19th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
3-6 June 2019, Bruges, Belgium

EVALUATION OF VERTICAL PROFILES OF TURBULENCE KINETIC ENERGY AND MEAN KINETIC ENERGY IN AN URBAN SITE

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Abstract: The Turbulence Kinetic Energy (TKE) is relevant for air pollution modelling specially in complex areas, such as an urban environment, while advection, modelled by the Mean Kinetic Energy (MKE), is relevant for the transport of the pollutant. In the framework of the VIEPI project, vertical profiles of TKE and MKE have been collected during the year 2018 by three sonic anemometers installed at different heights of a building located within the campus inside the University of Rome “La Sapienza”. The second site is located in Arctic, Ny-Ålesund (Svalbard), and meteorological data have been collected using the Amundsen-Nobile Climate Change Tower (CCT). This paper deals with the analysis of the vertical profiles of Turbulent Kinetic Energy (TKE), Mean Kinetic Energy (MKE) and friction velocity measured in correspondence of a street canyon located within the urban area of Rome and in flat terrain in Arctic sites. One of the objective of the work is to find possible relations between the characteristics of turbulence above the building top and those within the canyon. The results are also compared with vertical profiles of TKE and MKE taken in the Arctic region in order to highlight the main differences with the flat terrain case.

Key words: TKE, MKE, friction velocity, Arctic, Urban.

INTRODUCTION

Dispersion of pollutants depends mainly on the turbulence characteristics and on the advection terms (Fisher et al., 2006). The turbulent kinetic energy (TKE) is employed in air pollution modelling, while the mean kinetic energy (MKE) is employed in pollutant transport modelling. In urban areas, the ratio TKE/MKE is generally decreasing with the height and shows a value about 1.1 (Di Bernardino et al., 2015). The parameterization of the vertical variations of TKE and MKE can be relevant to model the wind variance and can be useful to understand dispersion of pollutant. However, the parametrization of TKE used in meteorological models shows generally too large values when applied to simulate the lower layers in urban areas with respect to the observed ones. The measured values of the vertical profiles of TKE and MKE can be employed to improve the parameterizations of then vertical profiles used in meteorological models in urban cases. For the above reasons, in this work two meteorological sites have been chosen to compare the relationships between the TKE and MKE vertical profiles.

In the framework of the VIEPI project (Integrated Evaluation of Indoor Particulate Exposure), meteorological data relative to an urban canyon have been collected during an intensive field campaign conducted in an urban area of Rome, i.e. the Department of Physics at the University of Rome “La

Sapienza" during the year 2018. The second site is located in Ny-Ålesund (Svalbard) and meteorological data have been collected and managed by the Italian National Council of Research (CNR) using the Amundsen-Nobile Climate Change Tower (CCT). In the proximity of the CCT site, the terrain is relatively flat and allows a selection of neutral atmospheric conditions.
This work is organized as follows: firstly, a brief description of the field campaigns is given together with the criteria for data selection; secondly, the results concerning the comparison between TKE and MKE inside the canyon are given together with the inter-comparison of dimensionless profiles for TKE and friction velocity (u_*) referred to the urban site and the flat terrain at the Ny-Ålesund site.

