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Impact of a Changing Climate on Fine Particulate Concentrations in Butte, MT

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IMPACT OF A CHANGING CLIMATE ON FINE PARTICULATE CONCENTRATIONS IN BUTTE, MT

by

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Abstract

A model was developed to assess the potential change in $PM_{2.5}$ concentrations in Butte, Montana over the course of the 21st century as the result of climate change and changes in emissions. The EPA AERMOD regulatory model was run using NARCCAP climate data for the years of 2040, 2050, 2060 and 2070, and the results were compared to the NAAQS to determine if there is the potential for future impacts to human health. This model predicted an average annual concentration of 15.84 $\mu g/m^3$ in the year 2050, which would exceed the primary NAAQS of 12 $\mu g/m^3$ and is a large increase over the average concentration from 2010 – 2012 of 10.52 $\mu g/m^3$. The effectiveness of a wood stove change out program was also evaluated to determine its efficacy, and modeled results predicted that by changing out 100% of inefficient stoves with an EPA approved model, concentrations could be reduced below the NAAQS.

Keywords: Fine Particulates, Climate Change, Air Dispersion Modeling

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1.0 Introduction

It is widely accepted that the emission of greenhouse gases such as CO_2 from human activities is leading to changes in the earth's climate at an accelerated rate. Air quality is directly related to meteorological conditions, since the diffusion and transport of airborne contaminants is influenced by weather patterns. Therefore, climate change will have an impact on air quality in the future, since it affects many aspects of regional and global meteorological trends. In the western United States specifically, recent climate models have predicted not only an increase in temperature, but also a decrease in precipitation and a reduction in atmospheric mixing, all of which could lead to increased frequency of days with elevated air pollutant concentration (Littell, Elsner, & Mauger, 2011).

Fine particulate matter, also known as $PM_{2.5}$, is one such pollutant that would be affected by changes in meteorological conditions. Historical air monitoring data in Butte, Montana has shown elevated levels of $PM_{2.5}$, especially during the winter months. These elevated concentrations could pose a potential health risk to sensitive groups, such as the young, the elderly, and those with respiratory conditions. The increased levels of $PM_{2.5}$ in residential areas can be largely attributed to emissions from wood combustion sources, the most common of which being wood burning stoves used as a heat source for personal residences (Ganesan, $PM_{2.5}$ Emissions from Wood Combustion in Butte, Montana, 2013).

This thesis research examines the interactions between changing future meteorological trends and ground level $PM_{2.5}$ concentrations in the Butte area. This is accomplished by processing a combination of predicted climatic values calculated by the North American Regional Climate Change Assessment Program (NARCCAP) and historical and projected emissions data using the AERMOD atmospheric dispersion modeling system. The results of this

research will provide insight into future trends in ground level particulate concentrations, and also provide insight as to whether actions need to be taken to reduce $PM_{2.5}$ concentrations.

1.1. Fine Particulates in Butte, Montana

This section provides background information on the airborne pollutant $PM_{2.5}$ and its sources in Butte, Montana.

1.1.1. Definition of Fine Particulates

Fine particulates, more commonly referred to as $PM_{2.5}$, are classified by the Environmental Protection Agency (EPA) as being any airborne particle with a diameter of 2.5 microns (2.5 millionths of a meter) or smaller. These particles can be composed of any number of materials, including organic chemicals, metals, or dust, and are commonly found in smoke and haze.

Fine particulates pose a risk to human health, because they are small enough that once inhaled, they can lodge deep within the lungs. Exposure can affect both the respiratory and cardiovascular systems, decreasing lung function, aggravating asthma symptoms and increasing the risk of heart attack or irregular heartbeat. $PM_{2.5}$ poses the highest risk to children, the elderly, and those with respiratory or cardiovascular diseases, but also poses health risks to healthy individuals. In addition to posing a health risk, $PM_{2.5}$ also has several detrimental environmental effects, such as reduction in atmospheric visibility and altering the chemistry of surface water and soil chemistry after settling (EPA, 2013).

1.1.2. National $PM_{2.5}$ Standards

Under the Clean Air Act of 1970, EPA was required to maintain standards for ambient concentrations for six criteria pollutants, including $PM_{2.5}$. These standards, called the National

Ambient Air Quality Standards (NAAQS), were designed to define the maximum allowable ambient concentrations of a contaminant that allowed for adequate protection of human health and the environment.

$PM_{2.5}$ standards were recently updated in December of 2012. The annual standards for $PM_{2.5}$ include a primary standard of 12 $\mu g/m^3$ (annual mean of the three year average), and a secondary standard of 15 $\mu g/m^3$ (annual mean of the three year average). A primary 24-hour standard of 35 $\mu g/m^3$ (98^{th} percentile, three year average), is also enforced (EPA, 2014).

1.1.3. $PM_{2.5}$ Concentrations in Butte

It has been observed that Butte, Montana experiences elevated levels of $PM_{2.5}$, especially during the winter months. A report titled "An Assessment of Ambient Particulates in Butte, Montana," published by Dr. Kumar Ganesan with Energy and Environmental Research and Technology LLC, describes the trends in $PM_{2.5}$ concentrations in the Butte area for the years of 2010 through 2012 (Ganesan, An Assessment of Ambient Particulates in Butte, Montana). The most detailed values for $PM_{2.5}$ provided in this report were recorded at the Greeley School monitoring site, operated by the Montana Department of Environmental Quality (DEQ). Figure 1 shows the Greeley School monitoring site. At this site, the observed 98th percentile values for $PM_{2.5}$ for 2010, 2011 and 2012 were 38 µg/m3, 38 µg/m3, and 34 µg/m3, respectively. These values are directly comparable to the 24-hour NAAQS primary standard of 35 $\mu g/m^3$, and indicate that the standard was exceeded in 2010 and 2011. The annual average values for these years were 9.8 $\mu g/m^3$, 9.6 $\mu g/m^3$ and 8.9 $\mu g/m^3$, meaning that the NAAQS annual standard of 12 $\mu g/m^3$ was met (Ganesan, An Assessment of Ambient Particulates in Butte, Montana, 2014).

Figure 1: Greeley School Monitoring Station

Monthly values for $PM_{2.5}$ concentrations at the Greeley School monitoring station were provided by Ganesan's 2014 report. These values, shown in Figure 2, illustrate that concentrations tend to vary across the year. Concentrations during the winter months (November through February) are notably higher than the warmer months of the year. This is the result of increased wood burning due to colder outdoor temperatures, leading to a greater release of $PM_{2.5}$ from residential wood burning sources. The largest short term spike occurred during August and September of 2012, and was the result of long range transport of $PM_{2.5}$ from forest fires in the western United States. This illustrates the impact that long range sources can have on local concentrations over a short time period (Ganesan, An Assessment of Ambient Particulates in Butte, Montana, 2014).

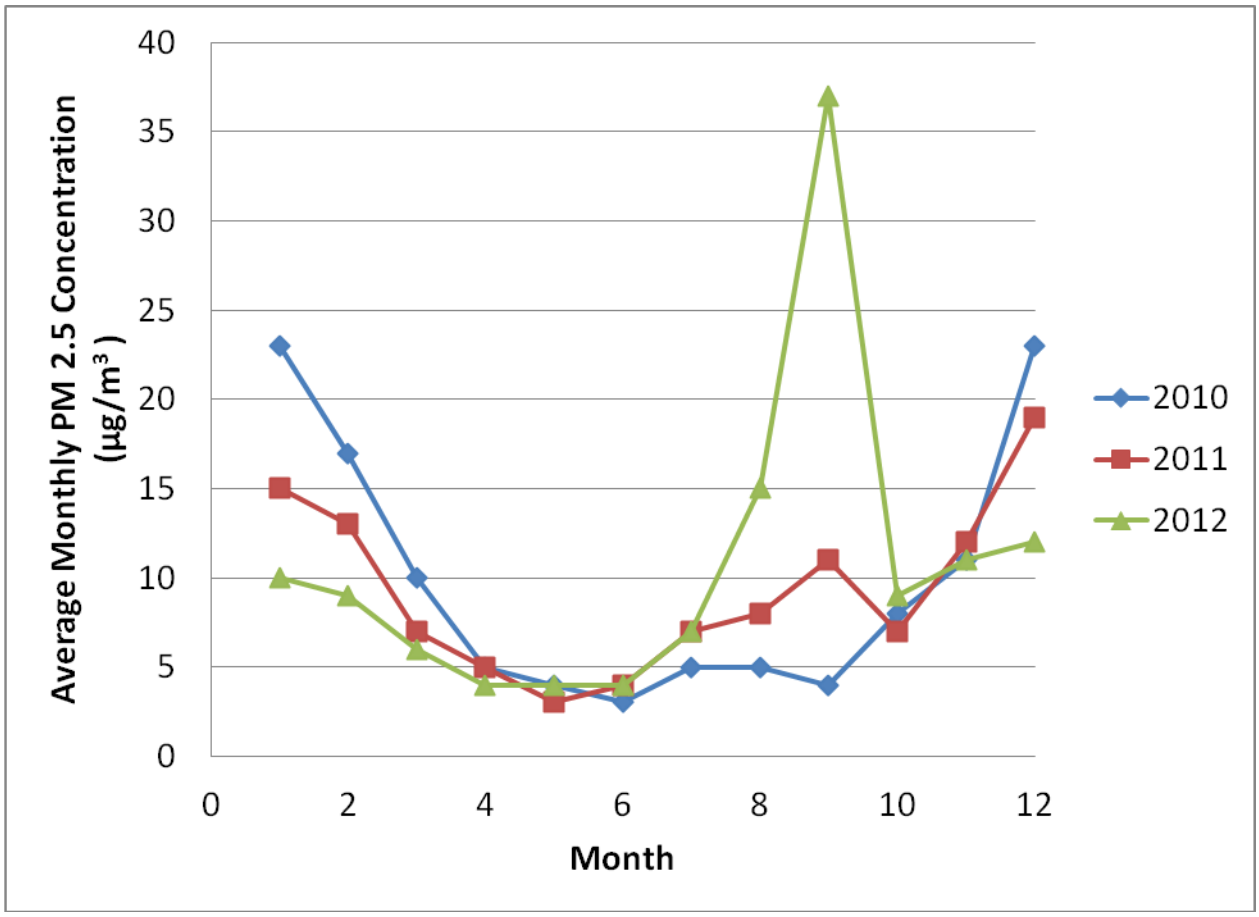

Figure 2: Average Monthly $PM_{2.5}$ Concentration at the Greeley School Site

(Ganesan, An Assessment of Ambient Particulates in Butte, Montana)

1.1.4. Sources of $PM_{2.5}$ in Butte

Observed $PM_{2.5}$ concentrations in Butte can be attributed to three major source types: residential wood combustion, industrial sources, and background concentrations.

1.1.4.1. Residential Wood Combustion

In 2013, a survey of Butte residents was conducted to determine how many households currently use wood burning devices as a source of energy and what type of devices they were using to burn wood. Conducted by Dr. Kumar Ganesan, this study determined that approximately 13% of Butte households burn wood, leading to an annual consumption of 5,659

tons of wood and 907 tons of pellets. Wood burning in Butte contributed to an annual release of 72.9 tons of $PM_{2.5}$. Residential wood burning is the largest source of $PM_{2.5}$ emissions in the Butte area (Ganesan, An Assessment of Ambient Particulates in Butte, Montana, 2014).

1.1.4.2. Industrial Sources

Three industrial sources in the Butte area are of sufficient size and close enough to contribute to $PM_{2.5}$ concentrations in Butte, according to emissions data provided by Dan Walsh of the Montana DEQ. Montana Resources is a mining operation located in northern Butte, REC Silicon is a manufacturing facility located west of Butte and Basin Creek Power is a natural gas-fired power plant located south of Butte.

