Analysis of the Air Pollution Index and Meteorological Factors and Risk Assessment for Tibet

Zhuoga Deqing\textsuperscript{1,4}, Shuyi Tang\textsuperscript{4}, Ren Ci\textsuperscript{2,*} and Da Qiong\textsuperscript{3}

\textsuperscript{1} Weather Bureau of TAR, Lhasa, 850000, China
\textsuperscript{2} Department of Earth Sciences and Resources, Tibet University Lhasa, 850000, China
\textsuperscript{3} Weather Bureau of Linzhi, Tibet, 860000 China
\textsuperscript{4} No.2 Linkuo North Road of Lhasa, Weather Bureau of TAR, China.
\textsuperscript{*}Corresponding author email: 2316507015@qq.com

Abstract. An analysis and statistical evaluation of the environmental air quality, meteorological conditions, and human health effects were carried out for major cities and towns in Tibet. The study selected PM\textsubscript{10}, SO\textsubscript{2}, NO\textsubscript{2}, PM\textsubscript{2.5}, O\textsubscript{3}, and CO atmospheric pollutant monitoring data, a pollutant index, and the air quality index for seven cities and towns in Tibet in the year 2017 and for the Lhasa urban area in the period from June 2000 to December 2017. The data were combined with meteorological elements, namely precipitation, temperature, wind, and total solar radiation, for the same period. Results show that the air quality index is highest in Nag Qu, among of the seven cities and towns, followed by Shigatse, which roughly reflects the characteristics of pollution emissions dominated by biomass fuels in agricultural and pastoral areas of Tibet, a lack of vegetation, strong winds and less rain, and increased particle concentration. These factors affects human health. The six pollutants had higher concentrations in the winter half of the year (November to April) and lower concentrations in the summer half of the year (May to October); i.e., the concentration of pollutants was 38% higher in the winter half of the year. The change trend of the six pollutants has changed over the years; the concentrations of NO\textsubscript{2} and PM\textsubscript{2.5} have increased, the concentration of PM\textsubscript{10} has decreased, and the concentrations of O\textsubscript{3} and SO\textsubscript{2} have not changed appreciably. According to national air quality standards, the percentage number of days with excellent air quality was 22.7%, the percentage number of days with good air quality was 62.7%, the percentage number of days with light pollution was 11.3%, and the percentage number of days with moderate or heavy pollution was 0.6%. Meteorological factors such as precipitation, wind speed, visibility, and total solar radiation affect air pollution.

1. Introduction

The effects of air pollution on humans and their living environment have gradually become better known with the advance of modern science and technology. Major air pollutants include nitrogen-containing compounds, mainly nitrogen oxide and nitrogen dioxide, hydrocarbons, and halogen compounds. Such pollutants enter the human body through three pathways: 1) through the inhalation of polluted air, 2) by the pollutants adhering to food and dissolving in water, and 3) through skin contact. The inhalation pathway is the dominant and most harmful among these pathways. Clean air is thus important to human survival. However, people are exposed to many harmful gases that are continuously discharged into the air in the contexts of daily life and industrial production.

Numerous studies [1–10] have shown that urban air pollution adversely affects the health of residents, and PM10 and SO2 are important pollutants that affect the quality of the air environment. A survey of air pollution and the number of outpatients in hospitals in Beijing showed that daily
increases in the number of outpatients relate to PM$_{10}$ and SO$_2$ levels [11]. However, fluctuations in weather conditions or atmospheric environmental conditions affect human health to varying degrees [12]. Many medical meteorological studies have shown [13–18] that changes in four meteorological factors, namely temperature, air pressure, humidity, and airflow, are closely related to human health. About 40% of deaths occur under abnormal meteorological conditions [19]. Meteorology is thus an important factor affecting air pollution that cannot be ignored. It affects air pollution independently or collectively through different meteorological (i.e., air movement, temperature inversion, and mixed layer height) conditions. It is therefore necessary to further study the effects of air pollution and meteorological factors on human health.