2. Material and methods

2.1 Experimental design description

The meteorological data refer to two sites, one corresponds to the Department of Physic of University of Rome "Sapienza" and the other is located in the Arctic region. The TKE, MKE and friction velocity have been obtained using three sonic anemometers installed in each of the two sites. For both the sites, we have considered averages over 30 min as suggested by Foken (2008). The data sets refer to the period April 1th to 30th 2018 for the first site and the three years 2013, 2014 and 2015 for the second site.
The diurnal cycle of winds in Rome is mainly from land-sea breezes (see e.g. Petenko et al., 2011; Pelliccioni et al., 2015). All this involves flows with complex pattern and high levels of air pollution (Monti and Leuzzi, 2005). The University of Rome is characterized by a typical urban complexity with building heights ranging from 15 m to 30 m. This location is representative of a typical urban site of Rome and the period was linked with one field campaign related with the spring season. Three sonic anemometers have been installed in correspondence of the building of Physics (height H=20 m, see Figure 1) at three different heights, Z=24, 16 and 8m agl, which refer to the dimensionless heights Z/H=1.2, 0.8 and 0.4, respectively. The aspect ratio of the canyon is about 0.4 (Di Bernardino et al., 2018), a value typically found for high-density urban areas (Grimmond and Oke, 1999). In details, two anemometers were located within the canyon (Z/H=0.4 and 0.8), while the third one was installed on the building roof top.

Figure 1. Pictures representing the three ultrasonic anemometers installed within the canyon (left and central panels) and on the roof top (right panel) of the building of Physics ("Sapienza" University of Rome) and the corresponding dimensionless heights.

The meteorological station installed in the second site, corresponding with the CCT in Ny-Ålesund, is composed of a set of fast response sensors that include ultrasonic anemometers and fast hygrometers installed at three levels (3.7, 7.5 and 20.5 m). Detailed description of the complete set up is presented in Mazzola et al. (2016). The dataset used consists of vertical profiles of wind speed, wind direction and other turbulence parameters.

2.2 Data selection

As is known, the neutral stability condition is the base for any wind-speed profile analysis. In our work, we use the stability classes assumption based on Holtslag's classification (Holtslag, 1984), but lowering the limit for neutral conditions at |L|>300 m instead of 1000 m, in order to include more cases in the analysis and to relax the constraint for the neutral limit condition (see e.g. Pellicciono et al., 2012). Furthermore, in order to evaluate the existence or not of the effect of the solar radiation on the turbulence profiles, we have separated each dataset in two periods for both sites. The first period includes all the hours from 7am to 7pm (daily cycle), while the second is composed of the remaining hours of the day (night cycle, from 7pm to 7 am). The total amount of data that satisfies the condition above are listed in Table 1.

Table 1. Number of data (N) collected in urban (Rome) and flat terrain (Arctic) areas.

Site or Location	N (total)	N (neutral)	N (night)	N (daily)
Rome	1185	208	148	60
Arctic	8669	345	31	27

The occurrence of neutral conditions in the Rome site covers around 17.6% of the total amount of data. Among them, the most frequent occurrence was during the night (71.2% nighttime and 28.8% daytime). The neutral profiles at Ny-Ålesund Arctic are 4.0% of total the amount of data (N=345).

To assure the constancy of the friction velocity profiles at Ny-Ålesund, we assume that the coefficient of variation CV is below 0.1, so we achieved 31 and 27 events of neutral conditions for the night and day, respectively (Table 1). With regard to the Rome data set, the calculation of the Obukhov Length (L) has been obtained by the sonic anemometer above the roof. On the other hand, for the Arctic site the selected neutral profiles have been chosen when the D class occurs at all the three measurement levels (Holtslag, 1984). The average absolute mean values of L is over the neutral threshold value of 300 m ($\bar{L}_{Rome}$ =1444 m and $\bar{L}_{\mathrm{Arctic}}$=2982 m). The threshold of neutrality justify the low number of cases from the night and day for two sites.

3. Material and methods

3.1 Relationship between vertical MKE and TKE in Rome Canyon

The results about the relationship between the TKE and MKE profiles referred to the three anemometer located in the Rome site are given in table 2. The table shows the mean values calculated at the three heights.

Table 2. Mean values profiles of TKE and MKE (both m^2/s^2) in for the Rome site.

