# MORNING SURFACE TEMPERATURE INVERSIONS (MSTIS) FROM ALLEGHENY COUNTY, PA TO BEIJING, CHINA: FORMATION FACTORS, HEALTH EFFECTS, AND APPLICATIONS

by

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## ABSTRACT

In recent years, concern about air quality has increased as we better understand the relationship between air pollution and health, not only of humans and animals, but also of the environment. This essay looks at the ways that scientists categorize air pollution as well as the types of air pollution and explores some of the health effects of exposure to air pollutants. Morning surface temperature inversions (MSTIs) are described and how air dispersion conditions might elevate the severity and duration of air pollution is explored. A method to use MSTIs to forecast potentially dangerous air pollution, developed in Allegheny County, Pennsylvania, is applied to data in Beijing, China, an approach that is supported by the similar geographical and environmental conditions the two regions share. This paper only utilize the MSTIs detecting method, part of the entire forecasting method, to test preliminarily if the method is applicable to Beijing, China. The emergency heavy pollution alerts in Beijing was introduced in this paper, as a potential application field for MSTIs forecasting method in Beijing, China.

Results of the preliminary test in Beijing data indicate that there are promising future for application MSTIs method of Allegheny County to Beijing, China with some criteria adjusted needed to fit Beijing's situation. A full-time and caliber-consistent equipment is suggested to collect more accurate data for future MSTIs research. Results of the use of the MTSIs method show that some opportunities to warn Beijing residents of potentially dangerous air pollution

were missed, and that alerts can sometimes be issued when none is warranted. **Public Health Statement**: Information sharing is one way that governments can help protect the health of their citizens; establishing policies that limit polluting emissions is another.

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# PREFACE

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**Statement:**

Because epidemiological and other kinds of data are not publicly available, some of the information used in this essay is taken from official media sources in China.

# 1.0 INTRODUCTION

All living organisms are in some way reliant on air for development and for health. In recent years, experts are becoming increasingly concerned about the quality of the air on which all living creatures rely for survival.

This essay looks at the ways that scientists categorize air pollution as well as the types of air pollution and explores some of the health effects of exposure to air pollutants. Then the essay describes morning surface temperature inversions (MSTIs): what they are and how air dispersion conditions might elevate the severity and duration of air pollution. Air pollution in Beijing, China, is discussed, as well as how geographical, demographic and meteorological conditions of Beijing might worsen air quality. Parallel conditions in Allegheny County (AC), Pennsylvania (PA), are also reviewed to provide support for applying the method of detecting MSTIs in AC to Beijing, where the air pollution alert program can benefit from the detection and potential forecasting used in the MSTI method.

The essay details method being used by the Allegheny County Health Department (ACHD) of detecting MSTIs and presents the results of retrospectively applying the method to explore MSTI conditions in Beijing in the first six months of 2018. The essay also shows that MSTIs and air quality have a positive relationship. In Beijing, between January and June 2018, the alert system was used; however, alerts could be more effectively issued if the MSTIs forecasting system described in this paper were utilized.

# 2.0 BACKGROUND

Air quality is important to human health, and exposure to various pollutants can lead to chronic and acute health conditions. In this section, the types of air pollution are discussed, as well as specific pollutants.

## 2.1 AIR POLLUTION IN GENERAL

### 2.1.1 Air Pollution Types

The United States (US) Environmental Protection Agency (EPA) has dichotomized air pollutants into two kinds: common air pollutants (criteria pollutants) and Hazardous Air Pollutants (HAPs). Criteria pollutants include particulate matter, ground-level ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide and lead (US Environmental Protection Agency, 2018).

HAPs are toxic and known or suspected to be carcinogenic. HAPs include many chemicals, such as benzene, perchloroethylene, methylene chloride, dioxins, asbestos, toluene, and metals such as cadmium, mercury, chromium and lead compounds. These pollutants are emitted from vehicle and industrial activities. For example, benzene is often found in gasoline, perchloroethylene comes from dry cleaning facilities, and methylene chloride is often used as a solvent and paint stripper in several industries (US Environmental Protection Agency, 2018). Like criteria pollutants, HAPs can be harmful to human health, resulting in cancer or damage to the immune system, neurological, reproductive, developmental, respiratory and other health problems (US Environmental Protection Agency, 2018).

Pollutants are categorized as primary and secondary pollutants. Primary pollutants include nitric oxide, volatile organic compounds (VOCs) and sulfur dioxide. Secondary pollutants include ozone, nitric acid, organic peroxyacetyl nitrate (PAN) production and are the result of tropospheric gas oxidization by reactions with free radicals (Mohnen, Chameides, & Lenschow, 1985).

The Air Quality Index (AQI) is an important indicator of air quality. It is usually calculated by integrating values of many real-time monitored air pollutants. The AQI calculation formulas of China and the United States are similar, but the AQI standard classification, pollutant items, average time and concentration limits are determined according to their respective ambient air quality standards. Both countries selected monitored data of $PM_{2.5}$, $PM_{10}$, $SO_2$, CO, $NO_2$ , and $O_3$ as indicators of AQI calculations (Gao, Liu, Li, & Gao, 2015)..

### 2.1.2 General sources, health effects, and guidelines

Ambient air pollution is often caused by a wide variety of human activities (World Health Organzation [WHO], 2018b). These include using motor vehicles with fuel combustion; manufacturing, mining and oil refining; generating power using oil and coal; treating municipal and agricultural waste; and cooking, heating and lighting with polluting fuels (World Health Organzation, 2018b).

According to the WHO (2018a), poor air quality may be related to 24% of deaths from stroke, 25% of deaths from heart disease, 43% of deaths from lung disease, and 29% of deaths from lung cancer.

#### 2.1.2.1 Particulate Matter (PM)

Particulate matter consists of a "complex mixture of solid and liquid organic and inorganic substances suspended in the air" (World Health Organzation, 2018b). The particles are small and difficult to distinguish with the eyes. Particles with aerodynamic diameters less than or equal to 10 micrometers ($d \leq 10$ μm) are called coarse particles, written as $PM_{10}$; particles whose diameter is less than or equal to 2.5 micrometers ($d \leq 2.5$ μm) are called fine particles, or $PM_{2.5}$ (U.S Environemental Protection Agency & Ministerio de Medio Ambiente y Recursos naturales, 2012). Usually it is not PM itself that is toxic, but the composition of the particles that are harmful to human health. These include sulfate, nitrate, ammonia, sodium chloride, black carbon, mineral dust, and heavy metal.

Although $PM_{10}$ can penetrate deep into the lungs, $PM_{2.5}$ is more detrimental to humans since it can enter the blood system through the lung barrier. Long-term exposure to these particles may increase the risk of cardiovascular and respiratory diseases, as well as lung cancer (World Health Organzation, 2018c).

Reports on air quality measurements typically involve daily or annual average $PM_{10}$ particle amounts per cubic meter ($m^3$) of air capacity. Conventional air quality measurements generally describe the concentration of particulate matter in micrograms per cubic meter (μg/m3). The concentration of fine particles ($PM_{2.5}$ or smaller) can also be reported if a sufficiently sensitive measuring device is available.

Exposure to $PM_{10}$ and $PM_{2.5}$ pollution, both daily and for a period of time, is associated with mortality and morbidity (Franklin, Zeka, & Schwartz, 2007). Small particulate pollution can have a health impact even at very low concentrations, although there is currently no confirmed minimum value that does not compromise health (World Health Organzation, 2018c). Different degrees of exposure to PM have an impact on health. If the concentration of small and fine particles is reduced, the associated mortality will also decrease, assuming other factors remain the same. Therefore, policymakers can substantially improve population health by passing laws to reduce air pollution from PM.

#### 2.1.2.2 Carbon Monoxide (CO)

Carbon monoxide is a colorless, odorless, and tasteless inorganic compound gas, slightly lighter than air. It combines with hemoglobin to produce carboxyhemoglobin, which prevents oxygen from reaching body tissues, resulting in a condition of blood oxygen deficiency. Concentrations as low as 667 ppm may result in up to 50% conversion of human hemoglobin to carboxyhemoglobin, which can lead to coma and death (Green, 2008).

The most common symptoms of carbon monoxide poisoning include “headache, nausea, vomiting, dizziness, fatigue and feeling of weakness” (Green, 2008). It also can cause retinal hemorrhage, as well as abnormal cherry red blood. Exposure to CO can severely damage the heart and central nervous system, with sequelae. CO can cause serious adverse effects in pregnant women (Green, 2008). CO usually is more common indoors, from sources such as cigarette smoke. However, in ambient (outdoor) air CO comes from a few sources, for example automobile exhaust.

#### 2.1.2.3 Nitrogen Dioxide ($NO_2$)

Nitrogen dioxide is a brownish red toxic gas at high temperatures. Nitrogen dioxide is a good oxidant and can react with the lung epithelium to produce reactive oxygen and nitrogen species. $NO_2$ plays an important role in the formation of ozone (American Lung Association, 2018).

A short-term $NO_2$ concentration in excess of 200 $\mu g/m^3$ in gas causes severe inflammation of the respiratory tract (World Health Organzation, 2018c). In addition, $NO_2$ is the main source of nitrate aerosols and constitutes a major part of $PM_{2.5}$ and ozone under ultraviolet light. The main source of anthropogenic release of $NO_2$ is combustion processes involved in heating, generating power, and providing energy for motor vehicles and ships (World Health Organzation, 2018c). Epidemiological studies (World Health Organzation, 2018c) have shown that increased bronchitis symptoms in children with asthma are associated with prolonged exposure to $NO_2$ .

#### 2.1.2.4 Sulfur Dioxide ($SO_2$)

Sulfur dioxide is a colorless gas with a pungent odor. It is derived from burning fossil fuels (coal and petroleum) and smelting minerals containing sulfur. The main source of man-made $SO_2$ is "burning fossil fuels for home heating, power generation and motor vehicles" (World Health Organzation, 2018c). $SO_2$ can affect the respiratory system and lung function and irritate the eyes. Inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis and makes people more susceptible to respiratory infections. On days when the level of $SO_2$ in the air is high, the number of people who go to the hospital due to heart disease increases, and the mortality rate increases (Frye et al., 2003).

Sulfuric acid is formed when $SO_2$ is combined with water; this is a major component of acid rain and is a cause of tree death. Exposure to $SO_2$ at a concentration of 500 $\mu g/m^3$ should not exceed 10 minutes on average. Studies (Frye et al., 2003) have shown that some asthmatic patients have changes in lung function and respiratory system after 10 minutes of exposure to $SO_2$. Although the effect of exposure to low concentrations of $SO_2$ is uncertain, reducing its concentration dioxide is likely to reduce the effects of exposure to mixed pollutants (World Health Organzation, 2018c).

#### 2.1.2.5 Ozone ($O_3$)

Unlike the upper atmospheric ozone layer, $O_3$ on the ground is a major component of photochemical smog. It is formed by the reaction of pollutants such as nitrogen oxides (NOx) released by vehicles and industries, and VOCs released by automobiles, solvents and industry. When the sun is shining, $O_3$ pollution is the most serious. Excessive $O_3$ in the air has a significant impact on human health. It can cause breathing problems and lung disease, trigger asthma, and reduce lung function (World Health Organzation, 2018b). As recent evidence indicates, between daily mortality and $O_3$ levels are linked; thus the previous limits recommended by the WHO Air Quality Guidelines (120 $\mu g/m^3$) are downgraded to 100 $\mu g/m^3$ 8-hour mean (World Health Organzation, 2018c).

