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Particulate pollution in Ulaanbaatar, Mongolia

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Abstract The World Health Organization (WHO) listed the air pollution in Ulaanbaatar (Mongolia) among the top 5 cities with the worst air quality in the world. Air quality in the winter season reaches highs of 750 μg/m^3 for daily average fine particulates (PM) due to increased coal combustion and lower mixing heights (<200 m), coupled with the city's geography surrounded by mountains, which further restricts the vertical and horizontal dispersion of the pollutants. The annual average concentrations in 2010–2011 ranged 136±114 μg/m^3 (the WHO guideline for fine PM is 10 μg/m^3). The single largest source of particulate pollution in Ulaanbaatar is coal and biomass combustion in households and heat-only boilers, followed by power plants. In this paper, we present sector-specific emissions for 2010 accounting for 62,000 tons of fine PM, 55,000 tons of sulfur dioxide, and 89,000 tons of nitrogen oxide emissions. The inventory is spatially disaggregated at 0.01° resolution on a GIS platform for use in a chemical transport model (ATMoS). The modeled concentrations for the urban area ranged 153±70 μg/m^3, when overlaid on gridded population, resulted in estimated 1,000–1,500 premature deaths per year due to outdoor air pollution. This study also highlights the linkages between indoor and outdoor air pollution. In these harsh temperate conditions, with 50 % of the emissions originating from Ger households, they are as big a health risk for indoor air quality as they are for outdoor air quality. Any intervention improving combustion efficiency or providing clean fuel for these stoves will have a combined benefit for indoor air quality, outdoor air quality, and climate policy. The analysis shows that aggressive pollution control measures are imperative to protect the population in Ulaanbaatar from excess exposure levels, and implementation of control measures like the introduction of heat efficient stoves, clean coal for heating boilers, and urban transport planning will result in significant health benefits, which surpass any costs of institutional, technical, and economic interventions.

Keywords SIM-air · ATMoS · Emissions inventory · Dispersion modeling · Air quality management · Health impacts

Highlights Fuel consumption and sector contributions to atmospheric emissions
Seasonal variation in particulate pollution via dispersion modeling
Winter pollution highs due to low inversion and high cookstove emissions
Review of air pollution control initiatives in Ulaanbaatar

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Introduction

Ulaanbaatar, the capital city of Mongolia, is the coldest national capital in the world. In the 2000s, rapid urbanization has led to deteriorating air quality in the city, with emissions originating from domestic heating and cooking needs, increasing number of vehicles, growing number of industries, construction activities, and higher electricity demand (World Bank 2004, 2011; Guttikunda 2007; Davy et al. 2011). The World Health Organization (WHO) studied publicly available air quality data from 1,100 cities and listed Ulaanbaatar among the top 5 cities with the worst air quality in the world (WHO 2011).

A summary of 24-h average $PM_{2.5}$ concentrations by month for the period 2008–2011 is presented in Fig. 1. $PM_{2.5}$ refers to particulate matter (PM) with an aerodynamic diameter <2.5 μm. The data were measured at the Institute of Meteorology, Hydrology and Environment in the center of the city using a nephlometer. The air quality data from four other monitoring stations operated by the City Air

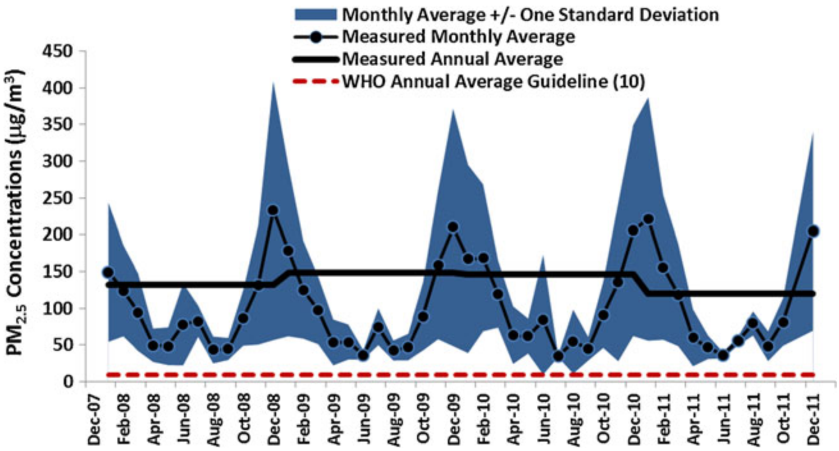


Fig. 1 Twenty-four-hour average $PM_{2.5}$ concentrations by month from a monitoring station located at the National Institute of Meteorology and Hydrology, Ulaanbaatar, Mongolia

Quality Department are available online (http://www.ub-air.info/ub-air/en/laq.html). In 2011, the annual average of 120 µg/m^3 is 12 times the WHO guideline of 10 µg/m^3, with highs in the winter months reaching 750 µg/m^3. A source apportionment study conducted between 2004 and 2008 estimated doubling of contribution from coal combustion to ambient $PM_{2.5}$ in the winter months (Davy et al. 2011). Measurements at 37 urban and residential locations between June (2009) and May (2010) reported daily average $PM_{2.5}$ of 22.8±9.0 µg/m^3 for the summer months and 147.8±61.2 µg/m^3 for the winter months (Allen et al. 2013).

Air pollution can affect our health in many ways, with both short-term and long-term effects (HEI 2004, 2010). The short-term effects can include irritation to the eyes, nose, and throat and upper respiratory infections such as bronchitis and pneumonia. The long-term effects can include chronic respiratory disease, lung cancer, heart disease, and even damage to the brain, nerves, liver, or kidneys. According to the Global Burden of Asthma report, there are 27.8 million people with asthma in China, Taiwan, and Mongolia region (Masoli et al. 2004). Mortality and hospitalization data presented in World Bank (2011) also reflect the burden of respiratory and cardiovascular diseases in the city. Allen et al. (2013) made a conservative estimate of 29 % of cardiopulmonary deaths and 40 % of lung cancer deaths in Ulaanbaatar attributable to outdoor air pollution, which accounts for 10 % of the city's all-cause mortality rate. A correlation between lead in the blood of children and neurological diseases was also reported (Burmaa et al. 2002; Dorogova et al. 2008). The overall lead levels are now under control after the introduction of unleaded petrol for all vehicles.

In Ulaanbaatar, the winter months are the worst. Besides the growing emissions, the city's geography and topography play a significant role in aggravating the pollution levels, peaking in December and January (Fig. 1). This is primarily due to two reasons: (1) in the winter months, continuous heating is required in residential and commercial sectors, which increases the total emissions from in situ heating boilers and at the power plants, and (2) the problem is further enhanced by lower mixing layer heights in the winter months. Mathematically, the concentration is defined as mass over volume. In the winter months, the total emission mass is higher and the volume of the air dispersed over the city is lower, resulting in peaking pollution levels. Mixing heights of lower than 200 m (Fig. 2), coupled with geography surrounded by mountains, restrict the vertical and horizontal dispersion of the pollutants in the winter months. At two urban and industrial sites, sulfur dioxide (SO_2) concentrations were three to five times higher during the winter months for the period 1996–2009 (Luvsan et al. 2012). Similar dispersion characteristics are reported for cities in similar temperate conditions: Delhi, India (Guttikunda and Gurjar 2012), and Urumqi, China (Mamtimin and Meixner 2011).