	MKE Z/H=1.2	MKE Z/H=0.8	MKE Z/H=0.4	TKE Z/H=1.2	TKE Z/H=0.8	TKE Z/H=0.4
Mean (Day)	**5.38**	**0.20**	**0.78**	**2.88**	**0.65**	**0.80**
Std (Day)	**4.67**	**0.12**	**0.63**	**2.57**	**0.68**	**0.65**
Mean (Night)	**1.41**	**0.16**	**0.28**	**0.76**	**0.20**	**0.34**
Std (Night)	**1.48**	**0.11**	**0.25**	**0.86**	**0.31**	**0.40**

The total mean values of MKE is greater than that of the total mean of TKE (around 146%) with a well-marked peak over the roof respect to inside the canyon. Regarding the TKE/MKE ratio, Figure 2 shows the observed neutral profiles during day and night, and they agree well with what reported in literature for similar urban situations (BSPR-Basel, no vegetation in canyon (Christen et al., 2003)).

In details, during the night, the maximum of TKE/MKE ratio, equal to 1.27, is observed at Z/H=0.8 (within the canyon). Similarly, the same behaviour, although less marked, was obtained in literature, when TKE/MKE is equal to 1.6 for Z/H=0.75 (Fisher et al, 2006).

3.2 Comparison between vertical profiles of TKE in urban and flat terrain

The height considered in the vertical profiles shown for the urban case are normalized by the building height H=20 m. For the Arctic site we assume H=0.066 m as reference length to normalize the height, obtained from a study we are running on considering the same data set. That value is in accordance with the typical roughness length linked with ice land surface (Brock, 2006).

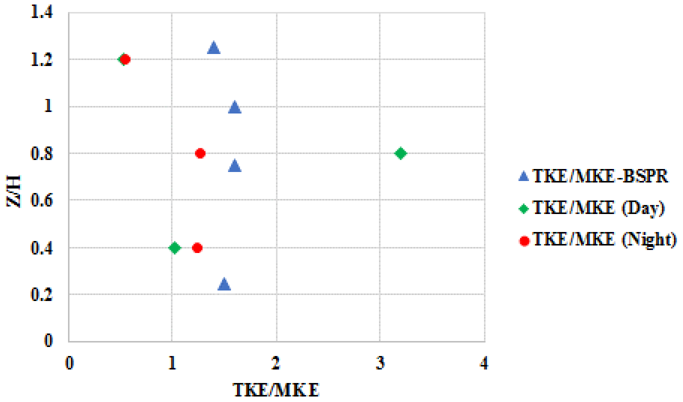

Figure 2. Comparison between the observed TKE/MKE ratio in Rome and in Basel (Christen et al. 2003).

The Figure 3 shows that the mean values of the friction velocities u_* inside the canyon are about half of that at the roof. Figure 3a depicts the values of u_* at the roof top and inside the canyon for the Rome site. To verify the u_* constancy in the Arctic site, we have reported in Figure 3b the u_* profiles calculated daytime and nighttime by considering the three anemometers. The results show very well the constancy with height of the friction velocity as usually observed for flat terrain (Figure 3b).

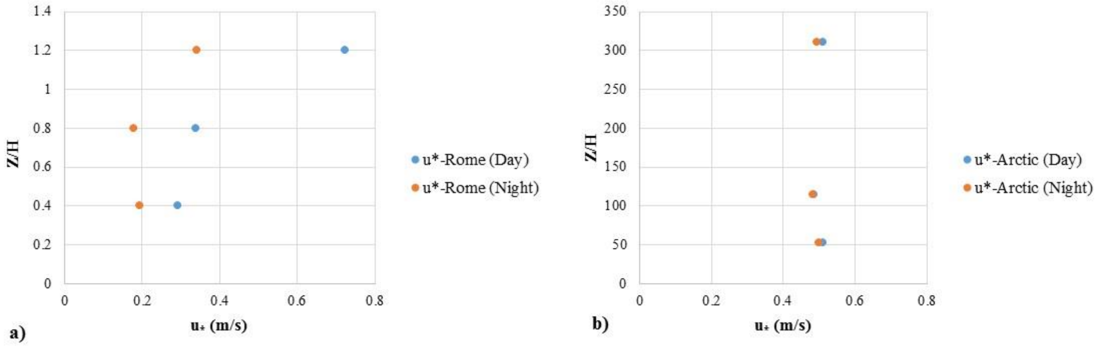

Figure 3. Vertical profile of friction velocity measured at Sapienza **(a)** and Arctic **(b)**.