See Table 1 for a summary of the information presented in this section.

**Table 1 Summary of Air Pollution Types, Major Sources and Health Impacts**

| | Major Sources | Guideline Values (WHO) | Health Impacts |
|---|---|---|---|
| Particulate Matter (PM) | Construction sites, unpaved roads, fields, smokestacks or fires; or complex reactions of chemicals such as sulfur dioxide and nitrogen oxides from power plants, industries and automobiles. | $PM_{2.5}$ 25 μg/m$^3$ $PM_{10}$ 50 μg/m$^3$ | Cardiovascular, respiratory diseases, and lung cancer |
| Ground-level Ozone ($O_3$) | VOCs from automobiles, solvents and industry react with sunlight. | 100 μg/m$^3$ (8 hrs average) | Asthma, lower lung function, cause lung disease |
| Carbon Monoxide (CO) | Gas-powered generators, motor vehicles, boats. | No guideline for ambient air. 1,200 as IDLH by the U.S.CDC NIOSH* | CO Poisoning can be fatal. |
| Sulfur Dioxide ($SO_2$) | Combustion of fossil fuels (coal and petroleum) for home heating, power generation and motor vehicles and the smelting of minerals containing sulphur | 20 μg/m$^3$ 24-hour mean 500 μg/m$^3$ 10-min mean | Affects respiratory and lung function and irritates the eyes. Inflammation of the respiratory tract causes coughing, mucus secretion, aggravation of asthma and chronic bronchitis and makes people more susceptible to respiratory infections, heart disease. |
| Nitrogen Dioxide ($NO_2$) | Combustion process (heating, power generation, and engines for motor vehicles and ships) | 40 μg/m$^3$ (year average) | Severe inflammation of the respiratory tract, asthma and bronchial inflammation in children, weakened lung function |

*Note that IDLH refers to Immediately Dangerous to Life or Health concentrations; CDC: Centers for Disease Control and Prevention. NIOSH is The National Institute for Occupational Safety and Health.

### 2.1.3 Other Effects

Besides impacting health, air pollution can have other adverse effects. A joint study of the World Bank and the Institute for Health Metrics and Evaluation (IHME) (The World Bank, 2016) estimated that the deaths from air pollution cost US $225 billion of the global economy.

### 2.1.4 General Methods to Eliminate Air Pollution

Policy efforts can be effective in mitigating air pollution. The WHO (World Health Organzation, 2018c) identifies several successful examples. These include policies aimed at industry, energy production, transportation and waste management. As noted by the WHO (2018c), policies can also be developed that help planners design and create greener urban areas (see Table 2).

**Table 2 Successful Examples of Air Pollution Control Policies**

| The policy filed | Policies |
|---|---|
| For industry | Clean technologies that reduce industrial smokestack emissions |
| | Improved management of urban and agricultural waste |
| | Capture of methane gas emitted from waste sites as an alternative to incineration (for use as biogas) |
| For energy | Ensuring access to affordable clean household energy solutions for cooking, heating and lighting |
| For transport | Shifting to clean modes of power generation |
| | Prioritizing rapid urban transit |
| | Walking and Cycling networks in cities as well as rail interurban freight and passenger travel |
| | Shifting to cleaner heavy-duty diesel vehicles and low-emissions vehicles and fuels, including fuels with reduced sulfur content |
| For urban planning | Improving the energy efficiency of buildings and making cities greener and more compact, and thus energy efficient; |
| For power generations | Increased use of low-emissions fuels and renewable combustion-free power sources (like solar, wind or hydropower) |
| | Co-generation of heat and power; and distributed energy generation (e.g. mini-grids and rooftop solar power generation) |
| For municipal and agricultural waste management | Strategies for waste reduction, waste separation, recycling and reuse or waste reprocessing |
| | Improved methods of biological waste management such as anaerobic waste digestion to produce biogas, as a low cost alternative to the open incineration of solid waste |
| | Where incineration is unavoidable, then combustion technologies with strict emission controls are critical |

## 2.2 SURFACE ATMOSPHERE TEMPERATURE INVERSIONS

A temperature inversion is a meteorological condition that usually results in a poor-dispersing atmospheric environment (Sadar, 2018). When temperature inversions occur, air pollutants are trapped and accumulate in the atmosphere, which leads to the high concentration of air pollutants that are harmful to human health.

### 2.2.1 Troposphere and Temperature

In the troposphere, every 1 km higher in altitude leads to an average temperature decrease of 6.5 Celsius. This cooling occurs as a result of the adiabatic process. At higher elevations, air pressure is lower, allowing a volume of air to expand. In order to achieve that, a certain amount of energy is needed to be applied in the surrounding area, thus the air temperature will go down, according to the first law of thermodynamics (Sadar, 2018).

### 2.2.2 Surface Temperature Inversions and Air Pollution Dispersion

During normal conditions, air temperature decreases with increasing altitude. Warm ground keeps low lying air warmer than air higher up. As warm air rises, it mixes with the layers higher up, as well as with the air pollutants present in the atmosphere.

At times, a different scenario occurs overnight, when ground cools, which in turn cools the air at ground level, resulting in air temperatures that increase with higher altitudes (Sadar, 2018). As a result, warmer, lighter air is found above cooler, heavier air. This is referred to as a temperature inversion. In such situations, air is stable and there is no mixing of pollutants with the higher atmosphere, so that pollution can be trapped.

### 2.2.3 Famous Cases Caused or Worsened by Temperature Inversions

Some notable cases of temperature inversions that have led to dangerous events caused by a high concentration of air pollution due to extremely poor air dispersion conditions usually lasting for more than one day are the following:

The Meuse Valley Incident in the Meuse Valley Industrial Zone in Belgium, from December 1-5, 1930, left about 6,000 residents with respiratory disease and more than 60 people dead (Jun, 2012).

The Donora Incident in Donora, Pennsylvania, USA, from October 26-31, 1948, accounted for 43% of the town's 5911 residents' respiratory problems and 20 people were killed (Bachmann, Calkins, & Oge, 2017).

Los Angeles (CA, USA) experienced periods of photochemical smog from 1940-1960. Some of the most serious situations, in December 1951 and September, 1955 led to more than 400 people 65 and older dying in each case (Tiao, Box, & Hamming, 1975)

The London (England) Smog from December 5-8, 1962, caused more than 4,000 deaths in four days according to a 1962 report, but some recent studies indicate the death toll might be over 12, 000 (Bell, Davis, & Fletcher, 2004).

In the Yokkaich (Japan) Asthma Incident, which occurred between 1960 and 1972, 817 people suffered from asthma and more than 10 people died (Guo, Yokoyama, Suenaga, & Kida, 2008).

The Bhopal (India) Gas Tragedy on December 3, 1984, caused the deaths of more than 2,500 people , injured 200,000 people, and blinded 50,000 of them (Eckerman, 2005).

## 2.3 GENERAL INFORMATION ON ALLEGHENY COUNTY, PENNSYLVANIA, UNITED STATES

Allegheny County is located in southwest PA, in the US. The Allegheny and Monongahela rivers meet in downtown Pittsburgh and form the Ohio River. Allegheny County gets its name from the river of the same name. The county covers an area of 1,930 square kilometers. Of that, 1,900 square kilometers is land and 36 square kilometers is water (United States Census Bureau, 2015).

Allegheny County, the biggest county in southwestern PA, is estimated to have reached 1.22 million population by July 2017, with the racial/ethnic profile at 80.3% white, 13.5% black/African American, and 4.0% Asian (United States Census Bureau, 2017). The municipality of Pittsburgh, with a reputation as "the city of three rivers," is the largest city in and the county seat of Allegheny County; it reached a population of about 0.3 million by 2015.

According to the Allegheny County Mortality Report 2015 which was published in January 2018, 13,844 deaths occurred in 2015; the all-cause age-adjusted mortality rate was 782.5/100,000, higher than those of PA (766.3/100,000) and the US (733.1 /100,000).

Pittsburgh's climate is referred to as temperate continental humid with distinct seasons. The winter is cold and damp with daily highest temperatures frequently below 0 ° C (32 ° F). During winter, on average the daily minimum temperature is lower than -10 ° C (14 ° F) on 22 days, and the daily minimum temperatures are lower than -15 ° C (5 ° F) on about seven days (NowData).

Pittsburgh is relatively hot and humid during the summer. On average, on about 29 days temperatures reach more than 30 ° C (86 ° F). Records show that temperatures reaching above 35 ° C (95 ° F) and higher occurred in only 20% of the years (NowData). The mean temperature during the summer is 22.6 ° C (72.6 ° F), and the extreme maximum temperature is 39 C (103 F), which occurred on July 16, 1988. The average frost-free period in Pittsburgh is 173 days. The average snowfall is measured between November 14 and April 6 of the next year. The average annual snowfall is 105 centimeters (41.4 inches). The largest snowfall on record was in the 1950-51 winter with 208 centimeters (82.0 inches) of accumulated snow (NowData) The annual precipitation is about 970 mm (38.2 inches), with a relatively average distribution. The annual extreme minimum precipitation was 575 mm (22.65 inches), recorded in 1930, and the maximum was 1,458 mm (57.41 inches), measured in 2004.

## 2.4 GENERAL INFORMATION ON BEIJING, CHINA

### 2.4.1 Air Pollution in Beijing

In 2008 when the Olympics were held in Beijing, China, US cyclists were seen at the Capital Airport of Beijing wearing masks specially designed to protect them from potential air pollution harm. The general public in China, despite their bafflement, had secretly worried about the air quality (Macur, 2008). For years Chinese people had been told that the weather that blurred the vision was fog, caused by excessive water in the air. Even though occasionally these “clean fogs” would happen in the dry winters and gave off a bad smell or even irritate the throat, the air quality reported by TV stations and various media was “good,” indicating that there were no air pollution problems in Beijing (Opinion, 2015).

In the same year as the Olympics, the US Embassy in Beijing started to post hourly AQI reports on Twitter, and the data were automatically collected and tweeted by air quality monitors installed on the rooftop of the US Embassy building in Beijing. These data were meant to inform US citizens living in China about air quality conditions and warn if a severe pollution day was happening (Opinion, 2015)[1].In 2010, the US Embassy in Beijing posted a daily air quality Twitter

[1] Author note: In normal cases, websites blocked in China are accessible within certain areas in China, so the US embassy staff and their families were able to read these posts on Twitter.

that described Beijing's air quality as "crazy bad" because the AQI exceeded the US EPA's highest level. After this tweet was widely circulated on social media, no matter how this information bypassed the firewall (CBS News, 2012), what people had suspected but with no solid evidence, was finally confirmed. According to a popular media source, Beijing's air quality has since become a part of daily concern for the general public (Opinion, 2015).

Beijing's air pollution fluctuates from good to very bad, but the government has taken a series of emission reduction measures, and the situation has improved (Beijing Municipal Bureau of Ecology and Environment, 2018). In 2018 for example, from January to October, the average $PM_{2.5}$ concentration was 49. Compared to the same period of time in 2017, the number dropped by 18.3%, and it is the lowest number based on available data (Beijing Municipal Bureau of Ecology and Environment, 2018). However, some severe air pollution still occurs and became more frequent beginning in November (see Table 3).