Tibet is a high-altitude area that has unique natural and social environments. The environmental protection of Tibet is important and has its own special requirements. However, the acceleration and development of urbanization in various parts of Tibet, on the one hand, has created much material wealth for Tibet to beautify its cities and improve people's lives. On the other hand, the air quality in cities has a tendency to gradually deteriorate owing to the continuous expansion of the scale of cities and continuous increases in the variety and amount of energy consumption. The thin air in the plateau area is responsible for a cold and dry climate and pollen and dust mites readily becoming airborne, resulting in the inhalation of various antigenic substances and thus asthma [20]. Lhasa, as the capital of the Tibet Autonomous Region, is a typical river valley city with a strong topography. The air pollution in Lhasa has unique characteristics. At present, there are two main sources of urban air pollutants: transportation and the blowing of sand. Lhasa's industrial development is relatively backward, with there being relatively few industrial pollution sources and a low emission intensity. However, the number of motor vehicles in the city has grown rapidly, and exhaust emissions have increased. As of July 2016, there were 200,000 motor vehicles in Lhasa. The speed of vehicles travelling in Lhasa has increased [21]. Sand-blowing weather is concentrated in winter and spring, and conditions are suited to dust generation [22]. In addition, Lhasa has entered a stage of rapid urbanization in recent years, many new cities are under construction, and earth and stone operations, such as infrastructure construction, generate much dust, which poses a risk to the health of local residents. The present paper therefore combines the monitoring data of various air pollutants recorded since June 2000 with meteorological data for the same period to evaluate and analyze the effects of environmental factors on human health in Tibet.

2. Materials and Methods
The present work selected data on the daily average concentrations of three major air pollutants, namely inhalable particulate matter (PM$_{10}$), sulfur dioxide (SO$_2$), and nitrogen dioxide (NO$_2$), recorded by the Lhasa Environmental Monitoring Center Station from June 2000 to December 2010. Daily air pollution index of key towns in Tibet, Lhasa, Xigaze, Qamdo, Zedang, Nagqu, Bayi, Shiquanhe and Lhasa City Environmental Monitoring Center, Barkhor Street, Municipal Environmental Protection Bureau, Najin in Lhasa Continuous monitoring data and average values of four stations in the township. From 2013 to 2017, the PM$_{2.5}$ particulate matter concentration and the AQI index data and the meteorological observation data of the TAR Meteorological Bureau over the same period.

The relationship between the three major air pollutants and the meteorological elements at various locations was established through correlation analysis. Tibet has obvious differences between winter and summer. Considering climate characteristics common throughout Tibet, two periods with obvious characteristics of winter and summer were selected. A statistical analysis was conducted for the relationships between PM$_{10}$ and precipitation, human comfort, and other factors by taking average values for the winter half of the year (November to March) and summer half of the year (June to September).

3. Analysis of Results

3.1 Air Quality Situation in Tibet and the Effect on Human Health
The average PM$_{10}$ pollution index of seven major Tibetan cities and towns in 2012 was monitored for 365 days (Fig. 1). The following results are obtained. 1) The PM$_{10}$ pollution index was highest in the
town of Nag Qu and lowest for the towns of Bayi and Nyingchi. 2) There were 233 days with excellent air quality in Lhasa, 177 days in Shigatse, 240 days in Qamdo, 217 days in Zedang, 102 days in Nag Qu, 265 days in Bayi, and 239 days in Shiquanhe; the number of days for Bayi accounted for 72.6% of the year. There were 114 days with good air quality in Lhasa, 167 days in Shigatse, 109 days in Qamdo, 127 days in Nag Qu, 85 days in Bayi, and 110 days in Shiquanhe; the number of days for Nag Qu accounted for 66.3% of the year. 3) There were 17 days of light pollution in Lhasa, 18 days in Shigatse, 19 days in Zedang, 19 days in Nag Qu, and 17 days in Shiquanhe; the number of days for Zedang and Nag Qu accounted for 0.05% of the year. (4) There were two days with moderate or severe pollution in Lhasa, three days in Shigatse, one day in Qamdo, two days Zedang, and three days in Nag Qu.

![Figure 1. Changes in the API index in major cities and towns of Tibet in 2012](image1)

The air quality index (AQI) was implemented in 2013 to monitor air quality. The AQI is different from the originally used air pollution index. The reference standard for the calculation of AQI classification is the new ambient air quality standard (GB3095-2012), and the pollutants involved in the evaluation are SO$_2$, NO$_2$, PM$_{10}$, PM$_{2.5}$, O$_3$, and CO.