In this paper, we present an analytical basis to underpin discussions on particulate pollution and its sources in Ulaanbaatar and possible short- and long-term strategies for reducing air pollution from various sectors, with special emphasis on the winter months. The emissions and dispersion modeling analysis is based on data collected from the statistical year book (NSO 2012) and discussions with multiple government agencies.

Emissions inventory

Every city has unique air quality challenges that require customized approaches to estimate emissions and model pollution. Critical pollutants, sources, meteorology, geography, population distribution, history, institutions, and information base vary for every city. The SIM-air (Simple Interactive Models for Better AIR quality) family of tools is developed in a customizable format using available information to provide a framework to organize and update critical data on air quality and support integrated urban air quality management. The modules are designed to estimate emissions and to simulate the interactions between emissions, pollution dispersion, impacts, and management options. These tools

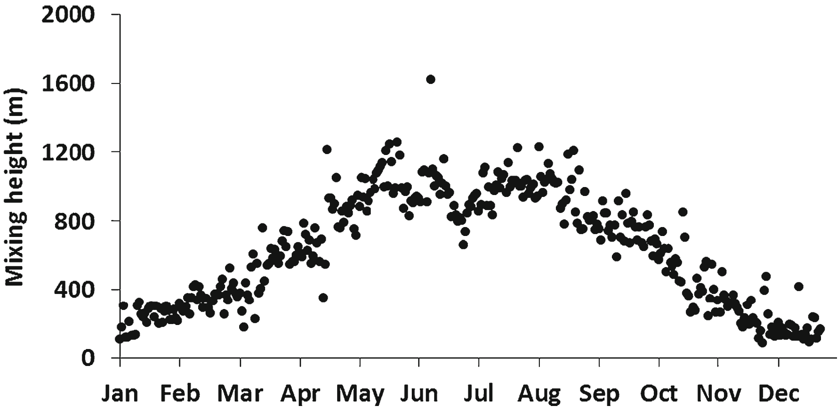


Fig. 2 Typical daily average harmonic mean mixing layer height (in meters) estimated from NCEP (2012) for Ulaanbaatar, Mongolia

and supporting documentation are distributed for free. All the databases, calculations, and interfaces are maintained in spreadsheets for easy access and model transparency. For the analysis of emissions inventory and health impacts, a database of emission factors and concentration–response functions are included in the tools, which can be adjusted with specific data from cities. The SIM-air tools were utilized for an initial assessment for Ulaanbaatar in 2006–2007 (Guttikunda 2007). The SIM-air framework applications in 2011–2012 include an assessment for three big and three medium-sized cities in India (Guttikunda and Jawahar 2012) and for one megacity, Delhi, India (Guttikunda and Calori 2013).

Emissions sources

Domestic cooking and heating

In Ulaanbaatar, the single largest emission source is coal and fuel wood combustion in residential areas, especially in the Gers. Traditional Gers, nomadic houses, consist of an expanding wooden circular frame carrying a felt cover made from wool for insulation. The heating requirements in these Gers and in conventional houses are met using cookstoves, accompanied by a chimney for ventilation. In 2010, 60 % of the 250,000 registered urban households lived in the Ger areas.

According to the UN Global Alliance of Clean Cookstoves Program (2012), only 28 % of the population in Mongolia has access to clean fuels in the form of electricity and gas. On average, households in the Gers are estimated to consume 5 tons of coal and 3 m^3 of fuel wood per year (Guttikunda 2007; World Bank 2011). Most of the coal consumption is during the winter, with 60 % reported between November and February. Fuel wood, often sold in sacks along the roadside, is common during spring and summer months. Another commonly used fuel is pressed coal, which is a mixture of powdered coal and adhesives and available at a price less than that of regular coal. This is known to produce higher ash in the cookstoves, resulting in the frequent removal and reloading of fuel. The charcoal briquette technology is garnering momentum among private manufacturers supplying small- and medium-scale industries and residential conglomerates. There is limited consumption of liquefied petroleum gas (LPG) in the Gers. Due to differential pricing, most of the LPG is utilized in housing complexes. There is anecdotal evidence of using rubber tubes and bricks dipped in coal tar as fuel, which adds to the uncertainty of the total emissions from cookstoves.

Kiosks and food shops are an unaccounted source of pollution using a mix of coal and wood. Since the expansion of Ger areas and increased in-migration from neighboring districts, the number of food shops has more than quadrupled between 2000 and 2010. In 2005, of 4,015 registered units, 62 % were food shops, 27 % are kiosks, 8 % are clothes shops, and the rest are large markets (NSO 2012). Food kiosks are estimated to consume on average 8 tons of coal per year.

Besides the emissions from coal and biomass burning in the Gers, a consequential environmental problem is fly ash from these cookstoves, which is often dumped in the neighborhood. On windy days, this adds to resuspended dust. While soil dust is coarser in nature contributing to PM_{10}, ash is generally of finer size and contributes substantially to both the PM_{10} and $PM_{2.5}$ fractions.

Electricity and space heating

There are three main sources: (a) power plants provide electricity, heat, and hot water to the urban center; (b) heat-only boilers (HOBs) meeting the needs of single buildings or a small central network of several buildings, industrial estates, and commercial sectors; and (c) in Ger areas, individual stoves burning coal and/or wood.

The three largest coal-fired power plants are an integral part of the energy sector that comprise all of the installed power capacity and the main source of district heating services—space heating and domestic hot water. They cover 40 % of the households in central Ulaanbaatar, supplying 80 % of the energy needs and consuming 3.6 million tons of coal per year—2.4, 1.0, and 0.2 million tons at power plants 4, 3, and 2, respectively (Guttikunda 2007).

In the city, there are approximately 2,500 HOBs producing hot water and steam, fueled by coal to meet the space heating and hot water needs. More than 60 % of these boilers are 100 kW or less in capacity and the remainder ranging between 0.1 and 3.5 MW. Most of the known large boilers use Russian combustion technology with heating efficiency of 40 % or less. With emerging technologies, there is room for substantial improvement in efficiency and clean supply in the decentralized HOB markets in the urban and rural sectors of the city.

Besides stack emissions at the power plants, an important and unaccounted source is fly ash from sediment deposit ponds. After fly ash is removed from the scrubbers and electrostatic precipitators, it is sent to settling tanks, where the sediment is collected and sent to ash deposit ponds. For power plants 2 and 3, these ponds are in the vicinity of the power plant; for power plant 4, it is 3 km to the west. These ash ponds are open and continuously subjected to wind erosion in the dry season. Due to the higher moisture content and snow cover, this is not an issue in the winter months.

