Science of the Total Environment 496 (2014) 424–434

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Impact of atmospheric boundary layer depth variability and wind reversal on the diurnal variability of aerosol concentration at a valley site

S. Pal *, T.R. Lee, S. Phelps, S.F.J. De Wekker

Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA

HIGHLIGHTS

- Role of atmospheric boundary layer depth on particle concentration variability
- Only accumulation mode particles are affected by boundary layer dilution effect.
- Effect of wind reversal in a valley on the diurnal cycle of particle concentrations.
- Decreasing trend in the boundary layer depths resulted in an increasing trend in aerosol concentration.
- Effect of boundary layer depth growth rate on aerosol concentration.

ARTICLE INFO

Article history:
Received 29 March 2014
Received in revised form 23 June 2014
Accepted 20 July 2014
Available online 6 August 2014

Editor: Xuexi Tie

Keywords:
Accumulation mode particles
Air quality
Atmospheric boundary layer
Dilution effect
Lidar
Valley-wind

ABSTRACT

The development of the atmospheric boundary layer (ABL) plays a key role in affecting the variability of atmospheric constituents such as aerosols, greenhouse gases, water vapor, and ozone. In general, the concentration of any tracers within the ABL varies due to the changes in the mixing volume (i.e. ABL depth). In this study, we investigate the impact on the near-surface aerosol concentration in a valley site of 1) the boundary layer dilution due to vertical mixing and 2) changes in the wind patterns. We use a data set obtained during a 10-day field campaign in which a number of remote sensing and in-situ instruments were deployed, including a ground-based aerosol lidar system for monitoring of the ABL top height (z_i), a particle counter to determine the number concentration of aerosol particles at eight different size ranges, and tower-based standard meteorological instruments.

Results show a clearly visible decreasing trend of the mean daytime z_i from 2900 m AGL (above ground level) to 2200 m AGL during a three-day period which resulted in increased near-surface pollutant concentrations. An inverse relationship exists between the z_i and the fine fraction (0.3–0.7 μm) accumulation mode particles (AMP) on some days due to the dilution effect in a well-mixed ABL. These days are characterized by the absence of daytime upvalley winds and the presence of northwesterly synoptic-driven winds. In contrast, on the days with an onset of an upvalley wind circulation after the morning transition, the wind-driven local transport mechanism outweighs the ABL-dilution effect in determining the variability of AMP concentration. The interplay between the ABL depth evolution and the onset of the upvalley wind during the morning transition period significantly governs the air quality in a valley and could be an important component in the studies of mountain meteorology and air quality.

1. Introduction

The development of the atmospheric boundary layer (ABL) plays a key role in the distribution of atmospheric constituents (Stull, 1988). It is recognized that atmospheric aerosols modify the climate either directly by scattering or absorbing the incoming solar and outgoing terrestrial radiation, indirectly via aerosol-cloud-microphysical processes, or semi-directly by favoring the evaporation of clouds (e.g., Ackerman et al., 2000). Additionally, aerosols influence air quality and environmental pollution (e.g., Aneja et al., 2008), and the effects of particle composition and size distribution on human health have yet to be fully elucidated (e.g., Davidson et al., 2005).

Thus, ABL features (e.g., depth, turbulent flux, entrainment processes, and growth rate) are important for understanding air quality impacts of aerosols, and the dispersion and transport of aerosols confined within the ABL. The temporal variability and the vertical distribution of aerosol concentrations are important for an understanding of changes in the

---

* Corresponding author at: Department of Environmental Sciences, University of Virginia, 291 McCormick Rd., Charlottesville, VA 22904-4123, USA. Tel.: +1 434 326 7706; fax: +1 434 982 2137.
E-mail address: sp5hd@Virginia.EDU (S. Pal).

http://dx.doi.org/10.1016/j.scitotenv.2014.07.067

aerosol concentrations at ground level and within the ABL. This information comes from vertically-pointing lidar systems from which the ABL top height (henceforth, denoted as z_i) can be estimated via separating the boundary between the aerosol-laden ABL and clean free atmosphere (FA) (e.g., Cohn and Angevine, 2000; De Wekker et al., 2004; Pal et al., 2010; Cimini et al., 2013).

Transport of aerosols and their vertical distributions strongly depends on meteorological conditions, boundary layer dynamics and physiochemical processes inside the ABL (e.g., De Wekker, 2002; Behrendt et al., 2011a; Pal et al., 2012, 2013). Fraigneau et al. (1996) suggested that the prediction of mean aerosol concentration might lead to erroneous results if the effects of ABL dilution and turbulence are neglected. In this context, ABL dilution refers to the combined effect of increase in the z_i and its growth rate on the tracer concentration in the ABL. For instance, ABL dilution during morning transition explains a drop in the concentration of tracers or pollutants due to increasing z_i. Gupta et al. (2006) illustrated the impact of z_i on the relationship between aerosol optical thickness and $PM_{2.5}$ concentration. In particular, aerosol distribution and transport processes in the ABL over mountainous regions are of high interest due to complexities in the flow pattern induced by diurnal cycles of ABL and thermally-driven up- and downvalley and up- and downslope winds (e.g., Whiteman, 2000; De Wekker et al., 2009; Emeis et al., 2009; Behrendt et al., 2011b). Additional factors include orography-induced gravity waves, cold-air pooling in valleys, plume impingement on higher terrain, and dynamical flows due to the presence of passes, peaks, crests, etc. (e.g., Gohm et al., 2009; Chow et al., 2013; De Wekker, 2002).