**Table 3 Pollution Levels Reported Since October 2018 in Beijing, China**

| Date | AQI | Level |
|---|---|---|
| 10/5/2018 | 107 | Light Pollution |
| 10/13/2018 | 109 | Light Pollution |
| 10/14/2018 | 190 | Medium Pollution |
| 10/15/2018 | 202 | Heavy Pollution |
| 10/21/2018 | 150 | Medium Pollution |
| 10/22/2018 | 158 | Medium Pollution |
| 10/25/2018 | 112 | Light Pollution |
| 11/2/2018 | 152 | Medium Pollution |
| 11/3/2018 | 211 | Heavy Pollution |
| 11/4/2018 | 102 | Light Pollution |
| 11/12/2018 | 132 | Light Pollution |
| 11/14/2018 | 270 | Heavy Pollution |
| 11/13/2018 | 230 | Heavy Pollution |

(Data were obtained from aqistudy.cn and translated into English by the author. The colors were used in the original database. Source:
https://www.aqistudy.cn/historydata/daydata.php?city=%E5%8C%97%E4%BA%AC&month=2018-11)

### 2.4.2 Emergency Response Plan for Heavy Air Pollution in Beijing

According to the very recently updated *Beijing Emergency Response Plan for Heavy Air Pollution (Revised in 2018)* released and immediately enforced on October 19, 2018 (People's Government of Beijing, 2018), air pollution alerts were segmented into three levels based on their severity and duration, from the most severe (red) to medium (orange) and least severe (yellow).

Red Level alert conditions occur when it is predicted that the daily AQI mean >200, will last for four days (96 hours) or more. In addition, the duration of AQI daily mean >300 will last for two days (48 hours) or more; or the daily AQI is predicted to reach 500.

Orange Level alert conditions indicate that the daily AQI mean is predicted to be >200, and it will last for three days (72 hours) or more. This does not reach higher alert level conditions.

Yellow Level alert conditions predict that the daily AQI mean >200, will last for two days (48 hours) or more, and does not reach a higher alert level condition.

Compared to the earlier version, which was updated in 2017, the latest version canceled the blue level alert. The blue level alert would be released when the city's AQI daily average value was predicted to be > 200, and it would last for one day (People's Government of Beijing, 2018). There were no other major changes in the updated version.

Air pollution alert levels result in a number of measures: Health Protection Guidance Measures, Suggested Emission Reduction Measures and Mandatory Emission Reduction Measures(People's Government of Beijing, 2018). For example, the Red Level involves Health Protection Guidance Measures, which include closing kindergartens, primary schools and high schools; Suggested Emission Reduction Measures encourage the public to travel by public transportation and shut off engines while waiting at traffic lights; Mandatory Emission Reduction Measures include stopping construction, permitting vehicle use based on odd-even end numbers, and ending or restricting production as mandated during the Red Level alert (People's Government of Beijing, 2018).

Addressing heavy air pollution caused by sandstorms is guided by the "*Beijing Dust Storm Disaster Emergency Plan*." Issuing health protection tips in a timely way for short-term heavy pollution or heavy air pollution caused by ozone that does not meet the conditions for early warning is a way that the government can help protect people's health (People's Government of Beijing, 2018).

### 2.4.3 Demography in Beijing

China is the largest populated country in the world. Beijing, as the capital city, had 21.71 million people as of 2016 (Beijing Statistic Bureau 北京市统计局, 2015). The ethnic distributions is as follows: Han account for 95% of the total population, followed by Manchu (1.84%) and Hui (1.74%) (Department of Population Social Science and Technology Statistics of the National Bureau of Statistics of China, Department of Economic Development of the State Ethnic Affairs Commission of China, & 2003).

The population of Beijing is about 22 times of that of Allegheny County. The large number of people and the high density worsen air pollution issues in Beijing. The expanding population contributes to air pollution, and it also has to bear the consequences of air pollution. More importantly, because the exposure base is so large, the impact of air pollution will be significant, which makes it urgent and vital to address air pollution in the area as soon as possible.

### 2.4.4 Geography

Generally speaking, geography and meteorological conditions are closely related. For example, air circulation in plains areas is better than in valley basins. Another example is that when the surface lacks vegetation, strong peak heating effects during the day will create an atmospheric inversion in the valley.

Beijing is located in the northwest edge of the north China plain (see Figure 1), backed by the Taihang Mountain, Yumai Mountain and Yanshan Mountain. It is about 150 kilometers southeast of the Bohai Sea. The city is about 160 kilometers from east to west, 176 kilometers from north to south, and covers 16,411 square kilometers in land area (Beijing Government).


**Figure 1 Map of China and the Relative Position of Beijing**

(The picture is a screenshot from Google Map 20181026 and Beijing is hand-marked by the author)

In general, Beijing is higher in the northwest and lower in the southeast. The geological structure under the city consists of two major features, the northwest mountainous area and the southeast plain (See Figure 2). The average altitude of Beijing is 43.5 meters; the altitude of the plain is 20-60 meters, while the mountain altitudes are generally 1000 – 1500 meters (Beijing Bureau of Soil Resource Management 北京市土壤资源管理局, 2011).


**Figure 2 Map of Beijing with Topography and Elevation**

(The picture is a screenshot from Google Map 20181201)

As noted, Beijing is the capital city of China and one of the four municipalities directly under the central government (The Central People's Goverment of the People's Republic of China, 2013). Beijing is an independent municipality and is surrounded by a same-level administrative region, Hebei Province. Tianjin, another Direct Controlled Municipality, is also located inside

Hebei Province, and linked to Beijing in its northwest (see Figure 3). Because these three administrative regions are closely connected to each other, the Beijing-Tianjin-Hebei Urban Agglomeration (Xin et al., 2012), also known as Jingjinji, or JJJ, was established by the Central Government of China in 2015. Together they made 1.1 billion US dollars in 2016, around 10% of China's Nominal GDP (China National Bureau of Statistics, 2018). This area is around 218,000 square kilometers and possesses about 0.1 billion people which is 10% of China's population.


**Figure 3 A Map of Beijing, Tianjin and Hebei (Jingjinji, JJJ) with Rough Outlines**
(The map is a screen shot from Google Map and outlines were hand drawn by the author.)

There are four mountains with a height of 2,000 meters in Beijing: the Baihua Mountains and Donling Mountains in the north, the Dahaituo Mountains and Wuling Mountains in the west. In addition, more than 17 mountains surround Beijing.

Forest covers 35.84% of Beijing, according to the eighth national forest resources inventory survey. The area of the forest is 5,881 thousand hectares and a forest reserve of 15.2533 million cubic meters (Beijing Bureau of Soil Resource Management 北京市土壤资源管理局, 2011) .

There are more than 80 major and minor rivers (Beijing Municipal Bureau of Agriculture, 2004). The major ones are Forever Peace (Yongding) River, White Tide (Chaobai) River, North Canal (Beiyun) River and No Horse (Juma) River. Beijing has no natural lake (Beijing Municipal Bureau of Agriculture, 2004).

Beijing is located in a warm temperate semi-humid region and the climate is referred to as warm temperate semi-humid continental monsoon. The average annual rainfall is about 600 mm on the plains with the largest 24-hour rainfall on record at 404.2 mm. The average annual maximum snow 7.5 cm with 33.5 cm historical maximum snow depth. Beijing has four distinct seasons: spring, which is windy and dusty; summer, which is hot and rainy; autumn, which is sunny and dry; and winter, which is cold and windy. Spring and autumn are short, and last about a month each; summer and winter are long, nearly five months each. Beijing experiences monsoon characteristics, with 60% of the annual precipitation concentrated in the summer months of July and August, while the air in other seasons is drier. The annual average temperature is 13.1 ° C. The average temperature of the coldest month (January) is -2.9 ° C. In July, the average temperature is 26.9 ° C (Han et al., 2015).

### 2.4.5 Epidemiology

In China, three million people die prematurely every year due to a number of preventable diseases, estimated by WHO (World Health Organzation, 2015). According to the news released by the Beijing Municipal People's Government Information Disclosure Platform "The Window of Beijing" (eBeijing 北京市人民政府, 2018), the 2017 Beijing Public Health and Population Report pointed out that the top three causes of death among Beijing civilians total were malignant tumors, heart disease and cerebrovascular diseases, accounting for 71.7% of all-cause death.

In 2017, the mortality rate of Beijing residents with malignant tumors was 183.76/100,000, accounting for 26.9% of the total mortality rate, which increased 3.6% compared to 2016. The mortality rate of males with malignant tumors was 220.00/100,000, and that of females was 147.67/100,000. The top three causes of death of for males with malignant tumors were lung cancer, liver cancer, and colorectal/anal cancer (author's note: these two cancers were calculated as one kind of cancer in China), which account for 55.9% of male malignant tumor death. For females the causes were lung cancer, colorectal/anal cancer, and breast cancer; these three account for 46.1% of female malignant tumor deaths (eBeijing 北京市人民政府, 2018).

Compared to 2015, the lung cancer incidence in 2016 increased 27.5%. Compared to 2016, the lung cancer in 2017 incidence increased by 24% (People' Daily News, 2015).

Beijing Municipal Commission of Health and Family Planning (北京市卫生和计划生育委员会) is studying the relationship between air pollution and the incidence of certain diseases, according to a news article released at Xinhuanet at the beginning of 2017 (Wu et al., 2017). Plans are to produce an official report by the government for the public that defines if air pollution in Beijing is responsible for the increase in malignant cancer and lung disease.(Wu et al., 2017).

# 3.0 DATA COLLECTION

## 3.1 METHOD TO DETERMINE AND FORCAST MSTIS

An Air Pollution Administrator at the ACHD in Pittsburgh, PA developed the procedure used in this paper. MSTIs data were examined beginning in 2008, and in 2014 forecasting began for the next morning's air dispersion conditions based on the empirical model. While the author worked as an intern at the ACHD during the summers of 2017 and 2018, she helped refine the procedure and tested how some certain meteorological factors might affect MSTIs. The usage of data and model in this article has been approved.

### 3.1.1 Collecting Upper Air Data as Weather Service Providers

To collect temperature and various other atmospheric conditions starting at the surface, a weather balloon is launched with a measurement transmitter (see Figure 4 below) into the atmosphere twice a day, once in the morning and once in the evening. There are approximately 900 locations around the world that launch balloons twice a day. In the US, the National Weather Service launches the balloons and collects the data.

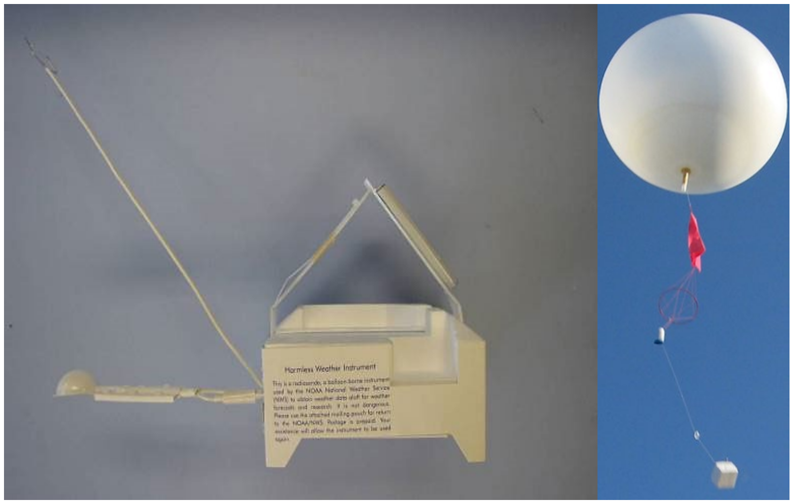


**Figure 4 Radiosonde with Balloon and Parachute vs. the Measurement Transmitter**

(The left photo is the measurement transmitter. Photo from U.S. National Weather Service www.weather.gov/upperair/factsheet. The right is Photo is the radiosonde with balloon and parachute, Photo from Radiosonde Museum of North America http://radiosondemuseum.org/what-is-a-radiosonde/)

Data from weather balloons are critical to show the big picture of global atmospheric conditions at two specific points in time: 00 Z and 12 Z. "Z" here stands for Zulu time, also known as UTC (Coordinated Universal Time, or Temps Universel Coordonné). UTC is a synchronized time based on the sun's movement and the time set by the regional meridian is abandoned. This time calculation system is derived from the world time. It avoids the complexity of daylight savings time system in some countries and regions. In Beijing, 00 Z = 8:00 am on the same day, and 12 Z = 8:00 pm same day. Beijing does not have daylight saving time. In AC, 00 Z = day before 8 PM Eastern Daylight Time (EDT) or 7 AM Eastern Standard Time (EST); 12 Z = same day 8 AM EDT or 7 AM EST same day.

