Air pollution and meteorological processes in the growing dryland city of Urumqi (Xinjiang, China)

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A B S T R A C T

Seven years (2000–2006) of monthly PM10 (particulate matter, d ≤ 10 μm), SO2, and NO2 concentrations are reported for Urumqi, the capital of Xinjiang in NW China. Considerably high mean annual concentrations have been observed, which ranged between 150 and 240 μg m⁻³ (PM10), 31 and 50 μg m⁻³ (NO2), and 49 and 160 μg m⁻³ (SO2). The shapes of seasonal variation of all pollutants were remarkably similar; however, winter/summer ratios of concentrations were quite different for PM10 (2–3) and NO2 (≈4) compared to SO2 (up to 30). Very high consumption rates of fossil fuels for energy generation and domestic heating are mainly responsible for high annual pollution levels, as well as the (very) high winter/summer ratios. Detailed analysis of the 2000–2006 records of Urumqi's meteorological data resulted in inter-annual and seasonal frequency distributions of (a) surface inversion events, (b) heights of surface inversions, (c) stability classes of Urumqi's boundary layer, and (d) the "Air Stagnation Index (ASI)". Urumqi's boundary layer is shown to be characterized by high mean annual and seasonal frequencies of surface inversions and by the dominance of stable dispersion classes. A further outcome of the meteorological analysis is the proof of Urumqi's strong diurnal wind system, which might have particularly contributed to the stabilization of the nocturnal boundary layer. Annual and seasonal variations of pollutant's concentrations are discussed in the context of occurrences of inversions, boundary layer, stability classes, and ASI. The trend of Urumqi's air pollution indicates a strong increase of mean annual concentrations 2000–2003, followed by a slight increase during 2003–2006. These are in strong contrast to (a) the growth of Urumqi's fleet of motor vehicles and (b) to the growing number of stable regimes of Urumqi's boundary layer climate during same period. It is concluded that the (regional and) local administrative technical countermeasures have efficiently lowered Urumqi's air pollution levels.

1. Introduction

Cities with more than ten million inhabitants are called Megacities, and at present, there are 20 such cities worldwide. The number of Megacities is expected to grow considerably in the near future due to rapid urbanization and population growth (Lawrence et al., 2007). There are many reasons to concentrate on Megacities (and also on big cities that soon will reach the status of Megacities). The most obvious is that these Megacities all have one in common. Urumqi, capital of the Uighur Autonomous Region Xinjiang (NW China), is one of the most rapidly growing big cities in the world, whose permanent residents had increased from 1.3 Million (1990) to more than 2.5 Million in August 2008 (Liu, 2008) and whose registered migrant workers are more than 800,000 per year. Urumqi is currently about 25% of the size of a typical Megacity. However, this city is prone to be become a Megacity (very) soon. In particular, Urumqi is and will remain that central economical attraction for Xinjiang's rural exodus. Nevertheless, one reason that Urumqi's population does not already exceed the 10 million mark is that the hinterland of Urumqi, as well as the entire Xinjiang region (95% mountains and deserts), constitutes the largest administrative province of China, while its population density is lowest in China (19 million inhabitants per 1.6 million km²). However, Urumqi as a regional (strongly developing) economic center is not only attractive for the people in Xinjiang; the number of industries, business people, and legions of migrant workers arriving in Xinjiang from all parts of China every year is substantially growing.

As Urumqi's population has grown, so too has the problem of air pollution as a result of the increasing consumption of energy by fossil fuels and the steady growing fleet of motor vehicles (Fig. 1). It is obvious that (a) the growing population, (b) the move towards urbanization and industrialization, and (c) the combustion of fossil fuel by industry and vehicles have produced a significant increase of air pollution. Moreover, it is becoming apparent that the topographical situation of the city, which is surrounded by high mountain ranges (c.f. Fig. 2), and the interaction between the geographical setting and...
meteorological processes have an important impact on the occurrence of air pollution events in the city. Meteorological factors, such as atmospheric stability and inversion layers, are of substantial importance for Urumqi’s air quality, since they reduce turbulent mixing and venting of the atmospheric boundary layer and hence prevent the dispersion of airborne material released into the atmosphere (e.g., Daoo et al., 2004). In cities like Urumqi, where awareness of the environmental impact of economic growth and changes of human settlement patterns is important for long-term city planning, meteorological factors need particularly to be taken into account when considering the air pollution problem.

Since the early fifties of the last century, various studies have been carried out to examine the relationship between air pollution and meteorological processes in different (Mega-)cities of the world, e.g., for Phoenix, Arizona (Ellis et al., 2000), Hong Kong (Chan and Kwok, 2000), Istanbul (Tayanc, 2000), Mexico City (Jauregui and Luyando, 1999), India (Lal et al., 2000), Bangi, Malaysia (Sani, 1987), Stockholm (Bringfelt, 1971), Nashville (Turner, 1961), and Dorona (Harold et al., 1949). Studies like the quality assessments for different Chinese (Mega-)cities (e.g., Staff Mestl et al., 2005; He et al., 2007; Wang et al., 2004; Tian et al., 2007; Yi et al., 2007; Chan and Yao, 2008) have, up to now, not been conducted for Urumqi. Moreover, only very few air pollution studies have been carried out in Urumqi (see Table 1, published in Chinese only). Only one recent study for the city of Urumqi has been published in English literature (Li et al., 2008).

The purpose of our study is to report first time the 2000–2006 air quality status of Urumqi and to discuss its relation to local meteorological processes. These aspects are pursued by reporting monthly means of PM$_{10}$, SO$_2$, NO$_2$ concentrations measured at four stations downtown Urumqi, by studying corresponding inter-annual and seasonal behavior of concentrations, by classifying the local air quality applying the China National Ambient Air Quality Standard (CNAAPS) and by documenting the national as well as regional management strategy for air pollution control. Furthermore, we quantify inter-annual and seasonal frequency distributions of the occurrence of (a) surface and elevated temperature inversions, (b) atmospheric stability classes (Pasquill/Turner), and (c) air stagnation events in Urumqi’s boundary layer. Characterization of local meteorological processes is completed by proof of Urumqi’s particular meteorological situation on its air quality is investigated. In addition, the historical efforts to improve the air quality in Urumqi city are discussed.

2. Data and methodologies

2.1. Study area and climate

The study area comprises Urumqi’s urban area (white bordered rectangular in Fig. 2). Urumqi is the remotest city from any ocean in the world, expressed by the shortest distance to any ocean of approx. 2500 km
Table 1
Chinese studies on air pollution problems of Urumqi, Xinjiang, PR China (published in Chinese only).

<table>
<thead>
<tr>
<th>Author</th>
<th>Air pollutants considered</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huang (2005)</td>
<td>PM$_{10}$</td>
<td>Daily data only for January 2004</td>
</tr>
<tr>
<td>Li et al. (2007)</td>
<td>PM$_{10}$, NO$_x$, and SO$_2$</td>
<td>Monthly data 2000–April 2006</td>
</tr>
<tr>
<td>Guo (2004)</td>
<td>Total suspended matter</td>
<td>Data of heating season 2002</td>
</tr>
<tr>
<td>Xu and Xu (2004)</td>
<td>PM$_{10}$ and SO$_2$</td>
<td>Data of heating season 2000–2002</td>
</tr>
<tr>
<td>Zhao et al. (2005)</td>
<td>Total suspended matter, PM$_{10}$</td>
<td>Data of heating and non heating season 2002</td>
</tr>
</tbody>
</table>

(to the Arctic Sea). The elevation of Urumqi's urban area (11739 km$^2$) ranges between 900 and 1300 (meter above sea level [m a.s.l.]). The west, east, and south of Urumqi are bordered by the Tianshan Mountains (3000–4500 m a.s.l.).

