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Study of the vertical variability of aerosol properties based on cable cars in-situ measurements

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A B S T R A C T

This work presents the methodology for obtaining the vertical profiles of aerosol optical and micro-physical properties based on cable-car and ground-based measurements in a mountain region. The presented data were collected during the winter workshop between 7th and 13th March 2016 in Krynica-Zdroj (southern Poland). During this campaign photoacoustic instruments were used to observe the single-scattering optical properties at two sites with a vertical separation distance of about 360 m. The micro-aethalometer AE-51 and the optical particle counter OPC-N2 were mounted on the cable car and used to measure profiles of black carbon concentration and aerosol size distribution. The mean extinction coefficients at the upper (37 Mm^{-1}) and lower (43 Mm^{-1}) sites were about three times lower than the long-term average for this season due to weather conditions, which did not favour the haze conditions. However, a significant correlation between temperature gradient and difference of extinction coefficient between the valley and mountain was found. During nights and stable thermodynamic conditions the values in the valley were higher than close to the top of the mountain. Profiles obtained from cable car measurements shown significant reduction of black carbon and aerosol concentration with altitude also during the day time. In addition, the effective radius, and the fine and coarse mode aerosol concentration was slightly changed with altitude when the relative humidity was below 100%. During condensation and cloud formation the significant variability in particles effective radius were found as a result of aerosol activation close to the top of the mountains.

1. Introduction

Recent years have brought an increase in the understanding of the influence of air pollution on human health (IPCC, 2013; WHO, 2016). Furthermore, many studies show that high concentration of aerosols in close vicinity to the Earth's surface has a negative influence on the health conditions and life expectancy of the human population (Mauderly and Chow, 2008; WHO, 2016). Because of the influence of aerosols on climate and health, it is important to characterise its concentration, size distribution and optical parameters at many different locations around the world at various times of the year and under a range of meteorological conditions, especially within the planetary boundary layer (PBL). Observation of PBL composition is also essential for understanding radiative balance in the atmosphere.

As a result of absorption of solar radiation by highly absorbing aerosols particles (e.g. soot), the vertical temperature and humidity profiles change. This effect has an impact on the PBL properties (Stull, 1988; Garratt, 1992). Although being a very important mechanism, feedback between aerosols and the PBL is still not very well understood. Previous analyses were performed using only numerical models (Yu et al., 2002; Wendisch et al., 2008). These

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papers show that the absorption of radiation by aerosols should result in a decrease of the PBL's height, which is an important parameter used in air pollution studies. Recent studies described by Sinha et al. (2013), Dumka et al. (2015a, 2015b) showed that the influence of the changes in PBL is associated with the aerosol scattering and absorption properties as well as CCN concentrations. In general it is assumed that absorption of radiation by aerosols particles at the top of the PBL causes a slowdown of the vertical transport and increase of the atmosphere stability (Ramanathan et al., 2005; Wendisch et al., 2008). With the assumption of a constant source of aerosols, the stabilisation of the PBL causes a constant increase of pollution concentration which leads to further warming of the air, and, as a result, causes further strengthening of the PBL stability and limits vertical mixing in the atmosphere, as well as a slowdown of the PBL development. This stabilisation has severe effects on the ventilation of the polluted PBL and may also suppress or delay convective cloud formation on many days with moist conditions close to the top of the PBL (Wendisch et al., 2008).

The newest studies are aimed mainly at miniaturisation and automatisation of equipment used for aerosol and meteorological observations. Since full-scale measurements from aeroplanes generate high costs, new methods of observation using small autonomous unmanned aerial vehicles (UAV) were developed in order to measure vertical profiles of BC (Ramana et al., 2007; Roberts et al., 2008; Corrigan et al., 2008; Chilinski et al., 2016). In addition, tethered balloons are used to profile the lowest troposphere and to measure aerosol optical and microphysical properties (Ferrero et al., 2011; Ferrero et al., 2016; Markowicz et al., 2017).

According to the European Environment Agency report for 2015 (EFA Report, 2015) several cities located in southern Poland are included among most polluted in Europe. One of the reasons for that particular situation is that the structure of the Polish energy economy is heavily based on coal (Zawadzka et al., 2013). In general, high air pollution episodes occur most often in large cities, but in small towns and villages in mountain regions too. During nights with low horizontal pressure gradient a mountain breeze in the valley leads to accumulation of air pollution in the surface layer (Wanner and Hertig, 1984; Baumbach and Vogt, 1999; Lang et al., 2015; Chilinski et al., 2016). Such a phenomenon has an impact on the propagation of both longwave and, what is more important, shortwave radiation. Interaction of the pollutants with shortwave radiation is most frequent during mornings (until the inversion disappears) or afternoons (when the inversion starts to develop) (Leukauf et al., 2015).