Marinoni et al. (2010) investigated the impact of valley-wind circulation patterns on aerosol transport to the adjacent high altitude site. Jiang et al. (2011) determined the impacts of mesoscale dynamics and turbulence on dust lofting and transport on the PM_{10} concentrations during different intensive observation periods of the Terrain-Induced Rotor Experiment (T-REX) in 2006 where they mainly focused on the processes governing the pronounced maximum in the dust particle concentrations in the valley in the late afternoon. Using scanning lidar measurements obtained during T-REX, De Wekker and Mayor (2009) investigated the roles of mountain-induced waves, hydraulic jumps, rotor-like circulations, and thermally-driven flows in lifting of aerosol particles.

Seibert et al. (1998) found a marked transport of highly polluted air from the Po Valley to the nearest mountain crest (3106 m). Gohm et al. (2009), among others, investigated the roles of upvalley, downvalley, upslope, and downslope winds on aerosol concentrations (PM_{10}) in an Alpine valley. Furger et al. (2000) studied the effects of thermal wind systems on horizontal and vertical ozone transport over various distances in the Mesolcina Valley in Switzerland. These studies mainly emphasized on venting and transport mechanisms and discussed low-level or elevated pollution episodes in the valley. In summary, previous studies have discussed the role of ABL dilution on near-surface pollutant concentration by showing a marked sensitivity to z_i: high particle number concentration in the shallow nocturnal boundary layer (NBL) and a rapid decrease in the concentration during the morning transition period consistent with the growth of the ABL. Also, effects of valley and slope winds have been found to play an important role in pollutant concentration variability due to trapping/venting in/out of the valley.

However, the impact of upvalley/downvalley circulations and the ABL dilution effect on the diurnal pattern of aerosol particle concentrations in a valley have not been discussed in detail. Additionally, the extent to which the ABL dilution effect and near-surface meteorological conditions influence the temporal variability in the aerosol particle concentration at different size ranges in valleys has not been clearly documented in the literature. In this paper, we present observations from a field campaign conducted in April 2013 at a valley site near Charlottesville, Virginia. The aim of the paper is to elucidate the role of boundary layer dilution and valley wind reversal during the morning transition period on the pattern of diurnal variability of aerosol concentrations in the valley.

2. Overview of the field experiment

2.1. Experimental site

A field campaign was conducted at Innisfree village (38.1809°N, 78.6856°W, 305 m MSL (mean sea level)) approximately 25 km northwest of Charlottesville, Virginia. The campaign was part of a practical course in boundary layer meteorology with the goal to study convective boundary layer (CBL) evolution in complex terrain. The field site is located on a 550 acres farm in the foothills of the Blue Ridge Mountains (Fig. 1). The site is located in a small, approximately 10 km long valley which runs approximately NNE-SSW, with peaks of 600 m MSL directly to the east and peaks of 815 m MSL directly to the west. However, the surrounding topography adjacent to the experimental site is highly complex, particularly due to the presence of a low-level crest located at few hundred meters northeast of the site. Thus, the experimental site is located within a narrow valley-like (NW-SE aligned) topographical setting which frequently channels the flow at the site.

2.2. Instruments

2.2.1. Aerosol lidar ALS-300 and ceilometer CT-12 K

A compact eye-safe aerosol lidar system (ALS-300, commercialized by Leosphere) and a CT-12 K laser ceilometer (manufactured by Vaisala Inc.) were deployed to monitor the temporal evolution of z_i, cloud base height (CBH), and relevant aerosol stratifications. The ALS-300 uses the frequency-tripled output of an Nd: YAG laser to transmit the laser radiation at a wavelength of 355 nm with pulse energy of 16 mJ and a pulse repetition rate of 20 Hz. The receiver unit consists of a telescope with a diameter of 15 cm. The full unit is connected to the data acquisition system and controlled with Labview software. The temporal and range resolution in the vertically resolved aerosol backscatter profiles are 30 s and 75 m, respectively. The lidar system provides a vertical range of up to several kilometers depending mainly on the optical thickness of the atmosphere (e.g., Pal et al., 2012; Lac et al., 2013).

The CT-12 K laser ceilometer is the standard National Weather Service ceilometer which detects CBH. The CT-12 K uses a dual lens arrangement: one optical path for the transmitter and a separate optical path for the receiver. The operating wavelength of the Gallium Arsenide pulsed laser diode transmitter is 904 nm. The CT-12 K is equipped with a heater and blower housing to prevent snow and ice accumulation on the windows of the instrument cover. The CT-12 K has maximum reportable cloud base detection range of 4000 m above ground level (AGL). During the field experiment the CT-12 K collected range-resolved measurements of aerosol backscatter with a temporal and spatial resolution of 30 s and 15 m, respectively. The quality of the aerosol backscatter signal was poor due to very low signal-to-noise ratio which was not sufficient to detect z_i from the CT-12 K measurements. However, CBH was determined successfully.

2.2.2. Particle counter

A particle counter (Model 212-2 Profiler, manufactured by Met One Instruments, Inc., USA) was deployed at 3 m AGL beside the lidar to monitor the number concentration of aerosol particles in the atmosphere. The particle counter uses a laser diode to detect and determine simultaneously the number of particles at eight different channels that are preset in the optical diameters (size ranges) from 0.3 μm to 10 μm. Output was given in counts/cm^3 with a time resolution of 1 s, which was subsequently integrated to 30-min integrals.

The particle counter counts individual particles using scattered laser light and calculates the size by the amplitude of scattered light from suspended particles to provide a continuous real-time measurement