According to the Koeppen–Geiger classification, Urumqi's (Northern Xinjiang) climate is considered as semi-arid steppe (BS; cf. Peel et al., 2007), Domroes and Peng (1988), referring to the climate regionalization scheme for China, defined the climate of Urumqi/Northern Xinjiang as the “arid type (II D)” of China’s “Middle Temperate Zone (II)”. Based on their 30-year analysis (1951–1980), Urumqi’s climate is characterized by short warm summers and long cold winters. We have calculated mean monthly temperatures and precipitation from the more recent 40-year climatological data set (1966–2006); results are shown in form of Urumqi’s climate diagram (c.f. Walter and Lieth, 1967) in Fig. 3. Since the air pollution data set that has been used in our study covers only the period 2000–2006, corresponding climatological data for that period are also shown.

Monthly mean temperatures ranged from −14 °C (January) to + 24 °C (July), while precipitation ranged between 7 (September) and 16 mm month$^{-1}$ (December), emphasizing the arid status of Urumqi. Like for China as a whole, winter and summer are regarded as the generally dominating seasons for Urumqi, while spring and autumn are only short transitional seasons (Domroes and Peng, 1988). According to Chang (1954), Urumqi’s summer lasts for only two, while the winter, for 5–6 months. For 1951–1980, Domroes and Peng (1988) evaluated a mean annual number of 46.5 snowfall days and more than 150 days year$^{-1}$ for the mean duration of the snow covered period. On climatological average (Zhang and Lin, 1985), Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period. On climatological average, Urumqi experiences about 7 months between the mean duration of the snow covered period.

2.2. Monitoring sites and analytical methods

For our study we consider the four air pollution monitoring sites of Urumqi’s urban area, namely the stations Beimen, Shoufeisuo, Jiancezhan, and Tiezhao. Locations of the sites, belonging to the Urumqi Environmental Monitoring Station Network and operated by the Xinjiang Autonomous Government, are shown in Fig. 4. Data of particle mass (PM$_{10}$), sulfur dioxide (SO$_2$), and nitrogen dioxide (NO$_2$) concentrations are available as 84 monthly means for the time period of 2000 to 2006.

Sampling procedures and analytical determination of PM$_{10}$, SO$_2$, and NO$_2$ concentrations have been performed according to the guidelines of the CNAQPs, namely GB 6921, GB/T 8970, and GB/T 15435 for PM$_{10}$, SO$_2$, and NO$_2$, respectively, which are published by the China Environmental Law Initiative SEPA (China State Environmental Protection Administration, SEPA, 1986, 1988, 1995). PM$_{10}$ concentration was determined gravimetrically (from 24-hour filter samples; SEPA, 1986). SO$_2$ concentration colorimetrically by the Tetrachloromercurate (TCM)-pararosaniline method (24-hour samples; SEPA, 1988), and NO$_2$ concentration also colorimetrically using the Griess-Salzmann method (24-hour samples; SEPA, 1995).

2.3. Data type and sources

Monthly mean concentrations of PM$_{10}$, SO$_2$, and NO$_2$ (January 2000–December 2006) have been supplied by the Environmental Protection Bureau of Urumqi (EPBU). These data are based on PM$_{10}$, SO$_2$, and NO$_2$ concentrations, which have been determined from 24-hour samples each, taken daily, starting at 09:00 (local time). To assess the geographical setting of the study area, the data of the Shuttle Radar Topography Mission (SRTM) satellite were used, which were supplied by the Consortium for Spatial Information of the Consultative Group for International Agricultural Research (CGIAR-CSi: http://srtm.csi.cgiar.org/). The data have a horizontal resolution of at 3 arc-seconds (90 m) and are distributed as results of a regular grid digital elevation model (DEM).

The 2000–2006 meteorological data set of the Urumqi city meteorological station (WMO Id. No. 514630, 43°48′N, 87°39′E; 947 m a.s.l.; Fig. 3) has been supplied by NOAA National Data Center (Ashville NC, USA) and by the German Meteorological Service (Hamburg, Germany). It comprises quality-controlled data of surface measurements of wind speed, wind direction, total cloud cover, cloud ceiling height, air temperature, dew point temperature, barometric pressure, and precipitation. For 2000 and 2001, data were available every 6 h (00, 06, 12, 18 local time; annual data coverage > 99%), while for 2005 and 2006, data availability increased to 8 day$^{-1}$ (00, 03..., 21 local time; annual data coverage > 99%). For 2002–2004, the transition process of data recording frequency is mirrored by annual data coverages of 58%, 90%, and 90%, respectively.

Data of the Urumqi radiosonde station (WMO Id. No. 514630) have been downloaded from the Integrated Global Radiosonde Archive (IGRA), NOAA National Climatic Data Center (Ashville NC, USA). Quality-controlled data (c.f. Durre et al., 2006) of barometric pressure, geopotential height, air temperature, dew point temperature, wind direction, and wind speed were available twice a day (11:00 and 23:00 local time) for the time period 01 January 2000 to 31 December 2006. Data coverage is > 98%, a maximum of 3 days are missing in the 2002 data set.

2.4. Data processing and analysis

2.4.1. Classification of surface concentrations

The 2000–2006 concentration data of Urumqi’s monitoring stations are not only used as time series to document seasonal and inter-annual trends, they were also evaluated in the context of Ambient Air Quality Standards, particularly those that are valid in
China. For that PM$_{10}$, SO$_2$ and NO$_2$ monthly concentrations were classified according to CNAAQS Air Quality Levels (GB3095/1996, based on PR China's law on Air Pollution Prevention and Control). In comparison to most other countries, China uses different levels for determining Ambient Air Quality Standards. Therefore, we like to briefly describe these CNAAQS Air Quality levels. Air Quality levels of the pollutants are given as upper concentration limits (in $\mu$g m$^{-3}$), which must not be exceeded for a given environmentally classified area (He et al., 2002).

Levels are categorized in five groups, the so-called Grade I to Grade V indices (see Table 2). These CNAAQS Air Quality levels are given in Table 2. For comparison, corresponding air quality levels of the United States Environmental Protection Agency (Yi et al., 2007) are also shown.

### 2.4.3. Mean zonal and meridional components of horizontal wind

To study the suspected influence of the local wind system on Urumqi's pollution levels (already suggested by Zhang et al., 2000...
and Huang, 2005), zonal (W–E) and meridional (S–N) components of horizontal wind vectors were considered. For that we used all individual wind speed and wind direction data of both data sets of Urumqi’s meteorological station, particularly those measured 3 (6) hourly at the surface (10 meters above ground [m a.gr.]), and those obtained for the 850 hPa level (11:00 and 23:00 local). Monthly means of the zonal and meridional wind components have been calculated and, for the sake of clarity, were averaged seasonally, i.e., for January–March, April–June, July–September, and October–December, respectively.

2.4.4. Mean occurrence of atmospheric stability classes

Urban air pollution concentrations are determined by both, emission strength of sources, and dispersion conditions of the urban mixed layer. The latter can be characterized in the form of atmospheric stability classes, usually the so-called Pasquill/Turner stability classes, which range from “extremely unstable” (1) to “neutral” (4), “slightly stable” (5), “stable” (6), and “extremely stable” (7). These stability classes are only dependent on surface wind speed and the Net Radiation Index (NRI), which is a function of solar altitude, total cloud cover, and ceiling height. We made use of all individual data of wind speed (measured at 10 m a.gr.), total cloud cover and ceiling height (the latter approximated by the observed height of lowest clouds) in the 2000–2006 data set of Urumqi’s meteorological station. For calculation of stability classes, applying the equations given by Pasquill (1961) and Turner (1964), we developed a simple, MATLAB software based algorithm; the corresponding time step was prescribed by the observation times of Urumqi's meteorological station. For each step, solar altitude was computed from Urumqi’s latitude (43°48’N), followed by the computation of inclination angle and solar hour angle. With these quantities and the observed total cloud cover and ceiling height follows the actual NRI. From NRI and wind speed follows the corresponding stability class of Urumqi’s mixed layer. Finally, the complete data set (2000–2006) of stability classes was used to calculate mean monthly frequencies of stability classes’ occurrence.

