|$  range. Instead, two sets of observed data appear depending on whether the observed  $\sigma_{i\_25}$  is normalized over  $u_{*5}$  or  $u_{*9}$ .

The vertical component shows the worst agreement among the three components in both cases, but also less variability in the  $z/L$  classes. For the horizontal components, a slightly better agreement is found for UTP-to-BBS. In any case, all functions lie inside the variability range of the observed data, besides some cases for the vertical component in UTP-to-BBS, where, however, the variability of the observations, given the limited measurement period, is very small.

4.2 From BBS to BBU

The availability of observations collected both at suburban and urban sites in BUBBLE experiments allows investigating (1) whether having available RSL observed data in a suburban site, it is possible to estimate ISL values that can be properly used also when applying atmospheric dispersion models over the urban area; (2) whether having observed RSL parameters in an urban site, empirical coefficients from a suburban site can be transferred to estimate the corresponding ISL standard deviations at that urban site.

For point (1), we can simply compare ISL values estimated from RSL 8.3 m BBS data with the wind velocity standard deviations measured in the ISL at 31.7 m for BBU. In Fig. 6, we plot the distributions of the along-wind and vertical standard deviations for the observed ISL BBS values at 15.8 m, the corresponding ones derived from the RSL values at 8.3 m, and the ISL observations from BBU at 31.7 m. We see that the distributions in the urban Basel

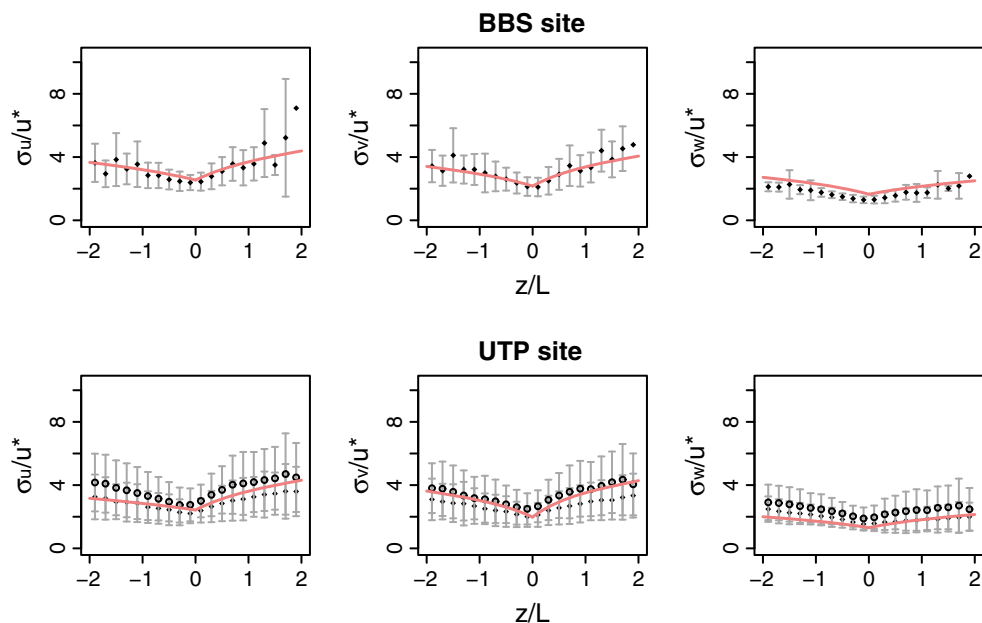
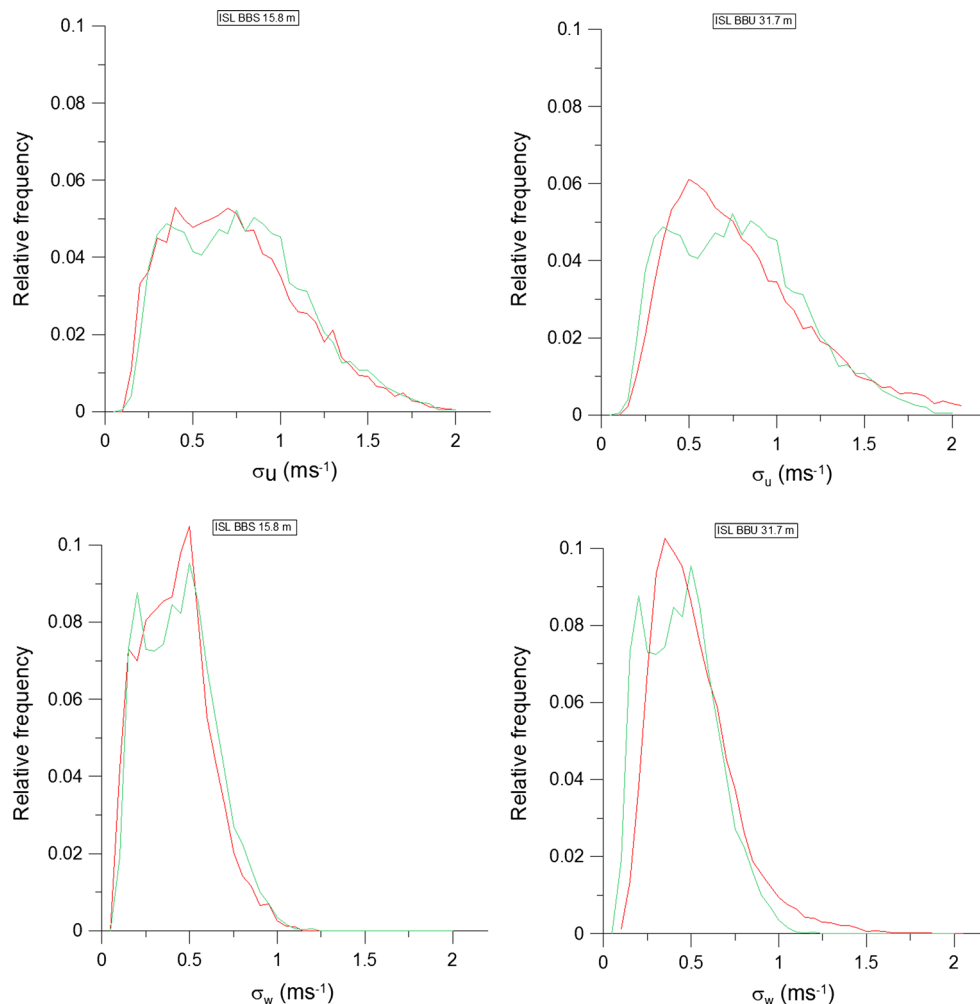


