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Influence of photochemical processes on traffic-related airborne pollutants in urban street canyon

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ABSTRACT

The urban street canyon of Legerova Street is part of the north-south trunk road that passes through the centre of Prague and remains an unresolved environmental issue for the capital of the Czech Republic. As many as one hundred thousand cars move through this region per day, and mortality has increased as a result of dust, NO_x and other exhaust pollutants. The spatial distribution of pollutants (i.e., NO_2, NO, and O_3) during a day was measured by combined DIAL/SODAR techniques and spot analyzers that were appropriately located near the bottom of the street canyon. The measurements were performed under different meteorological conditions (autumn versus summer period). A purely physical approach does not provide a true description of reality due to photochemical processes that take place in the street canyon atmosphere. Sunlight in the summer triggers the production of ozone and thereby influences the concentration of NO_2. The formation of an inverse non-diffuse vertical concentration distribution of NO_2 in the morning hours was found to be related to the direct emission of O_3 in the street and its background concentration. Rapid changes of NO_2 concentrations were observed over time and in the vertical profile. An approach using a photochemical reactor to describe processes in a street canyon atmosphere was developed and verified as a useful tool for prediction purposes.

1. Introduction

An urgent topic in urban air-quality studies is the dispersion of toxic pollutants within urban street canyons (Fenger, 2009) - streets that are lined with buildings on both sides. Within these domains, large quantities of emissions are released mainly from motor vehicle exhausts and are then trapped and concentrated within the canyon walls. Urban street canyons also contain many people inside the buildings and/or in the cars, potentially making these areas high-risk health zones (Gauderman et al., 2004, Riediker et al., 2003). Providing information on pollutant distribution is therefore a crucial starting point for planning effective measures to improve air quality and optimize urban design.

Monitoring of air pollution distribution requires a setup of a large and dense network of sample spots and/or the use of remote sensing techniques. The advantage of remote sensing techniques is their ability to provide information about the distribution of pollutants along with their radiation trajectories. For monitoring the distribution of gaseous pollutants, long-path absorption spectroscopy (Triantafyllou et al., 2008), Raman and differential absorption LIDARs (DIAL) are typically employed (Fredriksson, 1988; Svanberg, 1994; Weitkamp, 2005).

There are many studies that have utilized these remote sensing methods in real urban atmospheres (Schifter et al., 2008; Weitkamp, 2005; Střižík et al., 2008). The concentrations of O_3, NO_2 and SO_2 measured by differential optical absorption spectroscopy in a city were presented and compared against data obtained from a conventional ground station in a previous study (Triantafyllou et al., 2008). The spatial distribution of traffic-related pollutants within street canyons was monitored using a self-developed automatic sampling system of a vertical section in another previous

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Abbreviations: DIAL, **DI**fferential **A**bsorption **L**idar; SODAR, **SO**nic **D**etection **A**nd **R**anging

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study (Xie et al., 2003). A metropolitan area was monitored with a dispersive ultraviolet spectrometer for NO measurements (Schifter et al., 2003, 2008). These and other studies have identified many factors that affect the flow and dispersion of pollutants in street canyons, including ambient wind speed and direction, building geometry, and thermal stratification (Berger et al., 1997; Hu et al., 2012; Kang et al., 2008; Zelinger et al., 2004).

Mathematical models employing numerical calculations or methods based on physical modelling (Civis et al., 2001; Garcia Sagrado et al., 2002; Zelinger et al., 2009, 2006) are usually applied to overcome the lack of measurements obtained from the atmosphere. To validate the numerical models (Boehm and Aylor, 2005; Di Sabatino et al., 2007; Khan and Abbasi, 2000; Pospisil et al., 2004), the use of wind tunnel experiments (Baik et al., 2000; Kastner-Klein and Plate, 1999; Zelinger et al., 1999) is usually strongly recommended.

Most models of pollutant dispersion in street canyons are considered to be passive and consist of inert pollutants. There have been studies where the dispersion of reactive pollutants has been considered. Baker et al. (2004) examined the dispersion of reactive pollutants in a street canyon with an aspect ratio of one using a three-dimensional large-eddy simulation (LES) model, where the thermodynamic energy equation was not included. The authors included simple photochemistry involving NO, NO_2, and O_3. In contrast, Baik et al. (2007) developed a three-dimensional unsteady RANS (Reynolds-Averaged Navier–Stokes) model (Kauppinen et al., 2004; Li et al., 2012; Wilcken and Kauppinen, 2003). A thermodynamic energy equation and the photochemical processes mentioned above were used to examine the flow and dispersion of reactive pollutants in a street canyon; this model used an aspect ratio of one in the presence of street bottom heating. There are several papers that modelled photochemical processes in a city and in an urban street canyon (Dunker et al., 1996; Ji et al., 2001; Koskinen et al., 2008; Kuusela and Kauppinen, 2007; Zhou and Levy, 2008), and an accurate assessment of photochemical effects on secondary pollutants, such as ozone, has also been achieved (Ji et al., 2001).