![Figure 2. Trend of the AQI in major cities and towns of Tibet](image2)

Figures 1 and 2 show that the greatest difference in the pollution index is the difference between Nag Qu and Bayi, mainly owing to the large difference in climatic conditions between the two towns. The annual average precipitation is 449 mm in Nag Qu and 893 mm in Bayi, which is nearly a two-fold difference. The average temperature in Bayi is nearly 10 °C higher than that in Nag Qu. Furthermore, the vegetation coverage in the Bayi area of Linzhi reaches 80% to 90%. Plants have a certain effect in terms of reducing particulate pollution, and they absorb, transform, and decompose.
pollutants in the air [23]. The vegetation in Nag Qu is relatively scarce. Additionally, Nag Qu has a high frequency of windy weather, with there being 199 windy days per year on average. Such windy and dry weather has increased the concentration of particulate matter and the air pollution index. Furthermore, Tibet is a vast region with agricultural and pastoral areas accounting for more than half the land area, and Nag Qu is located in a high-altitude pastoral area. The climate is severely cold and the air is thin. Fires are needed for heating throughout the year. The fuel used by herders is mainly cow and sheep dung, which is a typical solid biomass fuel in Tibet. Compared with straw and woody biomass fuels, dung fuel has a high ash content and low calorific value and is consumed in large amounts, leading to increased pollution. Experts have tested and studied polycyclic aromatic hydrocarbons produced by the indoor burning of biomass in Tibet [24]. It has been pointed out that the air pollution generated by the burning of biomass such as cow dung is mainly high-molecular-weight particulate matter and toxic polycyclic aromatic hydrocarbons in the particulate matter, which are deposited in the respiratory tract and affect the human respiratory system and pose a high risk of lung cancer. This may be one reason for the high rate of respiratory disease and lung cancer in agricultural and pastoral areas of Tibet [25–26].

3.2 Annual Distribution and Change Trend of the Pollution Concentration from 2000 to 2010
In recent years, there has been slight air pollution from time to time in Tibet with the development of Tibet's economy and the booming tourism industry. Statistics from 2000 to 2010 show that the percentage number of days with excellent air quality in Lhasa is 46.8%, the percentage number of days with good air quality is 51%, the percentage number of days with light pollution is 1.7%, the percentage number of days with light pollution is 0.3%, and the percentage number of days with moderate or heavy pollution is 0.3%. The number of days is 0.05%.

Figure 3 (a, b, c) shows the annual distribution and change trend of the main pollutants that affect the air quality in Lhasa, namely PM$_{10}$, NO$_2$, and SO$_2$.

![Figure 3](image_url)

**Figure 3.** Annual changes and trends of PM$_{10}$ (a), NO$_2$ (b), and SO$_2$ (c) concentrations
Three findings are made from Figure 3.

1. Inhalable particulate matter ($PM_{10}$) has the highest concentration in the air, contributing 80% of the total concentration of the three pollutants. The 10-year change can be divided into two stages as follows. The air pollution concentration was highest in 2005, remaining at about 0.071 mg·m$^{-3}$. There was an obvious turning point in 2006. The concentration was lowest from 2008 to 2010, generally being around 0.051 mg·m$^{-3}$. The overall trend of the change in the past 10 years is downward.

2. Nitrogen dioxide ($NO_2$) is the second most abundant pollutant in the urban area of Lhasa. In a period of 10 years, the $NO_2$ concentration has not changed appreciably; i.e., the concentration has fluctuated in the range of 0.015 – 0.043 mg·m$^{-3}$.

3. The concentration of sulfur dioxide ($SO_2$) has not changed obviously in a period of 10 years. $SO_2$ is not a major contributor to urban air pollution, and the concentration of the pollutant fluctuates within the range of 0.001 to 0.012 mg·m$^{-3}$.

The state of $NO_2$ and $SO_2$ in the air is unstable and their chemical reactions are relatively active, leading to secondary pollution. The concentrations of $NO_2$ and $SO_2$ pollutants are mainly affected by exhaust emissions from industry, transportation, and energy production, and the annual concentration varies relatively smoothly.

3.3 Numbering Distribution Characteristics of the Air Quality in Lhasa

The Environmental Monitoring Center of the Tibet Autonomous Region has established four nationally unified atmospheric monitoring points in the urban area of Lhasa, namely the Lhasa Environmental Monitoring Center (at an altitude of 3647 m), Barkhor Street (at an altitude of 3656 m), Lhasa Environmental Protection Bureau (at an altitude of 3672 m), and Najin township of Lhasa (at an altitude of 3670 m) respectively located in the southwest, center, north, and southeast of the city. Among them, the Barkhor Street station concentrates the religious, political, economic, cultural, residential, and service functions of Lhasa. It is the core area of Lhasa and an area in which the use of large vehicles is restricted.