Transportation

The total number of registered vehicles increased from 82,000 in 2006 to 145,000 in 2009 to 200,000 in 2011. While the total number of vehicles in Ulaanbaatar is not comparable to those observed in other capital cities of Asia (for example, 6.7 million registered vehicles in Delhi, India; 7.4 million in Jakarta, Indonesia; and 1.8 million in Manila, Philippines, in 2010), given the limited highway and secondary street capacity, the city is now experiencing heavy traffic congestions. In the last decade, the percentage of passenger vehicles (cars, vans, jeeps, etc.) increased from 25 to 65 % of the total registered vehicles. The city road network is ill equipped to absorb the fast-growing vehicle population, resulting in severe congestion and higher incidences of transport emission-related health problems. There is also accompanying urban degradation through conversion of open space to accommodate vehicle movement and parking.

A side effect of increased motorization is longer travel times for surface public transport, which in turn induces more auto and taxi use, poor traffic safety, and the economic inefficiency of increased fuel use. In the last 5 years, micro-buses, which can operate at faster speeds compared to regular buses, have increased along with the taxis. These micro-buses take passengers for short distance (within the city) and long distance (to the neighboring districts). In the city, there is also an unofficial taxi culture which is easy to access. This increases the uncertainty in estimates of vehicle kilometers traveled and trip occupancy. An estimated 80 % of vehicles do not meet fuel or emission standards (World Bank 2004). Most of the passenger vehicles are operated on petrol and multi-utility vehicles on diesel, mostly imported from Russia and China. Some of the official taxis now operate on LPG fuel.

Fugitive dust

Dust emission from paved and unpaved roads is also a growing problem in Ulaanbaatar because of high “silt loading,” higher average weight of vehicles traveling on the road, and increasing vehicle kilometers traveled. Silt loading on the roads is 10–20 g/m^2 on the major paved roads and more than 100 g/m^2 on the unpaved roads due to continuous construction activities, activities associated with land clearing, and prevailing meteorological conditions (higher and drier winds during the spring and summer months). The fugitive dust problem on unpaved roads is more persistent, resulting in additional cleaning of homes and vehicles, low visibility, abrasion to mechanical equipment, and damage to electronic equipment (Davy et al. 2011; Gunchin et al. 2012). In the Ger areas, with the most amounts of unpaved roads, silt loading includes fly ash from the cookstoves often dumped along the roadsides and makeshift landfills.

Construction industry

The Gers are traditional nomadic houses common across the country. Besides the Gers, in the urban parts of the city, fired clay brick construction with central heating systems is a growing trend, with an estimated demand at 100 million bricks a year. The location of the brick kiln clusters is marked in Fig. 3. Brick manufacturing includes land clearing for sand and clay, combustion of fuel for brick burning, operation of diesel engines on site, and transport of the end product to various parts of the city. For example, the Mongol ceramic brick factory is the biggest brick supplier in town, with a production capacity of 12–15 million bricks a year. They operate two kilns with 48 and 28 burning chambers, consuming 50 tons of coal per week over a 6- to 8-month manufacturing period. Most of the coal is supplied from the Baganuur coal mine, and they operate a Chinese boiler for kilns. Along with the kilns, the plant also

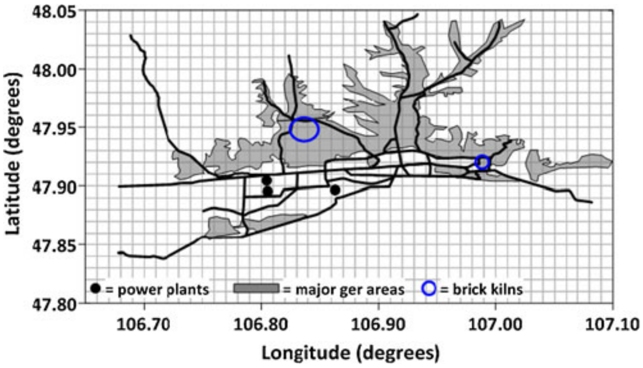


Fig. 3 Emissions and dispersion modeling domain for Ulaanbaatar at 0.01° grid resolution, along with the main roads, major Ger areas, locations of the three power plants, and brick kiln clusters

operates 25 pat-pats—small three-wheeler trolleys to convey bricks and fuel between stations. Because of carrying heavy load from the preparation site to the kilns and from the kilns to the distribution units, they have a lifetime of <3 years and tend to produce a lot of black smoke. They also operate ten units of heavy-duty vehicles for the transport of sand to the kilns and bricks from the kilns. The secondary sources of pollution from these sites include fly ash and fugitive dust on-site. The open-pit sand mining areas are 10 km from the city limits.

Garbage burning

Garbage burning in residential areas emits substantial amounts of pollutants and toxins, and this is a source with the most uncertainty in the inventories. Because of the smoke, air pollution, and odor complaints, local authorities have banned this activity, but it continues unabated at makeshift landfills. One of the immediate dangers of backyard burning, especially near Gers, is also indoor air pollution. Many of the emitted toxins become widely dispersed in the environment, contaminate the food chain, and accumulate to harmful levels in our bodies.

According to a survey by the Japan International Cooperation Agency (JICA), garbage generation ranges 555 tons/day in the winter and 248 tons/day in the summer, of which 17 and 10 % are self-disposed and nearly 20 % is illegally dumped. It is assumed that once a week, illegally dumped garbage is put to fire at an estimated 1,000 makeshift landfill sites in the Ger areas. Traditionally, city landfills do not accept medical waste from the hospitals and hospitals are required to install incinerators that burn trash and infectious medical waste (Shinee et al. 2008). About 35 hospitals practice biohazard waste burning at high temperatures.

Total emission estimates

We compiled an emissions inventory for the year 2010 based on fuel consumption data and emission factors for transport, industrial, and domestic sectors. We used the activity-based method to estimate the emissions inventory for PM, SO_2, and NO_x. The total emissions for the year 2010 are summarized in Table 1 and account for 88,000 tons of PM_{10}, 62,000 tons of $PM_{2.5}$, 55,000 tons of SO_2, and 89,000 tons of NO_x emissions in 2010.

For comparative purposes, the total $PM_{2.5}$ emission in 2010 for Delhi (India) is 63,000 tons (Guttikunda and Calori 2013). The city of Delhi, and its satellite cities, has 22.5 million inhabitants and a geographical size 15 times larger than that of Ulaanbaatar and is also listed among the top 10 cities with the worst air quality (WHO 2011). The cities have equivalent numbers of emissions in spite of the geographical and social differences due to the large coal consumption in the domestic sector of Ulaanbaatar, which is largely substituted with clean LPG in Delhi. For Ulaanbaatar, this is likely the largest contribution of indoor combustion to outdoor air pollution for a capital city in the world.