00Z and 12Z are important to this article because of the diurnal variation of temperature, sunlight intensity and vertical temperature profile in continental mid latitudes (see Figure 5). The figure depicts the usual sequence of events leading to the formation and dissipation of a ground-level radiation-type inversion (see Table 4). The graphs show the changes of sun radiation with time and temperature changes with height and time. The graph shows that temperature inversions usually form overnight, are the strongest before dawn, and begin to burn off after sunrise and disappear before noon. It is assumed that there is little or no cloud during the sequence of events shown and the wind speed remains light.

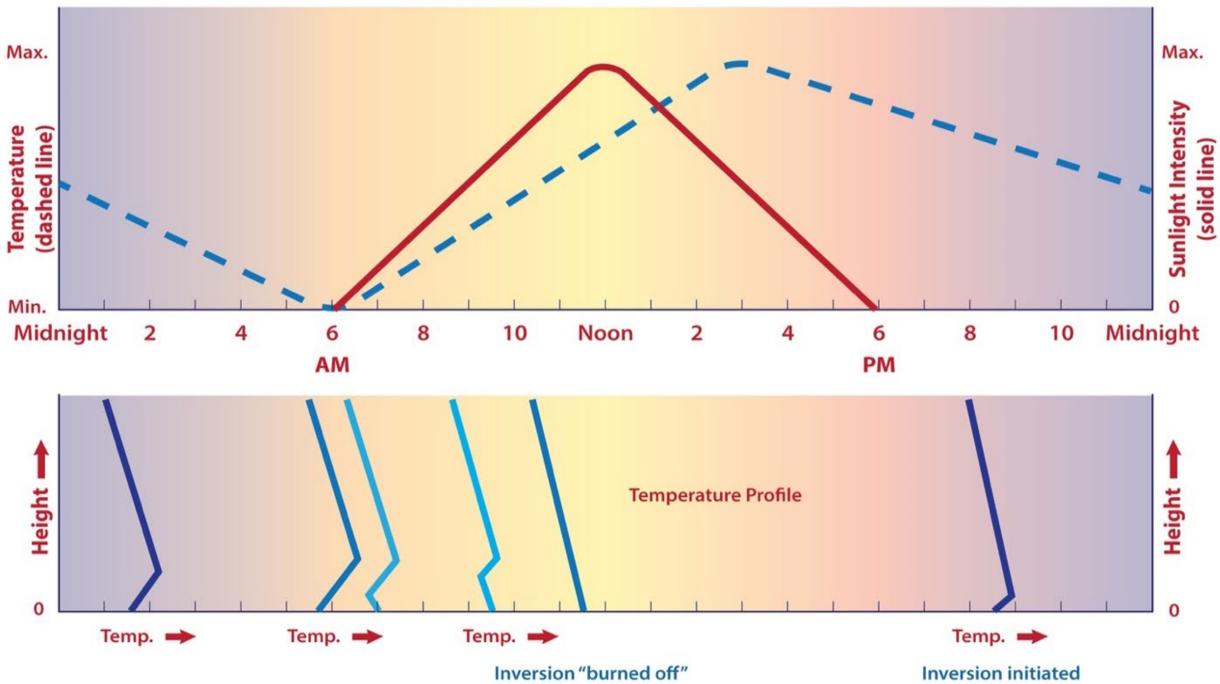


**Figure 5 Typical Stylized Diurnal Variation of Temperature, Sunlight Intensity, and Vertical Temperature Profile in Continental Mid-latitudes**
(Graph and explanation by Mr. Sadar with his permission to use)

**Table 4 Explanation of Figure 5**

| | |
|---|---|
| 6 AM - (Sunrise) Sunlight intensity at surface weak, temperature begins to increase from overnight minimum, ground inversion strongest. | Noon - Sunlight intensity maximum. |
| 7 AM - Sunlight intensity increases as sun rises and ground is warmed which in turn warms air. Thus, inversion "burns off" from ground up. | 3 PM – Approximate time of maximum temperature (because of time lag between ground heating and subsequent air heating). |
| 11 AM – Inversion completely burned off (i.e., isothermal or typical daytime profile developed). | 6 PM - (Sunset) Sunlight intensity negligible, temperature decreasing, ground inversion soon to begin. At night, temperature decreases, ground inversion strengthens. |

(Graph and explanation used with permission)

Allegheny County and Beijing have a 13-hour time difference during winter and 12 hours during summer; the two observation times have 12-hour interval as 00Z and 12Z. Since 12Z (7 AM EST at AC) data is used to identify MSTIs in AC, it is reasonable to use 00Z (8 AM at Beijing) data to identify MSTIs in Beijing.

Both AC and Beijing are located at continental mid-latitude, as mentioned in 2.3 and 2.4.4. The observation stations in Beijing and AC, coded as ZBAA for Beijing-Capital International station, and KPIT for the Pittsburgh International Airport station, have almost the same latitude (see Table 5.) at about +40. This similarity makes the ACHD procedure developed for AC applicable to Beijing.

**Table 5 Stations Information of ZBAA and KPIT**

| USAF | WBAN | STATION NAME | CTRY | CALL | LAT | LON | ELEV(M) |
|---|---|---|---|---|---|---|---|
| 545110 | 99999 | BEIJING-CAPITAL INTERNATION | CH | ZBAA | +40.080 | +116.585 | +0035.4 |
| 725200 | 94823 | PITTSBURGH INTERNATIONAL AIRP | US | KPIT | +40.485 | -080.214 | +0366.7 |

USAF = Air Force station ID. May contain a letter in the first position.
WBAN = NCDC WBAN number
CTRY = FIPS country ID
LAT = Latitude in thousandths of decimal degrees
LON = Longitude in thousandths of decimal degrees
ELEV = Elevation in meters above mean sea level

### 3.1.2 Collecting Upper Air Data as Researchers

The Integrated Global Radiosonde Archive (IGRA) consists of radiosonde and pilot balloon observations at over 2,700 globally distributed stations. The data included in the IGRA began in 1905. Observations are available at standard and variable pressure levels, fixed- and variable-height wind levels, and the surface and tropopause. Variables include pressure, temperature, geopotential height, relative humidity, dew point depression, wind direction and speed, and elapsed time since launch. The National Oceanic and Atmospheric Administration (NOAA) has the raw archived stored at https://www1.ncdc.noaa.gov/pub/data/igra/.

The Department of Atmospheric Science in the College of Engineering at the University of Wyoming (UWYO) built a website (http://weather.uwyo.edu/upperair/sounding.html) using the raw data from IGRA and integrated these data with the world map (see Figure 6). It is easy for researchers to visually locate the station in which they are interested by utilizing the map, especially when a comparison with a synoptic map or an upwind/downwind positioning is needed. More conveniently, the UWYO website provides 13 types of plots, including text, GIF and PDF. The Stuve Diagram (The Pseudo Adiabatic Diagram) and SkewT-LogP diagrams on this website are produced from the IGRA program and are very helpful for quickly and intuitively positioning MSTIs.


**Figure 6 A Screenshot of Website of UWYO**

When looking at IGRA data, only height and temperature data are used to determine MSTIs (as the red frame in Figure 7 shows). Other variables are also valuable, as they are important descriptive factors for the atmospheric conditions at the time of MSTIs. Further research on them helps to understand, describe and predict MSTIs.

## 72520 PIT Pittsburgh Observations at 12Z 04 Aug 2018

| PRES hPa | HGHT m | TEMP C | DWPT C | RELH % | MIXR g/kg | DRCT deg | SKNT knot | THTA K | THTE K | THTV K |
|---|---|---|---|---|---|---|---|---|---|---|
| 1000.0 | 171 | | | | | | | | | |
| 979.0 | 359 | 19.0 | 18.8 | 99 | 14.15 | 140 | 2 | 293.9 | 334.5 | 296.4 |
| 963.0 | 501 | 21.2 | 18.6 | 85 | 14.21 | 205 | 9 | 297.5 | 338.9 | 300.1 |
| 953.0 | 591 | 22.2 | 15.2 | 65 | 11.52 | 246 | 13 | 299.4 | 333.4 | 301.5 |
| 950.9 | 610 | 22.2 | 15.0 | 63 | 11.39 | 255 | 14 | 299.7 | 333.3 | 301.7 |
| 945.0 | 664 | 22.4 | 14.4 | 61 | 11.03 | 255 | 13 | 300.4 | 333.0 | 302.4 |
| 925.0 | 849 | 21.0 | 15.0 | 69 | 11.72 | 255 | 10 | 300.8 | 335.5 | 302.9 |
| 921.0 | 887 | 20.6 | 15.6 | 73 | 12.25 | 255 | 9 | 300.7 | 336.9 | 302.9 |
| 918.1 | 914 | 20.4 | 15.4 | 73 | 12.11 | 255 | 9 | 300.8 | 336.6 | 303.0 |
| 892.0 | 1163 | 18.4 | 13.4 | 73 | 10.94 | 267 | 7 | 301.2 | 333.7 | 303.2 |
| 886.2 | 1219 | 18.0 | 12.5 | 70 | 10.38 | 270 | 6 | 301.4 | 332.3 | 303.3 |
| 870.0 | 1377 | 17.0 | 10.0 | 63 | 8.93 | 270 | 6 | 301.9 | 328.7 | 303.6 |

**Figure 7 The Snap Shot of UWYO Text Plot**

(In this dataset, 72520 and PIT are the code of Pittsburgh Observations. 12Z is the time of the observations. PRES=Atmospheric Pressure, HGHT=Geopotential Height, TEMP=Temperature, DWPT= Dewpoint Temperature, RELH=Relative Humidity, MIXR=Mix Ratio, DRCT=Wind Direction, SKNT= Wind Speed, THTA: Potential Temperature, THTE: Equivalent Potential Temperature, THTV: Virtual Potential Temperature)

### 3.1.3 Identifying and Recording Morning Surface Temperature Inversions

Details on forecasting MSTIs have been described in an article by ACHD (Sadar, 2018). Accordingly, “Surface” is at or near ground level. “Morning” emphasized the time of the data collection each day, because MSTIs are usually the strongest near dawn, as mentioned in 3.1.1. The standards of MSTIs are defined as different from other existing surface temperature inversions metrics, as those usually have some other purpose such as preventing pesticides escaping from the air near crops, and so they typically use heights below three meters. The standards developed at ACHD are more related to public health.