Monitoring data recorded at the four monitoring points (see Figure 4) show that the $PM_{10}$ pollution concentration on Barkhor Street, ranging 0.009–0.052 mg·m$^{-3}$, is slightly lower than concentrations at the other three monitoring points. The city center is thus smaller than the other three traffic arterial stations; in particular, the $PM_{10}$ pollutant concentration at the Najin township station is about 2% higher.

![Figure 4. $PM_{10}$ concentrations at four monitoring stations in Lhasa](image-url)
3.4 PM$_{2.5}$ Concentration Distribution and AQI Change

Statistics of PM$_{2.5}$ data for the period from 2013 to 2016 (see Fig. 5) show obvious seasonal changes. The lowest concentrations are between 14.42 and 17.97 µg/m$^3$ from July to September while the highest concentration is 35.99 µg/m$^3$ from November to January. Between µg/m$^3$ and 55.40 µg/m$^3$, the relative concentration is 37.5% higher. In winter and spring, the sky over the plateau is affected by strong westerly air currents, and cold air activity is frequent. At the same time, owing to the downward transmission of high-altitude momentum, it is often windy at ground level, such that the concentration of particulate matter increases [27].

According to the AQI for the Lhasa urban area (see Fig. 6), the percentage number of excellent days is 22.7%, the percentage number of good days is 62.7%, the percentage number of days with light pollution is 14.3%, and the percentage number of days with moderate or heavy pollution is 0.3%.

In particular, from November to December, the Lhasa urban area has an average of 15 days of mild pollution, accounting for 57% of the total number of days with such pollution throughout the year.

4. Seasonal Characteristics of Air Pollutants and Changes in Meteorological Conditions

The main factors affecting air quality are pollutant emissions and meteorological conditions. However, for the same type of emission and the same emission level, the meteorological conditions have the greatest effect on air quality [28].

4.1 Seasonal Characteristics

Lhasa is located on a plateau and belongs to the monsoon climate of the Qinghai–Tibet Plateau. The climate has obvious seasonal characteristics. The air quality also varies obviously with changes in climate and season. As previously mentioned, the concentrations of NO$_2$ and SO$_2$ pollutants change relatively smoothly throughout the year. Therefore, we here discuss mainly the seasonal variation of the inhalable particulate matter (PM$_{10}$) pollution index.
Figure 7. Monthly average change trend of the air pollution index from 2000 to 2010

Figure 7 shows that the concentration of the primary pollutant PM$_{10}$ in the air fluctuates greatly with the season. The average pollution index in the winter half year (from November to March of the following year) is 62 while the average pollution index in the summer half year (from June to September) is 45; i.e., the air pollution index in the winter half of the year is 1.5 times that in the summer half of the year.

The overall analysis of air quality in the four seasons reveals that the air quality is worst in winter, with the PM$_{10}$ pollutant concentration being highest, at about 0.083 mg m$^{-3}$. The air quality in summer is better than that in the other three seasons, with the total pollutant concentration being about 0.041 mg m$^{-3}$.

4.2 Precipitation

Precipitation effectively absorbs and washes away various pollutants in the air. Some pollutant gases in the atmosphere dissolve in water, which reduces the concentration of pollutants in the air. Additionally, large rain and snow weather events affect air pollutants and dust particles and thus have an effective cleaning effect. According to precipitation observation data recorded at Lhasa Station from 2000 to 2010 and the analysis of daily average concentrations of PM$_{10}$, NO$_2$, and SO$_2$ (Fig. 8), the concentration of PM$_{10}$ decreases with an increase in precipitation when precipitation is high.

Figure 8. Relationships between the concentrations of three pollutants and precipitation
The concentrations of the two gaseous substances, SO\(_2\) and NO\(_2\), change little with the precipitation rate. This phenomenon is mainly due to their oxidation reactions. When the air humidity is high, SO\(_2\) and NO\(_2\) react quickly with H\(_2\)O to form H\(_2\)SO\(_4\) (sulfuric acid) and HNO\(_3\) (nitric acid). In addition, the concentrations of SO\(_2\) and NO\(_2\) decrease when it rains. This may relate to the fact that about 70% of Lhasa's precipitation falls in summer, a season characterized by high temperature and strong radiation energy, which are conditions most conducive to the oxidation of the gases.