Fig. 5 UTP-to-BBS (top) and BBS-to-UTP (bottom) cases. Normalized observed data (diamonds for UTP-to-BBS and BBS-to-UTP9m, circles for BBS-to-UTP5m) and the functions (solid line) derived in the ISL transferring empirical coefficients from one site to the other

**Fig. 6** Distribution of the wind velocity standard deviations derived from the RSL values at the suburban Allschwil site (green line) and observed in the ISL (red line) in Allschwil (left) and Basel (right), horizontal along-wind (top) and vertical (bottom) components



site (BBU) have different characteristics with respect to the suburban Allschwil site (BBS), in particular, for the lower values. Overall, the ISL-derived distribution for BBS does not depart too much from its own observed one, therefore, we can consider it as a reasonable approximation. Instead, the suburban ISL-derived distribution cannot be used with enough confidence as representative of the values observed for the urban ISL, especially for the smaller values.

For point (2), we considered the case BBS-to-BBU for which:

the ISL wind velocity standard deviation values in Basel site are calculated using the RSL parameters at 14.7 m from BBU data set and the empirical coefficients estimated for BBS set (Sect. 3.1). Then, they are compared with the BBU observations collected at 31.7 m, which we consider as representative of the ISL values at the urban site.

The results are plotted in Fig. 7, as similarly done for previous cases.

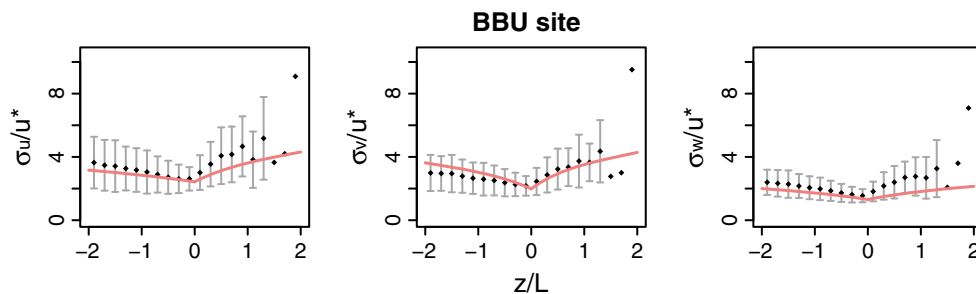
The derived functions keep lying inside the observed variability range, but a general worsening can be noted with respect to the use of local empirical coefficients (see Fig. 4), in particular in the stable range.

