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Impact of the Loess Plateau on the atmospheric boundary layer structure and air quality in the North China Plain: A case study

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HIGHLIGHTS

- Low mixed layer exacerbates air pollution over the North China Plain (NCP)
- Warm advection from the Loess Plateau leads to the lid formation over the NCP
- The Mountain-Plains Solenoid (MPS) circulation also suppresses the mixed layer.
- Different heating between Plateau and Plain affects boundary layer structure.

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ABSTRACT

The North China Plain (NCP), to the east of the Loess Plateau, experiences severe regional air pollution. During the daytime in the summer, the Loess Plateau acts as an elevated heat source. The impacts of such a thermal effect on meteorological phenomena (e.g., waves, precipitation) in this region have been discussed. However, its impacts on the atmospheric boundary layer structure and air quality have not been reported.

It is hypothesized that the thermal effect of the Plateau likely modulates the boundary layer structure and ambient concentrations of pollutants over the NCP under certain meteorological conditions. Thus, this study investigates such effect and its impacts using measurements and three-dimensional model simulations. It is found that in the presence of daytime westerly wind in the lower troposphere (~1 km above the NCP), warmer air above the Loess Plateau was transported over the NCP and imposed a thermal inversion above the mixed boundary layer, which acted as a lid and suppressed the mixed layer growth. As a result, pollutants accumulated in the shallow mixed layer and ozone was efficiently produced. The downward branch of the thermally-induced Mountain-Plains Solenoid circulation over the NCP contributed to enhancing the capping inversion and exacerbating air pollution. Previous studies have reported that low mixed layer, a factor for elevated pollution in the NCP, may be caused by aerosol scattering and absorption of solar radiation, frontal inversion, and large scale subsidence. The present study revealed a different mechanism (i.e., westerly warm advection) for the suppression of the mixed layer in summer NCP, which caused severe O_3 pollution. This study has important implications for understanding the essential meteorological factors for pollution episodes in this region and forecasting these severe events.

1. Introduction

Regional air pollution in terms of both ozone (O_3) and particulate matter (PM) in the North China Plain (NCP) has become one of the top environmental issues in China (He et al., 2001; Hao et al., 2005; Sun et al., 2006; Ding et al., 2008; Lin et al., 2008; Meng et al., 2009; Xu et al., 2011b; Zhao et al., 2011; Ma et al., 2012a,b; Huang et al., 2013; Lang et al., 2013; Chen et al., 2013; Hu et al., 2014). In addition to direct emissions (see NOx emission in Fig. 1a), meteorological conditions also play an important role in modulating ambient concentrations of pollutants in this region (Su et al., 2004; Chen et al., 2008; Zhang et al., 2009; Wang et al., 2009; Wang et al., 2010b; Gao et al., 2011; Wei et al., 2011; Yang et al., 2011; Zhang et al., 2012; Ji et al., 2012, 2014). A few

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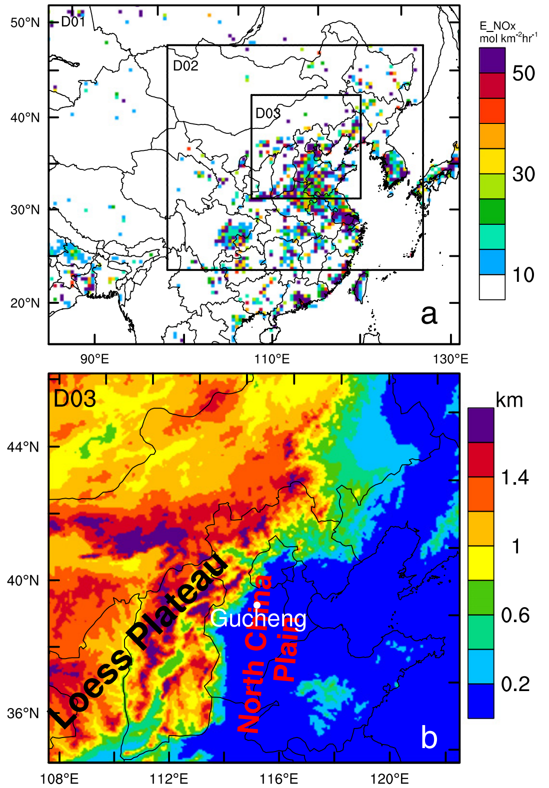

Fig. 1. (a) Domain configuration for the WRF simulation overlaid with NOx emission composed in Zhang et al. (2012) and (b) detailed terrain distribution around the North China Plain in domain 3. The location of the Gucheng research site is marked in panel b.

