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Quantifying stability influences on air pollution in Lanzhou, China, using a radon-based "stability monitor": Seasonality and extreme events

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HIGHLIGHTS

- Variability of near-surface pollutants is analyzed with radon based stability scheme.
- Ozone concentrations decrease with stability increase.
- Extreme pollution events occur mostly under stable condition.
- Prediction of haze events is demonstrated using radon measurement.

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ABSTRACT

A recently-developed radon-based technique is modified to quantify the seasonal influences of atmospheric stability on urban emissions in Lanzhou, China, based on 11 months of observations at three sites with contrasting pollution characteristics. Near-surface concentrations of primary (CO, SO_2, NO_X) and secondary (O_3) gas phase pollutants responded to changing atmospheric stability in markedly different ways in winter and summer, primarily because monsoonal fetch changes strongly influenced the distance between measurement sites and their nearest upwind pollutant sources, but also due to mean diurnal changes in mixing depth. Typically, morning peak primary pollution concentrations increased by a factor of 2–5 from the most well-mixed to stable conditions, whereas nocturnal ozone concentrations reduced with increasing stability due to surface loss processes and the progressively reduced coupling between the nocturnal boundary layer and overlying free atmosphere. The majority of pollution exceedance events (cf. China National Air Quality Standard guideline values) occurred in winter, when all measurement stations were downwind of the city's main pollution sources, and were directly attributed to morning periods and stable atmospheric conditions. In the sheltered valley region of Lanzhou, extremes of winter nocturnal stability states represented a change in mean nocturnal wind speed of only 0.25 m s^{-1} (from 0.6 to 0.85 m s^{-1}). Daily-integrated PM_{10} concentrations increased by a factor of 2 in winter from the most well-mixed to stable conditions, and were usually above guideline values at the industrial and residential sites for all atmospheric stability conditions. In summer, however, daily mean PM_{10} exceedances usually only occurred at the industrial site, under stable conditions. Finally, a simple

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model – based on mean radon concentrations between 1900 and 0400 h – is proposed to predict haze conditions in the city prior to commencement of the peak morning commuting time.

1. Introduction

China currently faces serious air quality issues due to particularly high levels of air pollution. Recent environmental reports indicate that ambient air quality levels meet China's new standards in only 8 of the 74 major cities (Chinese Ministry of Environmental Protection, 2015). Averaged across all major cities, 2014 pollutant concentrations included: 64 $\mu g/m^3$ for $PM_{2.5}$, 105 $\mu g/m^3$ for PM_{10} and 42 $\mu g/m^3$ for NO_2 (Chinese Ministry of Environmental Protection, 2015). While much is known about the health implications of fine particles and high concentrations of oxidising species frequently observed in urban centres (Kim et al., 2015; Cao et al., 2012; Guo et al., 2013), a clearer understanding of the variability in near-surface concentrations of gaseous and aerosol urban pollutants is essential for assessing the efficacy of emission mitigation strategies, and improving chemical transport models.

On diurnal to sub-diurnal timescales changes in atmospheric stability (aka mixing depth) can exert a comparable or greater influence on the variability of urban pollutant concentrations than typical changes in source strengths or advection (e.g. Perrino et al., 2001; Chambers et al., 2015a,b; Grundstrom, 2015; Williams et al., 2016). For example, in spite of similar traffic densities during the morning and evening rush hours, pollutant concentrations that the commuting public are exposed to are typically higher in the morning, before the shallow nocturnal inversion has been eroded, than in the evening, when turbulence from the deeper convective boundary layer is decaying (e.g. Williams et al., 2016). However, efforts to accurately forecast related risks and impacts have so far been hindered by the fact that shallow nocturnal mixing conditions are the most problematic for models to simulate, due primarily to limitations of their vertical resolution and the ability of parameterisations to accurately represent near-surface mixing processes (e.g. Holtslag, 2014). The potential benefits of improving current knowledge about atmospheric stability influences on pollutant concentrations and public health, either by direct investigation or providing datasets for the evaluation of chemical transport models, are clearly evident.