An activity-based methodology for building emissions inventory has been used in Kan et al. (2004) for Shanghai, China; Timilsina and Shrestha (2009) for Asia; Tung et al. (2011) for Hanoi, Vietnam; Yan et al. (2011) for global on-road transport; Guttikunda and Jawahar (2012) for six cities in India; and Guttikunda and Calori (2013) for Delhi, India. For the transport sector, we used the ASIF principles by Schipper et al. (2000) to calculate vehicle exhaust emissions using total travel activity (A), modal shares (S) in vehicle-kilometers traveled per day, modal energy intensity (I) representing energy use per kilometer, and an emission factor (F), which is the emitted mass per vehicle-kilometer travelled. Source apportionment studies like that of Davy et al. (2011) established the role of fugitive dust in Ulaanbaatar, and many studies have developed empirical functions that estimate resuspension rates. We estimated resuspension of dust on roads using the USEPA AP-42 methodology (USEPA 2006), which suggests its application for average road speeds <55 miles/h. The average speeds in Ulaanbaatar are <30 km/h. The kiln technology in use, emerging technologies, emission factors, and implication of the brick kiln emissions are studied and documented for Asian cities in CAI-Asia (2008), World Bank (2010), and Guttikunda et al. (2013). Emissions factors for power plants and diesel generators are from GAINS (2010) and Zhao et al. (2010). The transport emissions inventory also includes landing and take-off emissions at the airport, located 10 km west of the city center.

We acknowledge the uncertainty involved in the use of available emission factors instead of us calculating or measuring them for every activity. The applied methodology allowed us to better understand the data sources in the city and accordingly substitute with results from ongoing studies to improve the inventory. We estimate an overall uncertainty of ±20–30 % for the known sectors, primarily from estimates of the fuel consumption rates and emission factors.

An emission testing laboratory was established by the Asian Development Bank (ADB) in 2010, modeled on the SeTAR Centre's facility of the University of Johannesburg, to study the profile of emissions from the current cookstoves and the improved cookstoves being promoted by international groups like the World Bank and the Millennium Challenge Account. For traditional stoves, the average emission rate is estimated at 5–10 g PM per kilogram coal consumed. The variation in the emission factor is from the mix of coal and biomass fuels, ignition patterns, and coal reloading patterns (Lodoysamba and Pemberton-Pigott 2011). The total estimated emissions from cooking and heating in the households and kiosks account for 35,700 tons

Table 1 Activity-based emissions inventory (rounded to hundreds) by sector (percent total by pollutant) for Ulaanbaatar, Mongolia, in 2010

	$PM_{2.5}$ (tons)	PM_{10} (tons)	SO_2 (tons)	NO_x (tons)	CO_2 (million tons)
Domestic cookstoves	26,200 (42 %)	34,000 (39 %)	22,200 (40 %)	2,200 (2.5 %)	3.1 (25 %)
Kiosks	1,300 (2.1 %)	1,700 (1.9 %)	1,300 (2.4 %)	200 (0.2 %)	0.2 (1.2 %)
Heat-only boilers	11,600 (19 %)	16,500 (19 %)	13,800 (25 %)	10,200 (12 %)	1.2 (9 %)
Brick kilns	1,000 (1.6 %)	1,400 (1.6 %)	400 (0.7 %)	300 (0.3 %)	0.1 (0.4 %)
Vehicle exhaust	2,300 (3.7 %)	2,700 (3.1 %)	500 (0.9 %)	28,900 (33 %)	1.8 (14 %)
Power plants	16,900 (27 %)	21,100 (24 %)	16,300 (30 %)	47,100 (53 %)	6.0 (50 %)
Open waste burning	250 (0.4 %)	350 (0.4 %)	50 (0.1 %)	100 (0.1 %)	
Road dust	1,600 (2.6 %)	10,100 (12 %)			
Total	62,000	88,000	55,000	89,000	12.2

of PM_{10}, 27,500 tons of $PM_{2.5}$, 23,500 tons of SO_2, and 3.25 million tons of CO_2 emissions in 2010. A better understanding on the typical burn cycle in these stoves could result in a significant reduction in coal consumption and air emissions.

The total emissions testing carried out by JICA at power plants revealed control efficiencies of <30 % for power plant 2 and about 95 % for power plant 4. The latter operates an electrostatic precipitator which is expected to give a better performance than the observed rates (World Bank 2011). The total emissions from the three power plants account for 21,100 tons of PM_{10}, 16,900 tons of $PM_{2.5}$, 16,300 tons of SO_2, 47,100 tons of NO_x, and 6.0 million tons of CO_2 emissions.

Source contributions

The contribution of various sources to the total anthropogenic and biomass combustion emissions is also presented in Table 1. For total PM, emissions are dominated by coal and wood burning in households and kiosks, followed by coal burning in HOBs at the industries, power plants, and brick kilns. SO_2 emissions are linked to coal burning and highlighted with shares from power plants, HOBs, and stoves. While the total consumption at the power plants is at least three times higher than the combined coal consumption in the household and industrial sectors, because of the mandated flue gas desulfurization units at the power plants, this results in controlled emissions. For NO_x emissions, vehicle exhaust remains the dominant source. Power plants, industries, and brick kilns are elevated point source emissions which are likely to be dispersed to farther distances, while vehicle exhaust, road dust, and diffused domestic sources are at the ground level and tend to exacerbate exposure times.

In the current emissions inventory, we did not include dust storms, which are frequent in the spring and summer months. Also not included are forest and agriculture fires. Though a problem in Mongolia, the frequency of fires affecting the air quality in Ulaanbaatar has dropped significantly in the last 5 years. The number of fires reported in Ulaanbaatar in 2007, 2008, 2009, and 2010 were 47, 21, 4, and 0, respectively (NSO 2012).

Spatial and temporal allocation

We developed the emissions inventory on a GIS platform to spatially disaggregate the emissions for further use in atmospheric dispersion modeling. We subdivided the modeling domain presented in Fig. 3 into 45×25 grid cells at 0.01° resolution (corresponding to 1 km) ranging between 47.8° and 48.05° in latitudes and 106.65° and 107.1° in longitudes. We used spatial proxies to allocate the emissions for each sector to the grid, similar to the methodology utilized for six cities in India (Guttikunda and Jawahar 2012). In the case of the transport sector, we used grid-based population density, road density (defined as number of kilometers per grid), and commercial activity like HOBs, brick kilns, hospitals, and markets to distribute emissions on feeder, arterial, and main roads. Emissions from power plants, industries, and brick kilns were directly assigned to their respective locations. The domestic sector cookstove emissions are distributed to the Ger areas. The scattered garbage burning emissions were distributed using population density (GRUMP 2010) and land use data (USGS 2012). Gridded PM_{10} emissions from the vehicle exhaust and domestic sector cookstoves are presented in Fig. 4. Most of the vehicle exhaust emissions, including some congestion and idling emissions, are concentrated in the urban part of the city; most of the domestic emissions from cookstoves are concentrated in the Ger areas.