1.1.4.3. Background $PM_{2.5}$

In addition to being emitted by local sources, a portion of observed $PM_{2.5}$ concentrations are attributable to background levels. The study "Use of Satellite Observations for Long-Term Exposure Assessment of Global Concentrations of Fine Particulate Matter" contains data on ambient $PM_{2.5}$ concentrations for all of the United States. This study re-evaluated data captured from NASA satellites to determine $PM_{2.5}$ concentrations across the globe. A resulting map presented in Figure 3 shows the average concentrations of $PM_{2.5}$ from 2001-2006 across the US. These results show that the background concentration of $PM_{2.5}$ in western Montana are approximately 3 $\mu g/m^3$ (Donkelaar, Martin, Brauer, & Boys, 2015).

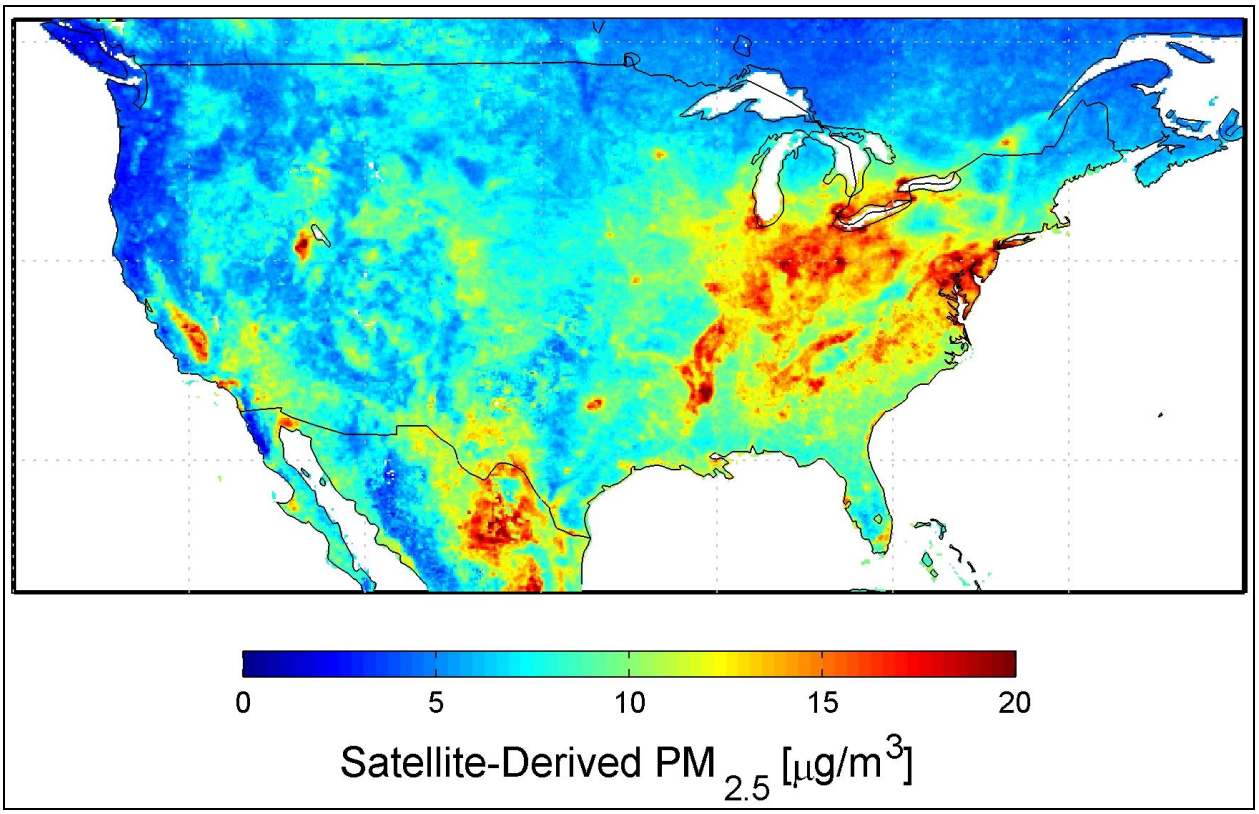

Figure 3: Satellite Derived Map of $PM_{2.5}$ Concentrations Across the US (Donkelaar, Martin and Brauer)

1.2. AERMOD Atmospheric Dispersion Model

AERMOD is an atmospheric dispersion modeling suite that is capable of predicting ground level concentrations of airborne pollutants released from stationary sources (EPA). It includes:

- The AERMOD steady-state dispersion model, which is capable of predicting the dispersion of airborne pollutants released from stationary sources. It is a short range model, with a range of 50 km.
- The AERMET meteorological preprocessor, which calculates necessary meteorological variables from surface meteorological data, upper air meteorological data and land use characteristics.

- The AERMAP terrain preprocessor, which accepts and formats topographical data, allowing AERMOD to account for the effects of terrain features on air pollution plumes.

AERMOD was developed by the American Meteorological Society (AMS), United States Environmental Protection Agency (EPA), Regulatory Model Improvement Committee, also known as AERMIC. It is an improvement over the EPA's ISCST model that was used until 2000, when AERMOD was adopted as the official US EPA regulatory model. It is a Gaussian model with the following features (Turner & Shulze, 2007):

- Accepts multiple point, area or volume sources
- Accounts for buoyancy of released source gases
- Accounts for wet or dry deposition of particulates and gases
- Incorporates terrain effects on plume dispersion
- Accounts for building downwash effects
- Incorporates meteorological data at both the surface and multiple heights

1.3. Predicted Climate Data

Various efforts have been undertaken to predict the impact that climate change will have on the climate of the future. This section describes the predicted climate data that was used for this project, and how it was generated.

1.3.1. NARCCAP Predicted Meteorological Data

Predicted climate change data was obtained through the North American Regional Climate Change Assessment Program (NARCCAP). This program is designed to produce high resolution climate data for various climate change scenarios over the bulk of North America.

According to the NARCCAP website, models are run by combining a regional climate model (RCM) with an atmosphere-ocean general circulation model (AOGCM). Data was generated for both a historical period of 1971-2000, and a future period of 2041-2070. Results were produced with a spatial resolution of 50 km, and a temporal resolution of three hours (NARCCAP, 2007).

1.3.1.1. Greenhouse Gas Emission Scenario

Changes in atmospheric greenhouse gas (GHG) concentrations are the largest driving factor of climate change. In order to conduct future climate modeling, future emissions of GHGs must be assumed. The International Panel on Climate Change (IPCC) has released various emission scenarios that predict future global releases of GHGs. The emission scenario used for NARCCAP modeling is the A2 Emissions Scenario, which was described by the IPCC in the Special Report on Emissions Scenarios (Nakicenovic, 2000). The A2 is the highest emissions scenario described in the report, leading to a conservative prediction of future climate conditions. This scenario assumes continual population growth, relatively slow development and adaptation of new technologies and steady economic growth. Figure 4 shows the predicted increase in global temperature in degrees Celsius for various emission scenarios through the end of the century, developed by NARCCAP. The A2 emission scenario is shown in red, and it predicts the largest increase in temperature by 2100 of the various scenarios shown.

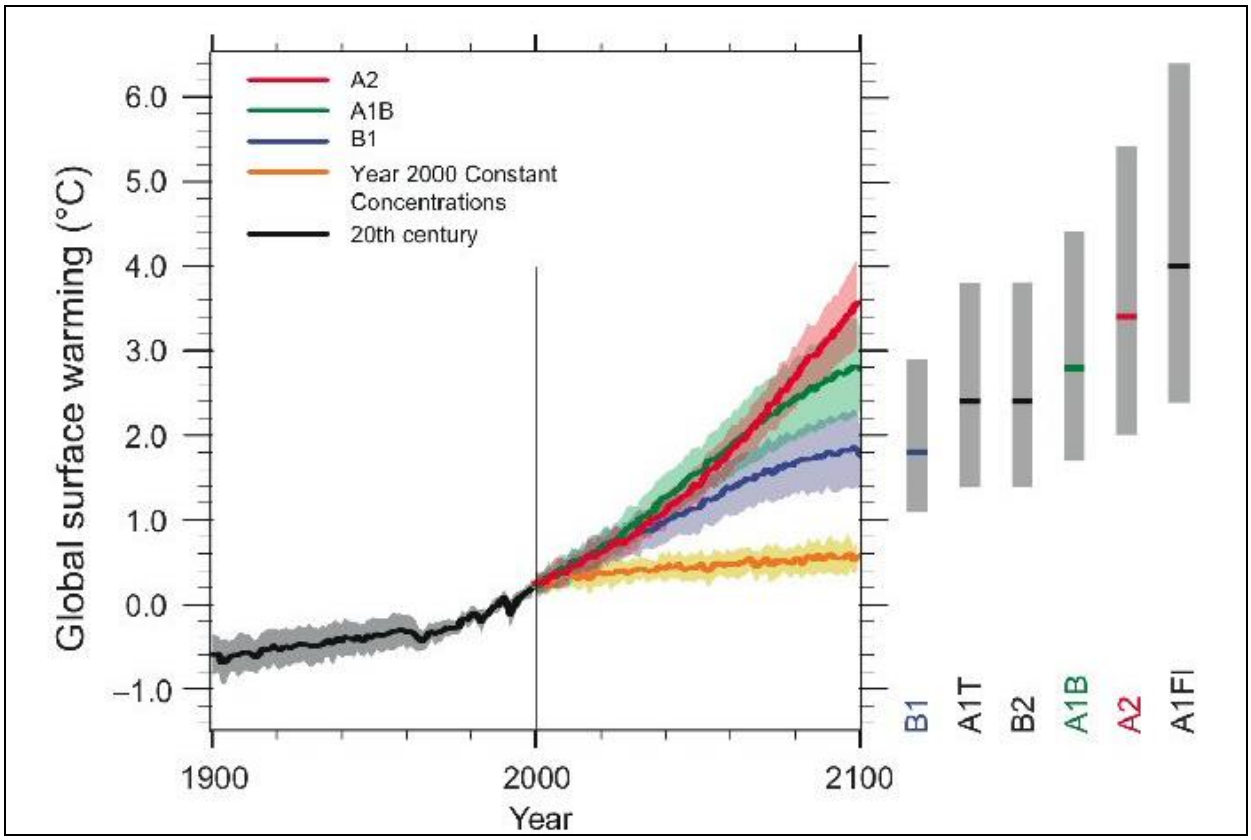

Figure 4: Predicted Increase in Surface Temperature from Various Emission Scenarios (Mearns et al)

1.3.1.2. CCSM Atmosphere-Ocean General Circulation Model

A general circulation model (GCM), is a climate model that predicts the circulation of the earth's atmosphere and ocean currents on a global scale. These results are computed using the Navier-Stokes equations for a rotating sphere while accounting for energy transfer from radiation or latent heat. The AOGCM used to generate the selected dataset was the Community Climate System Model (CCSM) (Mearns et al). This model was originally developed by the National Center for Atmospheric Research (NCAR) in 1983, was significantly updated in 1996 and has been improved incrementally since then (University Corporation for Atmospheric Research, 2015).

1.3.1.3. The WRF Regional Climate Model

While GCMs are capable of predicting the effects of climate change on large scale meteorological trends, they provide results with coarse resolutions (around 300 km), which is often unsuitable when working on a regional scale. A regional climate model (RCM) can improve the results generated by a GCM to resolutions as fine as 50 km. This is done by re-analyzing GCM data while accounting for small scale topographical and land use data, generating much more accurate local data (NARCCAP, 2007). The RCM used to produce the selected dataset was the Weather Research and Forecasting Model (WRF). This model was designed in the late 1990s to conduct atmospheric research as well as forecast local weather (Weather Research and Forecasting Model).

1.4. Project Scope

The purpose of this research project is to develop a methodology for predicting future $PM_{2.5}$ concentrations in Butte, Montana. Through the use of climate data obtained from NARCCAP and predictions in future emissions trends, and by using the AERMOD air diffusion modeling program, $PM_{2.5}$ concentrations were estimated for Butte. These results were compared to current levels and air quality standards to understand the potential for future human health risks, if any, and provide insight as to whether actions need to be taken to reduce future emissions.