2.4.5. Air Stagnation Index (ASI)

The presence of stagnating anticyclones is usually related to the occurrence of (major) air pollution episodes. This is due to the spatio-temporal persistence of these anticyclones (4 days or more) and the inherent incidence of (very) low surface wind speeds as well as (surface) inversions (Wang and Angell, 1999). Wang and Angell (1999) defined the term “air stagnation event” as the meteorological state, which is favorable to an air pollution episode: the air stagnation event identifies conditions, where near surface air may be trapped by poor ventilation (light or calm winds) and the presence of inversions; in case of persistent air stagnation, accumulated pollution results in poor air quality. For determination of the Air Stagnation Index (ASI) over the continental United States (2.5° × 2.5° resolution), Wang and Angell (1999) used the following atmospheric circulation variables: daily mean surface wind (inferred by a horizontal pressure gradient technique), daily 500 hPa wind speed, daily precipitation, and daily temperature inversion below 850 hPa. Corresponding data were taken from 51 years of the NCEP/NCAR reanalysis/CDAS system and the Climate Prediction Center of the National Weather Service (USA). Based on historical studies of the 1948 Donora (Pennsylvania, USA) smog disaster (e.g., Fletcher, 1949), the critical duration for an air stagnation event has been chosen to 4 days, and the critical surface pressure gradient wind speed to ≤8 m s⁻¹ (corresponding to ≤3.2 m s⁻¹ at anemometer level, i.e., 10 m above ground), being relaxed by 10%, if an inversion (ΔT<0; Δz>0) existed below 850 hPa. Furthermore, the state of an air stagnation event was not given, if there was (even a trace of) precipitation and a wind speed of >13 m s⁻¹ at the 500 hPa level. For our analysis of the ASI over Urumqi, we made use of the criteria given by Wang and Angell (1999), except that of the 500 hPa wind speed, because the nature of this criterion tended to be a continental US specific, semi-empirical one, most likely not appropriate for Central Asian conditions. For the determination of the ASI, the following steps have to be performed: (1) check air stagnation criteria for each day of the 2000–2006 period, (2) count whether there are 4 consecutive days (or more) of air stagnation conditions, (3) accumulate those days in each month and count every consecutive 4-day period as an air stagnation case, (4) calculate the monthly ASI (in %), i.e., the ratio of “stagnation days” (a multiple of four) and the total number of days per month.

3. Results

3.1. Air quality status of Urumqi

3.1.1. Inter-annual variation of pollutants

Inter-annual variations (2000–2006) of PM₁₀, SO₂, and NO₂ concentrations spatially averaged over all four monitoring stations of Urumqi are shown in Fig. 5a, c, and e. There, mean annual concentrations are given as averages (full circles); also shown are corresponding medians (50 percentile, horizontal bars), 25% and 75% percentiles (boxes’ lower and upper boundaries), as well as 10% and 90% percentiles (lower and upper whiskers). Underlying color shaded (vertically fading) areas in Fig. 5a, c, and e represent the annual Grade II CNAQS Air Quality Levels of the individual pollutants, namely 100, 40, and 60 μg m⁻³ for PM₁₀, NO₂, and SO₂, respectively. Mean annual PM₁₀ concentrations (Fig. 5a) range between 150 and 240 μg m⁻³, the highest value occurred in 2001, the lowest in 2003. The 75% percentile ranges between 200 and 270 μg m⁻³, while the 25% percentile is between 90 and 170 μg m⁻³. It is obvious that the mean (and median) annual PM₁₀ concentration in Urumqi exceeded China’s national standards (Grade II) every year. During the entire study period, mean annual NO₂ concentrations (Fig. 5e) were in a rather narrow range of 31–50 μg m⁻³. However, mean annual NO₂ concentrations exceeded the CNAQS Grade II NO₂ standard (40 μg m⁻³) during 2000–2002, while means as well as medians fell below it during 2003–2006. The mean annual concentration of SO₂ (up to 165 μg m⁻³; Fig. 5c) exceeded the annual Grade II of CNAQS (60 μg m⁻³) every year, with the exception of 2003, when mean annual SO₂ concentration was just below the standard. There is a remarkable feature, common to all three pollutants: annual means are generally in excess of their corresponding medians, which was most striking for SO₂. This points to annual frequency distributions of the observed data, which are skewed to high concentrations, extremely skewed in case of SO₂ (where medians hardly exceed 20 μg m⁻³).

3.1.2. Seasonal variation of pollutants

Considering the time series (2000–2006) of the individual mean monthly PM₁₀, SO₂, and NO₂ concentrations (Fig. 5b, d, f), it becomes obvious that the distribution’s skewness of annual concentrations is entirely due to the (very) high concentrations, which occurred during winter (December–February). PM₁₀ concentrations during June–September were about one half (2000–2002) to one-third (2003–2006) of those during winter. In case of NO₂, summertime (May–July) concentrations were always about one-fourth of those found in winter. But SO₂ wintertime concentrations were at least 30-fold higher than summertime concentrations (consequently, a “broken scale” for SO₂ concentration was introduced in Fig. 5d).

Even though the three concentrations revealed quite different annual amplitudes, there are surprisingly a couple of features, which the seasonal behavior of PM₁₀, SO₂, and NO₂ has in common. Through the entire study period, highest monthly concentrations were always found in January or February, with the exception of 2002 and 2003, when the wintertime maximum of PM₁₀, SO₂, and NO₂ concentrations...
was already in previous December. Summertime minima of mean monthly concentrations were well-defined for each pollutant, they occurred regularly in August (PM$_{10}$), June (SO$_2$), and July (NO$_2$). More similarities were observed for the months of seasonal transition, i.e., March/April vs. October/November. Every year, higher monthly SO$_2$ and NO$_2$ concentrations were observed for October compared to April (by 10% and 5%, respectively), while SO$_2$ and NO$_2$ concentrations were consistently $\approx$ 15% lower in November than those in March. Also every year, just after the summertime minimum (July), there was a step-like increase of mean NO$_2$ concentration in August, followed by an insignificantly higher concentration in September. The same peculiarity, however less pronounced, was observed for SO$_2$, but never for PM$_{10}$. But every year, the strong decrease from high wintertime to low summertime PM$_{10}$ concentrations was regularly broken by a more or less distinct peak in May (not observed for SO$_2$ and NO$_2$). According to Li et al. (2008), who studied the characteristics of air-borne particulate material in Urumqi during 2004–2006 (Section 3.1), these enhanced PM$_{10}$ concentrations could be attributed to dust storms, which originate from the Gurban-Tonggut desert ("A" in Fig. 2) and occur regularly in springtime.

3.2. Characteristics of Urumqi’s boundary layer

Two large Central Asian surface pressure systems control the climate of Urumqi/Northern Xinjiang, (a) the intensively developed continental anticyclone over mid-Siberia and Mongolia (so-called Mongolian anticyclone) during winter and (b) a strong cyclone over northern Pakistan and India during summer (Ding and Krishnamurti, 1986; Domroes and Peng, 1988; Ding, 1991; Gong and Ho, 2002). Due to the long distance to the core of this cyclone, the surface pressure field over Xinjiang in summer exhibits only weak pressure gradients, resulting in weak to moderate surface winds from northwesterly directions. However, the cyclone quickly disappears in September, while the Mongolian anticyclone, the largest one in the northern hemisphere, establishes itself in October/November and lasts to April. Despite the high surface pressure (1020–1040 hPa) of the Mongolian anticyclone, its characteristic feature is that of a rather shallow pressure system, which does not extend above 850 hPa; at the 700 hPa level, it turns into a ridge of high pressure, which is no longer existent at the 500 hPa level. Hence, surface winds of Northern Xinjiang are from the NW–N–NE sector during winter; during summer generally westerly surface winds may occasionally be interrupted by winds from the SW–S–SE sector, and persistent westerly winds overlay above 2000 m (agr) the shallow surface winds (c.f. Domroes and Peng, 1988). As reported by Ding (1991), the dynamic structure of the wintertime Mongolian anticyclone results in air mass convergence at the 700 hPa level, causing eventually subsidence inversions. Moreover, the snow-covered surface results in strong cooling of the adjacent air, which in turn is prone for the built-up of surface inversions. Since subsidence inversions, particularly surface inversions of the boundary layer over Urumqi own a high potential to enhance Urumqi’s pollution levels, we studied the frequency of their occurrence, as well as the temporal distribution of their heights in detail.