The transferability of the empirical coefficients between sites with a different morphology is more critical, but still, it seems feasible.

### 4.3 Analysis of the results

As in former Sect. 3.2, here we address quantitatively, whether the transferability of the approach between different cases is reasonable, responding to the questions:

- Are the empirical coefficients from one case “transferable” to other cases where hypothetically parameters are available only at one level in the roughness sublayer, in case of complex geometry?
- What happens in case of similar type of sites? (i.e., considering two suburban sites, UTP and BBS sets)?



**Fig. 7** BBS-to-BBU case. Normalized observed data (*diamonds*) and the functions derived in the ISL at Basel site using Allschwil empirical coefficients

**Table 3** Statistics of the wind velocity standard deviations for ISL data calculated from RSL parameters compared to the actual observations, transferring empirical coefficients from a site to another

Case	Observed mean	Predicted mean	CORR	RMSE	FB	FA2
UTP-to-BBS						
$\sigma_u$	0.73	0.80	0.92	0.17	-0.10	0.99
$\sigma_v$	0.66	0.70	0.88	0.17	-0.06	0.98
$\sigma_w$	0.40	0.53	0.95	0.17	-0.29	0.99
BBS-to-UTP5m						
$\sigma_u$	0.46	0.41	0.91	0.18	0.11	0.92
$\sigma_v$	0.42	0.38	0.88	0.16	0.10	0.91
$\sigma_w$	0.32	0.23	0.92	0.15	0.34	0.84
BBS-to-UTP9m						
$\sigma_u$	0.48	0.54	0.94	0.15	-0.11	0.93
$\sigma_v$	0.43	0.49	0.90	0.16	-0.12	0.91
$\sigma_w$	0.33	0.30	0.94	0.09	0.12	0.93
BBS-to-BBU						
$\sigma_u$	0.80	0.76	0.80	0.26	0.05	0.94
$\sigma_v$	0.68	0.71	0.79	0.23	-0.05	0.93
$\sigma_w$	0.49	0.43	0.81	0.15	0.13	0.96

- What happens in case of different type of sites? (i.e., passing from a suburban to an urban site in the same area, BBS and BBU sets)

When computing the ratios between the RSL-derived, with a transfer of coefficients, and ISL-observed wind velocity standard deviations as functions of  $z/L$  classes, the agreement between the predicted and observed values worsens a bit with respect to the ‘site-local’ ratios. The ratios can take higher values, but generally they range from 0.8 to 1.4. Using UTP empirical coefficients produces values always higher than observed at BBS site, while more variability is shown vice versa, using BBS coefficients for UTP site, with some underprediction for  $\sigma_v$  and  $\sigma_w$  in the unstable range and a general overprediction in the other cases. The case BBS-to-UTP9m shows a larger discrepancy than BBS-to-UTP5m. The median values of  $\sigma_{u\_p}/\sigma_{u\_o}$ ,  $\sigma_{v\_p}/\sigma_{v\_o}$ , and  $\sigma_{w\_p}/\sigma_{w\_o}$  are 1.15, 1.09, and 1.34 for UTP-BBS, 1.01, 1.11, and 0.82 for BBS-to-UTP5m and 1.23, 1.34 and 0.95 for BBS-to-UTP9m. The transfer of suburban coefficients,

BBS, to an urban site, BBU, has analogous performances as for suburban-to-suburban cases, but with a tendency to underpredict  $\sigma_v$  and  $\sigma_w$  in the stable range, instead: the median values of the three ratios are 1, 1.11, and 0.87, respectively. Thus, the transferability of the empirical coefficients between sites with a similar morphology or meteorology could be practicable but within a deviation from the real values ranging from 20 to 40 %

Following the discussion based on comparisons between the stability-dependent functions and ratios, in Table 3, we report the statistics of the wind velocity standard deviations calculated for the different cases, referring to the same metrics as in Table 2.