2. Methodology

This section describes the methods and techniques used to predict future $PM_{2.5}$ concentrations in the Butte area, including the model development process, assumptions made and sources of input data.

2.1. Sources of Meteorological Data

2.1.1. Current Meteorological Data

Data for the current time period (2010-2012) was obtained through the Weather Underground website. This site maintains a database of a wide range of recorded weather values for a large number of sites across the world. The selected data was measured at Bert Mooney Airport weather station (Station ID KBTM), located at a latitude of 45.9549º N and a longitude of 112.5025º W. Data was downloaded using the Historical Data tool in a Comma Separated Value (.CSV) format (Weather Underground, 2015).

2.1.2. Predicted Future Meteorological Data

Predicted Future Meteorological Data was obtained through the NARCCAP National Center for Atmospheric Research Earth System Grid data portal. The data retrieved for the purposes of this study was obtained from a location centered on a point at a latitude of 45.9824º N and a longitude of 112.5719º W. The selected dataset was modeled using the WRF Regional Climate Model, and the CCSM Atmosphere-Ocean General Circulation Model (Mearns, et al. 2007).

2.2. Model Setup and Verification

Before future values of $PM_{2.5}$ could be predicted, an instance of AERMOD was constructed to incorporate all sources of data. Once the model was constructed, it was run with

historical data over the time period of 2010-2012. The results of this effort were compared to measured values from the Greeley School monitoring site in order to verify that the model was constructed properly and that assumptions made during this process were valid.

2.2.1. Software Used

As previously mentioned, the model used to predict future concentrations was the AERMOD atmospheric dispersion modeling suite. A more user friendly version of AERMOD, Breeze AERMOD, was used. Produced by Trinity Consultants, this program offers a graphical user interface, streamlining data inputs and allowing for more direct control over modeling options. This software incorporates all three modules of the AERMOD software (AERMOD, AERMET and AERMAP) and provides several additional options for analysis of data outputs. The versions of the software used for this study were Breeze AERMOD Version 7.9.1 and Breeze AERMET Version 7.5.2 (Trinity Consultants, 2014). The most recent release of the AERMOD executable, Version 14134, available at the time of writing was used.

2.2.2. AERMET Setup

AERMET is the meteorological preprocessor for AERMOD that formats input meteorological data and calculates key parameters necessary for the dispersion modeling process. This program incorporates surface data measured near ground level, upper air data measured at incremental heights above ground level, and land use data to calculate variables for albedo, Bowen ratio and surface roughness.

2.2.2.1. Surface Data

Surface weather data was downloaded from the Weather Underground website, and formatted into the SCRAM format. This format is a simplified format of the NOAA CD-144

data format that was created by the US EPA to reduce the size of stored meteorological files, and only contains variables necessary for the air dispersion modeling process. This format is unique to the EPA Support Center for Regulatory Air Models (SCRAM) website, but can be directly input into the AERMET pre-processor. The general format of a SCRAM file as described by the EPA is provided in Table I (EPA, 2011).

Table I: SCRAM Data Format

Field Position	Parameter Name	Units
1-5	National Weather Service Station Number	
6-7	Year	
8-9	Month	
10-11	Day	
12-13	Hour	
14-16	Ceiling Height	Hundreds of Feet
17-18	Wind Direction	Tens of Degrees
19-21	Wind Speed	Knots
22-24	Dry Bulb Temperature	Degrees Fahrenheit
25-26	Total Cloud Cover	Tens of Percent
27-28	Opaque Cloud Cover	Tens of Percent

2.2.2.2. Upper Air Data

Upper air data incorporates meteorological data measured at height intervals from ground level in order to account for wind direction and speed, temperature and pressure within the upper atmosphere. Values are generally presented from ground level to heights around 1,000 feet. Since EPA's SCRAM database only contains data through the year 1992, data for the time period of 1990 – 1992 was used in place of current data. These values were measured at Great Falls International Airport. While these values are not a perfect representation of upper air conditions during the time period in question, they should still represent seasonal trends in Montana's

weather patterns. Upper air data was obtained from WebMet.com, a site operated by Lakes Environmental Consulting (Lakes Environmental, 2002).

The upper air data obtained was provided in the TD-6201 format, another AERMOD specific format created by SCRAM. The general format of TD-6201 upper air data files as described by the EPA is shown in Table II (EPA, 2011).

Table II: TD-6201 Data Format

Field	Character	Description
1	001-008	Station Id
2	009-012	Latitude
3	13	Latitude Code N/S
4	014-018	Longitude
5	19	Longitude Code E/W
6	020-029	Date And Time (Yr/Mo/Dy/Hr)
7	030-032	Number Of Data Portion Groups
8	33	Level Quality Indicator
9	034-037	Time (Elapsed Time Since Release)
10	038-042	Pressure
11	043-048	Height
12	049-052	Temperature
13	053-055	Relative Humidity
14	056-058	Wind Direction
15	059-061	Wind Speed
16	062-067	Quality Flags
17	68	Type Of Level

2.2.2.3. Land Use Data

AERMET takes land use around the area being modeled into account in order to calculate the variables of surface roughness, albedo and Bowen ratio.

- **Surface roughness** is a measure of the average height of objects on the ground's surface which can cause turbulence in air flowing over the ground. Land such as

coniferous forest may have a high roughness value due to the height of tall trees, whereas water has a surface roughness very near zero.

- **Albedo** is a function of how much incoming radiation is reflected by a surface. A surface such as snow will have a high albedo (near 1), indicating that nearly all incoming radiation is reflected, while a surface such as asphalt will have a very low albedo (near zero) indicating that nearly all incoming radiation is absorbed, and can be released as convective heat. This convective heat leads to increased atmospheric mixing as energy is transferred from the ground's surface to the air, especially close to the surface.
- **Bowen ratio** is a measure of a material's heat transfer properties. A surface with a high Bowen ratio will readily transfer heat, leading to increased convective mixing.

There are eight different land use classifications available for selection in AERMET: water, deciduous forest, coniferous forest, swamp, cultivated land, grassland, desert shrubland, and urban. In order to calculate surface roughness, AERMET requires inputs of land use in discrete sectors in a one kilometer circle around the modeled area. For the purposes of this project, the Greeley School monitoring site was selected as the center point. Eight sectors were selected, and are shown in Figure 5. The land use assignment of each sector is provided in Table III. Albedo and Bowen ratio are calculated based on weighted averages for each land use type within a 10 km by 10 km square. This area is shown in Figure 6, and the resulting land use assignments are provided in Table 4. Surface roughness, albedo and Bowen ratio values were calculated seasonally, with dry soil conditions assumed. These values are provided as a table in Appendix A.

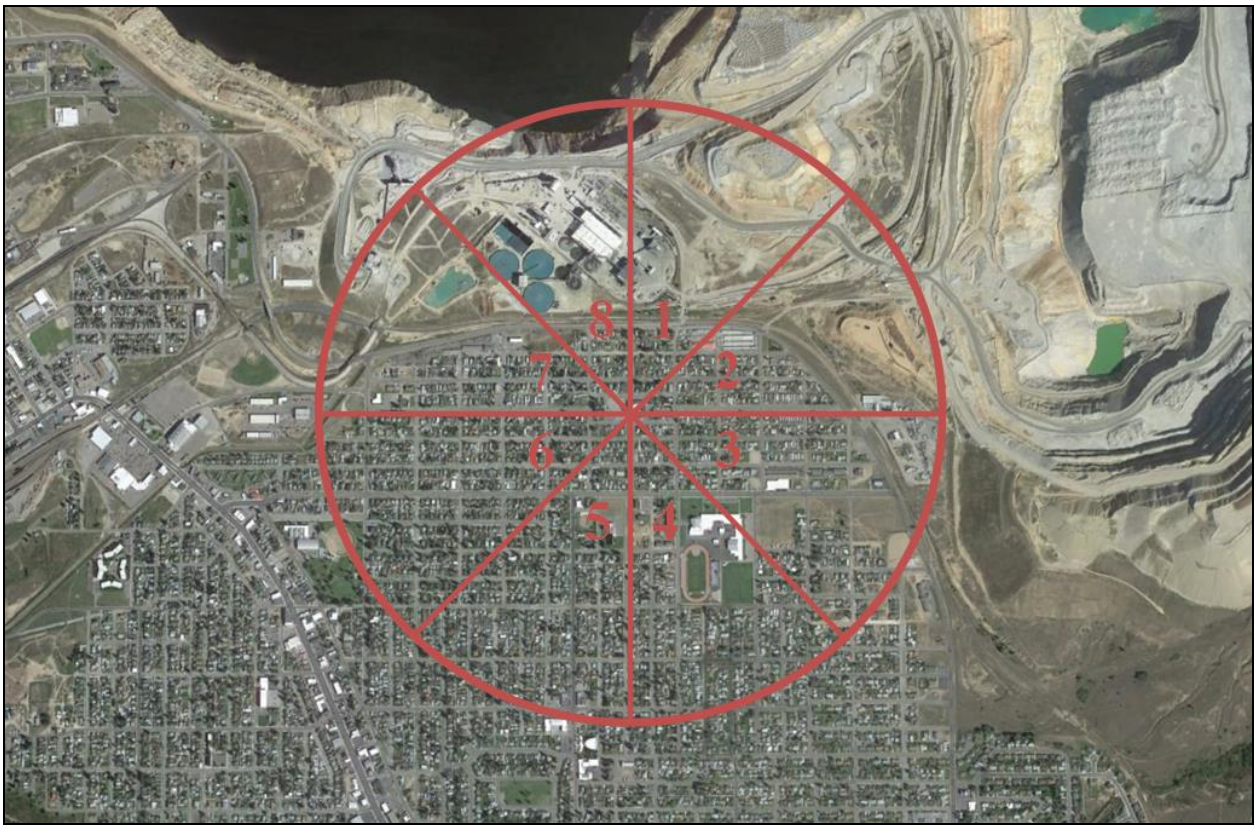

Figure 5: Land Use Sectors for Surface Roughness Calculation

Table III: Land Use Values for Surface Roughness Calculation

Sector	Starting Degree	Ending Degree	Category
1	0	45	Desert Shrubland
2	45	90	Desert Shrubland
3	90	135	Urban
4	135	180	Urban
5	180	225	Urban
6	225	270	Urban
7	270	315	Urban
8	315	360	Desert Shrubland