After collecting height and temperature data from UWYO, one can identify if there is a MSTI. First of all, in the troposphere, temperature inversion means that temperature increases with rising height. Since the research is more concerned with human health, the inversion layer begins at the ground or below 130 meters from surface and is typically not over 700 meters above the surface. The temperature should be substantial, so within the observation height, the temperature increase should be at least 1.0 ˚C.

The depth of the inversion layer is the height difference of the start and end of the temperature inversion. When the inversion layer is at least 15 meters thick, it is recorded as a MSTI, if the temperature conditions mentioned above have been met. This thickness is required to assure that a substantial ground-level inversion is present. If the temperature decreases before increasing as height goes up, it will still qualify as a temperature inversion if the decrease is less than 1.0 ˚C.

When recording MSTIs, the quantitative strength (˚C) is calculated as the temperature difference at the top of inversion layer and at the surface. Quantitative strength is categorized as follows: None to weak (~0.4 ~3 ˚C), Moderate (~3~5 ˚C), and Strong (>=~5 ˚C). The depth (m) is recorded as the elevation of the layer top (m) reduced by the elevation of the ground (m). With respect to public health, the air within the depth of the inversion layer is confined; therefore, pollution emitted into this layer can increase to unhealthy concentrations rather quickly.

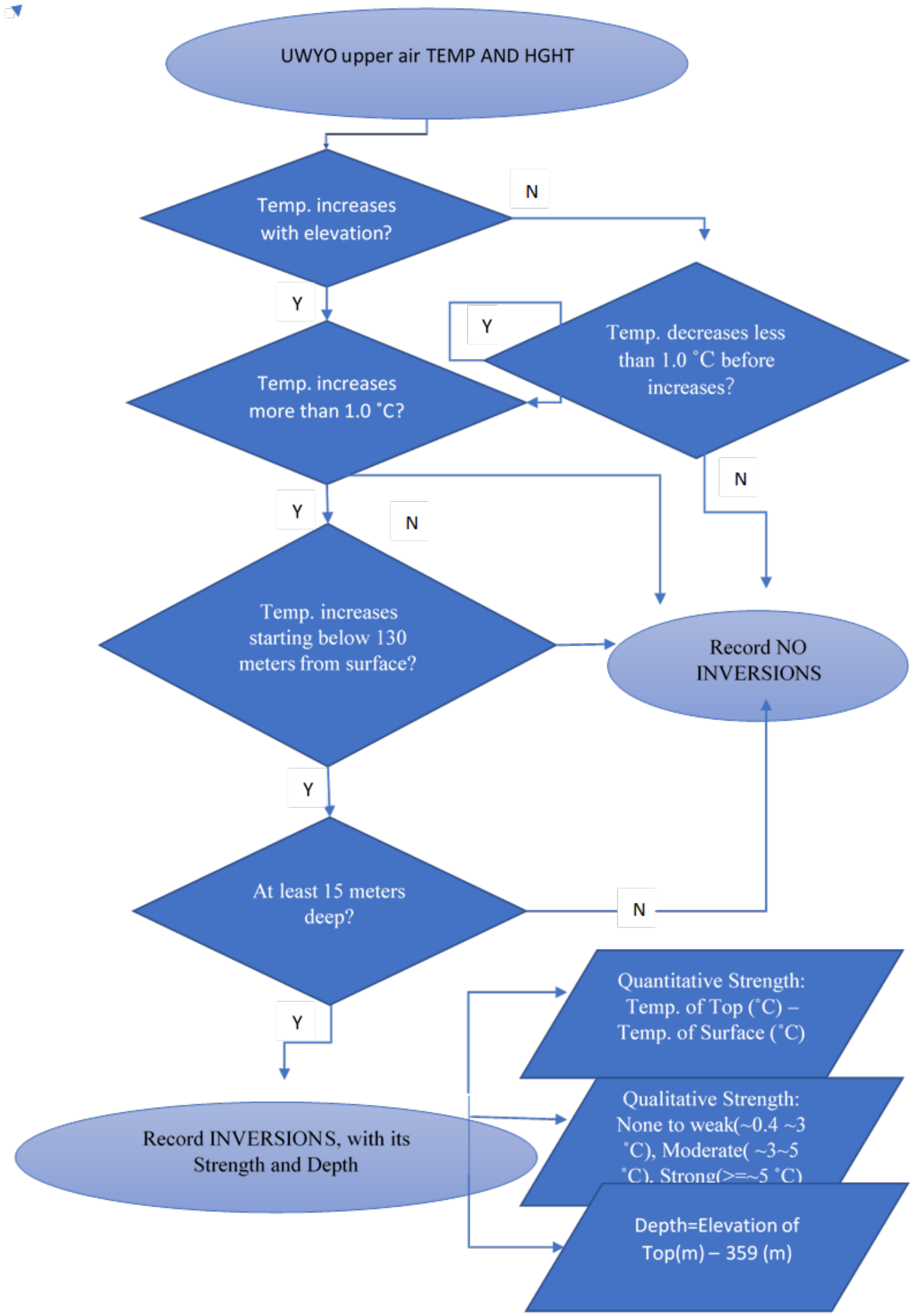


**Figure 8 The Flow Chart of Method of Identifying MSTIs in AC**

## 3.2 MSTIS IN BEIJING

### 3.2.1 2018 MSTIs in Beijing

Utilizing the method of collecting data and identifying MSTIs by ACHD, the author looked back to the Beijing data from January 2018 to June 2018 (see Table 6). These retrospective data included the strength and thickness of MSTIs as well as the air pollution situation (AQI index and pollution duration days). The measure the author is using is exactly as described in Figure 7 in section 3.1.3 for AC except that the depth of the inversion is calculated from the elevation of Beijing, which is 35 meters.

The author collected the meteorological data of the first half year of 2018. The air quality of Beijing usually worsens during cold seasons and improves during warm seasons (Che et al., 2009; Han et al., 2015). The half-year data included the cold months as well as warm months.

The average MSTIs strength of each month varied between 0 ˚ C to 5.0 ˚ C with the largest average strengths happened in March 2018. February had the most days that had MSTIs. During May and June there were no to very weak MSTIs.

**Table 6 Summary of 2018 January – June MSTIs**

| Month (2018) | Avg. Strength (˚C) | Strength Std. Dev. (˚C) | Avg. Top (m) | Top Std. Dev. (m) | Total Days of Inversion (%) |
|---|---|---|---|---|---|
| Jan | 4.6 | 3.2 | 218 | 155 | 48 |
| Feb | 3.8 | 2.2 | 177 | 160 | 61 |
| March | 5.0 | 3.9 | 380 | 306 | 45 |
| April | 3.2 | 1.5 | 268 | 89 | 13 |
| May | 0.0 | 0.0 | 0 | 0 | 0 |
| June | 0.5 | 0.9 | 91 | 177 | 29 |

To test if having MSTIs means higher AQI, an unpaired two sample t-test is used here. From January 1 to June 30, 2018, 124 days had no MSTIs, and 57 days had MSTIs. AQI of days with MSTIs and AQI of days without MSTIs were two sample groups to be tested. First, to test if two groups (no MSTIs and MSTIs) have the same variances, a F-test was used. The p-value is 0.7426 at the significant level of 0.05. The result shows that two groups have the same variances (as in Table 7).

**Table 7 Results of F-test for AQIs of Days with MSTIs and With No MSTIs**

```
. sdtest NoMSTIsAQI == MSTIsAQI

Variance ratio test
------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
NoMSTI~I |     124    98.84677    4.836862    53.86101     89.2725     108.421
MSTIsAQI |      57     99.7193    7.381849    55.73174    84.93168    114.5069
---------+--------------------------------------------------------------------
combined |     181    99.12155    4.036327    54.30323    91.15694    107.0862
------------------------------------------------------------------------------
    ratio = sd(NoMSTIsAQI) / sd(MSTIsAQI)                         f =   0.9340
Ho: ratio = 1                                    degrees of freedom =  123, 56

    Ha: ratio < 1               Ha: ratio != 1                 Ha: ratio > 1
  Pr(F < f) = 0.3713         2*Pr(F < f) = 0.7426           Pr(F > f) = 0.6287
```

Next, an unpaired two-sample t-test with equal variances was used to test if two groups have significant different means, in other words, to test if days with no MSTIs and days with MSTIs have significant different AQIs. The p-value is 0.9204 at the significant level of 0.05 (as in Table 8). This result shows that there was no significant difference in AQIs for the two groups, meaning that MSTIs do not affect AQI in Beijing.

**Table 8 Results of Unpaired Two Sample T-test with Equal Variances for AQIs of Days with MSTIs and With No MSTIs**

```
. ttest NoMSTIsAQI == MSTIsAQI, unpaired

Two-sample t test with equal variances
------------------------------------------------------------------------------
Variable |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
NoMSTI~I |     124    98.84677    4.836862    53.86101     89.2725     108.421
MSTIsAQI |      57     99.7193    7.381849    55.73174    84.93168    114.5069
---------+--------------------------------------------------------------------
combined |     181    99.12155    4.036327    54.30323    91.15694    107.0862
---------+--------------------------------------------------------------------
    diff |           -.8725241    8.713934               -18.06778    16.32273
------------------------------------------------------------------------------
    diff = mean(NoMSTIsAQI) - mean(MSTIsAQI)                      t =  -0.1001
Ho: diff = 0                                     degrees of freedom =      179

    Ha: diff < 0                 Ha: diff != 0                 Ha: diff > 0
 Pr(T < t) = 0.4602         Pr(|T| > |t|) = 0.9204          Pr(T > t) = 0.5398
```

The conclusion from the unpaired two-sample t-test with equal variances that AQI of days with MSTIs and with no MSTIs were not significantly different seems to contradict the hypothesis that MSTIs affect AQI. However, it could be explained by recognizing that AQI is 24-hour daily value, and MSTI value is an average for only one hour in the morning. It could also be that the criteria for AC might not be applicable for Beijing, because some higher inversions did not qualify as MSTIs (see Appendix A for MTSI records for Beijing from January to June 2018).

To test if the strength of MSTIs affect the level of AQI, another test of linear regression was used among days with MSTIs. Fifty seven days had MSTIs based on criteria established at ACHD. A linear regression of MSTI strength and AQI was conducted to see their relationships. The P value of strength is 0.013 with the confidence interval of 95% (as in Table 9). This result indicates that the strength of MSTIs has significant effect on AQI, and AQI increases with the increase of MSTIs in Beijing during the observation period.

**Table 9 Result of Linear Regression of AQI and MSTIs Strength**

```
. regress AQI Strength

      Source |       SS           df       MS      Number of obs   =        57
-------------+----------------------------------   F(1, 55)        =      6.60
       Model |  18645.3093         1  18645.3093   Prob > F        =    0.0129
    Residual |  155292.199        55  2823.49454   R-squared       =    0.1072
-------------+----------------------------------   Adj R-squared   =    0.0910
       Total |  173937.509        56  3106.02694   Root MSE        =    53.137

------------------------------------------------------------------------------
         AQI |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    Strength |   6.079112   2.365641     2.57   0.013     1.338262    10.81996
       _cons |   75.01891   11.91323     6.30   0.000     51.14426    98.89355
------------------------------------------------------------------------------
```

### 3.2.2 MSTIs, Air Quality, and Air Pollution Alerts in Beijing in 2018

Data on MSTIs, AQIs and pollution duration days from January to June 2018, the details of the heavy air pollution alerts issued by the Beijing government over the past few months from the news released by the media are shown in Appendix B.