Summarizing, the cases considered here are:

UTP-to-BBS: derivation of the values at 15.8 m in Allschwil site using (1) BBS RSL parameters available at 8.3 m and (2) UTP empirical coefficients

BBS-to-UTP5m and BBS-to-UTP9m: derivation of the values at 25 m in UTP site using (1) UTP RSL parameters



available, respectively, at 5 and 9 m and (2) BBS empirical coefficients

BBS-to-BBU: derivation of the values at 31.7 m in Basel site using (1) BBU RSL parameters available at 14.7 m and (2) BBS empirical coefficients

Comparing Table 3 with Table 2, we note a significant worsening of the FB for the vertical wind velocity standard deviation for UTP-to-BBS and BBS-to-UTP5m cases, due to the poorer agreement between the observed and predicted mean, while the FA2 keeps being satisfactory. The common feature of these sets is the use of the 5-m data of UTP data set. We also note that the 25-m observed means calculated for the two cases UTP and BBS-to-UTP9m are the same, while the ones in BBS-to-UTP5m are a bit lower.

We mention that the BBS coefficients are calculated on data covering a very limited period, five weeks, which are not fully representative of the seasonal variability of the atmospheric conditions.

If, just as an exercise, we compare the median values of the metrics relative to the studied cases, we find that:

mCORR = 0.89, mRMSE = 0.160, mIFBI = 0.05, mFA2 = 0.93 for Table 2,

mCORR = 0.91, mRMSE = 0.165, mIFBI = 0.11, mFA2 = 0.93 for Table 3,

where the initial 'm' indicates that we take the median of the metrics from the table. The values corresponding to the two tables are comparable.

In general, the transferability of the empirical coefficients from one site to another yields to derived wind velocity standard deviation functions that represent the observed ISL values within the variability of the measurements themselves. It thus follows that empirical coefficients can be used at other sites, when they have similar morphological and wind-regime characteristics. Also using suburban values in urban context proved to be acceptable, in the case considered when the two sites are in the same area.

## 5 Conclusions

In this work, wind velocity standard deviations at suburban (UTP and BUBBLE-Allschwil sets) and urban (BUBBLE-Basel set) sites have been estimated in the inertial sublayer using parameters from the underlying roughness sublayer, by means of fit procedures to estimate the empirical coefficients in a standard formulation. By comparing the actual observed data with the values predicted with this approach, it was shown that the representativeness of the predictions is fair, as quantified also by the statistical analysis. We can conclude that it is reasonable to derive the wind velocity standard deviations in the inertial sublayer by a scaling on the roughness sublayer parameters. This approach may be useful when inputs are needed in atmospheric dispersion

models where the Monin–Obukhov similarity theory, valid for the inertial sublayer, is applied, but quantities, like the Obukhov length and the friction velocity, are only available from measurements in the roughness layer.

A second aspect treated was to evaluate whether the estimated empirical coefficients, then used in the formulations for the wind velocity standard deviations, can be transferred from one case to other cases. With this purpose, the empirical coefficients for UTP were used to calculate the standard deviations at the BUBBLE-Allschwil site using the local roughness layer parameters, and viceversa. In this case, both sites are suburban, with similar morphological characteristics. The agreement between predictions and observations worsen with respect to using the local coefficients, but still, the predicted curves lie inside the variability range of the observed data. This result supports the general idea that the empirical coefficients estimated at a certain site can be suitable also for the estimation of the ISL standard deviation at a comparable site. Thus, empirical coefficients can be used in other morphologically similar cases when data are not available, and there is not the possibility to derive specific coefficients directly from the experimental observations.

It was also investigated whether it is possible to export the formulations based on the empirical coefficients in case, instead, of different type of sites. For this purpose, the empirical coefficients calculated at the BUBBLE-Allschwil suburban sites were used to calculate the standard deviations in BUBBLE-Basel urban site, using the local roughness layer parameters. Comparing the inertial sublayer values calculated at the urban site from the local roughness sublayer parameters and the local empirical coefficients or using, instead, the coefficients 'imported' by the suburban site, seems to suggest that the presence of a different morphology, rather than different meteorological conditions, is a limitation to the transferability of the empirical coefficients. Yet, the statistical analysis indicates that, using in urban context, empirical coefficients from suburban values are acceptable, at least when the two sites are in the same area, which is the case of interest. The main finding is that the 'error' done when using empirical coefficients (1) derived in the same site from RSL parameters or (2) taken from similar sites, might be acceptable when other options for the parameterization are not available. The statistical metrics show that the deviations of the estimated values from the real observed ones are analogous to values calculated with other approaches. We cite that the metrics are similar to the ranges found in our previous studies and in other related empirical studies. Luhar et al. (2006) found that 93 % of their predictions for the vertical component of wind velocity standard deviations are within an FA2 of the observations. Venkatram and Princevac (2008) through their empirical parameterization

found that over 80 % of the standard deviations of the turbulent velocities are within an FA2 of the observations. Analogous figures are given in Qian et al. (2010) when considering different statistics, the geometric means and the standard deviations of the ratio observed/predicted.