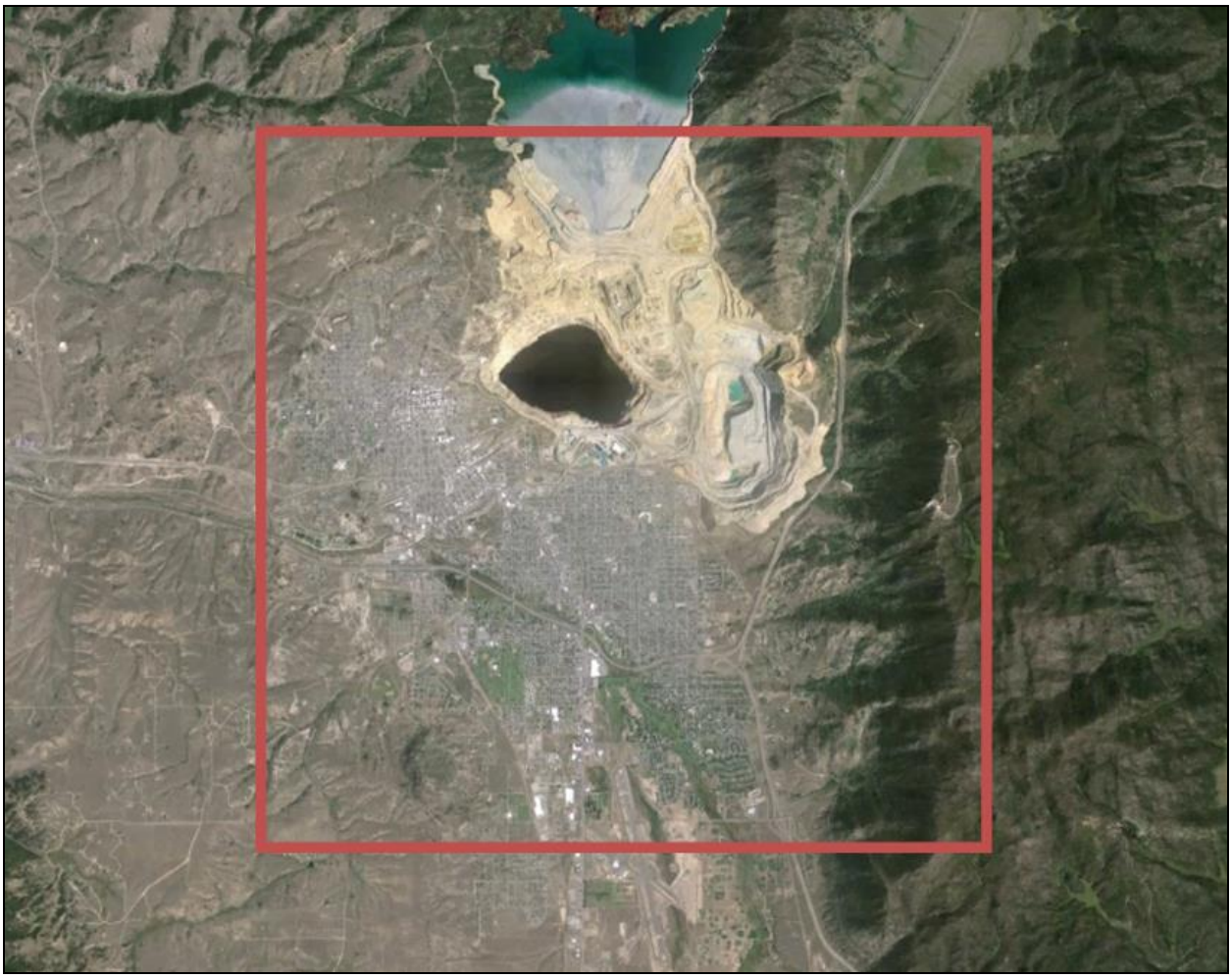

Figure 6: Land Use Area for Albedo and Bowen Ratio Calculation

Table IV: Land Use Coverage for Albedo and Bowen Ratio Calculation

Category	Coverage (%)
Water	5
Deciduous Forest	0
Coniferous Forest	10
Swamp	0
Cultivated Land	0
Grass Land	10
Urban	45
Desert Shrubland	30

2.2.2.4. AERMET Outputs

After inputting all variables, AERMET was run in order to create the meteorological input files used by AERMOD. Two files were produced after running AERMET, a surface meteorology file with the extension "*.SFC," and an upper air profile file with the extension "*.PFL."

2.2.3. AERMAP Setup

AERMAP, the terrain data preprocessor for AERMOD, was run in order to account for terrain effects on local meteorology, particle deposition and plume dispersion, as well as calculate the base heights of receptors and sources in the area. Terrain data in the form of four 7.5 min DEM files was obtained from the US Geological Survey (USGS) EarthExplorer data management tool.

2.2.4. AERMOD Setup

This section describes the data inputs, options selected and assumptions made to create the AERMOD model instance.

2.2.4.1. Model Options

An input summary file, listing all selected model options is provided in Appendix B. The following control options were selected:

- A projection of Universal Transverse Mercator (UTM) in units of meters, and the World Geodetic System 1984 datum
- AERMOD Version 14134
- Pollutant $PM_{2.5}$ with units of $\mu g/m^3$
- Calculation of particulate deposition

- Output tables including average annual concentrations, average monthly concentrations and 98th percentile 24 hour concentrations
- No building downwash was accounted for

2.2.4.2. Emission Source Parameters

This section describes the source parameters for releases from residential wood burning and industrial sources. A background concentration of 3 µg/m^3 was added to modeled results afterwards.

2.2.4.2.1. Residential Wood Burning

It was found in Dr. Ganesan's 2013 study that releases of $PM_{2.5}$ from wood burning sources in Butte was 72.9 tons per year. However, the amount emitted varies greatly from month to month throughout the year, with much higher emissions during the winter months. This variation was accounted for by correlating wood smoke emissions with heating degree days in Butte. Heating degree days (HDD) is a metric of how much energy is required to heat a building, and is a function of the difference between the outdoor temperature and the indoor temperature maintained within a building (Bailes, 2014). This relationship is described in equation 1:

$$HDD = (T_i - T_o) * \Delta t \quad (1)$$

where HDD is the number of heating degree days for the month in units of degrees Fahrenheit multiplied by days, T_i is the average monthly indoor temperature, T_o is the average monthly outdoor temperature and Δt is the number of days in the month.

By assuming a linear relationship between the heating degree days for a month, the amount of wood used for heating during that month, and therefore the emission of $PM_{2.5}$ during that month, we can assign each month a portion of the total annual emissions with equation 2:

$$E = E_{TOT} * \frac{HDD_{Mon}}{HDD_{TOT}} \quad (2)$$

where E is the emission for a given month in tons, E_{TOT} is the total annual emission in tons, HDD_{Mon} is the heating degree days for a month, and HDD_{TOT} is the total number of heating degree days in a year. These equations were used to calculate the monthly emission of $PM_{2.5}$ sources for each month in 2010 – 2012, and a full table of these results is provided in Appendix C.

In order to input these results into AERMOD, variations in emission rates were converted to a fraction of a baseline emission rate. Table V shows the calculated emission factor for each month, as well as the emission rate for that month in grams per second.

Table V: Monthly Emissions from Wood Burning Sources

Month	Emission Factor	Monthly Emission (g/s)
January	1.76	2.810E-07
February	1.56	2.554E-07
March	1.29	2.810E-07
April	1.02	7.663E-08
May	0.73	2.554E-08
June	0.43	2.554E-08
July	0.18	2.299E-07
August	0.27	2.554E-07
September	0.52	2.427E-07
October	1.01	2.171E-07
November	1.45	2.299E-07
December	1.79	4.343E-07

Wood burning emissions were treated as a polygon area source over the residential areas of Butte, with user defined points. This area source is shown in Figure 7, along with all other model objects input to the model run. Within AERMOD, concentrations at a receptor resulting from an area source are calculated by integrating across the source in the upwind and crosswind directions from the receptor. This is used to generate an initial plume dispersion, which acts as a modifier for the Gaussian plume equation. The overall effect is that the plume resulting from an area source starts as a plume with characteristics in the X and Y directions, and those characteristics become modified as the plume travels downwind. Since AERMOD only incorporates values upwind of a receptor, it is possible to place receptors within an area source and receive an accurate prediction of concentrations (EPA 1995).

For the purpose of this study, emissions from wood burning sources were assumed to be constant across residential areas in Butte near the Greeley School receptor. However, in order to better estimate emissions, it would be possible to correlate emissions to population density based on US census data. By dividing the area into many smaller areas (for example, city blocks), and treating each area as its own source, each section could be allotted a portion of the total annual emissions by assuming a linear relationship between population density and wood smoke emissions.

2.2.4.2.2. Industrial Sources

In order to estimate emissions from industrial sources in the Butte area, emission inventories were obtained through Dan Walsh with the Montana DEQ. These inventories provide a detailed listing of releases for all major emitting facilities in the Butte area. Based on the data provided, there are three facilities in the Butte area with large enough emissions and a close enough proximity to contribute meaningfully to $PM_{2.5}$ concentrations. These sources are

shown in Table VI. Industrial sources were modeled as point sources with an emission rate averaged over the years of 2010 – 2012.

Table VI: Industrial Source Locations and Emission Rates

				$PM_{2.5}$ Emissions (tpy)			
Facility	**UTM X**	**UTM Y**	**Zone**	**2010**	**2011**	**2012**	**Avg**
Basin Creek Power	381780	5087373	12	0.97	0	1	0.66
Montana Resources	383568	5095907	12	44.77	45.09	46.47	45.44
REC Advanced Silicon	369020	5091951	12	6.29	7.41	8.81	7.50

While emission inventories provide details on the quantity of pollutant released from a source, they do not include the conditions under which those pollutants were released. Many source parameters required by AERMOD were missing, including stack height, stack gas temperature, stack flow velocity and stack diameter. Therefore, the following assumptions were made according to the AERMOD User's Guide (EPA, 2004):

- Stack height of 65 m
- Stack velocity of 0.001 m/s
- Stack gas temperature of 0 K (model will assume ambient air temperature)
- Stack diameter of 1 m

A full listing of all point sources, their emission rates in grams per second, their locations in UTM coordinates and their source parameters is provided in Table VII. A diagram showing the geographical relation of all sources is provided in Figure 7 in the next section (Section 2.3.3.3).

Table VII: Industrial Source Locations and Parameters

Source ID	UTM X	UTM Y	Elevation	Emission Rate	Stack Height	Stack Temp	Stack Velocity	Stack Diameter
	(m)	(m)	(m)	(g/s)	(m)	(K)	(m/s)	(m)
REC_SILI	369020	5091951	1669	0.2159	65	0	0.001	1
BASINCRE	381780	5087373	1723	0.0189	65	0	0.001	1
MTRESOUR	383568	5095907	1680	1.3074	65	0	0.001	1

2.2.4.2.3. Background $PM_{2.5}$ Concentrations

Based on the reanalysis of NASA satellite data conducted by Donkelaar, Martin, Brauer, and Boys, the background concentration of $PM_{2.5}$ from long range sources was assumed to be a constant 3 $\mu g/m^3$, and was added to the results of all model runs (Donkelaar, Martin and Brauer).

2.2.4.2.4. Secondary Sources of $PM_{2.5}$

$PM_{2.5}$ released directly from a source is known as Primary $PM_{2.5}$. However, particulate matter can also be generated in the atmosphere through the photochemical reaction of several precursor compounds, producing what is known as Secondary $PM_{2.5}$. These chemical precursors can include SO_2, NO_2 and various volatile organic compounds (VOCs), which react when exposed to sunlight to form particulate matter (Weber, Sullivan and Peltier). While it is entirely possible to estimate PM2.5 formation through these processes, the process requires concentrations of precursor compounds present. Since no source of data for SO_2, NO_2 nor VOCs in the Butte area is maintained, it is impossible to accurately predict the effects of these processes without further monitoring of air quality in Butte, and as such this study does not account for the effects of secondary $PM_{2.5}$ formation.

2.2.4.3. Selected Receptor

Since detailed $PM_{2.5}$ concentration data was available for the Greeley School monitoring site, it was selected as the receptor at which AERMOD would calculate modeled concentrations. This will provide a direct comparison between historical $PM_{2.5}$ concentrations at this location and concentrations calculated through modeling, giving a means of verifying that the assumptions and data used in the model are accurate. Located at a latitude of 46.0026º N and a longitude 112.5013º W, this source is shown in Figure 7 as a yellow plus sign. All previously described sources are also included in this figure, giving a complete picture of the geographical relation between all model objects.