The table in Appendix B lists 92 dates, MSTI strength level, and AQI. These dates were selected based on their daily average AQI, days with AQI>100, because at this level, pollution has the potential to be harmful to sensitive populations (Ministry of Environmental Protection of the People's Republic of China, 2012).

A total of seven alerts were issued by the government of Beijing. However, when looking at the air pollution levels from June 1 to June 23, AQI of 200 was reached, but no alerts were issued. These two cases were considered as type I error, which means there should have been an alert, but none was issued. In the meantime, between January 13 and April 18 the AQI never reached 200. These two cases were considered as type II error, which means that conditions did not qualify for alerts but alerts were issued. For the two cases of missing alerts, June 2 could be predicted by correctly forecasting MSTIs.

# 4.0 DISCUSSION

## 4.1 LIMITATIONS

There are several limitations of the radiosonde data from weather balloons. Approximately 900 observation points around the world launch weather balloons (usually 60 to 45 minutes earlier) to collect atmosphere data at 0 UTC and 12 UTC daily to obtain meteorological data. Since all the stations send balloons at these time spots to look at the atmosphere around the world in two given hours, there are inevitably a few regions that can use these data to predict MSTIs. These areas must meet the following condition: the sun rises at/around 12 Z or 00 Z, then the weather data for this area can be used as a reference for forecasting, especially for detecting MSTIs.

Both Beijing and AC meet this basic standard as sunrise time is around 00 Z or 12 Z—0Z for Beijing and 12 Z for AC. However, because the sunrise times in summer and winter are different, as the sun angle changes throughout seasons, while the time to launch the balloon remains fixed, it will lead to some errors. For example, for Beijing, on December 22, 2017, the sunrise was at 7:32 am. It was around half an hour before 00 Z local time of Beijing as 8 am. On June 21, 2018, the sun rose at 4:45 am, more than three hours earlier than 00 Z (Beijing does not have daylight saving time). This time difference means that the radiation from the sun to the ground may cause some MSTIs to begin to weaken during summer. As of 00 Z (8 am Beijing local time), inversions may be completely broken. This can result in weather balloon measurements at 00 Z that may miss many MSTI cases during summer time. The author suggests utilizing data from other equipment if conditions permit. The time of the sounding data should match with the sunrise time. This requires some round-the-clock testing tools, such as SODAR (Sound Detection and Ranging) and RASS (Radio Acoustic Sounding System) integrated sounding system.

In addition, the author found several errors in the UWYO Beijing data (see examples in Figure 8). Because of the particularity of IGRA's data, the initial data from the surface are generated by ground detectors and not by weather balloons. Different detection instruments will produce some deviations and can cause some data to be skewed. The discovery and collection of MSTIs are highly dependent on the relative relationship between the first and second sets of data on the surface. When these two sets of data are not generated by the same instrument, MSTIs may not be accurately captured. This is another reason to apply a similar sodar-RASS system: all data are collected by the same device in the same manner.

**54511 ZBAA Beijing Observations at 12Z 02 Jun 2018**

| PRES hPa | HGHT m | TEMP C | DWPT C | RELH % | MIXR g/kg | DRCT deg | SKNT knot | THTA K | THTE K | THTV K |
|---|---|---|---|---|---|---|---|---|---|---|
| 1003.0 | 55 | 31.2 | 9.2 | 26 | 7.33 | 205 | 6 | 304.1 | 326.4 | 305.4 |
| 1000.0 | 55 | 31.6 | 7.6 | 22 | 6.59 | 205 | 8 | 304.8 | 325.0 | 306.0 |
| 925.0 | 747 | 25.8 | 4.8 | 26 | 5.86 | 210 | 19 | 305.7 | 323.8 | 306.8 |
| 899.0 | 994 | 23.6 | 3.2 | 27 | 5.40 | 210 | 17 | 305.9 | 322.7 | 306.9 |

**54511 ZBAA Beijing Observations at 00Z 10 Jun 2018**

| PRES hPa | HGHT m | TEMP C | DWPT C | RELH % | MIXR g/kg | DRCT deg | SKNT knot | THTA K | THTE K | THTV K |
|---|---|---|---|---|---|---|---|---|---|---|
| 1002.0 | 55 | 19.4 | 14.4 | 73 | 10.39 | 45 | 6 | 292.4 | 322.1 | 294.2 |
| 1000.0 | 44 | 19.6 | 13.6 | 68 | 9.88 | 45 | 6 | 292.8 | 321.1 | 294.5 |
| 955.0 | 438 | 17.3 | 9.6 | 61 | 7.92 | 40 | 10 | 294.3 | 317.4 | 295.7 |
| 946.0 | 519 | 16.8 | 8.8 | 59 | 7.56 | 44 | 9 | 294.6 | 316.7 | 295.9 |
| 925.0 | 710 | 15.2 | 7.2 | 59 | 6.93 | 55 | 8 | 294.8 | 315.2 | 296.1 |

**Figure 9 Samples of Questionable Data Caused by Different Detectors at the Surface and in the Upper Air**

(At normal situations, with altitude increases, atmospheric pressure should decrease. Also, the latitude of Beijing Observation Station is 55 meters, so there should not be a situation that the air balloon reaches below the ground. Photos from screen shot of UWYO website. )

Another limitation of this method is that the categorized inversion strength is concluded arbitrarily. A literature review reveals that how different degrees of inversions affect air quality has not been addressed. Future research on this would look at the temperature inversion conditions when severe air pollution occurred: how many degrees (˚C) were there when these cases happened? And, how long did the inversion last?

This paper is based on MSTI data for Beijing from January to June in 2018. This may not be sufficient to accurately determine the relationship between MSTIs and Beijing's air pollution. In addition, AC and Beijing are not identical; some cases that are not counted as MSTIs in AC might be MSTIs in Beijing. The strict application of AC standards might not capture of some MSTIs in Beijing. It is recommended that future research reviews more years of data and compare it with air pollution data, and that standards be developed to more accurately identify and capture MSTIs in Beijing. Forecasting MSTIs can be added to the research direction to be more helpful in air pollution prediction.

## 4.2 RECOMMENDATIONS FOR BEIJING

### 4.2.1 Link Emergency Response System with MSTIs

Since air pollution in Beijing during 2018 appears to be related to MSTIs, it is important to observe the next morning's air dispersion condition closely. When poor air dispersion is forecasted, the potential for poor air quality rises. The early warning system/alarm system is an important link between forecasting MSTIs and administrative regulations.

ACHD has been posting air dispersion reports every morning (see example in Figure 10). These are available to the public so that agencies like the PA Department of Environmental Protection (DEP) can use the information to help predict local air quality.

ALLEGHENY COUNTY, PENNSYLVANIA
**AIR DISPERSION CONDITIONS & OUTLOOK**

**This AM Sfc. Inv.:** 3.2 °C, 307 m. Est Brk Time: 10:30am. Upper Inversion(s)*: Yes ☐ / No. ☑

* Starting at ≤ ~1000 m.

Sfc. Inv. Characterization: None ☐ / Slight ☐ / Weak ☐ / Moderate ☑ / Strong ☐

| Forecast Period | Dispersion Potential | Mixing Height (ft) | Transport Wind (dir,mph) | Ventilation Rate (mph-ft) | Wind (dir,mph) | Nite Wind (dir, mph) |
|---|---|---|---|---|---|---|
| TODAY | Fair | 7740 | W 7 | 54,180 | SW 5 | SW 5 then Lgt & Var |
| TMRW | Good | 8210 | SW 9 | 73,890 | | |

| Tomorrow Wind (dir,mph) | Tomorrow AM Sfc Inv Strength |
|---|---|
| SW 5 | Moderate to Strong |

**Substantial Precip.:** Not Expected ☑ / Begin AM ☐ / Begin PM ☐ / Begin Overnite ☐ /
Begin Tmrw AM ☐ / Begin Tmrw PM ☐ / Continue thru: ___________.

**Figure 10 An Example of Air Dispersion Conditions and Outlook**

(The daily report is accessed via internet at https://www.alleghenycounty.us/Health-Department/Programs/Air-Quality/Monitored-Data.aspx. For past data, please contact Mr. Sadar ACHD/AQP)

Beijing already has an emergency response system as mentioned in section 2.4.2. The system has been effective; the alerts issued for the first six months of 2018 had also reached 5/9 correction rate. However, as noted above, two alerts were not given on time or were never released, and there were two false alarms. One could potentially have been avoided by correctly predicting MSTIs. If the air dispersion outlook can be added into the system, and a relatively accurate method or model to forecast MSTIs can be developed, the government will have better data and evidence on which to make decisions about issuing alerts.

Besides the accuracy of alert release, the daily post of air dispersion might be helpful. The daily average AQI of 200 is a benchmark for releasing any level of alert, but 101-200 daily AQI are harmful to sensitive populations such as children, the elderly and patients with heart and respiratory disease. The ACHD air dispersion outlook is a good example of releasing the forecasting of MSTIs so that people can better plan their daily activities if they are vulnerable to air pollution below the level of alert.

### 4.2.2 Information Transparency

The ACHD has been effective in sharing information with the public. For instance, ACHD has a complete list of annual reports from the last 13 years, emission inventory reports from the last 15 years and an archive of air quality studies available to the public for downloading, studying and citing. The figure below is a screen shot of the report section of ACHD air quality.

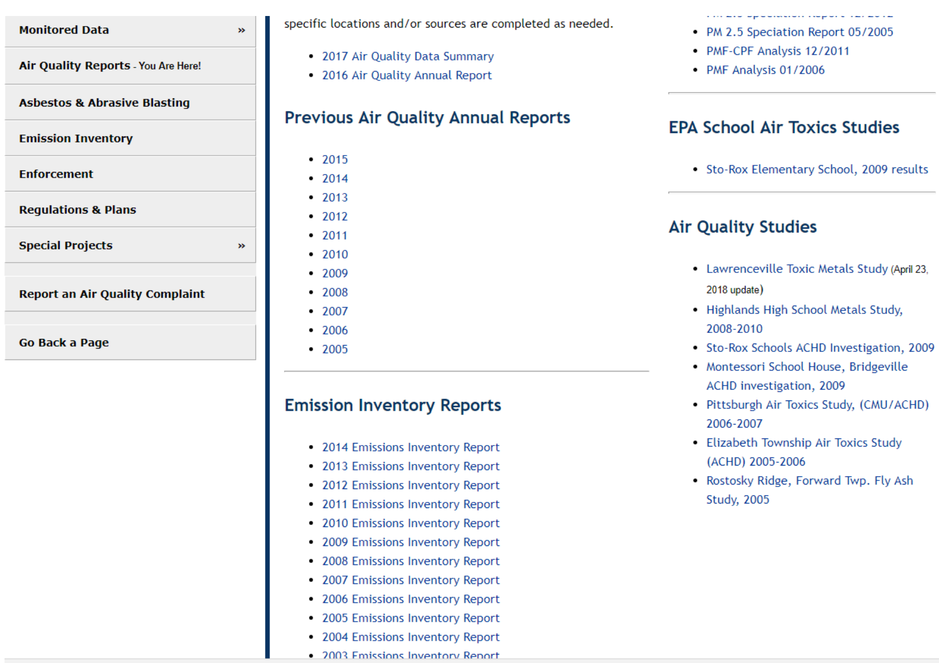


**Figure 11. The Screen Shot of the Report Section of ACHD Air Quality Website**

As of June/8/2018 3:25 am(Allegheny County Health Department, 2018)
http://www.achd.net/air/reports.html

This level of transparency is one example of how public health agencies can use best practices to communicate effectively and efficiently about public health issues with the population served, to help those served by these agencies understand the data that inform public health activities in the community; and provide resources for other organizations, including the media, that work to improve public health outcomes in the community.