recent studies investigated the relationship between synoptic weather patterns and air quality in the NCP. It was concluded that variation of the synoptic patterns modulated the abundance of ambient pollutants and likely provided the primary driving force for the day-to-day variations in regional pollutant concentrations (Chen et al., 2008; Wang et al., 2009; Zhang et al., 2012; Wei et al., 2011). Southwesterly surface wind was found more likely to lead to severe air pollution in the NCP (e.g., Chen et al., 2008; Wang et al., 2010a; Xu et al., 2011a; Wang et al., 2013b; Zhang et al., 2012). However, only few studies investigated the atmospheric boundary layer structure and its impact on air quality in this region (Quan et al., 2014). Previous studies did not ascribe the root causes of the day-to-day variation of pollutants in the NCP to the different boundary layer structures. The thermal and dynamic characteristics of the atmospheric boundary layer and their relationship with air pollution in the NCP remain to be further studied (Liu et al., 2013; Zhao et al., 2013). One objective of the present study is to reveal the crucial role of the atmospheric boundary layer structure and air flow above the surface (in addition to the surface wind) in causing severe air pollution in this region.

The Loess Plateau, with altitudes of 1000-2000 m above sea level (asl), is located to the west of the NCP (with altitudes of less than 50 m asl) (Fig. 1b). During the daytime in the summer, the Loess Plateau acts as an elevated heat source in the vicinity of the low-lying NCP (He and Zhang, 2010; Sun and Zhang, 2012). Due to intense solar radiation, the near-surface air temperature over the Plateau is normally higher than air temperature at the same height over the adjacent Plains (Gao et al., 1981). This thermal effect of the Plateau likely modulates the atmospheric boundary layer structures over the NCP under certain meteorological conditions. While much effort has been made in understanding impacts of different heating/cooling between mountains and adjacent plains on meteorological phenomena such as waves and precipitation (e.g., Tripoli and Cotton, 1989; Wolyn and Mckee, 1994; Zhang and Koch, 2000; Koch et al., 2001; Zaitchik et al., 2007; Carbone and Tuttle, 2008; He and Zhang, 2010; Sun and Zhang, 2012; Bao and Zhang, 2013), its impacts on the atmospheric boundary layer structure and air quality remain poorly understood (Lanicci and Warner, 1991, 1997; Luke et al., 1992; Ryan et al., 1992; Warner and Sheu, 2000; Pagnotti, 1987; Seaman and Michelson, 2000).

Resulting from heating over the Plateau and sloping terrains during the afternoon in summer and autumn months, upslope wind develops along the sloping terrains. Simultaneously, a downward return flow develops over the adjacent Plains. Such thermally driven phenomenon is termed the Mountain-Plains Solenoid (MPS) circulation (Tripoli and Cotton, 1989; May and Wilczak, 1993; Sun and Zhang, 2012). A few studies (e.g., Liu et al., 2009; He and Zhang, 2010; Sun and Zhang, 2012; Bao and Zhang, 2013; Zhang et al., 2014) reported that precipitation occurs on the slopes of the Plateaus usually during midday or early afternoon associated with the upward branch of the MPS circulation and propagates to the adjacent Plains during the nighttime. This study will extend previous investigations to illustrate the impact of MPS on the atmospheric boundary layer structure and air quality.

During summer 2013, a research field campaign was conducted at Gucheng, a rural site in the north part of the NCP (Fig. 1b). Vertical profiles of chemical and meteorological variables were measured in addition to surface measurements. These data together with three-dimensional air quality simulation results are analyzed in this study to investigate the impacts of the thermal effects of the Loess Plateau on the atmospheric boundary layer structure and the O_3 concentrations in the NCP.

2. Methods

2.1. In-situ measurements at Gucheng

2.1.1. Site description

The Gucheng site (39°08′N, 115°40′E, 15.2 m asl) in Hebei Province is an Integrated Ecological-Meteorological Observation and Experiment Station of the Chinese Academy of Meteorological Sciences. The site is located in the northern part of the NCP, ~120 km southwest of the Beijing–Tianjin metropolitan area, 35 km north of the Baoding city (Fig. 1b). The Gucheng site is surrounded by farms, villages/towns, and transportation network in the NCP. The main crop around this site is corn in the summer and fall (Lin et al., 2009). Starting from the summer of 2006, several institutions have measured atmospheric chemical species near the surface at Gucheng, in order to monitor regional background concentrations of air pollutants in the NCP (Lin et al., 2009; Wang et al., 2013a).

2.1.2. Field experiment in the summer of 2013

In the summer of 2013, instruments from Thermo Environmental Instruments, Inc. were used to measure ground-level chemical species at Gucheng, including O_3 (model TE 49C), CO (TE 48C), NH_3 (DLT-100),

Table 1
Sigma levels and mid-layer heights (m AGL) of the lowest 20 WRF model layers.

Sigma levels	1.0	0.997	0.994	0.991	0.988	0.985	0.975	0.97	0.96	0.95
Mid-layer heights	12	37	61	86	111	144	186	227	290	374
Sigma levels	0.94	0.93	0.92	0.91	0.895	0.88	0.865	0.85	0.825	0.8
Mid-layer heights	459	545	631	717	826	958	1092	1226	1409	1640