3.2.1. Temperature inversions

For the entire study period, mean annual and mean monthly frequency distributions of occurrence of temperature inversion events, as well as monthly means of inversion heights have been

![Fig. 5. PM$_{10}$, SO$_2$, and NO$_2$ concentrations for 2000–2006 averaged over all four monitoring stations of Urumqi. Panels (a), (c), and (e) show the inter-annual variations, where full circles represent annual means; horizontal bars, annual medians; lower and upper boundaries, the 25% and 75% percentiles; and the lower and upper whiskers, the 10% and 90% percentiles. Color shaded (vertically fading) areas in panels (a), (c), and (e) represent the annual Grade II CNAAGS Air Quality Levels of the individual pollutants, namely 100, 40 and 60 $\mu$g m$^{-3}$ for PM$_{10}$, NO$_2$, and SO$_2$, respectively. Panels (b), (d), and (f) show the monthly medians of PM$_{10}$, SO$_2$, and NO$_2$ concentrations (starting with January 2000 and ending with December 2006).]
calculated from radiosonde data (Section 2.4.4). The mean annual and monthly frequency distributions of temperature inversion events for Urumqi are given in Fig. 6. Considering the inter-annual variability of inversion events (see insert of Fig. 6), there is not much variation; tentatively, a slight increase of the surface inversions’ occurrence may be suggested. However, more than 190 days of each year (probability $\approx 52\%$) experienced surface inversion events, on more than 237 days (probability $\approx 65\%$), there were inversions between the surface and the 850 hPa level ($\approx 570$ m a.gr.). Regarding the 2000–2006 seasonal variation of monthly frequencies of inversion events (Fig. 6), at least 14 days of each month (probability $\approx 55\%$) was characterized by the occurrence of temperature inversions between the surface and the 850 hPa level.

However, these high probabilities were not limited to the winter months only (i.e., November–March, where monthly mean surface temperature fell below zero; c.f. Fig. 3). Monthly probabilities between 59% and 67% were also found between July and October. To examine this aspect more closely, daytime and nighttime monthly probabilities of surface inversion events were studied. For that, we separated the 2000–2006 data of radiosonde ascents performed at 11:00 (local time) from those performed at 23:00 (local time). The result is shown in Fig. 7 together with the mean monthly height of daytime and nighttime surface inversions. Remarkably, nighttime monthly probabilities of surface inversions were between 45% and 65% throughout the year, while those during daytime were existing only for half a year, namely from October to March. On average, 12 and 14 days in January and December were characterized by daytime surface inversions, less than 4 days during February/March and October/November. During nighttime, monthly median heights of surface inversions were remarkably constant from April to October ($\approx 220$ m a.gr., Fig. 9). During daytime, however, the surface inversions disappeared entirely between April and August, eventually followed/substituted by elevated inversions, but with (very) low probabilities (Fig. 6). From October to March, monthly median heights of surface inversions were similar for nighttime and daytime, ranging 220 to 620 m (agr).

### 3.2.2. Zonal and meridional wind components

Our analysis of meridional and zonal wind vector components from the 2000–2006 meteorological data set (Section 2.4.5) demonstrates the existence of a diurnal wind system (“mountain–valley breeze”) within a $\leq 600$-m deep layer over Urumqi (Fig. 8a–c).
Considering only surface winds (Fig. 8a), there was a diurnal change of wind direction from SSW (00:00, 03:00, 06:00 local) to NE, N, and NNW (12:00, 15:00, 18:00) during all seasons. Observations of surface winds at 09:00 and 21:00 have not been considered in Fig. 8a, because corresponding wind speeds were (very) low and wind directions were highly variable. Minimum diurnal wind speeds at 10:00 and 21:00 (local) were also reported for the Tianchi region (at the slope of the Tianshan mountains; “D” in Fig. 1), indicating the times of daily reversion from the northbound winds (mountain breezes) to the southbound winds (valley breezes) (Domroes and Peng, 1988; referencing Zhang and Lin, 1985).

However, surface wind measurements, performed at 10 m (agr) at Urumqi’s city meteorological station, might necessarily not be representative for Urumqi’s entire urban area. Therefore, the more representative wind data of Urumqi’s radiosonde (23:00 and 11:00 local) have also been considered. Corresponding wind vectors are shown in Fig. 8b and c together with those of the surface station at 00:00 and 12:00, respectively. During October to March, mean noon-time winds (of 1–2 m s\(^{-1}\)) were persistently from north-easterly directions, at the surface as well as at the 850 hPa level (Fig. 8b), while during April to September, strong valley breezes (2–5 m s\(^{-1}\)) arrived Urumqi around noon-time from NNE (surface level) and from NNW (850 hPa level), respectively. Around midnight (Fig. 8c), during October to March, very low mountain breezes (<0.5 m s\(^{-1}\)) arrived Urumqi from the south, while at 850 hPa higher winds were persistently from the east. During April to September, there were considerable midnight surface winds from SW and SSW, while a remarkable 110° change of wind direction occurred towards the north at 850 hPa level (winds from NNW, Fig. 8c).

3.2.3 Atmospheric stability classes of Urumqi’s boundary layer

Pasquill/Turner stability classes, ranging from “extremely unstable” (1) to “unstable” (2), “slightly unstable” (3), “neutral” (4), “slightly stable” (5), “stable” (6), and “extremely stable” (7) have been determined for every 3 (6) h of the study period (2000–2006). On basis of this data set, mean monthly frequencies of the occurrence of each stability class have been calculated and are given in Fig. 9.

Annual frequency distributions of atmospheric stability classes are shown in Fig. 9a. For the entire study period (2000–2006), the annual frequency of the total of stable classes (“slightly stable” + “stable” + “extremely stable”) was between 41% and 50%, i.e., between 150 and 183 days each year experienced stable if not stagnant conditions. Between 73 and 91 days each year (2000–2003) were characterized by neutral dispersion conditions. Consequently, the contribution of the total of unstable classes ranged between 34% (2003) and 28% (2004). There were three remarkable features with respect to the inter-annual variation of atmospheric stability classes: (1) between 2000 to 2003, the contributions by the total of stable and the total of unstable classes were 42% and 33%, while this changed to 49% and 29% between 2004 to 2006; (2) there was a step-like change of contributions by the sum of “extremely stable” and “stable” classes between the periods 2000–2003 and 2004–2006; and (3) from 2000 to 2004, the contribution of the “extremely stable” class more than doubled (8% to 18%) on the costs of the “slightly stable” and “stable” classes.

Considering the 2000–2006 mean seasonal frequency distributions of atmospheric stability classes (Fig. 9b), the dominance of the total of stable classes during winter is obvious. Between November and February, the contributions of the total of stable classes were between 57% and 68%; during March and October, they were still about 44%. The contributions of the total of unstable classes were always less than 44%, even during June, July, and August, the three hottest months of the year (c.f. Fig. 3); during these 3 months, the total of stable classes still contributed by 27%

3.2.4 Air Stagnation Index (ASI)

Annual and monthly means of the “Air Stagnation Index (ASI)” for Urumqi have been calculated after Wang and Angell (1999). The ASI is defined as the ratio of the number of persistent “stagnation days” (i.e., at least 4 consecutive days) and the total number of days per year and month, respectively (Section 2.4.5). The results for 2000–2006 are shown in Fig. 10. Like for atmospheric stability classes, we have not considered separate daytime/nighttime behavior of the ASI. The mean annual ASI (insert of Fig. 10) ranged between 8.8% (2000 & 2002) and 24% (2004); this would translate to 8 and 22 air stagnation periods per year (considering only 4 consecutive days of stagnation). The inter-annual variation of the ASI was characterized by consistently higher values of ASI during from 2004 to 2006 (23 ±1%) exceeding those of 2000–2003 by a factor of 2.6 (2000 and 2002) and 1.5 (2001 and 2003), respectively.