The emissions inventory also includes temporal profiles by season and by hour for further use in atmospheric dispersion modeling. In Fig. 5, we present the hourly average measured $PM_{2.5}$ concentrations at the Institute of Meteorology, Hydrology and Environment for all the data between 2008 and 2011 (Fig. 1). This presents an average estimate for the emissions diurnal cycle marked (a) by the highs at nighttime linking increased coal consumption for cooking and heating, and (b) peaks between 9 AM and 12 PM

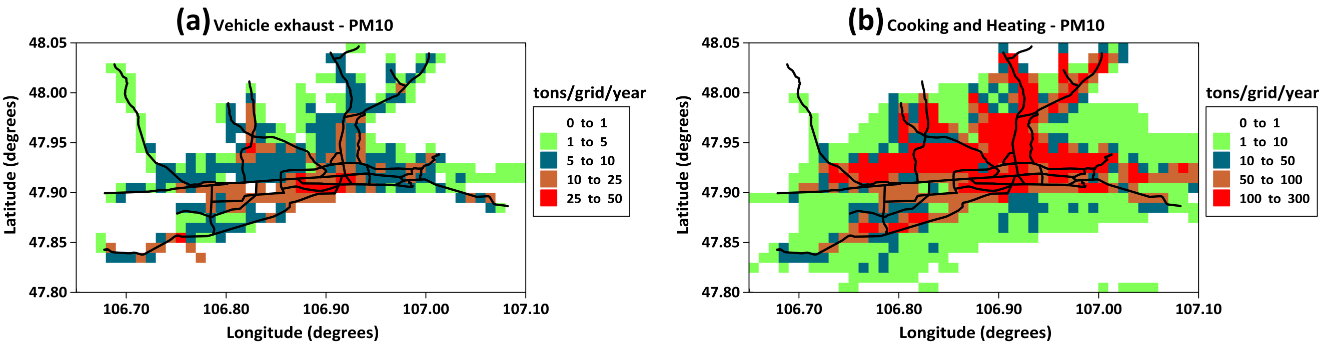


Fig. 4 Gridded PM_{10} emission inventory at 0.01° resolution for vehicle exhaust (**a**) and cooking and heating in households and kiosks (**b**) in Ulaanbaatar, Mongolia

in the morning and between 6 PM and 8 PM in the evening refer to rush hours with higher vehicle movement and vehicle exhaust emissions. We utilize a similar temporal allocation of the emissions by sector. The seasonal diurnal cycles based on measurements from multiple urban and residential locations are discussed in Allen et al. (2013).

The total emissions are segregated by season. For example, due to heavy snow cover and higher humidity in the winter months, road dust resuspension is suppressed. Hence, we do not include limited road dust resuspension emissions in these months. This is allocated in conjunction with the meteorological data. For the domestic emissions, most of the stoves are operational 24/7 during the colder months and less during the summer months. This is taken into account by allocating 60 % of the emissions between October and March. The vehicle exhaust emissions are kept constant for all months. The power plant emissions are distributed over months based on monthly coal consumption rates, obtained from the power plant annual reports.

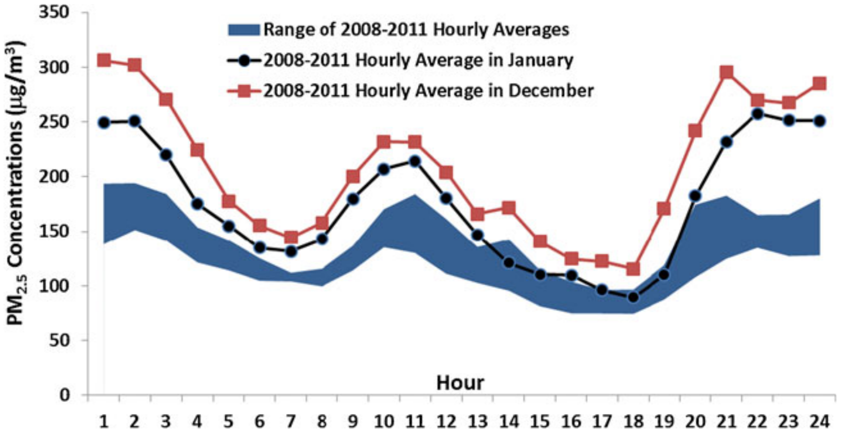
Dispersion modeling

We utilized the Atmospheric Transport Modeling System (ATMoS) dispersion model, a mesoscale forward trajectory Lagrangian puff-transport model to estimate ambient PM concentrations (Calori and Carmichael 1999). The dispersion model was previously utilized for many urban studies (Guttikunda and Calori 2013), including Ulaanbaatar (Guttikunda 2007). The horizontal resolution of the model is 0.01° and the vertical resolution is maintained in three layers: surface, mixing layer, and upper layer, reaching up to 6 km. The multiple layers allow the model to differentiate the contributions of near-ground diffused area sources, like transport and domestic sectors and elevated sources like industrial, brick kilns, and power plant stacks. The model also includes first-order chemical reactions for SO_2 and NO_x emissions to estimate the secondary contributions in the form of sulfates and nitrates, added to the total $PM_{2.5}$ concentrations. The meteorological data for wind speed and wind direction, mixing heights, and precipitation patterns are derived from the National Center for Environmental Prediction program (NCEP 2012).

Annual and winter average concentrations

The modeled annual average $PM_{2.5}$ concentrations are presented in Fig. 6a. Similar plots are also available for PM_{10} and for other months, but not presented in this paper. Clearly, the total $PM_{2.5}$ concentrations exceed the WHO

Fig. 5 Diurnal variation of $PM_{2.5}$ concentrations from a monitoring station located at the National Institute of Meteorology and Hydrology, Ulaanbaatar, Mongolia



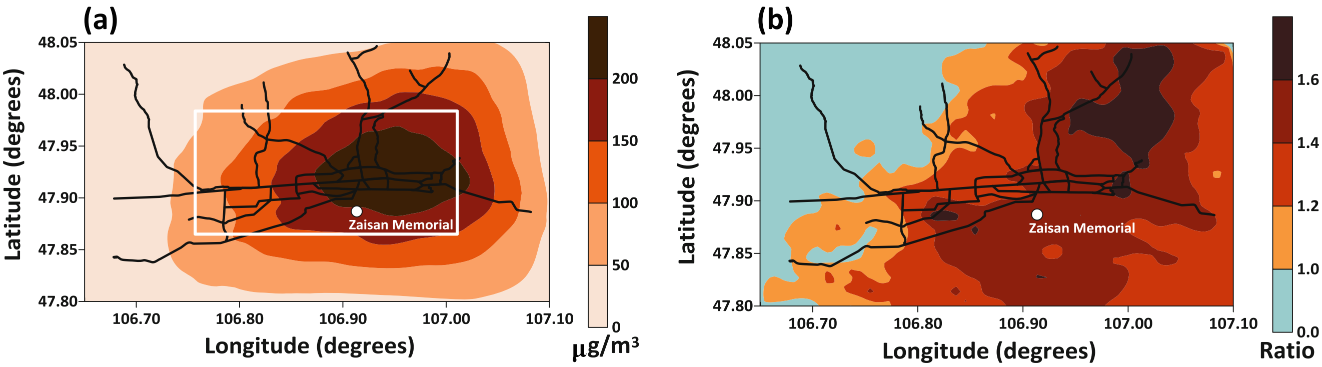


Fig. 6 **a** Modeled annual average $PM_{2.5}$ concentrations. **b** Modeled ratio of $PM_{2.5}$ concentrations for winter months (December and January) to annual average