In conclusion, the estimation of wind velocity fluctuations in the inertial sublayer from a scaling of roughness sublayer parameters might be a suitable approach when the observations are not available in the inertial sublayer. Moreover, the set of coefficients estimated at a site showed to be exportable both to other sites with similar morphological characteristics and to sites with a different morphology but in the same area, sites thus subject to a similar meteorological regime.

This method might, therefore, help overcoming the restrictions in the applicability of the MOST formulations for atmospheric dispersion modeling, when (1) measurements are available only in the roughness sublayer over a heterogeneous suburban and urban terrain and (2) no detailed morphological parameters can be derived by the available information. The effect of using derived wind velocity standard deviations has to be assessed in a tracer dispersion study. In Trini Castelli et al. (2014a), we performed a dispersion modeling exercise using locally derived standard deviations and compared them to Hanna (1982) surface layer parameterizations, but no observed data were available. Thus, future works will have to consider real case studies where observed concentration data are available.

**Acknowledgments** We are very grateful to Prof. Mathias Rotach and Prof. Andreas Christen for providing us the BUBBLE data sets used in this work and for their precious support.

## References

- Anfossi D, Oetl D, Degrazia G, Goulart A (2005) An analysis of sonic anemometer observations in low wind speed conditions. *Bound Layer Meteorol* 114:179–203
- Bendat JS, Piersol AG (2000) *Random data: analysis and measurement procedures*, 3rd edn. Wiley, Oxford, p 594
- Christen A, Vogt R (2004) Energy and radiation balance of a central European city. *Int J Climatol* 24(11):1395–1421
- Christen A, van Gorsel E, Vogt R (2007) Coherent structures in urban roughness sublayer turbulence. *Int J Climatol* 27:1955–1968
- Christen A, Rotach MW, Vogt R (2009) The budget of turbulent kinetic energy in the urban roughness sublayer. *Bound Layer Meteorol* 131:193–222
- Feigenwinter C, Vogt R, Parlou E (1999) Vertical structure of selected turbulence characteristics above an Urban Canopy. *Theor Appl Climatol* 62:51–63
- Ferrero E, Anfossi D, Richiardone R, Trini Castelli S, Mortarini L, Carretto E, Muraro M, Bande S, Bertoni D (2009) Urban turbulence project—the field experimental campaign. Internal Report ISAC-TO/02-2009, p 37, October 2009, Torino, Italy
- Fisher B, Joffre S, Kukkonen J, Piringer M, Rotach MW, Schatzmann M, Eds. (2005) *Meteorology applied to urban air pollution problems*. Final Report COST Action 715. Demetra Ltd Publishers, Bulgaria. ISBN 954-9526-30-5, p 275
- Fisher B, Kukkonen J, Piringer M, Rotach MW, Schatzmann M (2006) *Meteorology applied to urban air pollution problems: concepts from COST 715*. *Atmos Chem Phys* 6:555–564
- Foken T (2006) 50 years of the Monin–Obukhov similarity theory. *Bound Layer Meteorol* 119:431–447
- Fortuniak K, Pawlak W, Siedlecki M (2013) Integral turbulence statistics over a Central European City Centre. *Bound Layer Meteorol* 146:257–276
- Grimmond CSB, Oke TR (1999) Aerodynamic properties of urban areas derived from analysis of surface form. *J Appl Meteorol* 38:1262–1292
- Grimmond CSB, King TS, Roth M, Oke TR (1998) Aerodynamic roughness of urban areas derived from wind observations. *Bound Layer Meteorol* 89:1–24
- Hanna SR (1982) Applications in air pollution modelling. In: Nieuwstadt F, Van Dop H (eds) *Atmospheric turbulence and air pollution modelling*. Reidel, Dordrecht, pp 275–310
- Klipp CJ, Mahrt L (2004) Flux-gradient relationship, self-correlation and intermittency in the stable boundary layer. *Q J R Meteorol Soc* 130:2087–2103
- Luhar AK (2012) Lagrangian particle modeling of dispersion in light winds. In: Lin J, Brunner D, Gerbig C, Stohl A, Luhar A, Webley P et al (eds) *Lagrangian modeling of the atmosphere*. American Geophysical Union, Washington, DC, pp 37–51. doi:10.1029/2012GM001264
- Luhar AK, Venkatram A, Lee SM (2006) On relationships between urban and rural near-surface meteorology for diffusion applications. *Atmos Environ* 40:6541–6553
- Mahrt L (2010) Computing turbulent fluxes near the surface: needed improvements. *Agric For Meteorol* 150:501–509
- McMillen R (1988) An eddy correlation technique with extended applicability to non-simple terrain. *Bound Layer Meteorol* 43:231–245
- Moraes OLL, Acevedo OC, Degrazia GA, Anfossi D, Da Silva R, Anabor V (2005) Surface layer turbulence parameters over a complex terrain. *Atmos Environ* 39:3103–3112
- Mortarini L, Ferrero E, Richiardone R, Falabino S, Anfossi D, Trini Castelli S, Carretto E (2009) Assessment of dispersion parameterizations through wind data measured by three sonic anemometers in an urban canopy. *Adv Sci Res* 3:91–98
- Mortarini L, Ferrero E, Falabino S, Trini Castelli S, Richiardone R, Anfossi D (2013) Low-frequency processes and turbulence structure in a perturbed boundary layer. *Q J R Meteorol Soc* 139:1059–1072
- Pahlow M, Parlange MB, Porte-Agel F (2001) On Monin–Obukhov similarity in the stable atmospheric boundary layer. *Bound Layer Meteorol* 99:225–248
- Princevac M, Venkatram A (2007) Estimating micrometeorological inputs for modeling dispersion in urban areas during stable conditions. *Atmos Environ* 41:5345–5356
- Qian W, Princevac M, Venkatram A (2010) Using temperature fluctuation measurements to estimate meteorological inputs for modelling dispersion during convective conditions in urban areas. *Bound Layer Meteorol* 135:269–289
- Rotach MW (1999) On the influence of the urban roughness sublayer on turbulence and dispersion. *Atmos Environ* 33:4001–4008
- Rotach MW (2001) Simulation of urban-scale dispersion using a lagrangian stochastic dispersion model. *Boundary-Layer Meteorol* 99:379–410
- Rotach MW, Gryning SE, Batchvarova E, Christen A, Vogt R (2004) Pollutant dispersion close to an urban surface—the BUBBLE tracer experiment. *Meteorol Atm Phys* 87:39–56
- Rotach MW, Vogt R, Bernhofer C, Batchvarova E, Christen A, Clappier A, Feddersen B, Gryning SE, Martucci G, Mayer H,