The 2004–2006 mean seasonal variation of ASI (Fig. 10) reveals high (November–March) and low (May–July) occurrences of stagnant conditions of Urumqi’s boundary layer. On average, Urumqi experienced between one and two stagnation events (lasting for 4 consecutive days) between September and April, and less than one during May–August. The maximum of mean ASI in October is due to high ASI values identified for 2003–2006 and will be discussed below (Section 4.3.2).

4. Discussion

4.1 Comparison to other concentration measurements in Urumqi

For Urumqi, only one pollutant monitoring data set has been found for comparison with the data used in this study. From January 2004 to December 2006, Li et al. (2008) operated a TEOM series 1400a PM\(_{10}\) monitor (Rupprecht & Patashnick Co. Inc., Albany, NY, USA) for...
sampling PM$_{10}$ concentrations on-line. Samples have been obtained from 30 m above street level on the roof of the Institute of Desert and Meteorology building (downtown Urumqi), which is situated very close to one of Urumqi’s municipal highway about 1.3 km ESE of the station “Beimen” (Fig. 4). Since Li et al. (2008) reported their data as means of 3 months (winter, spring, summer, and fall), we have averaged PM$_{10}$ concentrations obtained at the station “Beimen” correspondingly for the period 2004–2006. Results are shown in Fig. 11. Considering the indicated temporal variability of both data sets, the winter and spring data are not different ($P = 0.5$) from each other, those from summer are likely different ($P = 0.1$), and those from fall are different ($P = 0.01$). However, with regard to the different locations of sampling sites, the different nature of sampling and analysis of PM$_{10}$ concentrations, satisfying agreement between is sustainable between both data sets.


As already shown above (Fig. 5a, c, e), the status of the 2000–2006 air pollution in Urumqi was characterized by the fact that mean annual PM$_{10}$, SO$_2$, and NO$_2$ concentrations mostly have exceeded China’s CNAAGS Grade II national standards. Mean annual PM$_{10}$ concentration never met its standard (100 μg m$^{-3}$; Table 2) and the exceedance factor for Grade II was between 1.5 (2003) and 2.4 (2001). Mean annual SO$_2$ concentration exceeded its Grade II standard (60 μg m$^{-3}$) by 1.4–2.7, only in 2003 it went just below (49 μg m$^{-3}$). During 2000–2002, mean annual NO$_2$ concentration exceeded its annual standard (40 μg m$^{-3}$) by a factor of up to 1.3; during 2003–2006, it was even more than 90% of the annual Grade II standard. With respect to the US Environmental Protection Agency’s National Ambient Air Quality Standards (Table 2), mean annual PM$_{10}$ and SO$_2$ concentrations exceeded primary and secondary limits on average by 3.8 and 1.4, respectively (omitting the SO$_2$ value for 2003). Since EPA’s primary and secondary annual NO$_2$ standard (100 μg m$^{-3}$) is 2.5-fold of the CNAAGS Grade II standard (Table 2), mean annual NO$_2$ concentrations fell always below the EPA limits.

In order to value Urumqi’s air pollution status, PM$_{10}$, SO$_2$, and NO$_2$ concentrations of Urumqi were put into context of those published for three other growing dryland cities of Central Asia, namely Hohhot (capital of Inner Mongolian Autonomous Region, PR China), Lanzhou (capital of Gansu province, PR China), and Ulan Bator (capital of PR Mongolia). Sun et al. (2005) reported PM$_{10}$, SO$_2$, and NO$_2$ data for Hohhot, which were given as 1995–2001 means of winter, spring, and summer + fall. For Lanzhou, Ta et al. (2004) published SO$_2$ and NO$_2$ concentrations, which have been obtained at four different city stations and which were presented as 1999–2001 means for winter, spring, summer, and fall. Mean monthly SO$_2$ and NO$_2$ concentration data for 2002–2006, measured at three stations downtown Ulan Bator, were found in the report of Guttikunda (2007). Mean seasonal PM$_{10}$, SO$_2$, and NO$_2$ concentrations (and ranges) of Hohhot, Lanzhou, and Ulan Bator are listed in Table 3, together with those from Urumqi, which have been adequately averaged for the given time periods and seasons. All four cities are located in the 35°–50°N belt and above 1000 m (a.s.l.) altitude, they experience arid (semi-arid) cold climates, and they are more or less surrounded by mountains. During 1999–2001, Lanzhou’s boundary layer was characterized by 510, that of Urumqi by 302 inversion days per year; even though no corresponding data were available for Hohhot and Ulan Bator, their geographical location and setting suggests similar numbers of inversion days per year. Urumqi’s wintertime PM$_{10}$ concentrations doubled those of Hohhot, while in springtime, concentrations were very similar. Wintertime SO$_2$ concentrations in Urumqi were up to 5-fold higher than those in Hohhot, Lanzhou, and Ulan Bator; also during the other seasons, Urumqi’s mean SO$_2$ concentration was generally higher. This was most likely due to the enormous coal consumption of Urumqi: the per capita coal consumption exceeds 4 tons/year (Xia, 2008; EPBU, 2008) and is the highest in China, where the nationwide average is about 1 ton per person/year (recent coal consumption (used for >70% of the total energy production) is more than 12 million tons/year). Only in winter and spring and only regarding Ulan Bator, about 30% more NO$_2$ was observed in Urumqi; otherwise NO$_2$ concentrations in Hohhot, Lanzhou, and Ulan Bator were generally either higher or (more or less) equal. Since Urumqi’s fleet of motor vehicles was at least 3-fold during all periods (Table 3), higher mean NO$_2$ concentrations in the three other cities must be explained by other NO$_2$ sources or insufficient/lacking NO$_2$ emission reducing technologies (see below).

Returning to Urumqi’s air pollution status during 2000–2006, there were a couple of features, which were remarkably common to all three pollutants. Mean annual concentrations increased from 2000 to 2001, decreased from 2001 to 2003, increased again (only slightly) during 2003–2006, and there was a distinct concentration minimum in 2003 (Fig. 5a, c, e). If one compares the 2004–2006 mean concentration level of pollutants to that observed between 2000 and 2001, it becomes obvious that PM$_{10}$, SO$_2$, and NO$_2$ concentrations dropped by 27%, 39%, and 23%, respectively. In contrast, considering the same reference years, Urumqi’s population and its fleet of motor vehicles has grown by 21% and 29% (Fig. 1). Still considering the same reference years, this contrast becomes even more striking, if one compares the use of fossil fuels: Urumqi’s annual consumption of diesel oil, crude oil, raw coal, and coke has increased by 12%, 27%, 68%, and 92%, respectively (Fig. 1; c.f. Urumqi Statistical Yearbook, 2001–2007).
Unfortunately, there is lack of published and detailed information about the temporal development of Urumqi’s PM$_{10}$, SO$_2$, and NO$_X$ emission rates. Nevertheless, in order to elucidate the apparent discrepancy between decreasing annual concentrations and increasing growth rates, the following facts and findings should be considered (Table 4).