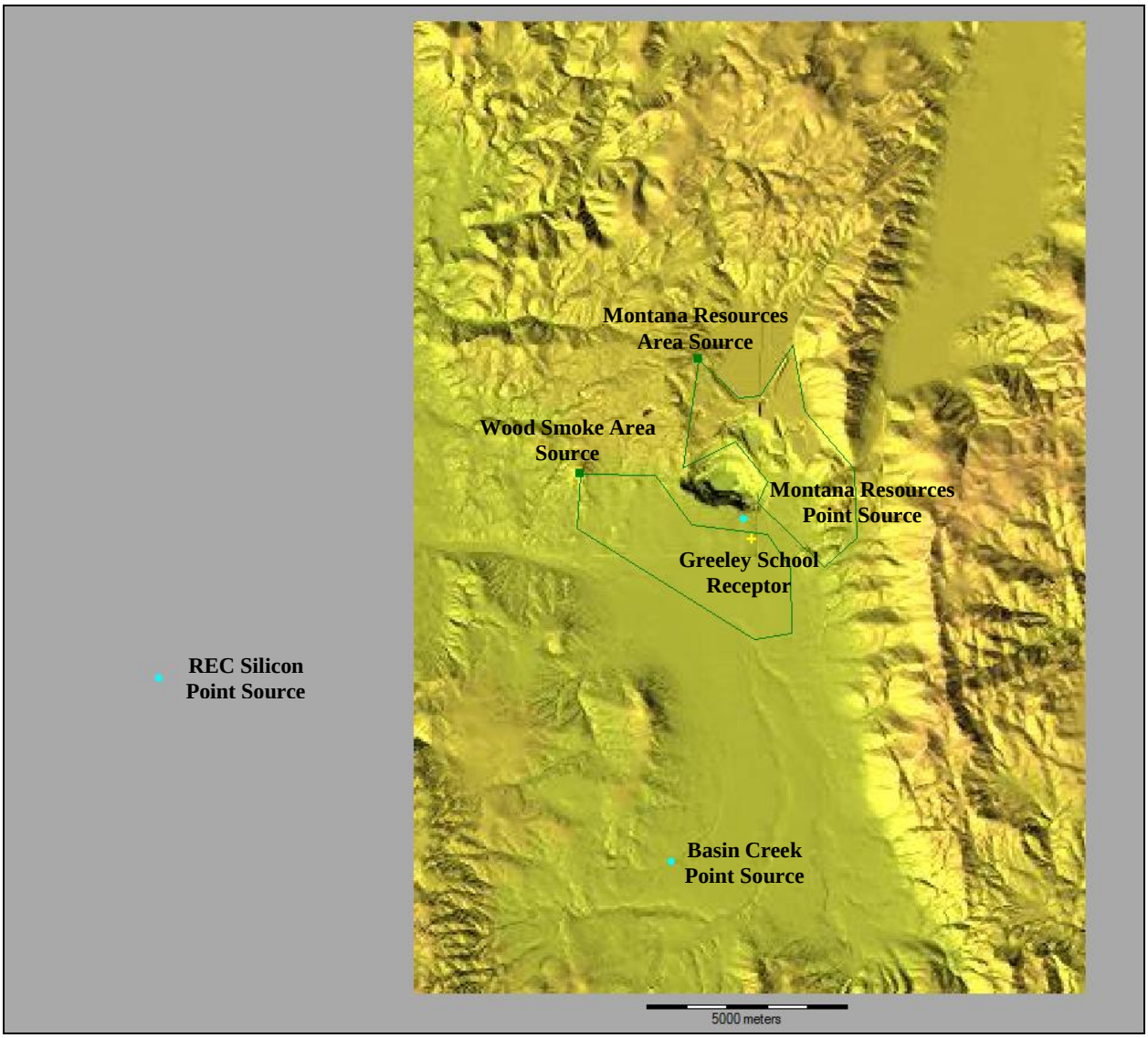

Figure 7: Location of Sources and Receptor

2.2.5. Model Verification Results

After completing the model setup process, AERMOD was run for the years of 2010 – 2012. The results of this analysis were then compared to measured values recorded at the Greeley School monitoring site to verify that all assumptions and data inputs were acceptable. In order to fine tune modeled results, the size and location of area source emissions was adjusted to

better match measured values. A full log of the changes made to the wood emission sources is provided in Appendix D.

After several iterations, agreement between modeled results and historical measured results was generally acceptable. The results of the model optimization process are plotted for the years of 2010 – 2012 in Figures 8 - 10, versus the actual measured values taken from the Greeley School monitoring station. Input, output and report files generated by AERMOD for the verified model are provided in Appendix E.

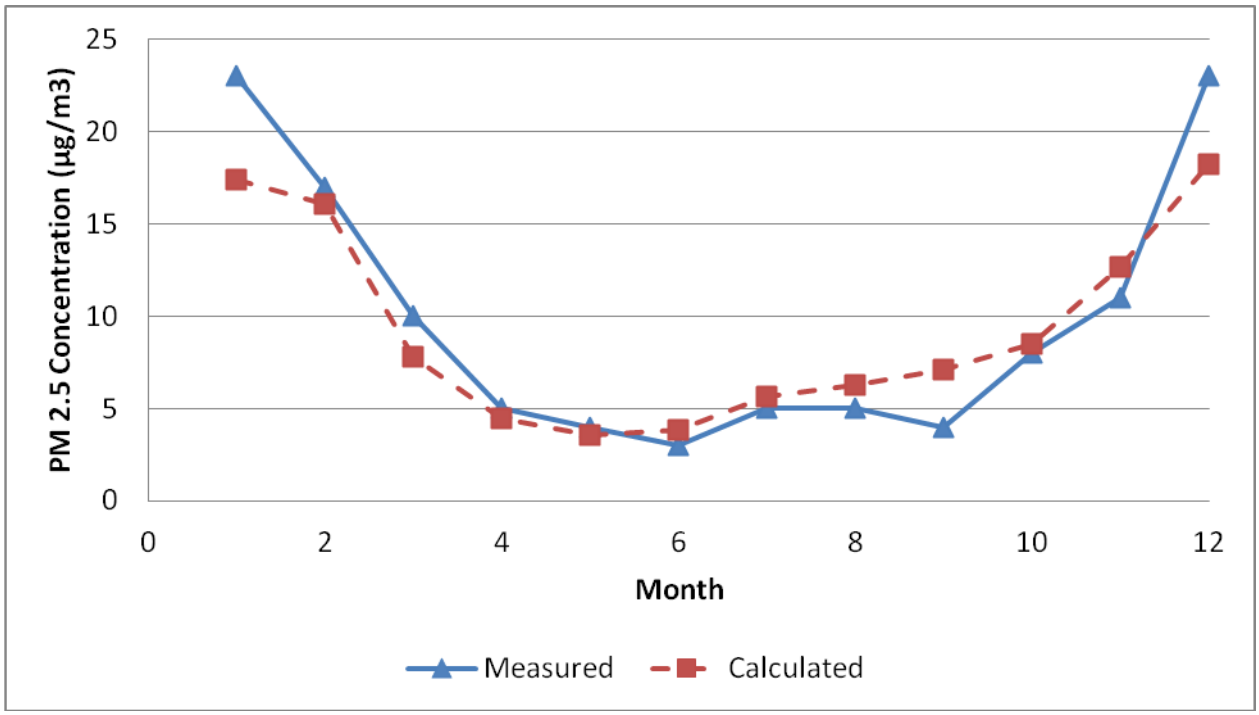

Figure 8: Modeled Versus Measured $PM_{2.5}$ Concentrations for 2010

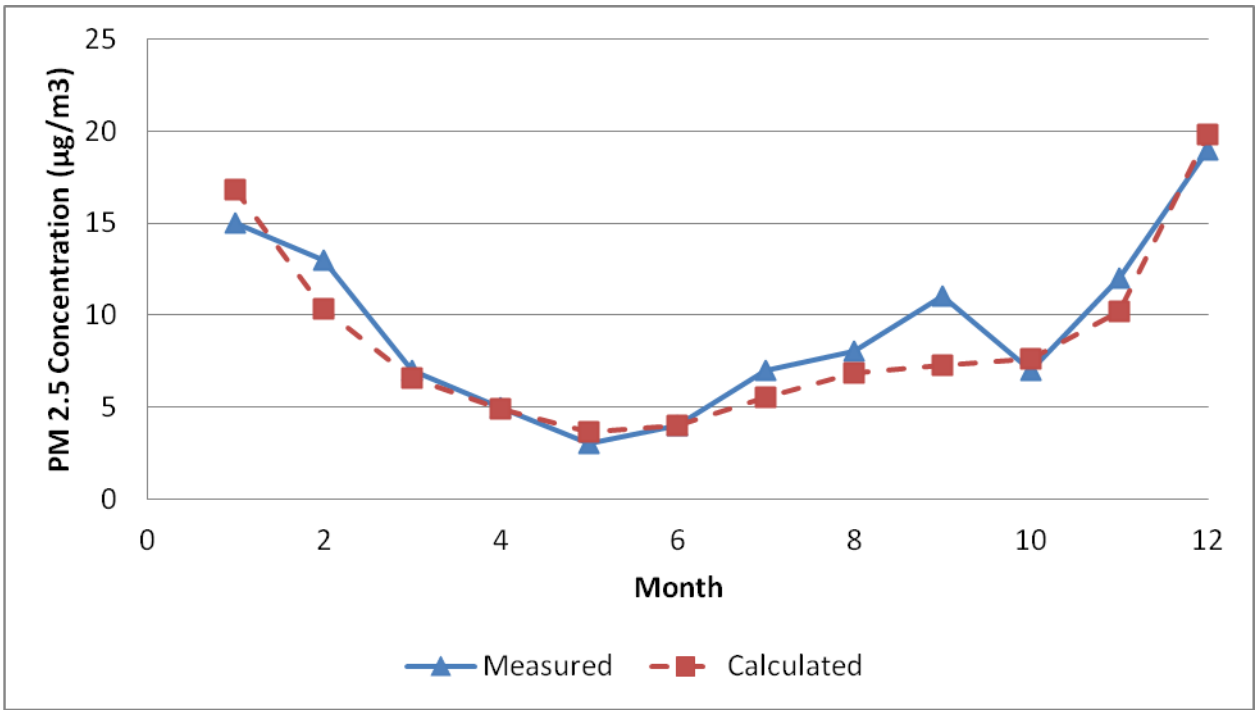

Figure 9: Modeled Versus Measured $PM_{2.5}$ Concentrations for 2011

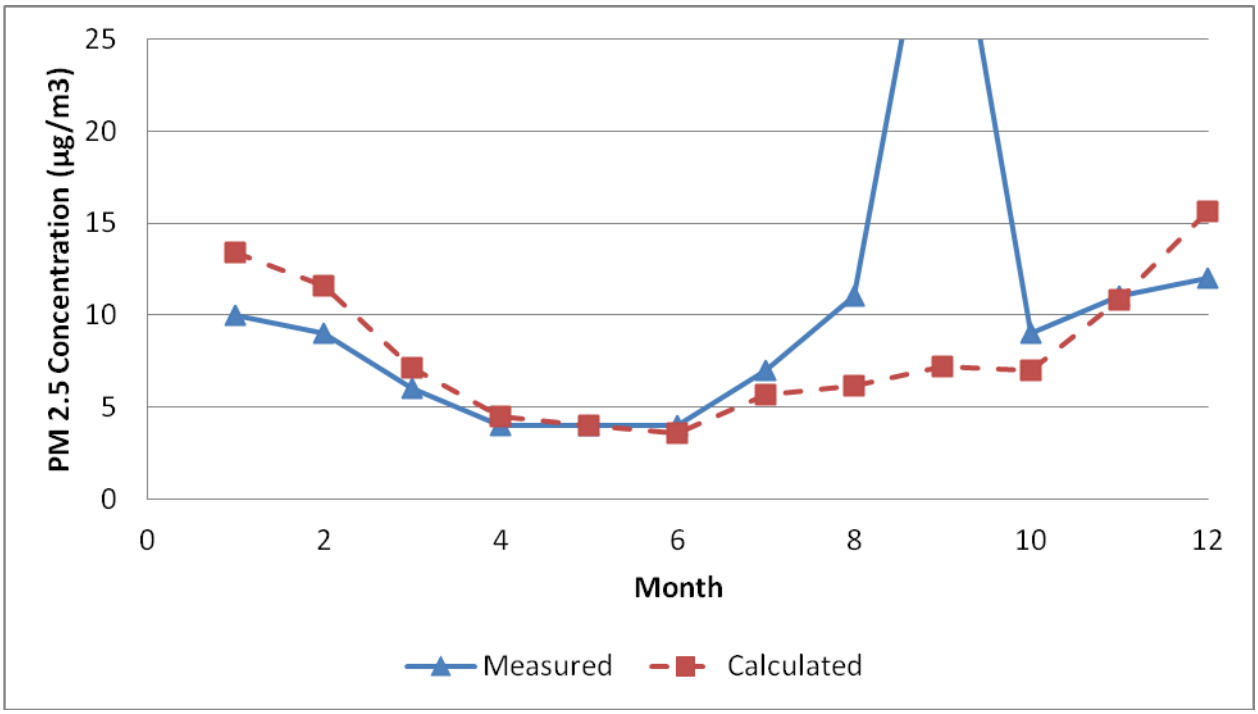

Figure 10: Modeled Versus Measured $PM_{2.5}$ Concentrations for 2012

As is shown in the above figures, there was a general agreement between the modeled concentrations and measured values, with a few obvious exceptions. During September of 2012, an extremely high average monthly concentration of 36 $\mu g/m^3$ was observed. This concentration was not the result of emissions occurring within the Butte area, but primarily the result of the long range transport of pollutants released by several large fires in the western United States. A similar (but less pronounced) peak can be seen in September of 2011, also the result of forest fires. While these events contributed significantly to $PM_{2.5}$ concentrations during this time period, this is not something that can be quantified through modeling efforts, and as such the contribution of forest fire events to local $PM_{2.5}$ concentrations was not taken into account during the model verification process, or any other modeled scenarios.