- Mitev V, Oke TR, Parlow E, Richner H, Roth M, Roulet YA, Ruffieux D, Salmond J, Schatzmann M, Vogt J (2005) BUBBLE—an urban boundary layer meteorology project. *Theor Appl Climatol* 81:231–261
- Roth M (2000) Review of atmospheric turbulence over cities. *Q J R Meteorol Soc* 126:1941–1990
- Trini Castelli S, Falabino S (2013) Parameterization of the wind velocity fluctuation standard deviations in the surface layer in low-wind conditions. *Meteorol Atmos Phys* 119:91–107
- Trini Castelli S, Falabino S, Mortarini L, Ferrero E, Anfossi D, Richiardone R (2011) Analysis of urban boundary-layer turbulence on the basis of an experimental campaign in Turin city—UTP project. In: *Proceedings of the 14th international conference on harmonisation within atmospheric dispersion modelling for regulatory purposes*, Kos, Greece, 2–6 October 201, pp 414–417
- Trini Castelli S, Falabino S, Mortarini L, Ferrero E, Richiardone R, Anfossi D (2014a) Experimental investigation of the surface layer parameters in low wind conditions in a suburban area. *Q J R Meteorol Soc* 140:2023–2036
- Trini Castelli S, Falabino S, Anfossi D (2014b) Effect of the turbulence parameterizations on the simulation of pollutant dispersion with the RMS modelling system. In: Steyn DG, Builtjes P (eds) *Air pollution modeling and its application XXII*. Springer, Berlin, pp 529–534
- Venkatram A, Princevac M (2008) Using measurements in urban areas to estimate turbulent velocities for modelling dispersion. *Atmos Environ* 42:3833–3841
- Vickers D, Mahrt L (2003) The cospectral gap and turbulent flux calculations. *J Atmos Oc Tech* 20:660–672
- Wilson JD (2008) Monin–Obukhov functions for standard deviations of velocity. *Bound Layer Meteorol* 129:353–369