In 2001, China’s State Environment Protection Agency (SEPA) established an emission standard for coal-burning, oil-burning, and gas-fired boilers (GB 13271): maximum permissible effluent concentrations of flue dust, SO$_2$, and nitrogen oxides (NO$_X$), as well as limits of dust blackness of coal-fired boilers has been clearly defined. The authorities of Urumqi City responded to GB 13271 by developing a central heating system (Table 4). As observed for the majority of Chinese cities, the shift of emissions from ground level sources to the high stacks of power plants has most likely caused much of substantial improvement of air quality in urban areas (Cao et al., 2009). However, the point is that coal is still the major fuel used for Urumqi’s energy production and the overwhelming part of Urumqi’s SO$_2$ burden is originating from it. With reference to 2005, Zhao et al. (2008) reported that only 5% of Xinjiang’s coal fired power plants were equipped with flue gas desulfurization (FGD) systems, but fortunately ≈95% of the raw coal used in Xinjiang’s power plants had a sulphur content of only <0.5 up to 1%. But since 2003, Urumqi city has realized “clean coal” and “conversion from oil to gas” projects (Table 4). Raw coal using power plants were obligated to use cleaned coal, otherwise awaiting penalty (Wang and Wang, 2006). Coal washing before combustion might reduce 40% of inorganic sulphur, and reduction of SO$_2$ emission may reach 20% (Xu et al., 2000). Wang (2005) reported that the use of cleaned coal in Urumqi could reduce smoke concentration from boilers by up to 70% and SO$_2$ emission by 30%. Further consequences of air pollution management regulations on regional and local levels are listed in Table 4. Even though Urumqi’s fleet of civil motor vehicles increased by 36%, the average annual consumption of diesel oil increased only by 12%, while that of gasoline even decreased by 36% (from 2000/2001 to 2004/2006; c.f. Urumqi Statistical Yearbook, 2001–2007). The latter was certainly due the growing fraction of modern civil motor vehicles that own lower fuel consumption. Assuming that most of these cars are equipped with catalytic (three-way) converters, a substantial reduction of transport related NO$_X$ emissions was most likely.

### Table 3

<table>
<thead>
<tr>
<th>City</th>
<th>Geographic position</th>
<th>Population [10$^3$]</th>
<th>Motor vehicles [10$^3$]</th>
<th>Inversions [days a$^{-1}$]</th>
<th>Period</th>
<th>Season</th>
<th>PM$_{10}$ Avg [μg m$^{-3}$]</th>
<th>PM$_{10}$ Range [μg m$^{-3}$]</th>
<th>SO$_2$ Avg [μg m$^{-3}$]</th>
<th>SO$_2$ Range [μg m$^{-3}$]</th>
<th>NO$_X$ Avg [μg m$^{-3}$]</th>
<th>NO$_X$ Range [μg m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urumqi</td>
<td>43°50’N, 87°35’E</td>
<td>1.54</td>
<td>3.17</td>
<td>300</td>
<td>2000–2001</td>
<td>Dec–Feb</td>
<td>365 266, 454 266</td>
<td>420 260, 887 207</td>
<td>83 69, 110</td>
<td>207 59</td>
<td>45 18, 79</td>
<td></td>
</tr>
<tr>
<td>Xinjiang PR</td>
<td>1000 m a.s.l.</td>
<td>1.02</td>
<td>1.02</td>
<td>n.a.</td>
<td>1995–2001</td>
<td>Dec–Feb</td>
<td>184 159, 215 15</td>
<td>35 35, 65</td>
<td>115 91, 136</td>
<td>65 56, 63</td>
<td>35 35, 65</td>
<td></td>
</tr>
<tr>
<td>PR China</td>
<td>1000 m a.s.l.</td>
<td>1.02</td>
<td>1.02</td>
<td>n.a.</td>
<td>1995–2001</td>
<td>Dec–Feb</td>
<td>186 206, 289 19</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td></td>
</tr>
<tr>
<td>Gansu PR</td>
<td>1000 m a.s.l.</td>
<td>1.02</td>
<td>1.02</td>
<td>n.a.</td>
<td>1995–2001</td>
<td>Dec–Feb</td>
<td>186 206, 289 19</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
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<tr>
<td>PR China</td>
<td>1000 m a.s.l.</td>
<td>1.02</td>
<td>1.02</td>
<td>n.a.</td>
<td>1995–2001</td>
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<td>PR China</td>
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<td>PR China</td>
<td>1000 m a.s.l.</td>
<td>1.02</td>
<td>1.02</td>
<td>n.a.</td>
<td>1995–2001</td>
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<td>184 206, 289 19</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td></td>
</tr>
<tr>
<td>Urumqi</td>
<td>47°55’N, 9°32’E</td>
<td>0.91</td>
<td>0.91</td>
<td>n.a.</td>
<td>2002–2006</td>
<td>Dec–Feb</td>
<td>186 206, 289 19</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td></td>
</tr>
<tr>
<td>PR Mongolia</td>
<td>106°55’E, 9°32’E</td>
<td>0.91</td>
<td>0.91</td>
<td>n.a.</td>
<td>2002–2006</td>
<td>Dec–Feb</td>
<td>186 206, 289 19</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
<td>25 25, 46</td>
<td>66 48, 63</td>
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### Table 4

<table>
<thead>
<tr>
<th>Regional level (Xinjiang Uighur Autonomous Region)</th>
<th>Consequences</th>
<th></th>
<th>Local level (Urumqi City)</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulations</td>
<td></td>
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<td>Regulation</td>
<td></td>
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<tr>
<td>2003: “clean coal” and “conversion from oil to gas” projects (Li, 2005; Wang and Wang, 2006)</td>
<td>(a) Average consumption of cleaned coal increased by 186% (from 2000/2001 to 2004/2006); (b) average consumption of natural gas increased by more than 60% (from 2000/2001 to 2004/2006); (c) 515,000 households used natural gas for domestic heating (Zhan and Zhang, 2007); 11,555 motor vehicles were powered by liquified gas (Gas.NE-EN, 2007)</td>
<td></td>
<td>2002: Central heating system of the urban area (Li et al., 2005)</td>
<td>(a) Central heating system increased by 45.5% (from 2000 to 2004); (b) in total 3733 coal burning boilers decreased from 2002 to 2004 (Li et al., 2005)</td>
</tr>
</tbody>
</table>
The change of (a) fuel combustion technologies, (b) mix of fuels for Urumqi’s energy production, and (c) composition of Urumqi’s car fleet was obviously mirrored in the decrease of all three pollutants, starting in 2002 (Fig. 5a, c, e). However, there were distinct minima of annual PM10, SO2, as well as NO2 concentrations in 2003, which turned out to be 66%, 33%, and 64% of the average of annual concentrations found in 2001–2002 (90%, 53%, and 84% of those found in 2004–2006). However, 2003 was an exceptional year concerning Urumqi’s annual precipitation. There was 32% more precipitation in 2003 compared to 2001–2002 (49% more than for 2004–2006). Particularly the winter rains (November and December 2003) were enhanced by 92% (90%), and 298% (140%) compared to 2000–2001 (2004–2006). It is most likely, that atmospheric scavenging (in-cloud, below-cloud) have caused the 2003 minima of PM10, SO2, and NO2 concentrations. The mentioned reduction of 2003 mean annual concentrations of PM10, SO2, and NO2 resembles the ranking of scavenging coefficients, which is highest for SO2 (e.g., Pruppacher and Klett, 1997).

