JOURNAL OF ENVIRONMENTAL SCIENCES XX (2017) XXX–XXX

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JES JOURNAL OF ENVIRONMENTAL SCIENCES www.jesc.ac.cn

Thermal internal boundary layer and its effects on air pollutants during summer in a coastal city in North China

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ARTICLE INFO

Article history:
Received 7 July 2017
Revised 14 October 2017
Accepted 8 November 2017
Available online xxxx

Keywords:
Thermal internal boundary layer
Ceilometer
Air pollutants
Sea breeze

ABSTRACT

The thermal internal boundary layer (TIBL) is associated with coastal pollution dispersion, which can result in high concentrations of air pollutants near the surface of the Earth. In this study, boundary layer height data which were obtained using a ceilometer were used to assess the effect of the TIBL on atmospheric pollutants in Qinhuangdao, a coastal city in North China. A TIBL formed on 33% of summer days. When a TIBL formed, the sunshine duration was 2.4 hr longer, the wind speed was higher, the wind direction reflected a typical sea breeze, and the boundary layer height was lower from 9:00 LT to 20:00 LT compared to days without a TIBL. If no TIBL formed, the average concentrations of $PM_{2.5}$ and PM_{10} decreased with increasing boundary layer height. However, when a TIBL was observed, the average concentrations of $PM_{2.5}$ and PM_{10} increased with increasing boundary layer height. Because the air from the sea is clean, $PM_{2.5}$ and PM_{10} concentrations reached minimums in the daytime at 16:00 LT. After 16:00 LT, the $PM_{2.5}$ and PM_{10} concentrations increased rapidly on days when a TIBL formed, which indicated that the TIBL leads to the rapid accumulation of atmospheric pollutants in the evening. Therefore, the maximum concentrations of particulate matters were larger when a TIBL formed compared to when no TIBL was present during the night. These results indicate that it is suitable for outdoor activities in the daytime on days with a TIBL in coastal cities.

Introduction

The atmospheric boundary layer is the lowest atmospheric layer, located 1 to 2 km above the surface of Earth. This is the main layer where human activities take place, and the emission, transmission and transformation of pollutants occur in this layer. Therefore, the environmental problems within the atmospheric boundary layer directly influence the survival and health of human beings (Tang et al., 2017a).

The height of the atmospheric boundary layer can be defined as the height at which the turbulent momentum flux and heat flux caused by the ground both decrease to minimum values (such as 1% of the surface value) (Stull, 1988). The height of the atmospheric boundary layer is an important parameter that

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https://doi.org/10.1016/j.jes.2017.11.006

Please cite this article as: Wei, J., et al., Thermal internal boundary layer and its effects on air pollutants during summer in a coastal city in North China, J. Environ. Sci. (2017), https://doi.org/10.1016/j.jes.2017.11.006

influences the diffusion of air pollutants, and an important physical quantity that reflects the convection and diffusion characteristics of vertical atmospheric circulation. Multiple approaches have been used to measure the height of the atmospheric boundary layer, and these approaches have been summarized in previous studies (Beyrich, 1997; Emeis et al., 2008; Seibert et al., 2000). Recently, light detection and ranging (LIDAR) has experienced rapid development, and numerous studies have used LIDAR to detect the height of the atmospheric boundary layer (Scarino et al., 2014; White et al., 2010; Wiegner et al., 2006). Additionally, an eye-safe ceilometer has been developed that uses near-infrared band lasers to detect the height of the boundary layer. Due to its low cost, easy accessibility and consecutive detection ability, ceilometer detection has become the optimal method for the detection of the atmospheric boundary layer height (Emeis and Schäfer, 2006; Tang et al., 2015, 2016; Zhu et al., 2016).