Figures 4a and 4b show the TKE profiles measured at Sapienza (a) and Arctic (b) sites respectively. In the latter case (flat terrain), a light decrease with the height of the TKE within the canyon is present, in line with literature data. That is not the case of the Arctic site, where the ratio between the TKE at Z=7.5 m and that at Z=20.5 m is around unit, while within the canyon in the Rome urban site the ratio between the TKE values calculated at the average dimensionless of Z/H=0.8 and Z/H=1.2 is about 0.24.

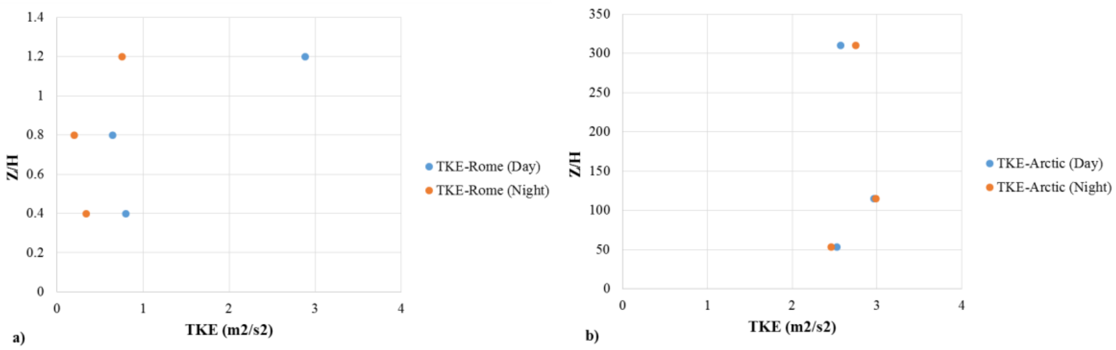

Figure 4: As Figure 3 for TKE.

Furthermore, the ratio between the TKE over the roof and that inside the canyon is about 3.7 times, independently of the values of Z/H. These results show that the theoretical model of TKE in flat terrain cannot be used for modelling the TKE inside an urban canyon, and suggest the decrease factor to apply starting from the TKE over the roof. The measured profiles of turbulence kinetic energy in Rome are in accordance with the Nantes wind-tunnel study by Kastner-Klein and Rotach (Kastner-Klein and Rotach, 2004), above all during night conditions. The TKE profiles in Rome during the day show higher values of TKE than those measured in the wind-tunnel, which may be due to the absence of the convection contribution in the simulation.

4. Conclusions

The results of this comparison could suggest a more reliable assumption for the closure of TKE to be adopted in meteorological models for urban cases. In particular the results suggest the existence of a non-linear increasing trend of TKE with the height within the canyon up to Z/H=1. In this case, the mean values of TKE and MKE are about 0.3 m^2/s^2 during the day and 0.6 during the night and increase, for the same cycles, of the values between 3 m^2/s^2 to 5.4 m^2/s^2 and 1.1 m^2/s^2 to 2 m^2/s^2, respectively. In case of flat terrain, the decrease with height of TKE during the night is lesser emphasized respect to the daytime cases. The numerical values of TKE used in numerical meteorological models are often too large when applied to urban cases. This work shows the main differences observed for TKE and MKE profiles in the two different conditions. The results of this comparison could suggest a more reliable assumption for the closure of TKE and MKE to be adopted in meteorological models applied in urban environment. The results, obtained for the Arctic site, confirm the model profiles of TKE used in literature.

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