4.3. The boundary layer climate of Urumqi (2000–2006)

4.3.1. The mountain–valley breeze of Urumqi

A striking feature of Urumqi is its geographical setting (Fig. 2). The urban area (11739 km²) of this the growing (Mega) city is spreading between 900 and 1100 m (a.s.l.). Only within a 90°-wide sector (NW–N–NE), the landscape is widening downward (within 40–50 km) to the Gurban-Tongtug desert of the Jungar basin (∼500 m a.s.l.; “A” in Fig. 2). Within the remaining 270°-wide sector (NE–S–NW), particularly to E, S, and W, the elevation of the landscape rises to more than 1500 m (a.s.l.) within 30 km and to more than 2500 m (a.s.l.) within 50 km from Urumqi’s city center. Summits of the Tian Shan mountains, ∼80 km east and southwest of Urumqi, exceed 4000 m (a.s.l.). There are two other marking landscape features, namely (1) the Nanshan valley, southwest of Urumqi (ending after 100 km at the Baiyanggou pass, 4000 m a.s.l.; “B” in Fig. 1), and (2) the Bogda plateau stretching ESE for 80–100 km from Urumqi to the Dabancheng pass (1100 m a.s.l.; “C” in Fig. 1). Due to this particular geographical setting, the existence of thermobarographic winds and/or a diurnal wind system (mountain–valley breeze) must be expected. For their 1951–1980 data set, Domroes and Peng (1988) presented a sectional analysis of mean wind directions of Urumqi’s surface winds (for January and July only). Without separating daytime and nighttime conditions, they identified a strong bimodal frequency distribution of wind directions. Surface winds were only from the NW–N–NE sector or from the SE–S–SW sector; corresponding frequencies in January were 28% vs. 58%, and for July, 45% vs. 37%. For the period 2004–2006, Li et al. (2008) reported seasonally averaged wind direction frequencies for Urumqi. They confirmed the existence of the strong bimodal distribution of wind directions already reported by Domroes and Peng (1988). Winds from SSW (i.e., down from the Baiyanggou pass) occurred within or just above the surface inversion layer of the cold seasons (which extended up to 600 m a.s.l., Fig. 7). During April to September, however, there was a striking difference (more than 110°) between nighttime wind directions at surface and 850 hPa levels (Fig. 8b). This was certainly due to the fact that the 850 hPa level (∼600 m a.g.l.) was always situated well above the nighttime surface inversion layer (extending only to ∼220 m a.g.l., Fig. 7). Hence, 850 hPa airflows could develop entirely decoupled from surface flows occurring in the shallow surface inversion layer of April–September. In any case, colder and more humid air masses, originating from the surrounding mountains, were transported during nighttime into Urumqi’s urban area throughout the year (not shown here).

4.3.2. Temperature inversions, atmospheric stabilities, and air stagnation events

During the entire study period (2000–2006), the boundary layer climate of Urumqi was predominantly characterized by frequent occurrence of temperature inversions. This is primarily due to large-scale synoptic situations. Urumqi’s geographical (arid) position anticipates frequently cloudless skies and only weak pressure gradient winds in summer, while close neighborhood to the core of the rather shallow, but very persistent wintertime anticyclone over mid-Siberia and Mongolia strongly favors the occurrence of subadiabatic and surface inversions. It was therefore not surprising that Urumqi experienced quite high monthly probabilities of surface inversions, ranging between 45% (April) and 72% (January), i.e., throughout the year, 14 to 22 days each month were characterized by the occurrence of surface inversions. But surface inversions prevailed not only during winter (November–March), when snow covered grounds provided essential prerequisites for their built-up; also between July (the hottest month of the year, Fig. 2) and October, monthly surface inversion probabilities ranged between 59 and 65%. However, our detailed analysis (Fig. 7) has demonstrated that during these months, surface inversions were occurring only during nighttime. Nighttime built-up of surface inversions by surface cooling (under summertime cloudless skies) is likely, but the continuous and strong nighttime supply of cold air by Urumqi’s mountain breeze (Section 4.3.1), resulting in strong stabilization of Urumqi’s nocturnal boundary layer, is consequently considered as the more dominant (dynamic) process.

The remarkably high occurrence of (surface) inversions during the entire study period anticipates that atmospheric stabilities of Urumqi’s boundary layer should be dominated by stable classes. Indeed, our analysis of annual and seasonal occurrences of Pasquill/Turner stability classes showed that Urumqi experienced stable, if not stagnant conditions on 150 to 183 days each year during the entire study period (2000–2006). Moreover, the particular daytime–nighttime partitioning of surface inversion occurrences can be generalized to the partitioning of occurrences of stable vs. unstable classes in Urumqi’s boundary layer. It is not shown here, but 2000–2006 monthly frequencies of occurrence of stability classes, which have been computed for nighttime and daytime hours separately, exhibited two important features: (1) during night, frequencies were entirely lacking any contributions of the unstable classes, and (2) during day, there were no contributions from stable classes (on average, only 6% of “slightly stable” in January). Hence, for all seasons during 2000–2006, monthly contributions of all unstable classes have to be assigned to daytime conditions, while those of stable classes exclusively to nighttime conditions.

The shape of the mean seasonal variation of Urumqi’s “Air Stagnation Index” (ASI; Fig. 10) resembles broadly the shapes of (a) mean monthly frequency of inversions between surface and 700 hPa (Fig. 6) and (b) the contribution of the sum of all stable classes (5–7) to the mean monthly frequency of atmospheric stability classes (Fig. 9b). However, a closer look reveals two noticeable discrepancies: both the apparent ASI maximum in October and the wintertime ASI minimum in December are not reflected in the annual course of occurrences neither of the inversions between surface and 700 hPa, nor of the sum of all stable classes (5–7). There is currently no explanation for this discrepancy. However, there are significant correlations (P = 0.05) between mean monthly ASI and mean monthly occurrences of surface–700 hPa inversions ($R^2 = 0.393$) and mean monthly occurrences of stable classes ($R^2 = 0.557$), respectively. If we exclude October and December from
our considerations, these correlations become highly significant \((P = 0.01; R^2 = 0.864)\) and \(R^2 = 0.931\), respectively). This suggests that basically the concept of ASI may be suitable for characterizing Urumqi’s (Xinjiang’s) atmospheric pollution potential.

4.4. Urumqi’s air pollution and local meteorology

Highest frequencies of occurrence of inversion layers were observed during winter (December–February), when mean air temperatures fell below \(-10^\circ\text{C}\), and consequently there is the highest need for fossil fuel combustion, mainly for domestic heating. Then nighttime and daytime frequencies of surface inversion occurrence were found to be comparable (Fig. 7) and average heights of daytime and nighttime inversions were surprisingly similar (about 600–620 m a.g.r.). These are perfect conditions for spatially and temporally persistent surface inversions, which might prevail over extended periods, resulting in equally long periods of strong accumulation of pollutants in the boundary layer over Urumqi. Consequently, highest mean seasonal ASIs have been attributed to January and February.

But also for the remaining part of the year, when Urumqi’s demand for energy still keeps emissions of PM\(_{10}\), SO\(_2\), and NO\(_2\) continuously on high levels, any restriction of optimal boundary layer dispersion of (near surface released) pollutants immediately runs the risk to experience high air pollution levels. This is confirmed by the following similarities between the mean annual course of monthly of PM\(_{10}\), SO\(_2\), and NO\(_2\) concentrations (not shown here) and that of Pasqual/Turner stability classes (Fig. 9b): (a) the annual minimum of all pollutant’s concentrations occurred in June and July, where the occurrence of the sum of all unstable classes (1–3) was highest; (b) the annual maximum of all pollutant’s concentrations occurred in December–February, where the occurrence of the sum of all stable classes (5–7) was highest; and (c) the ratios between maximum and minimum monthly mean PM\(_{10}\), SO\(_2\), and NO\(_2\) concentrations (PM\(_{10}\): 3.2; ln(SO\(_2\)): 2.5; NO\(_2\): 5.0) correspond to ratios of 2.6, 2.8, and 4.4 for the sum of all stable classes (5–7), the sum of “slightly stable + stable” classes (6–7), and the “extremely stable” class (7), respectively.

However, the minimum of the occurrence of stable classes (5–7) in May was not reflected in any of the pollutants’ concentrations, also the strong decrease of PM\(_{10}\) and SO\(_2\) concentrations from February to March were not reflected, neither by a corresponding decrease of the sum of all stable classes (5–7) nor by an increase of the sum of all unstable classes (1–3). Nevertheless, the mean 2000–2006 seasonal occurrences of the sum of all stable classes (5–7) are correlated at the highly significant level \((P = 0.01)\) with the mean 2000–2006 seasonal PM\(_{10}\), ln(SO\(_2\)), and NO\(_2\) concentrations \((R^2 = 0.769, 0.846, 0.816, \text{respectively})\). Corresponding correlations with the mean 2000–2006 seasonal occurrences of inversions below 700 hPa are somewhat weaker \((R^2 = 0.597 \text{ (PM}\(_{10}\)), 0.785 \text{ (ln(SO}\(_2\)), and 0.816 \text{ (NO}\(_2\)), respectively)\). However still highly significant \((P = 0.01)\). Correlations of the mean 2000–2006 seasonal ASI with the three mean 2000–2006 seasonal concentrations are statistically not significant for PM\(_{10}\) and SO\(_2\), for NO\(_2\) only on the \(P = 0.05\) level (mainly due to the fact that the exceptional mean ASI values for October and December can currently not be explained). However, excluding ASI values of October and December, highest correlations were obtained for ln(SO\(_2\)) and NO\(_2\) \((R^2 = 0.938 \text{ and 0.915, respectively})\) at the \(P = 0.01\) significance level \((R^2 = 0.688 \text{ for PM}\(_{10}\)). Moreover, the minimum of mean monthly SO\(_2\), and NO\(_2\) concentrations in June and July are remarkably well mirrored by the corresponding minimum values of ASI, as well as the following relative increase of SO\(_2\), and NO\(_2\) concentrations in August and September.