Accumulation of absorbing anthropogenic aerosols in basins during nocturnal temperature inversion creates favourable conditions for observations of mutual interactions between aerosols and the PBL (Cordova et al., 2016). Additionally, in some locations it is possible to install measurement devices on a cable car to perform vertical profiles of aerosol properties using in-situ methods (Seidel et al., 2016). So far the measurements of aerosols properties in mountainous areas have been carried out, among others, in the Alps on Jungfraujoch (Collaud Coen et al., 2011), in the laboratory in Zugspitze (Krüger et al., 2014), and in the region of Chamonix (Greenwald et al., 2006), but there was no profiling of aerosol properties during those measurements.

In Poland, a very small number of regular observations of aerosol optical properties in mountainous areas is carried out. In-situ measurements of the concentration of particulate matter with particle diameter below 2.5 μm (PM2.5) or below 10 μm (PM10) are conducted by the air quality network of the Inspectorate of Environmental Protection. Nevertheless, those measurements are carried out mostly at the bottoms of valleys. What is more, the vertical structure of the atmospheric pollution is not studied. One of the longest series of aerosol optical properties observations are based on direct solar radiation measurements (Linke Turbidity Factor) and were carried out in the Polish Tatra Mountains, in Zakopane and on Kasprowy Wierch (Markowicz and Uscka-Kowalkowska, 2015). However, those measurements do not allow the determination of detailed parameters characterising optical and microphysical properties (single scattering properties, size distribution) of atmospheric aerosols as in the case of data obtained from sunphotometers (Dubovik and King, 2000), and they do not allow the determination of the vertical profiles of those properties. Recent technical development has also brought new applications of mobile *in-situ* vertical profile measurements (Chilinski et al., 2016). Observations with the use of a mobile set for determining black carbon concentration were performed in Strzyzow in the region of Podkarpacie (Markowicz et al., 2014). In that case the profiles were performed carrying the measuring equipment during an uphill/downhill walk or using unmanned aerial vehicles (UAV). Due to the location of those measurements, the height of the profiles was small (approx. 100 m), and the measurement method is slow and limits the number of profiles taken during the day.

Use of cable cars can be convenient for PBL observation in mountainous areas. Such a situation allows continuous measurement the of air's vertical composition, such as exemplary liquid water content in relation to height (Wieprecht et al., 1970). Seidel et al. (2016) presented an example of comprehensive atmospheric observations that cover *in-situ* observation with ground-based mobile measurements (on a bus, on a vessel on a lake) and with airborne platforms (on a cable car, on a UAV and on a tethered balloon probe). It should be emphasised that all of the presented techniques have different characteristics related to spatial coverage, specific carrier system, climate elements measured and data analysis and evaluation. Cable car measurements can be deemed particularly interesting because of the existence of thousands of similar scheduled carrier systems in nearly all mountain areas of the world (Seidel et al., 2016). However, as in the case of all described systems, measurements can be affected simply by the moving platform. Moreover, the temporal and spatial bias of a moving sensor system should be taken into account.

This paper is the result of a workshop organised by University of Warsaw in cooperation with the Institute of Oceanology of the Polish Academy of Sciences, the Institute of Geophysics of the Polish Academy of Sciences and Poznan University of Life Sciences, all belonging to the Poland-AOD consortium (www.polandaod.pl). The main aim of the workshop was to improve understanding of the physical processes involving atmospheric aerosol phenomena occurring in the lower troposphere in mountainous regions. The workshop concentrated on expansion of knowledge on modern research techniques, including *in-situ* and remote sensing methods and numerical tools used to conduct computer simulations of physical processes in the atmosphere. In addition to the lectures, the field measurements were conducted in the Beskid Mountains. The classes covered field observation of the optical and microphysical structure of smog forming in the region of Krynica-Zdroj and its impact on the local thermodynamic conditions. The results of these measurements are presented in the following paper.

Section 2 contains a description of the strategy of observations, measurement sites, as well as used equipment. The next section is dedicated to analysis of the meteorological conditions during field measurements. Afterwards, in Section 4, temporal variability of single-aerosol properties obtained from optical devices is discussed. Section 5 is focused on vertical variability of the aerosol number and BC concentration. The last part of the paper contains a summary and discussion of the presented results as well as possible extension of the described measurements.

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