In this paper, we used remote sensing DIAL measurements and spot analyzer monitoring to obtain 2D and 3D profile measurements of NO_2 and O_3. DIAL is a laser remote sensing technique that belongs to a group of LIDAR techniques (Fredriksson, 1988; Střížík et al., 2008; Svanberg, 1994). The DIAL technique has the ability of not only determining the ground concentration levels but also the altitude distributions, which can add insight on transport of pollutants. Spot measurements add further information on the concentrations of pollutants in places that are inaccessible by DIAL and on other pollutants such as NO, CO, and SO_2.

The measurements were performed in a real urban street canyon, Legerova Street, with an extensive amount of traffic (about 45,000 vehicles per day, Fig. 1) in sunny and cloudy days. This street is a part of a north-south trunk road that passes through the centre of Prague and remains an unresolved environmental issue for the capital of the Czech Republic that significantly influences inhabitants living at various heights of the street canyon. People from this street have a drastically higher risk of developing lung cancer (growth 52%) and cardiovascular disease (growth 44%) (Hertel et al., 2001; Kazmarová et al., 2015). The part of north-south arterial going through Prague in the meridian direction is known as extremely traffic weighted communication in the town. A part of this communication is Legerova street created really canyon of the latitude 55 m and with five floor houses on both sides from the beginning of twentieth century. The length of this part of arterial is 700 m. The strictly meridian direction of this street, where prevailed winds here are from west side is very important from the point of view dispersion of pollutants created by extremely car traffic mainly in the time of traffic peak. Second reason for this measurement is the possibility to locate lidar system on the opposite side of Nusle valley important for the limited minimal distance for serious lidar measurement. The Legerova street is a part of arterial road going through Prague. It is known by extremely traffic nearby the historical centre of the city and the urban population living in the buildings at different levels above street is strongly exposed to atmospheric pollutants. The simple canyon configuration with strictly meridian direction and with prevailed winds from the west side is convenient for modelling of pollutants distribution. Another reason for these measurements is the location of lidar system on the opposite side of Nusle valley that is important for the limited minimal distance between lidar and measurement area.

Experimental results from our measurements were compared using a model based on dividing a street canyon into layers with homogenous concentrations and including photochemical processes.

2. Experimental methods

2.1. Urban street canyon

Legerova Street, one of the main through traffic roads of Prague City (Czech Republic), was chosen as a typical street canyon of urban agglomeration with a well-defined (quasi)line pollution source (Fig. 1). The height of the linked buildings, which formed the walls of street canyon, was approximately 25 m on the ridge. However, the canyon of Legerova Street was not fully homogeneous. Its walls are interrupted by crossings with other streets. The monitored street canyon area was 700 m long. There is one-way traffic in the street, which is kept in four lines. Traffic density was estimated to increase from 100 to 200 vehicles/h during the night (from LT 2:00 to LT 4:00) to 1000–2000 vehicles/h in early morning (from LT 5:00 to LT 7:00) based on typical daily value for the Legerova street (about 45 000 street vehicles/day) and diurnal variation of traffic relevant to annual Prague statistics. Typical daily value for the Legerova street is 45 000 vehicles/day, including about 43,500 passengers cars per day and about 1500 slow vehicles, i.e. trucks and buses, per day. Another street canyon runs parallel with Legerova Street at the distance of 90 m to the west, where four lines of traffic are led in the opposite direction.

2.2. Remote sensing measurements

The DIAL/SODAR system was located approximately 650 m from the traffic entry point of the street canyon. This distance was ideal with regards to the geometric compression of the measuring system and influenced the correct evaluation of measured data as one of the major factors. The monitored street canyon area was 700 m long. Vertical distribution was mapped repeatedly by means of two-dimensional vertical scans above the street. The scans through the atmosphere were performed in such manner that they followed the diagonal of the street canyon's ground plan. The LIDAR laboratory used in all the performed experiments consists of two parts. The first is the DIAL LIDAR 510 M system manufactured by the German company, Elight Laser Systems GmbH. The second part is the customary Doppler SODAR PA2 produced in France by REMTECH. The system was integrated in a van and equipped with a trailer diesel-powered generator, which made the system fully mobile.

The LIDAR used a tunable pulse Titan-Sapphire (Ti^{3+}:Al_2O_3) laser pumped by xenon flash lamps with a repetition rate of 20 Hz. The tuning range was 760–880 nm. The pulse duration with a Q-switch was less than 30 ns. A specially designed 'double oscillator' permitted the cycling between two wavelengths, λ_{ON} and