Concerning both the inter-annual variations of Pasqual/Turner stability classes and ASI, there is a remarkable similarity. A step-like change of contributions by the sum of “extremely stable” and “stable” classes occurred between the periods 2000–2003 and 2004–2006 (Fig. 9a); analogously, the inter-annual variation of ASI was characterized by consistently higher values during 2004–2006 compared to those of 2000–2003, particularly 2000 and 2002 (insert of Fig. 10). In this context, it should also be mentioned that the contribution of the “extremely stable” class more than doubled from 2000 to 2004 (8% to 18%), namely on the costs of “slightly stable” and “stable” classes. Both findings eventually indicate that Urumqi’s boundary layer climate has obviously shifted to a more stable/stagnant regime during the last 3 years of our study period, i.e., there was, on average, some restriction for boundary layer dispersion of pollutants during 2004–2006. However, even under conditions of temporally constant emissions, restricted dispersion conditions usually lead to higher concentrations of pollutants in the boundary layer. But quite the opposite was the case for Urumqi’s mean annual PM\(_{10}\), SO\(_2\), and NO\(_2\) concentrations, which were observed to have decreased from 2000–2001 to 2004–2006. This is all the more remarkable, as Urumqi’s population, its fleet of motor vehicles, and the consumption of fossil fuels have continuously grown over the entire study period. At last, there seems to be only one explanation to resolve the apparent discrepancy: all the above mentioned legal, administrative, and technical countermeasures carried out to lower the air pollutants’ burden for Urumqi must have been efficient.

5. Conclusions

For the first time, the status of particulate, as well as gaseous pollutants, is reported for Urumqi, capital of the Uighur Autonomous Province Xinjiang (NW China) and one of the most rapidly growing big cities in the world. The 7 years (2000–2006) long record of monthly PM\(_{10}\), SO\(_2\), and NO\(_2\) concentrations, obtained from four monitoring stations downtown Urumqi, exhibited remarkable interannual, as well as seasonal variations. Even though primarily dominated by emissions from coal combustion needed to heat the city during the 5-month long winter, the latter are controlled by Urumqi’s boundary layer dispersion conditions, which – generally dominated by stable conditions – also revealed strong seasonal variations. Summarizing, we would like to emphasize the following:

(1) Considering the entire observation period (2000–2006), Urumqi has to be considered as highly polluted, at least with respect to annual PM\(_{10}\) and SO\(_2\) national standards. Annual China National Ambient Air Quality Standards (CNAAsQS) Grade II, 100\(\mu\)g m\(^{-3}\) (PM\(_{10}\)) and 60\(\mu\)g m\(^{-3}\) (SO\(_2\)) were exceeded by factors of 1.5–2.4 and 1.4–2.7, respectively. Mean annual NO\(_2\) concentrations were within +30 and \(-10\%\) of the corresponding Grade II standard (40\(\mu\)g m\(^{-3}\)).

(2) Compared to other fast growing Central Asian dryland cities of similar geographical settings (Lanzhou, Hohhot, Ulban Bator), mean seasonal NO\(_2\) concentrations were generally lower, while mean seasonal SO\(_2\) (and PM\(_{10}\)) concentrations were considerably higher in Urumqi. The latter is certainly due to Urumqi’s tremendous consumption of coal, which is the highest for entire China (4 tons per person/year).

(3) Comparing mean 2000–2001 and mean 2004–2006 concentrations of all three pollutants, a distinct decrease was observed, namely \(-27\%\), \(-39\%\), and \(-23\%\) for PM\(_{10}\), SO\(_2\), and NO\(_2\). However, this is in strong contrast to Urumqi’s population, motor vehicles, and consumption rates of diesel oil, crude oil, raw coal, and coke, which have increased by 21\%, 29\%, 12\%, 27\%, 68\%, and 92\%, respectively. It is suggested that this apparent discrepancy of trends might be resolved (at least qualitatively) by Urumqi’s legal, administrative, and technical countermeasures against PM\(_{10}\), SO\(_2\), and NO\(_x\) emissions, which have been started in 2002.

(4) Due to large-scale synoptic conditions of Xinjiang and to Urumqi’s geographical and local setting, Urumqi’s urban boundary layer turned out to be generally dominated by stable conditions and hence, to be highly inversion-prone. During
2000–2006, more than 237 days of each year experienced those inversion events, where the inversion height was below the 850 hPa level (≈570 m a.g.l.); more than 190 days of each year was characterized by surface inversion events. Consequently, the analysis of atmospheric stabilities (Pasquill/ Turner) of Urumqi’s boundary layer revealed that between 150 and 183 days each year experienced stable if not stagnant conditions. Considering the inter-annual variation of the distribution of individual stability classes, there was a remarkable change between the periods 2000–2003 and 2004–2006, annual contributions by “extremely stable” and “stable” classes increased by 13%, and the contribution of the “extremely stable” class has more than doubled (8% to 18%) on the costs of the “slightly stable” and “stable” classes. This effect is even more pronounced considering Urumqi’s Air Stagnation Indices (ASI; after Wang and Angell, 1999).

(5) However, daytime surface inversions entirely vanished during April–August, while there was a 45–65% probability for nighttime surface inversions throughout each year. The corresponding analysis of Pasquill/Turner stabilities confirmed this finding in so far, as nighttime dispersion conditions were exclusively characterized by stable classes only, while daytime conditions predominately by unstable classes.

(6) Within a 270°-wide sector (NE–S–NW), Urumqi is surrounded by the Tianshan mountains (summits exceeding 4000 m a.s.l.), and two marked landscape features, the Nanshan valley and the Bogda plateau are stretching into SSW and SSE directions. The year round existence of the diurnal mountain–valley breeze (nighttime: northbound; daytime: southbound), already suggested by earlier investigations, has clearly be identified through our analysis of Urumqi’s meteorological data (surface and radiosonde). Colder and more humid air masses, originating from the surrounding mountains, were transported during nighttime into Urumqi’s urban area throughout the year, enhancing the stability of the nocturnal boundary layer, especially during spring, summer, and fall.

(7) Particularly during winter, when both the probabilities of occurrence and the heights of daytime and nighttime surface inversions became comparable, there was substantial enhancement of persistent stagnant air conditions. From November to February, 17–21 days of each month was characterized by slightly stable, stable, or extremely stable dispersion conditions. ASI values for Urumqi indicated between one and two stagnation events (lasting for 4 consecutive days) between September and April, less than one during May–August. This had substantial impact on the observed high winter/summer ratios of mean monthly concentrations, which were 2–3 for PM10, generally about 4 for NOx, and up to 30 for SO2.

(8) Hence, there were highly significant correlations of the mean monthly concentrations of all three pollutants with the mean occurrence of the sum of all stable classes, as well as with the occurrence of inversions below the 700 hPa level. Most significant correlations of mean monthly concentrations were obtained with mean monthly ASIs; however, only if ASI values for October and December were neglected. If ASI would be considered as a tool for future assessments for the pollution potential of Urumqi, there is certainly the need for more detailed research on the transferability of ASI’s parameterizations (originally developed for continental US).

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