Lanzhou is one of China's most polluted cities (Ta et al., 2004; Zhang et al., 2014; Christopher et al., 2015). Industries and local population aside, this reputation is largely attributable to its location in a narrow valley of the Yellow River that is prone to atmospheric stagnation events. Mean annual wind speeds of only 0.8 m s^{-1} (or 0.3 m s^{-1} in the case of the long-term winter average; Zhang et al., 2001), result in minimal dispersion of locally generated emissions. Of the atmospheric stability classification tools most readily available for routine use (i.e. the Pasquil-Gifford "turbulence" (PGT) and "radiation" (PGR) schemes; Pasquil, 1961; Turner, 1964; Pasquill and Smith, 1983), the PGT scheme is unusable at Lanzhou, due to the consistently low wind speeds, and the PGR scheme has been demonstrated to consistently misrepresent pollutant concentrations around Lanzhou city under stable atmospheric conditions (Chambers et al., 2015a).

Radon-222 (radon), an inert naturally-occurring radioactive gas ($t_{0.5}$ = 3.8 d), has long been recognised as a convenient passive tracer of vertical mixing (e.g. Wigand and Wenk, 1928; Moses et al., 1960; Jacobi and Andre, 1963; Liu et al., 1984; Butterweck et al., 1994; Williams et al., 2011, 2013; Pal et al., 2014) and horizontal transport (e.g. Lambert et al., 1970; Balkanski and Jacob, 1990; Chambers et al., 2008) from and within the atmospheric boundary layer. More recently, a growing number of studies have demonstrated the value of radon as an alternative to conventional meteorological approaches for characterising nocturnal atmospheric stability (Perrino et al., 2008, Perrino 2012; Chambers et al., 2015b, 2016; Crawford et al., 2016; Podstawczyńska, 2016; Williams et al., 2016), since its near-surface concentrations are closely matched with pollutant transport and dispersion processes (Williams et al., 2013).

The aim of this study is to build upon recent prior studies in Lanzhou (e.g. Wang et al., 2013a; Chambers et al., 2015a) by (i) modifying the stability classification scheme described in Chambers et al. (2015)a,b to account for seasonal variations in day length, and (ii) extend the general analysis of Chambers et al., 2015a by performing a seasonal characterisation of stability effects on pollution concentrations in Lanzhou over the diurnal cycle at sites representative of industrial, residential and rural background conditions. Particular attention is paid to meteorological conditions and pollutant concentrations characteristic of extreme pollution events in winter under very stable atmospheric conditions and a method proposed by which nocturnal radon observations could be routinely used to predict haze conditions prior to the commencement of the morning peak commuting period.

2. Methods

2.1. Site and observations

This study is based on 11 months of meteorological and pollutant observations at Lanzhou, China, conducted between July 2007 and May 2008. Detailed descriptions of the site, surrounds and observations have previously been given by Wang et al. (2013a) and Chambers et al. (2015a). Radon and pollution measurements were conducted by the Environmental Monitoring Center of Lanzhou at three contrasting sites (Fig. 1):

Station B "Residential" (103°42′21″E, 36°06′59″N; 1526 m a.s.l.), representative of residential areas; Station C "Industry/traffic" (103°43′32″E, 36°04′30″N; 1512 m a.s.l.), representative of industrial emissions and high-traffic areas; Station D "Background" (104°08′48″E, 35°56′34″N; 1765 m a.s.l.), representative of rural background regions.

Radon progeny sampling was conducted from 3 m above ground level (a.g.l.) at Station C using an SM200 "stability monitor" (OPSIS AB, Furulund, Sweden) consisting of a particulate matter sampler that alternates between two sampling filters on which beta measurements are made by a Geiger–Muller counter for determining the total beta activity of the short-lived radon progeny. For more details about the operation of the SM200 to the reader is referred to Perrino et al. (2001) and Opsis AB (2005). As explained in Chambers et al. (2015a) output from the SM200 is in raw counts, not a calibrated concentration (because an absolute calibration to radon concentration was not possible in the mode the instrument was operated in), and will henceforth be denoted Rn* to indicate that it is a proxy only of ambient radon progeny activity. The relative counts of the SM200 are quite stable in time. Since our application of these observations (described in Section 2.2) relies upon relative