health guideline of 10 µg/m^3. The highest concentrations to the east of the city are due to the presence of industrial HOB units, the largest Ger areas, and predominant northwesterly winds. The rectangular area in the middle of Fig. 6a covers approximately 400 km^2 encompassing most of the urban parts of the city, industrial estates, and the Ger areas. The modeled annual average $PM_{2.5}$ concentration for this area is 153±70 µg/m^3. The variation is among the 0.01° grid cells. From the measurements presented in Fig. 1, the average concentration is 136±114 µg/m^3. Please note that the comparison is not point to point since the monitoring station is located to the central–east of the city and located on top of the building, while the model average is for the city domain including the largest Ger areas (white box in Fig. 6a).

The difference between seasons is very prominent. The monthly average concentrations extracted for all grids covering the 400-km^2 area are presented in Fig. 7. The general pattern is similar to that observed in the monitoring data (Fig. 1)—highs in the winter months and lows in the summer months. For the winter months, low wind speeds and lower mixing layer heights restrict the movement of the low-lying emissions and further exacerbating the ambient pollution levels. Coal consumption in the winter months is also higher than the spring and summer months for households, kiosks, power plants, and HoBs. In Fig. 6b, we present the ratio of the concentrations for the months of December and January (worst months of air pollution in Ulaanbaatar) to annual averages. In the Ger areas, on average, the December–January months tend to receive at least 50 % more pollution than the annual average.

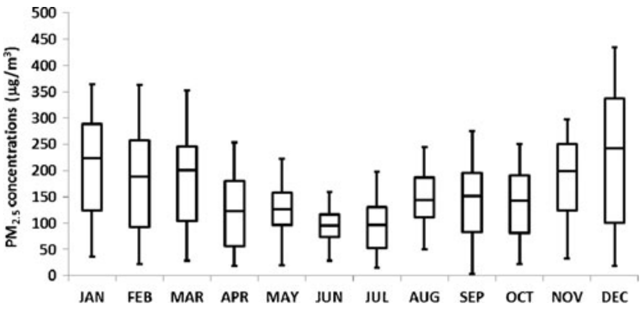


Fig. 7 Modeled $PM_{2.5}$ concentrations by month for 400 model grids covering the city center and Ger areas (Fig. 6a); *box plots* represent the 25th and 75th percentile grid concentrations over 1 standard deviation *error bars*

Source contributions

Ground-level sources contribute significantly more to the ambient air pollution problem than the elevated sources to the total emissions (Table 1). In general, the low-lying sources, for obvious reasons, contribute the most to the ground-level concentrations than the elevated sources like power plants (with stacks of at least 150 m) and HOBs and industrial units with smaller stacks. Using the ATMoS dispersion model, we also evaluated the contributions by modeling the emissions (PM, SO_2, and NO_x) by source and aggregated them for total PM pollution. We present in Fig. 8a–d the modeled contributions from vehicle exhaust, household cooking and heating, industrial units including brick kilns, and power plant emissions to the annual average $PM_{2.5}$ concentrations. The largest contributions come from coal and biomass burning in cookstoves (in the Ger areas), followed by exhaust emissions from 200,000 vehicles (mostly along the main roads and feeder roads), and from coal combustion at HOBs. The power plants with the highest stacks contribute <5 % to the urban center, dispersing most of the emissions to the south of the city.

For the select 400-km^2 region in Fig. 6a, the average source contributions based on source modeling to the total $PM_{2.5}$ pollution are 56 % from coal and biomass combustion in cookstoves in households and kiosks, 18 % from vehicle exhaust emissions, 14 % from industrial units including brick kilns, 6 % from power plants, 6 % from resuspended road dust due to vehicular movement, and 1 % from open waste burning. Comparatively, resuspended road dust, due

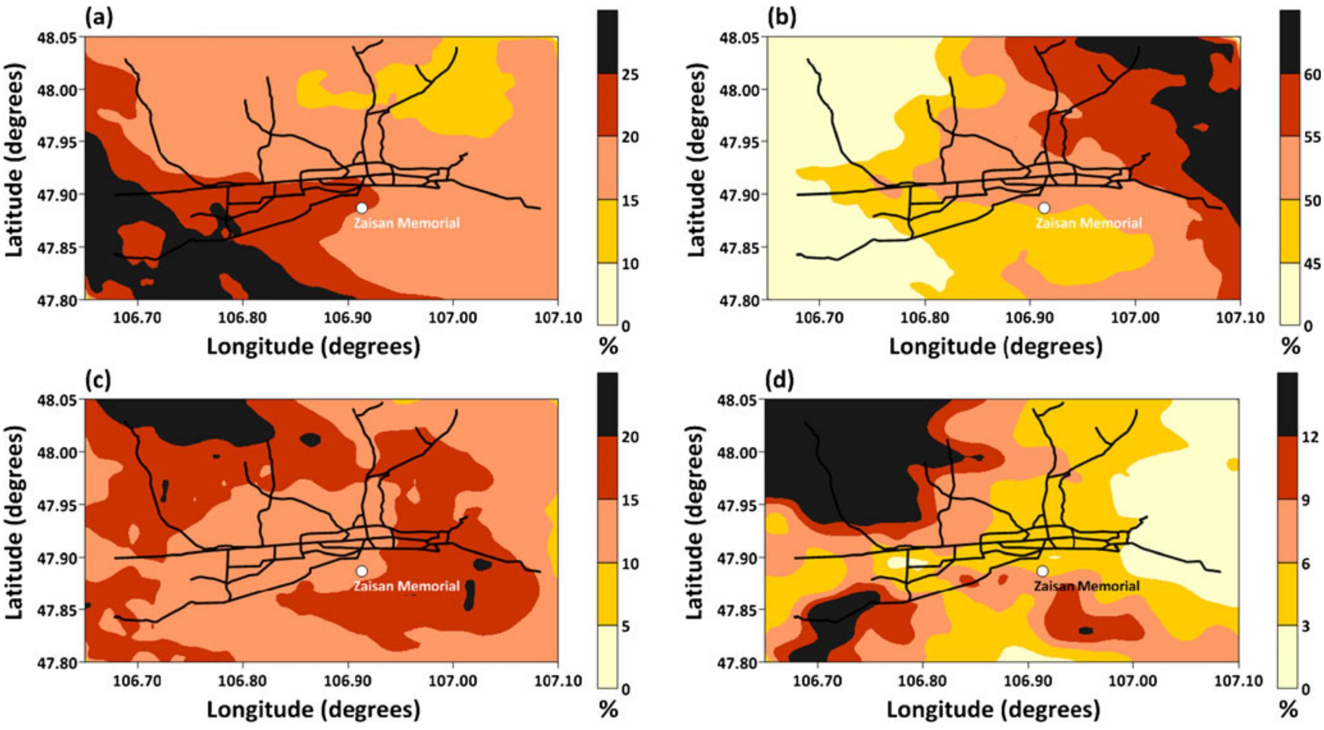


Fig. 8 Modeled percent contributions to annual average $PM_{2.5}$ concentrations from vehicle exhaust emissions (**a**), households cooking and heating (**b**), industrial units including brick kilns (**c**), and power plants (**d**)