The general practice when constructing a model involves the construction of the model based on one time period, and the verification of that model over another time period. However, due to only having three years of measured $PM_{2.5}$ data available, model verification and construction was conducted in one step. While this does weaken the results generated by this model, since this study is more concerned with comparing future $PM_{2.5}$ concentrations with current day concentrations than actually predicting future values, modeled results will still provide useful information. These results should not be taken as absolute predictions of future concentrations, but compared to current day trends to examine whether conditions will worsen or improve in future years.

2.3. Examined Scenarios

After model verification was completed, three different scenarios were created and examined to assess potential for future $PM_{2.5}$ concentrations for the years 2040, 2050, 2060, and 2070:

- A Baseline Scenario, in which predicted future climate values were paired with current emissions values.
- A No Control Scenario, in which predicted future climate values were paired with projected trends in emissions from wood burning sources and industrial sources.
- A Control Scenario, in which predicted future climate values were paired with projected trends in emissions after some method of reduction of $PM_{2.5}$ emissions had been implemented.

These scenarios and the assumptions that were made during their development are described in greater detail in the following sections.

2.3.1. Baseline Scenario

The first future scenario replaced historical meteorological values with predicted NARCCAP data. All source emissions, terrain data and land use values were kept constant with the 2010 – 2012 time period. This was done purely to determine the effect of future meteorological conditions on the dispersion of $PM_{2.5}$. Trends in changing meteorological variables will greatly affect the dispersion of airborne pollutants, and may increase or decrease observed ground level concentrations drastically.

2.3.2. No Control Scenario

This scenario combines future NARCCAP climate values with projected emission trends in order to predict future concentrations of $PM_{2.5}$ if no control measures are enacted to reduce emissions in the Butte area. Terrain and land use data remained the same. This scenario adjusts emissions from both residential wood burning and industrial sources.

The amount of wood burned in order to maintain a certain temperature in a house is largely a function of the outdoor temperature. By using the methodology described in Section 2.3.4.2.1 of this report, future $PM_{2.5}$ emission rates were correlated with outdoor temperature through the monthly heating degree days for each month. The monthly emissions from wood burning sources for each year modeled are provided in Appendix C.

In order to account for increases in productivity at Montana Resources, emissions from this source were assumed to increase at a rate of 30% per ten years. However, due to the finite amount of resources available at the Montana Resources mining operation, emissions were assumed to halt after 2050.

2.3.3. Control Scenario

The Control Scenario was designed to determine the effectiveness of a control method to reduce $PM_{2.5}$ emissions in the Butte area to lower ground level concentrations of the pollutant. It was determined in Dr. Ganesan's 2014 study that wood smoke emissions are the largest contributor to $PM_{2.5}$ concentrations at the Greeley School receptor. Therefore, the most effective means of pollution control would be to target this source through a wood stove change out program. This type of program incentivizes homeowners to replace inefficient wood burning stoves with EPA certified stoves.

In order to adjust emissions from wood stoves after the implementation of a stove change out program, data on the number and type of stove used in Butte was gathered from Dr. Ganesan's 2013 report on wood smoke emissions in Butte. Data included the annual wood usage by wood burning device type, an emission factor for $PM_{2.5}$ emitted and total annual emissions of $PM_{2.5}$ from each device type. This summary is provided in Table VIII (Ganesan, $PM_{2.5}$ Emissions from Wood Combustion in Butte, Montana, 2013).

Table VIII: Current Types of Wood Burning Devices and Amount of Wood Burned

Type of Device	% of Devices	% of Wood Burned by Device	Total Annual Tons of Wood	$PM_{2.5}$ EF (lb/ton)	$PM_{2.5}$ Emissions (lb)
Fireplace	23.20	11.44	751	35	25,984
Pre-Certified	39.29	33.9	2,226	31	68,120
Phase II Catalytic	8.93	19.6	1,287	16	20,856
Phase II Non-Catalytic	7.14	16.34	1,073	14	15,020
Cord Wood Furnace	1.80	4.91	322	31	9,849
Pellet Stoves	19.64	13.81	907	7	5,989
Total	**100**	**100**	**6,566**		**145,818 (72.9 tons)**

When examining a stove change out program, two different scenarios were created. One in which 50% of all devices such as fireplaces, pre-certified and cord wood furnace devices were replaced with a Phase II Non-Catalytic stove (emission factor of 14 lb $PM_{2.5}$ per ton of wood burned), and another scenario in which 100% of such devices were replaced with Phase II Non Catalytic stoves. The same amount of total wood usage was assumed to remain constant. Table IX provides the updated emissions after the implementation of a change out program.

Table IX: Amount of Wood Burned After Change Out Program

50% Change Out					
Type of Device	**% of Devices**	**% of Wood Burned by Device**	**Total Annual Tons of Wood**	**$PM_{2.5}$ EF (lb/ton)**	**$PM_{2.5}$ Emissions (lb)**
Fireplace	11.60	5.72	376	35	13,143
Pre-Certified	19.65	16.95	1113	31	34,503
Phase II Catalytic	8.93	19.60	1287	16	20,592
Phase II Non-Catalytic	39.29	41.47	2723	14	38,115
Cord Wood Furnace	0.90	2.46	161	31	4,991
Pellet Stoves	19.64	13.81	907	7	6,349
Total			**6,566**		**117,693 (58.8 tons)**

100% Change Out					
Type of Device	**% of Devices**	**% of Wood Burned by Device**	**Total Annual Tons of Wood**	**$PM_{2.5}$ EF (lb/ton)**	**$PM_{2.5}$ Emissions (lb)**
Fireplace	0.00	0.00	0	35	0
Pre-Certified	0.00	0.00	0	31	0
Phase II Catalytic	8.93	19.60	1287	16	20,592
Phase II Non-Catalytic	71.43	66.59	4372	14	61,208
Cord Wood Furnace	0.00	0.00	0	31	0
Pellet Stoves	19.64	13.81	907	7	6,349
Total			**6,566**		**88,149 (44.1 tons)**

Using the values in Table IX, the baseline emission rate for $PM_{2.5}$ emission from wood burning sources was adjusted. The results of this adjustment are provided in Table X.

Table X: $PM_{2.5}$ Emission Rates After Change Out

% of Stoves Replaced	**Annual $PM_{2.5}$ Emissions (tons)**	**$PM_{2.5}$ Emission Rate (g/s)**
0	72.9	6.67E-08
50	58.8	5.38E-08
100	44.1	4.03E-08

These emission rates were then adjusted on a monthly basis according to the monthly heating degree days as in the No Control Scenario. All other assumptions made in the No Control Scenario remained constant, including increases in industrial emissions, replacement of meteorological data with future predicted values, and current terrain and land use data.

3. Results

This section describes the results of the various scenarios examined through the AERMOD modeling software suite.

3.1. Baseline Scenario

The results of the AERMOD analysis of the Baseline Scenario as described in Section 2.3.1 are provided in this section. Results for the years 2040, 2050, 2060 and 2070 are provided below in Table XI. These results are also displayed graphically in Figures 11 - 13 with the predicted concentration plotted versus the average modeled concentration over the 2010 – 2012 time period for the sake of comparison. The x-axis is the month of the year, and the y-axis is $PM_{2.5}$ concentration in $\mu g/m^3$.

Table XI: Results of Baseline Modeling Scenario

Month	Monthly $PM_{2.5}$ Concentration (µg/m^3)				
	2010 - 2012 Avg	2040	2050	2060	2070
Jan	15.9	16.7	14.1	19.0	20.7
Feb	12.7	15.3	13.9	14.3	13.6
Mar	7.2	9.0	6.7	8.1	9.4
Apr	4.6	5.5	4.4	4.4	4.7
May	3.7	3.2	3.5	4.0	3.5
Jun	3.8	3.3	4.1	4.4	3.4
Jul	5.6	4.0	4.4	6.2	3.7
Aug	6.4	5.5	6.2	6.1	5.3
Sep	7.2	5.2	6.8	6.6	5.6
Oct	7.7	6.4	6.7	6.9	6.8
Nov	11.2	8.8	14.0	12.3	8.4
Dec	17.9	20.9	18.8	20.7	23.4