In coastal regions, the formation of a thermal internal boundary layer (TIBL) is a common boundary layer phenomenon. In the sunny daytime, the sea breeze will blow the stable or neutrally stratified air over the sea towards land. The surface heating effect and dynamic disturbance effect intensify the turbulence in the lowest atmospheric layer to form an unstable layer, which develops into the TIBL. Notably, the TIBL progressively grows from the coastline to inland areas. Garratt (1990) systematically summarized the TIBL. Sicard et al. (2006) utilized elastic-backscatter LIDAR to measure the boundary layer height in the coastal city Barcelona. They found that the relatively low boundary layer height is related to the mesoscale compensatory subsidence over the sea and TIBL formation in summer. Prabha et al. (2002) studied the influence of changing synoptic scale conditions on the turbulent characteristics of the TIBL using a mini-sonic detection and ranging (SODAR) system, and concluded that the TIBL characteristics over the coastal land after the onset of the sea breeze are similar to those of the shallow convective boundary layer commonly observed over plain areas. Therefore, the height of the TIBL can be considered the height of the shallow convective boundary layer.

Several methods can be used to estimate the height of the TIBL. Using the results of a large eddy simulation, Calmet and Mestayer (2016) noted that the inversion height may indicate the top of the TIBL, and the TIBL depth may be determined by three methods, including from potential temperature profiles, heat flux profiles or turbulent kinetic energy (TKE) profiles. However, they found that the height of the TIBL can be best determined from the minimum of heat flux profiles. Hara et al. (2009) simulated the TIBL using a wind tunnel and direct numerical simulations and found that the TIBL height could be estimated from the vertical profile of the local Richardson number. Levitin and Kambezidis (1997) utilized the Boundary Layer Transformation Model (BLTM) and defined the TIBL height as the level at which the eddy diffusivity value returns to the background, or over-sea, value. Moreover, the observed TIBL heights were estimated using tethered balloons and defined as the first inversion base height in the temperature profiles. The TIBL height is mainly affected by turbulence, and the turbulence properties within the TIBL can be related to three external parameters: the surface sensible heat flux over land, the onshore low-level wind speed, and the stability of the onshore airflow (Shao et al., 1991; Smedman and Högström, 1983). The TIBL grows rapidly in neutrally stratified regions and slowly in higher regions of stable stratification (Luhar et al., 1998). Levitin and Kambezidis (1997) suggested that the main input parameters that affect TIBL development are the land-sea temperature difference and wind speed. Kang et al. (2010) analyzed radiosonde data from three stations in a coastal region of Shandong Province and derived the variation in the TIBL height with inland distance, thereby yielding an empirical model of TIBL height.

The Qinhuangdao downtown area is adjacent to Bohai Bay to the east and the Yanshan Mountain chains to the west in North China. The unique geographical position results in a complicated meteorological environment. The formation of the TIBL is a common boundary layer phenomenon in the coastal region in summer. When hazardous gases are emitted into the atmosphere, the emitted gases are dispersed more horizontally than vertically in the inversion layer above the TIBL. However, once the pollutants enter the TIBL, they are dispersed both horizontally and vertically due to convective motions in the TIBL. When the pollutants reach the ground through convection, they become harmful to humans. In this paper, we first introduce the data and methods used in the study and describe the ceilometer. Second, we then analyze the differences in meteorological conditions and air pollutant characteristics between the days with and without TIBL formation. Finally, the causes of these differences are explained.

1. Data and methods

1.1. *Ceilometer and the determination of the boundary layer height*

This experiment adopted an enhanced single-lens LIDAR ceilometer (CL51, Vaisala, Finland). This instrument utilizes pulsed diode laser LIDAR technology to detect the profile of the atmospheric-attenuated backscattering coefficient. The ceilometer was located at the Chinese Environmental Management College in Qinhuangdao, 1.13 km away from the coastline. The longitude and latitude of the station were 39.914°N and 119.556°E, and it was settled 18 m above ground level. The main parameters of the CL 51 are presented in Table 1.

Due to the long lifetime of fine particles, ranging from several days to dozens of days, the concentration of particulate matter in the atmospheric mixing layer is much more homogeneous than those of gaseous pollutants. Moreover, a large difference exists in the particulate concentration between the atmospheric boundary layer and the free atmosphere. By analyzing the attenuated backscattering coefficient profiles of atmospheric particulates, the position where a sudden change occurs in the

Table 1 – Main parameters of the CL51 ceilometer.

Performance	Parameter
Measurement range	13 km
Reporting period	6–120 sec
Reporting precision	10 m
Peak power	27 W
Wavelength	910 nm

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