4.3 Wind Speed
Tibet has a windy season from October to May of the following year. Windy weather occurs most frequently from February to March, with this period accounting for about 80% of windy days during the year. The maximum wind speed exceeds 40 meters per second, and the duration is generally 3 to 5 days. The analysis of daily wind speed data recorded at Lhasa Station from 2001 to 2017 reveals that the PM\(_{10}\) concentration increases with the wind speed when there is a windy weather, which affects the air quality in the Lhasa urban area (Table 1). This may be because the wind transfers small particles on the ground or vegetation into the atmosphere, such that the concentration of PM\(_{10}\) contains a large number of small particles, which increases the value of PM\(_{10}\).

As an example, from February 14 to 19, 2010, there were strong winds at stations in Ali, Nag Qu, Shigatse, and Lhasa and along the Yarlung Zangbo River Valley. Among these stations, 18 stations recorded strong winds from 14 to 18 February. In Lhasa, the maximum instantaneous wind speed reached 21.5 m/s (equivalent to a level-9 gale) at 14:15 pm on the 16th and 19.9 m/s (equivalent to a level-8 gale) at 13:36 pm on the 17th. Affected by the windy weather, three planes returned to Lhasa Kongga International Airport on February 14–16. The Lhasa urban area experienced sandy weather for two consecutive days on the 14th and 15th. The air was turbid and the air quality was slightly polluted. The air quality for the next three consecutive days (the 16th, 17th, and 18\(^{th}\)) was worse. Such poor air quality for five consecutive days is rare in Lhasa.

Table 1. Number of days of strong wind and the air quality in the Lhasa urban area from 2000 to 2017

| Year | Days of strong wind | Air quality when strong winds occur |
|------|---------------------|-----------------------------------|
| 2001 | 3 days              | 3 days slightly polluted.         |
| 2002 | 3 days              | 1 day slightly polluted, 2 days good. |
| 2003 | 1 day               | 1 day light pollution.            |
| 2004 | 3 days              | 1 day light pollution, 2 days good. |
| 2005 | 4 days              | 1 day moderate pollution, 2 days light pollution, 1 day good. |
| 2006 | 5 days              | 2 days light pollution, 2 days good. |
| 2007 | 3 days              | 3 days slightly polluted.         |
| 2008 | 1 day               | 1 day light pollution.            |
| 2009 | 3 days              | 2 days light pollution, 1 day good. |
| 2010 | 6 days              | 4 day slightly polluted, 2 days good. |
| 2011 | 4 days              | 4 day slightly polluted, 2 days good. |
| 2012 | 7 days              | 1 day moderate pollution, 3 days light pollution, 1 day good. |
| 2013 | 3 days              | 1 day moderate pollution, 3 days light pollution, 3 days good. |
| 2014 | 10 days             | 4 days slightly polluted, 6 days good. |
| 2015 | 6 days              | 2 days light pollution, 4 days good. |
| 2016 | 12 days             | 1 day moderate pollution, 4 days light pollution, 7 days good. |
| 2017 | 6 days              | 2 days light pollution, 4 days good. |
5. Conclusion

The following conclusions are drawn from the analysis of the temporal and spatial characteristics of air quality from 2000 to 2017 in seven main cities and towns in Tibet and at four measuring stations in the Lhasa urban area and the relationship of these characteristics with meteorological conditions.

1. Air pollution was classified according to national standards. (i) The PM$_{10}$ pollution index for Nag Qu is slightly higher than that for other locations; the index is second highest for Shigatse. The pollution index is lowest for Bayi in Nyingchi Prefecture. (ii) The proportion of Grade-I air quality was highest (94.14% of all days) in Bayi in Nyingchi Prefecture; the proportion of Grade-II air quality was highest (77.93% of all days) in Nag Qu; the proportion of Grade-III air quality was highest (1.35% of all days) in Zetang and Nag Qu; and Grade-IV air quality has not yet been observed.

2. The air quality is improving in general. Among the three main pollutants, the primary pollutant is PM$_{10}$ and the secondary pollutant is NO$_2$; both have a decreasing trend. The concentration of SO$_2$ has changed little.

3. Among pollutants, inhalable particulate matter (PM$_{10}$) fluctuates most with the season. The air pollution index in the winter half of the year is 1.5 times that in the summer half of the year; meanwhile, there are little or no obvious change in the NO$_2$ or SO$_2$ concentration with the season.

4. Precipitation and strong wind are the main weather phenomena that affect urban environmental pollution. The concentration of pollutants is low in the rainy season.

5. Particulate pollution has a greater effect on human health, especially for residents in Nag Qu and Shigatse. These two areas have low vegetation coverage, high winds, less rain, and more severe weather, while dry air increases the concentration of pollutants in these areas. The air pollution index is thus higher in these areas.

6. References

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