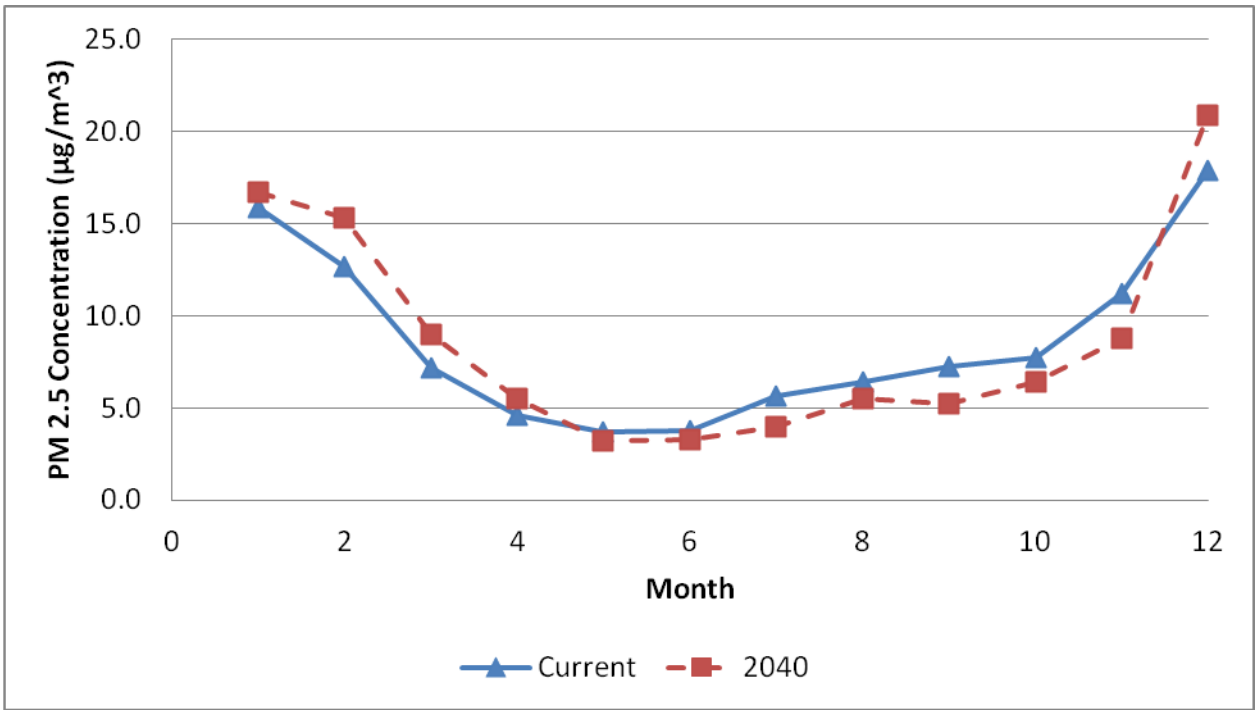

Figure 11: Modeled $PM_{2.5}$ Concentrations for the 2040 Baseline Scenario

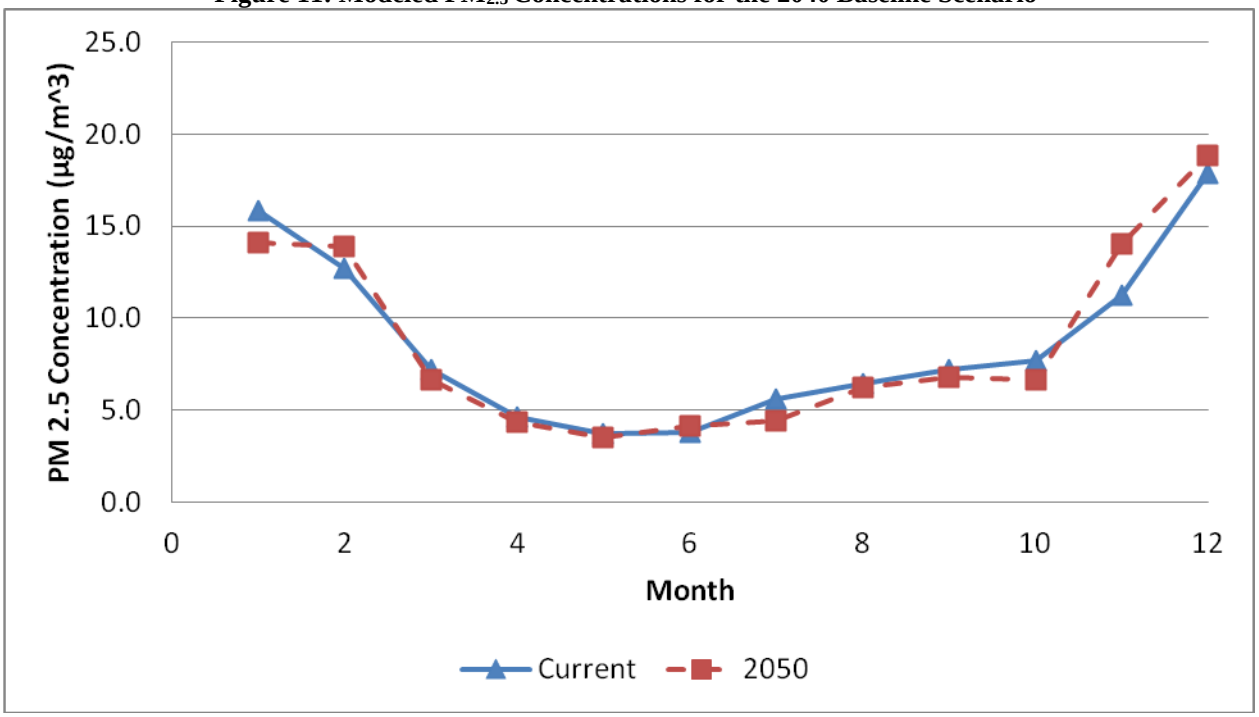

Figure 12: Modeled $PM_{2.5}$ Concentrations for the 2050 Baseline Scenario

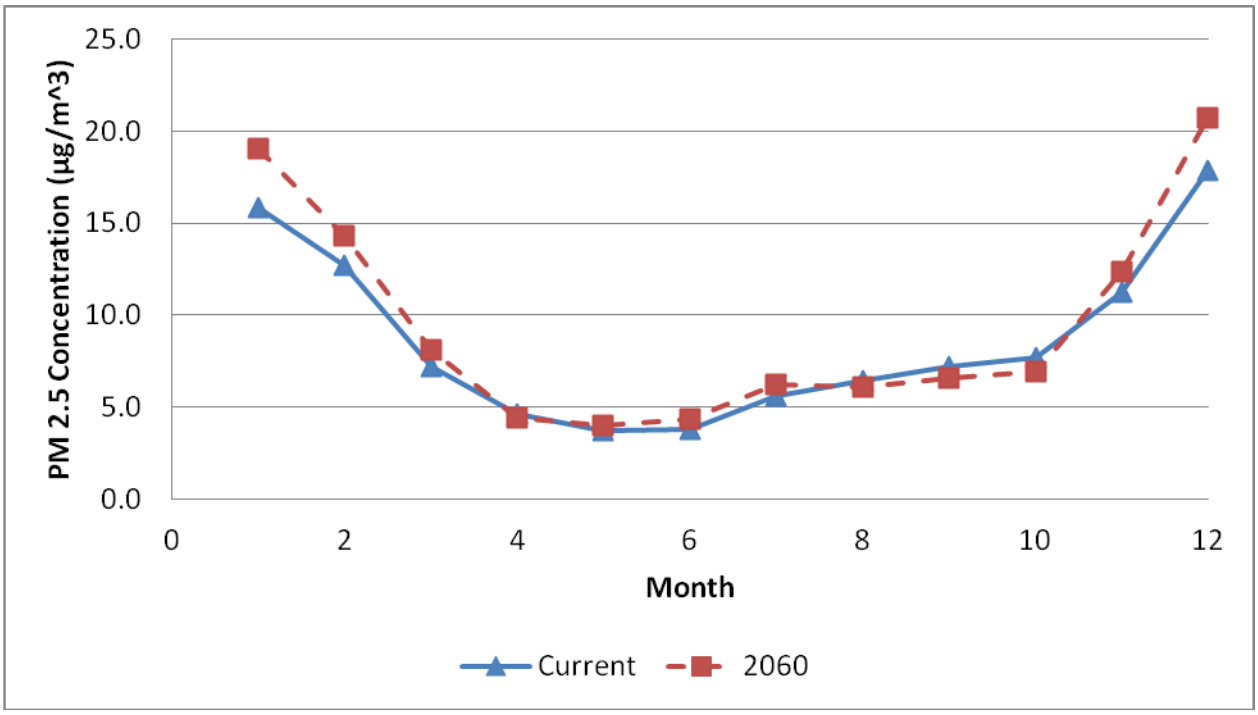

Figure 13: Modeled $PM_{2.5}$ Concentrations for the 2060 Baseline Scenario

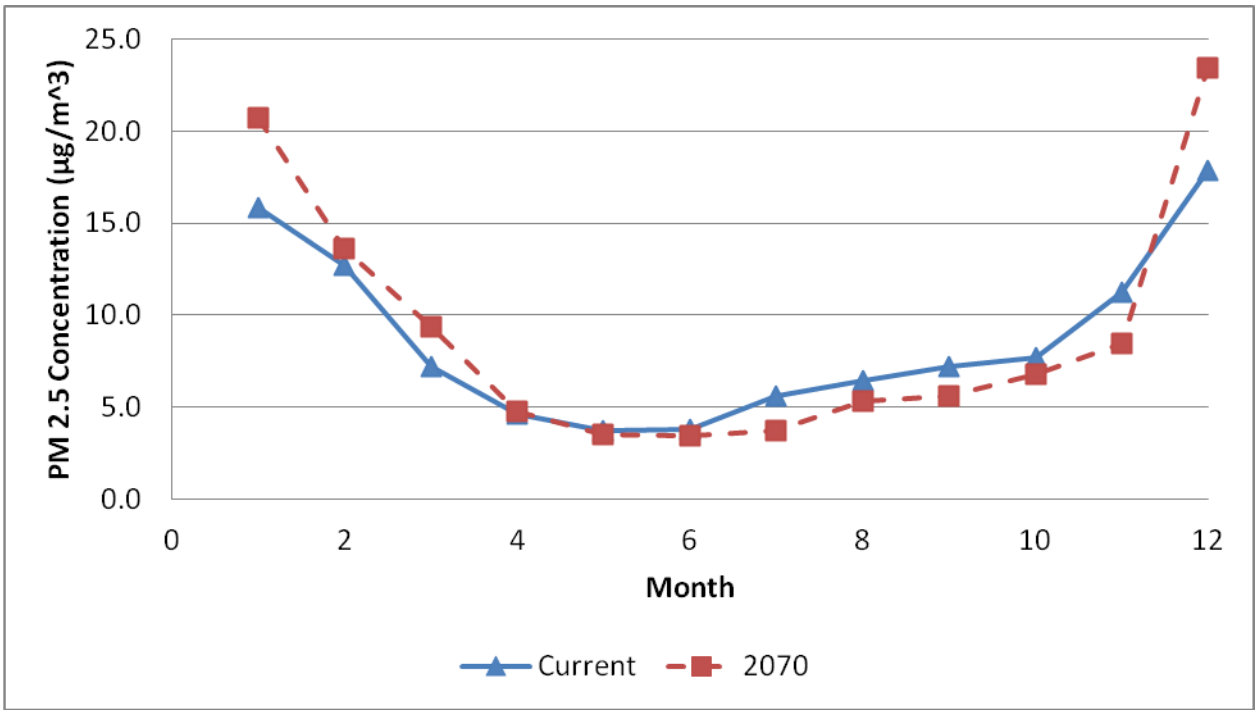

Figure 14: Modeled $PM_{2.5}$ Concentrations for the 2070 Baseline Scenario

3.2. No Control Scenario

The results of the AERMOD analysis of the No Control Scenario as described in Section 2.3.2 of this report are provided in this section. Results for the years 2040, 2050, 2060 and 2070 are provided below in Table XII. These results are also displayed graphically in 15 - 18 with the predicted concentration plotted versus the average modeled concentration over the 2010 – 2012 time period for the sake of comparison. The x-axis is the month of the year, and the y-axis is $PM_{2.5}$ concentration in $\mu g/m^3$.