to its coarser nature, contributes 21 % to the total PM_{10} concentrations. Allen et al. (2013) made PM measurements at multiple fixed and mobile stations for land use regression analysis and estimated $PM_{2.5}/PM_{10}$ ratios of 0.26±0.10 for the summer months and 0.78±0.12 for the winter months. This further highlights the shares of coarse dust from paved and unpaved roads in the summer months due to dry conditions and the prevalence of coal and biomass burning in the winter months resulting in finer PM.

For 224 samples collected at the National University of Mongolia, 4–5 km east of the city center, between the periods 2004 and 2008, receptor modeling results concluded that coal combustion accounts for 67 % of the total $PM_{2.5}$ concentrations (Davy et al. 2011). Another study for a site north of the center and closest to the Ger areas estimated 87 % contribution from coal combustion to $PM_{2.5}$ pollution (World Bank 2011). While receptor modeling is based on measurements and chemical analysis, they are also biased to the sampling site location and often represent the sources within 2–3 km of the site. A major drawback of receptor modeling is not being able to distinguish between coal consumption in a stove and a boiler, which tends to either exaggerate the contribution of stoves or underestimate the contribution of industries and heat-only boilers. In order to get a better understanding of source contributions for the entire city, we need sampling results from multiple locations representing traffic, industrial, and residential areas (Johnson et al. 2011). Because of this reason, the source modeling results in this study compliment receptor modeling results to apportion contributions for the city as a whole.

Health impacts

HEI (2004, 2010) presents a detailed analysis on the current scientific literature and epidemiological studies related to the health impacts of outdoor air pollution. Wong et al. (2008) present results from epidemiological studies in Asia, conducted under the Public Health and Air Pollution in Asia (PAPA) program. The total health risk for mortality and morbidity is quantified using the population-attributable fraction (PAF) defined as (WHO 2004)

$$\mathrm{PAF} = \delta P_{\exp} \times \frac{\mathrm{RR}_i - 1}{\mathrm{RR}_i}$$

where $\delta P_{\exp}$ is the prevalence of exposure to the total pollution level i and RR_i is the relative risk for mortality and morbidity end points at the total pollution level i.

This equation is simplified for presentation as follows:

$$\delta E = \beta \times \delta C \times \delta P$$

where

δE is the number of estimated health effects (various end points for mortality and morbidity)

β the concentration–response function which is defined as the change in number cases per unit change in concentrations per capita, linking to the relative risk coefficient RR_i

δC the change in annual average $PM_{2.5}$ concentrations, although WHO states that there is no threshold over which the health impacts are measured. In this paper, we considered this counter factual concentration as 10 μg/m^3; this input is available at the model grid resolution of 0.01°.

δP the population exposed to the incremental concentration δC, defined as the vulnerable population in each grid, of age <65 years; this input is available at the model grid resolution of 0.01° (GRUMP 2010).

The methodology utilized to estimate the health impacts in terms of mortality and morbidity was previously applied for similar studies: Ostro (2004) for global disease burden; Bell et al. (2006) for Santiago, Mexico City, and Sao Paulo; GAINS (2010) for Asia and Europe regional studies; Cropper et al. (2011) for power plant pollution in India; and Guttikunda and Jawahar (2012)) for six cities in India.

In the case of mortality, Atkinson et al. (2011) present a meta-analysis of 115 epidemiological studies conducted around the world and the range of concentration–response function—0.34 and 0.75 % change in the all-cause mortality rate per 10 μg/m^3 change in ambient $PM_{2.5}$ concentrations for low and high estimates, respectively. A combined analysis for the four cities in Asia under the PAPA program estimated an average of 0.55 % change. A health study in Ulaanbaatar estimated an increase of 0.5 % in premature mortality and a 0.8 % increase in cardiovascular admissions (morbidity) per 10 μg/m^3 increase in $PM_{2.5}$ concentrations (World Bank 2011. The health impacts in this study are estimated for the range of 0.55 and 0.8 % change in all-cause premature mortality due to outdoor air pollution. The all-cause mortality rates (Wang et al. 2012) are adjusted for those due to lower and upper respiratory illnesses (including bronchitis and asthma) and cardiovascular diseases to calculate the final concentration–response function. Among the reported number of deaths, these account for 10.0 % of the annual death rate in Ulaanbaatar (Allen et al. 2013).

For the modeled annual average $PM_{2.5}$ concentration (Fig. 6), we estimate 1,000–1,500 premature deaths due to outdoor air pollution caused by aggravation in respiratory and cardiovascular patients for a total city population of 1.2 million in 2010.

Our estimates are comparable to the levels presented for other cities and regions. For example, Colbeck et al. (2009) reviewed air pollution in urban centers of Pakistan, estimating 21,000 premature deaths per year. Yim and Barrett (2012) concluded that fossil fuel combustion causes 13,000 premature deaths per year in the UK, while an additional 6,000 deaths are caused by long-range transport of combustion emissions from the European Union. Guttikunda and Jawahar (2012) estimated an annual premature mortality due to PM_{10} pollution of 15,200 for six Indian cities—Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot, with a combined population of 32.5 million in 2010. The Health Effects Institute estimated an annual mortality of 3,000 in Delhi due to on-road exposure based on the proximity of inhabitants along the major and arterial roads in the city (HEI 2010).

Air quality management

In Ulaanbaatar, the city infrastructure is ill equipped to absorb a fast-growing population, vehicle fleet, and energy demand; consequently, severe problems such as waste management, lack of clean water and sanitation, and high levels of air pollution are prevalent. The bad air quality is estimated to result in premature deaths of 1,000–1,500 inhabitants per year. This study also highlights the linkages between indoor and outdoor air pollution. In these harsh temperate conditions, with 50 % of the emissions originating from coal and biomass burning in households, they are as big a health risk for indoor air quality as they are for outdoor air quality. A summary of the results from this study and other studies on air quality in Ulaanbaatar is presented in Table 2. Any intervention improving the combustion efficiency or providing clean fuel types for these stoves will have a combined benefit for indoor air quality, outdoor air quality, and climate policy.