# 5.0 SUMMARY AND CONCLUSION

Morning surface temperature inversions are a meteorological condition that usually weakens air dispersion potentials. Poor air dispersion conditions often lead to unhealthy air quality. Air pollution is a public health issue of great concern. A method to identify and collect data about MSTIs, developed at the ACHD, was used to retrospectively identify MSTIs in Beijing from January to June 2018. Beijing MSTI data were used to compare with the date-corresponding AQI and air pollution alert data of Beijing. The results show a relatively close relationship between MSTIs and AQI of Beijing. The alert system was not used in every case when conditions would have predicted its use. Among the missing cases, 50% could be predicted based on MSTI forecasting.

Application in Beijing of the method described in this paper can help to better detect possible poor air quality on the next day, and to issue early warnings of heavy air pollution more accurately, thereby reducing the number of exposures and consequent negative health outcomes. In the long run, this can contribute to reductions in morbidity and mortality caused by air pollution in Beijing, thus improving public health.

The limitations of the paper include the weaknesses in using radiosonde data, lack of sufficient data, and application of a method developed in Allegheny County, PA that may not be perfectly suitable for Beijing. It is recommended that future research should review more data and develop standards particular to Beijing. Forecasting MSTIs is also suggested for future research direction.

Air pollution is the result of a combination of excessive air pollution emissions and poor air dispersion. While making air dispersion conditions more predictable is important, efforts to minimize emissions of pollutants are a more manageable approach because humans cannot control the weather. Knowing what MSTIs are, how to collect and identify MSTIs, or even develop a perfect prediction tool only help us better understand air dispersion. Instead of shutting down factories and reducing the number of vehicles on the road every time poor air dispersion conditions are predicted, promoting near-zero emissions is a more effective long-term approach. With fewer pollutants in the air, air dispersion may be less important for public health.

# APPENDIX A

## MSTIS RECORDS OF ZBAA FROM JANUARY TO JUNE 2018

Note:

The grey area are days with no MSTIs. The “note” at the right records some situations that did not qualify for ACHD criteria, but the author thought worth noting. Neither the strength nor the thickness of MSTIs of these days in grey are calculated in the monthly summary located at the blue section at the bottom of each month’s table. The color in the date area (blue, orange and yellow) indicates the air pollution alert level released for those days. These tables are created by the author and the data were collected from the UWYO website.

| Date | Bot Temp | Top Temp | Strength | Start (m) | Ends (m) | Thickness (m) | Notes |
|---|---|---|---|---|---|---|---|
| 1-Jan | -6.1 | -0.9 | 5.20 | 55 | 315 | 260 | |
| 2-Jan | -5.1 | -3.8 | 1.30 | 55 | 215 | 160 | |
| 3-Jan | | | | | | | 1 inversion from 952-1028 |
| 4-Jan | | | | | | | |
| 5-Jan | -8.3 | 3.7 | 12.00 | 55 | 163 | 108 | |
| 6-Jan | -6.1 | -2.9 | 3.20 | 55 | 576 | 521 | |
| 7-Jan | | | | | | | 0.4 inversion from 55-183m |
| 8-Jan | | | | | | | |
| 9-Jan | -4.9 | -1.9 | 3.00 | 55 | 233 | 178 | |
| 10-Jan | | | | | | | |
| 11-Jan | | | | | | | |
| 12-Jan | -10.5 | -3.7 | 6.80 | 55 | 463 | 408 | |
| 13-Jan | -9.1 | -0.1 | 9.00 | 55 | 633 | 578 | |
| 14-Jan | -5.7 | -2.7 | 3.00 | 55 | 159 | 104 | |
| 15-Jan | -2.9 | -0.9 | 2.00 | 55 | 262 | 207 | |
| 16-Jan | | | | | | | |
| 17-Jan | -3.1 | -1.5 | 1.60 | 55 | 161 | 106 | |
| 18-Jan | -4.9 | -0.7 | 4.20 | 55 | 163 | 108 | |
| 19-Jan | -6.1 | 2.0 | 8.10 | 55 | 281 | 226 | |
| 20-Jan | -6.1 | 1.0 | 7.10 | 55 | 197 | 142 | Isothermal 197-229m |
| 21-Jan | | | | | | | 0.4 773m-983m |
| 22-Jan | | | | | | | |
| 23-Jan | | | | | | | |
| 24-Jan | -10.1 | -9.1 | 1.00 | 55 | 115 | 60 | |
| 25-Jan | | | | | | | |
| 26-Jan | | | | | | | Isothermal 55m-302m, -11.5 |
| 27-Jan | -10.7 | -9.1 | 1.60 | 55 | 128 | 73 | |
| 28-Jan | | | | | | | |
| 29-Jan | | | | | | | |
| 30-Jan | | | | | | | |
| 31-Jan | | | | | | | |
| | Avg. Strength | Strength Std. Dev. | Avg. Top (m) | Top Std. Dev. (m) | Total Days of Ivn. (d) | Percentage of Ivn. (%) | |
| | 4.6 | 3.2 | 215.93 | 156 | 15 | 48 | |

| Date | Bot Temp | Top Temp | Strength | Start (m) | Ends (m) | Thickness (m) | Note |
|---|---|---|---|---|---|---|---|
| 1-Feb | -7.9 | -2.1 | 5.8 | 55 | 431 | 376 | |
| 2-Feb | | | | | | | |
| 3-Feb | -8.1 | -6.1 | 2.0 | 55 | 117 | 62 | |
| 4-Feb | -8.9 | -7.7 | 1.2 | 55 | 116 | 61 | |
| 5-Feb | | | | | | | |
| 6-Feb | -11.7 | -7.3 | 4.4 | 55 | 121 | 66 | |
| 7-Feb | -4.3 | -3.1 | 1.2 | 55 | 94 | 39 | |
| 8-Feb | -10.9 | -5.9 | 5.0 | 55 | 323 | 268 | |
| 9-Feb | -6.3 | -2.1 | 4.2 | 55 | 510 | 455 | |
| 10-Feb | -8.5 | -6.7 | 1.8 | 55 | 338 | 283 | |
| 11-Feb | | | | | | | |
| 12-Feb | | | | | | | |
| 13-Feb | -5.7 | 2.8 | 8.5 | 55 | 581 | 526 | |
| 14-Feb | | | | | | | |
| 15-Feb | -8.3 | -2.9 | 5.4 | 55 | 102 | 47 | |
| 16-Feb | | | | | | | 0.2 inversion 55m-165m |
| 17-Feb | | | | | | | 3.2 inversion 300m-692m |
| 18-Feb | -4.7 | -1.7 | 3.0 | 55 | 149 | 94 | |
| 19-Feb | | | | | | | 1.6 inversion 376m-490m |
| 20-Feb | 0.0 | 1.2 | 1.2 | 55 | 96 | 41 | |
| 21-Feb | -5.5 | -0.3 | 5.2 | 55 | 217 | 162 | Isothermal 209m-217m |
| 22-Feb | -4.7 | 2.0 | 6.7 | 55 | 148 | 93 | |
| 23-Feb | -3.1 | 2.2 | 5.3 | 55 | 412 | 357 | |
| 24-Feb | | | | | | | |
| 25-Feb | -6.9 | -5.5 | 1.4 | 55 | 81 | 26 | |
| 26-Feb | -3.1 | -0.7 | 2.4 | 55 | 107 | 52 | 3.7 inversion 461-713 m |
| 27-Feb | | | | | | | 3.5 inversion 528m-1222m |
| 28-Feb | | | | | | | |

| Avg. Strength | Strength Std. Dev. | Avg. Top (m) | Top Std. Dev. (m) | Total Days of Ivn. (d) | Percentage of Ivn. (%) |
|---|---|---|---|---|---|
| 3.8 | 2.2 | 177 | 160 | 17 | 61 |

| Date | Bot Temp | Top Temp | Strength | Start (m) | Ends (m) | Thickness (m) | Note |
|---|---|---|---|---|---|---|---|
| 1-Mar | -2.1 | -0.3 | 1.8 | 55 | 101 | 46 | |
| 2-Mar | | | | | | | 0.2 invresion 55m-97m |
| 3-Mar | | | | | | | 1.4 inversion 299m-509m |
| 4-Mar | | | | | | | 1.6 inversion 501m-603m |
| 5-Mar | -1.5 | 0.0 | 1.5 | 55 | 103 | 48 | |
| 6-Mar | | | | | | | 1 .0 inversion 731m-882m |
| 7-Mar | | | | | | | |
| 8-Mar | -3.5 | -1.7 | 1.8 | 55 | 97 | 42 | |
| 9-Mar | -4.1 | -2.3 | 1.8 | 55 | 824 | 769 | |
| 10-Mar | 1.2 | 8.6 | 7.4 | 55 | 423 | 368 | |
| 11-Mar | -2.7 | 0.2 | 2.9 | 55 | 110 | 55 | |
| 12-Mar | 0.2 | 2.6 | 2.4 | 55 | 228 | 173 | |
| 13-Mar | 3.4 | 19.4 | 16.0 | 55 | 951 | 896 | |
| 14-Mar | | | | | | | 6.2 inversion 367m-861m |
| 15-Mar | | | | | | | |
| 16-Mar | | | | | | | |
| 17-Mar | | | | | | | |
| 18-Mar | | | | | | | |
| 19-Mar | 2.8 | 7.8 | 5.0 | 55 | 354 | 299 | |
| 20-Mar | | | | | | | |
| 21-Mar | | | | | | | 0.2 inversion 55m -197m |
| 22-Mar | 2.2 | 5.2 | 3.0 | 55 | 527 | 472 | |
| 23-Mar | | | | | | | 2.5 inversion 524m-818m |
| 24-Mar | 6.0 | 11.4 | 5.4 | 55 | 308 | 253 | |
| 25-Mar | 8.2 | 16.8 | 8.6 | 55 | 778 | 723 | |
| 26-Mar | 12.2 | 17.6 | 5.4 | 55 | 591 | 536 | |
| 27-Mar | 11.8 | 19.8 | 8.0 | 55 | 831 | 776 | |
| 28-Mar | | | | | | | 0.4 inversion 55m-85m |
| 29-Mar | | | | | | | |
| 30-Mar | | | | | | | 0.6 inversion 55m-212m |
| 31-Mar | | | | | | | |
| | Avg. Strength(˚ C) | Strength Std. Dev.(˚ C) | Avg. Top (m) | Top Std. Dev. (m) | Total Days of Ivn. (d) | Percentage of Ivn. (%) | |
| | 5.1 | 3.8 | 390 | 297 | 14 | 45 | |