The problem of air pollution is complex and there are no cookie-cutter solutions. Interventions need tailoring and should build on existing practices and institutional setup with a large awareness campaign implemented at all levels: among the citizens, industry, municipality, non-governmental organizations, and donor agencies. We present below a summary of the initiatives led by the national and international agencies with air quality as one of the key indicators.

Most important of the air quality management programs is monitoring and dissemination of data for public and policy dialogue. Since 2008, air quality monitoring has improved significantly, with nine continuous stations operated by the National Agency for Meteorology and Environmental Monitoring and Ulaanbaatar City Air Quality Department measuring SO_2, NO_x, CO, and PM_{10} (http://www.ub-air.info/ub-air/en/laq.html). The monitoring efforts are supported by JICA and German International Cooperation (GIZ) programs. Some episodic measurement campaigns were previously supported by the World Bank an ADB.

With 50 % of the ambient PM pollution (and more in the winter months) originating from household stoves for

Table 2 Air quality and health impacts in Ulaanbaatar

	Summary results
Wintertime average $PM_{2.5}$ at 37 locations (Allen et al. 2013)	147.8±61.2 μg/m^3
Annual average and winter time peak $PM_{2.5}$ concentrations in the city center (measured)	136±114 and 750 μg/m^3
Major contributors to annual $PM_{2.5}$ emissions (modeled, this study)	Domestic cookstoves (42 %), heat-only boilers (19 %), power plants (27 %), vehicle exhaust and road dust (6.5 %)
Major contributors to annual PM_{10} emissions (modeled, this study)	Domestic cookstoves (29 %), heat-only boilers (19 %), power plants (24 %), vehicle exhaust and road dust (15 %)
Annual average $PM_{2.5}$ concentrations (modeled, this study)	153±70 μg/m^3
Major contributors to annual average $PM_{2.5}$ concentrations in the city (modeled, this study)	Coal and biomass combustion in cookstoves (56 %), vehicle exhaust (18 %), industrial units including brick kilns (14 %), power plants (6 %), resuspended road dust due to vehicular movement (6 %), open waste burning (1 %)
Share of air pollution in the all-cause mortality in Ulaanbaatar (Allen et al. 2013)	10 % of cardiopulmonary and lung cancer deaths
Total annual mortality attributable to outdoor air pollution in the city (modeled, this study)	1,000–1,500

cooking and heating, this sector tops the list of the most opportunistic of the interventions for better air quality. Stove emissions and efficiency testing laboratory supported by ADB conducts studies on stove designs to improve heat efficiency and burn cycle to reduce indoor and outdoor emissions. Specific improvements tested include (a) a change from traditional front-lift–up-draft, which burn fuel from the front to the back, to a top-lift–up-draft model, which burns fuel with the flame, and (b) a provision to channel all emissions and flames into a pipe placed at the back of the combustion chamber, which will allow for the mixing of smoke with the flames and burning inside the pipe. The newer stoves with these modifications in the burn cycle are expected to reduce the total PM emissions between 50 and 80 % (Lodoysamba and Pemberton-Pigott 2011). In 2011, the Government of Mongolia and Millennium Challenge Account of USA (MCA) launched a program to introduce low-emission and high-efficiency stoves for 50,000 households in the highly polluted Ger areas (http://www.mcc.gov). The World Bank introduced improved cookstove models G2-2000 and TT-03 designed with metal flangs on each side to improve heat radiation in the room, clay lining to hold heat in the burning chambers, and a chimney valve to help control the burn rate (ESMAP 2005). A series of workshops were also conducted to train the local manufacturers to adapt the model designs, with marginal benefits.

Addressing the provision of clean and affordable heating will require first tackling current inefficiencies in both the supply of and demand for heating services. Heat supply costs are relatively high in part because of losses in the heat transmission and distribution system. As a result of a lack of insulation and heat controls on the consumer end, the estimated space heat consumption is nearly five times higher than that in northern European countries (World Bank 2007). USAID, in partnership with GIZ, is implementing a project focusing on thermo-technical retrofitting for three selected school buildings designed to introduce energy-efficient technologies in the construction sector to reduce heat losses (http://mongolia.usaid.gov). An aggressive replication of these pilot programs will have a direct implication on the coal consumed at the district heating systems and power plants.

Power plants 2 and 3 are small and soon to grow old and outdated by 2015. The Ministry of Mineral Resources and Energy is currently planning the construction of power plant 5 with a minimum capacity of 300 MW. While this is bound to support the growing demand for electricity and heat in the city, this will negatively affect the city's air quality. In 2005, the government also passed the Renewable Energy Program, mandating that alternative energy sources (solar and wind) should account for at least 20 % of Mongolia's needs by 2020 (http://www.nrec.mn). Already, it is common to see Gers fitted with solar panels for lighting. A joint venture with the European Bank for Reconstruction and Development is expected to see a 50-MW commercial wind farm situated on Salkhit Mountain, 78 km south of Ulaanbaatar. Though an expensive proposal compared to a power plant using the vast reserves of coal in the country, the opportunity to harvest wind for electricity makes for the most suitable renewable energy in Mongolia. This program, combined with MCA, is also expected to improve energy efficiency at the HOBs via central heating systems and supporting purchases of energy-efficient appliances.

The growing number of vehicles on the road with limited road infrastructure results in increasing congestion and idling times. While the total vehicle exhaust emissions are small compared to cookstoves and power plants, they still need priority in order to manage/reduce air pollution on the roads and reduce daily exposure rates, idling times, and fuel consumption in Ulaanbaatar. Some suggestions include (a) a national fuel economy policy for faster enforcement of stricter fuel standards (this is likely to affect the vehicles currently imported into Mongolia and effectiveness of emission standards). (b) Maintenance of roads and road conditions is important to reducing the resuspended road dust due to constant vehicle movement. (c) Traffic demand management can yield some benefits in reducing congestion using intelligent transport systems which can provide the drivers with reliable traffic information, real-time traffic signaling for efficient road utilization, prioritize movement of traffic at rush hours, and improve overall road and environmental safety. (d) Most efficient of the transport interventions is the promotion of public transport and non-motorized transport (walking and cycling), both of which have limited modal shares in the city. Two proposals under implementation to ease the growing congestion problems in the central district are: (1) every day, 20 % of the cars, based on their registration number, are not allowed to travel on-road and (2) the introduction of bus rapid transit systems with special lanes for buses along the main corridor.

The interventions listed in this discussion include institutional, policy, economic, and technical options which vary from the traditional command-and-control to more innovative, flexible, and market-oriented solutions. Long-term measures such as district heating systems and building public transportation infrastructure (paving roads) require action at the institutional level, large capital investments, and have a long gestation period. On the other hand, short-term actions such as installing solar panels, introducing efficient stoves, and education and awareness on the proper ventilation of kitchens are less capital-intensive and require mobilization at the user level with relative ease of implementation. Hence, a successful strategy to address air pollution should include a combination of short-term and long-term solutions. Of the interventions, the sectors with the largest marginal benefits in reducing the premature mortality rate are domestic cookstoves and power utilities.

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