| Date | Bot Temp | Top Temp | Strength | Start (m) | Ends (m) | Thickness (m) | Note |
|---|---|---|---|---|---|---|---|
| 1-Apr | 11.4 | 15.8 | 4.4 | 55 | 423 | 368 | |
| 2-Apr | | | | | | | 0.2 55-48 then 8.6 from 226m-1192m |
| 3-Apr | | | | | | | |
| 4-Apr | | | | | | | |
| 5-Apr | | | | | | | |
| 6-Apr | | | | | | | |
| 7-Apr | | | | | | | |
| 8-Apr | | | | | | | 1.6 from 625m-917m |
| 9-Apr | | | | | | | 3.0 inversion from 328m-897m |
| 10-Apr | 12.2 | 17.0 | 4.8 | 55 | 312 | 257 | |
| 11-Apr | | | | | | | 0.6 inversion from 55m-112m |
| 12-Apr | | | | | | | 2 inversion from 151m-802m and isothermal 802m-847m |
| 13-Apr | | | | | | | |
| 14-Apr | | | | | | | |
| 15-Apr | | | | | | | 0.6 inversion from 55m-167m |
| 16-Apr | | | | | | | 0.6 inversion from 55m-793m and isothermal from 793m-893m |
| 17-Apr | | | | | | | 0.2 inversion from 55m-92m then 1.3 inversion from187m-558m |
| 18-Apr | | | | | | | |
| 19-Apr | | | | | | | 0.2 inversion from 55m-92m then 1.3 inversion from187m-558m |
| 20-Apr | | | | | | | 3.6 inversion from 229m-492m |
| 21-Apr | | | | | | | |
| 22-Apr | | | | | | | |
| 23-Apr | | | | | | | |
| 24-Apr | 13.8 | 14.8 | 1.0 | 55 | 184 | 129 | |
| 25-Apr | 14.4 | 16.8 | 2.4 | 55 | 372 | 317 | |
| 26-Apr | | | | | | | 1.8 inversion from 321m-609m |
| 27-Apr | | | | | | | |
| 28-Apr | | | | | | | Isothermal from 55m-154m |
| 29-Apr | | | | | | | 4.2 inversion from 485m-875m |
| 30-Apr | | | | | | | |
| | Avg. Strength | Strength Std. Dev. | Avg. Top (m) | Top Std. Dev. (m) | Total Days of Ivn. (d) | Percentage of Ivn. (%) | |
| | 3.2 | 1.5 | 268 | 89 | 4 | 13 | |

| Date | Bot Temp | Top Temp | Strength | Start (m) | Ends (m) | Thickness (m) | Note |
|---|---|---|---|---|---|---|---|
| 1-May | | | 0.0 | | | 0 | |
| 2-May | | | 0.0 | | | 0 | |
| 3-May | | | 0.0 | | | 0 | |
| 4-May | | | 0.0 | | | 0 | |
| 5-May | | | 0.0 | | | 0 | 1.4 306m-404m |
| 6-May | | | 0.0 | | | 0 | |
| 7-May | | | 0.0 | | | 0 | 1.2 643m0-744m |
| 8-May | | | 0.0 | | | 0 | |
| 9-May | | | 0.0 | | | 0 | |
| 10-May | | | 0.0 | | | 0 | |
| 11-May | | | 0.0 | | | 0 | |
| 12-May | | | 0.0 | | | 0 | |
| 13-May | | | 0.0 | | | 0 | |
| 14-May | | | 0.0 | | | 0 | 2.0 360m-714m |
| 15-May | | | 0.0 | | | 0 | |
| 16-May | | | 0.0 | | | 0 | |
| 17-May | | | 0.0 | | | 0 | |
| 18-May | | | 0.0 | | | 0 | |
| 19-May | | | 0.0 | | | 0 | |
| 20-May | | | 0.0 | | | 0 | |
| 21-May | | | 0.0 | | | 0 | |
| 22-May | | | 0.0 | | | 0 | |
| 23-May | | | 0.0 | | | 0 | |
| 24-May | | | 0.0 | | | 0 | 6.6 240m-662m |
| 25-May | | | 0.0 | | | 0 | 4.0 290m-968m |
| 26-May | | | 0.0 | | | 0 | 0.4 55-55 data error |
| 27-May | | | 0.0 | | | 0 | |
| 28-May | | | 0.0 | | | 0 | |
| 29-May | | | 0.0 | | | 0 | |
| 30-May | | | 0.0 | | | 0 | |
| 31-May | | | 0.0 | | | 0 | |
| | Avg. Strength | Strength Std. Dev. | Avg. Top (m) | Top Std. Dev. (m) | Total Days of Ivn. (d) | Percentage of Ivn. (%) | |
| | 0.0 | 0.0 | 0 | 0 | 0 | 0 | |

| Date | Bot Temp | Top Temp | Strength | Start (m) | Ends (m) | Thickness (m) | Note |
|---|---|---|---|---|---|---|---|
| 1-Jun | 25.0 | 26.8 | 1.8 | 55 | 547 | 492 | |
| 2-Jun | 24.6 | 25.8 | 1.2 | 55 | 362 | 307 | |
| 3-Jun | 22.0 | 25.2 | 3.2 | 55 | 183 | 128 | |
| 4-Jun | 22.8 | 24.4 | 1.6 | 55 | 609 | 554 | |
| 5-Jun | 22.8 | 24.4 | 1.6 | 55 | 609 | 554 | |
| 6-Jun | | | | | | | |
| 7-Jun | | | | | | | |
| 8-Jun | | | | | | | |
| 9-Jun | | | | | | | 0.2 from 55m-73m |
| 10-Jun | | | | | | | |
| 11-Jun | | | | | | | |
| 12-Jun | | | | | | | |
| 13-Jun | | | | | | | |
| 14-Jun | | | | | | | |
| 15-Jun | | | | | | | |
| 16-Jun | | | | | | | |
| 17-Jun | 20.0 | 22.8 | 2.8 | 55 | 321 | 266 | |
| 18-Jun | | | | | | | |
| 19-Jun | | | | | | | |
| 20-Jun | | | | | | | |
| 21-Jun | | | | | | | |
| 22-Jun | | | | | | | |
| 23-Jun | | | | | | | |
| 24-Jun | | | | | | | |
| 25-Jun | | | | | | | |
| 26-Jun | | | | | | | |
| 27-Jun | | | | | | | |
| 28-Jun | | | | | | | |
| 29-Jun | 26.8 | 28.8 | 2.0 | 55 | 387 | 332 | |
| 30-Jun | | | | | | | |

| Avg. Strength | Strength Std. Dev. | Avg. Top (m) | Top Std. Dev. (m) | Total Days of Ivn. (d) | Percentage of Ivn. (%) |
|---|---|---|---|---|---|
| 2.0 | 0.7 | 376 | 150 | 7 | 25 |

## APPENDIX B

## SELECTED DAYS WITH MSTIS STRENGTH, AQI, AND RELEASED ALERT FROM JANUARY TO JUNE 2018

Note:
UA stands for upper-level inversions.
Alert information was obtained from Beijing http://www.bjft.gov.cn/kqyj/
The Actual AQI and Actual PM 2.5 is calculated by aqistudy.cn using data from local air quality bureau. They are average of hourly data. There exits data losing situation.

| Date | MSTIs Strength | AQI | Alert Released |
|---|---|---|---|
| 12-Jan | 6.8 | 94 | |
| 13-Jan | 9.0 | 137 | Orange |
| 14-Jan | 3.0 | 175 | Orange |
| 15-Jan | 2.0 | 64 | Orange |
| 16-Jan | 0.0 | 114 | |
| 17-Jan | 1.6 | 77 | |
| 18-Jan | 4.2 | 101 | |
| 19-Jan | 8.1 | 107 | |
| 20-Jan | 7.1 | 65 | |
| | | | |
| 16-Feb | 0.0 | 105 | |
| 17-Feb | 3.2 UA | 108 | |
| 18-Feb | 3.0 | 152 | |
| 19-Feb | 1.6 UA | 188 | |
| 25-Feb | 1.4 | 82 | |
| 26-Feb | 2.4 | 163 | |
| 27-Feb | 3.5 UA | 219 | Yellow |
| 28-Feb | 0.0 | 117 | Yellow |
| | | | |
| 2-Mar | 0.0 | 105 | |
| 3-Mar | 1.4 UA | 221 | |
| 4-Mar | 1.6 UA | 126 | |
| | | | |

| | | | |
|---|---|---|---|
| 8-Mar | 1.8 | 61 | |
| 9-Mar | 1.8 | 137 | |
| 10-Mar | 7.4 | 156 | |
| 11-Mar | 2.9 | 85 | |
| 12-Mar | 2.4 | 195 | Orange |
| 13-Mar | 16.0 | 294 | Orange |
| 14-Mar | 6.2 UA | 287 | Orange |
| | | | |
| 18-Mar | 0.0 | 138 | |
| 19-Mar | 5.0 | 94 | |
| | | | |
| 22-Mar | 3.0 | 115 | |
| 23-Mar | 2.5 UA | 144 | |
| 24-Mar | 5.4 | 120 | |
| 25-Mar | 8.6 | 78 | |
| 26-Mar | 5.4 | 162 | Orange |
| 27-Mar | 8.0 | 247 | Orange |
| 28-Mar | 0.0 | 0 | Orange |
| 29-Mar | 0.0 | 112 | |
| 30-Mar | 0.0 | 69 | |
| 31-Mar | 0.0 | 137 | |
| | | | |
| 1-Apr | 4.4 | 226 | Blue |
| 2-Apr | 8.6 UA | 273 | |
| | | | |
| 15-Apr | 0.0 | 66 | |
| 16-Apr | 0.0 | 106 | |
| 17-Apr | 0.0 | 133 | |
| 18-Apr | 0.0 | 144 | Yellow |
| 19-Apr | 0.0 | 160 | Yellow |
| 20-Apr | 3.6 UA | 165 | Yellow |
| | | | |
| 24-Apr | 1.0 | 64 | |
| 25-Apr | 2.4 | 87 | |
| 26-Apr | 1.8 UA | 122 | |
| 27-Apr | 0.0 | 113 | |
| 28-Apr | 0.0 | 150 | |
| 29-Apr | 4.2 UA | 195 | Blue |
| | | | |
| 6-May | 0.0 | 120 | |
| 7-May | 1.2 UA | 104 | |
| 8-May | 0.0 | 91 | |

| | | | |
|---|---|---|---|
| 9-May | 0.0 | 120 | |
| 10-May | 0.0 | 146 | |
| 11-May | 0.0 | 108 | |
| 12-May | 0.0 | 185 | |
| 13-May | 0.0 | 119 | |
| 14-May | 2.0 UA | 178 | |
| 15-May | 0.0 | 90 | |
| 16-May | 0.0 | 152 | |
| | | | |
| 22-May | 0.0 | 102 | |
| 23-May | 0.0 | 139 | |
| 24-May | 6.6 UA | 151 | |
| 25-May | 4.0 UA | 162 | |
| | | | |
| 1-Jun | 1.8 | 129 | |
| 2-Jun | 1.2 | 200 | |
| 3-Jun | 3.2 | 87 | |
| 4-Jun | 1.6 | 104 | |
| 5-Jun | 1.6 | 164 | |
| 6-Jun | 0.0 | 172 | |
| | | | |
| 10-Jun | 0.0 | 106 | |
| 11-Jun | 0.0 | 100 | |
| 12-Jun | 0.0 | 135 | |
| | | | |
| 14-Jun | 0.0 | 125 | |
| 15-Jun | 0.0 | 136 | |
| 16-Jun | 0.0 | 141 | |
| 17-Jun | 2.8 | 98 | |
| 18-Jun | 0.0 | 148 | |
| 19-Jun | 0.0 | 118 | |
| 20-Jun | 0.0 | 97 | |
| 21-Jun | 0.0 | 157 | |
| 22-Jun | 0.0 | 100 | |
| 23-Jun | 0.0 | 203 | |
| 24-Jun | 0.0 | 185 | |
| 25-Jun | 0.0 | 126 | |
| 26-Jun | 0.0 | 163 | |
| | | | |
| 29-Jun | 2.0 | 103 | |
| 30-Jun | 0.0 | 186 | |

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