Table XII: Results of Baseline Modeling Scenario

Month	**Monthly $PM_{2.5}$ Concentration (µg/m^3)**				
	2010 - 2012 Avg	2040	2050	2060	2070
Jan	15.9	22.2	20.0	15.6	17.8
Feb	12.7	19.7	10.7	12.0	15.5
Mar	7.2	8.9	6.6	8.0	7.5
Apr	4.6	4.4	4.6	4.3	4.0
May	3.7	3.6	3.6	4.0	3.6
Jun	3.8	3.8	4.0	3.6	3.8
Jul	5.6	4.2	4.3	4.9	5.6
Aug	6.4	5.6	5.9	5.4	6.1
Sep	7.2	4.9	6.3	5.0	7.4
Oct	7.7	6.6	6.6	5.1	9.0
Nov	11.2	13.7	10.0	8.7	12.3
Dec	17.9	22.5	22.2	15.7	20.1

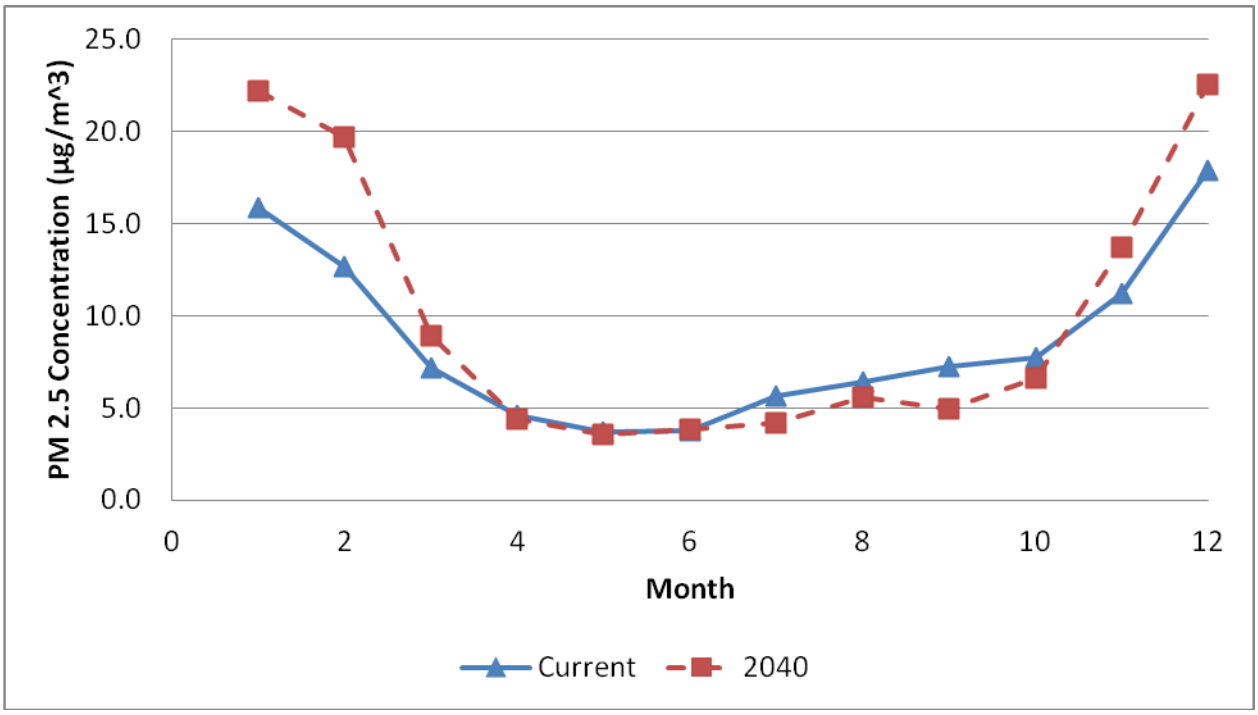

Figure 15: Modeled $PM_{2.5}$ Concentrations for the 2050 No Control Scenario

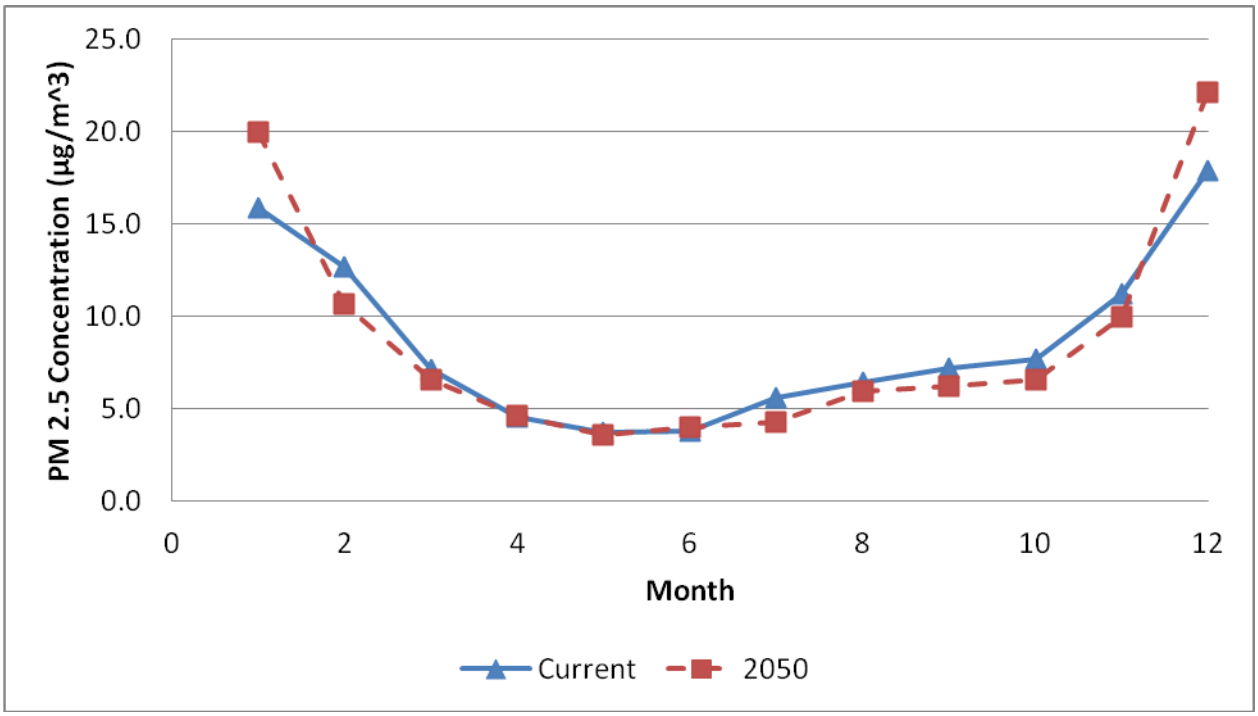

Figure 16: Modeled $PM_{2.5}$ Concentrations for the 2050 No Control Scenario

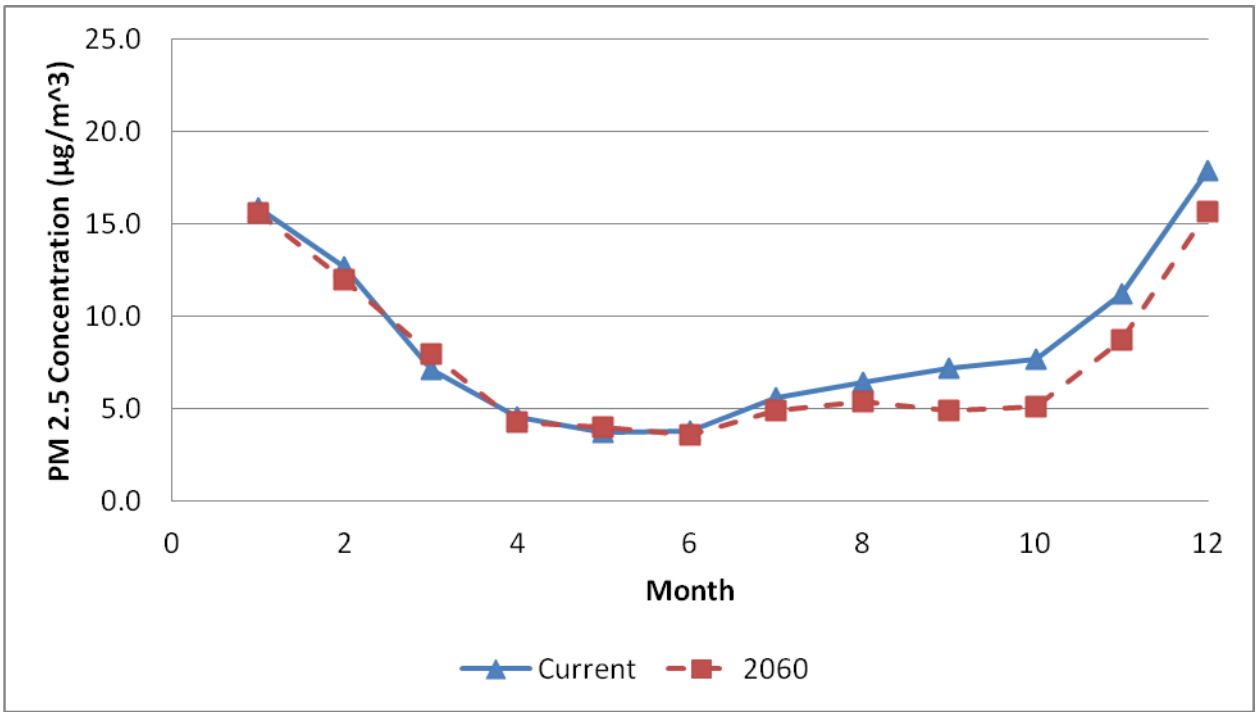

Figure 17: Modeled $PM_{2.5}$ Concentrations for the 2060 No Control Scenario

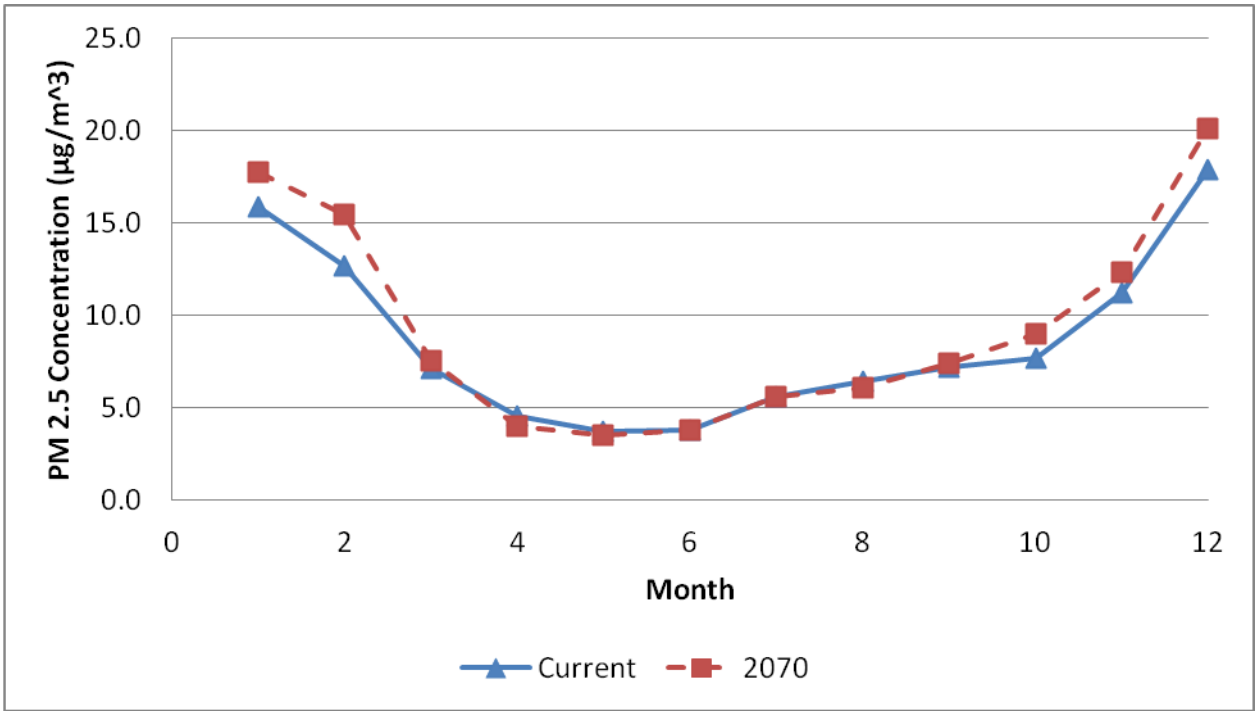

Figure 18: Modeled $PM_{2.5}$ Concentrations for the 2070 No Control Scenario

3.3. Control Scenario

The results of the AERMOD analysis of the Control Scenario as described in Section 2.3.3 of this report are provided in this section. Due to the large amount of data, results for the years 2040, 2050, 2060 and 2070 are provided in Appendix F. The three scenarios (no change out, 50% change out and 100% change out) are displayed in Figures 19 - 22 with the predicted concentration plotted versus the average modeled concentration over the 2010 – 2012 time period for the sake of comparison. The x-axis is the month of the year, and the y-axis is $PM_{2.5}$ concentration in $\mu g/m^3$.

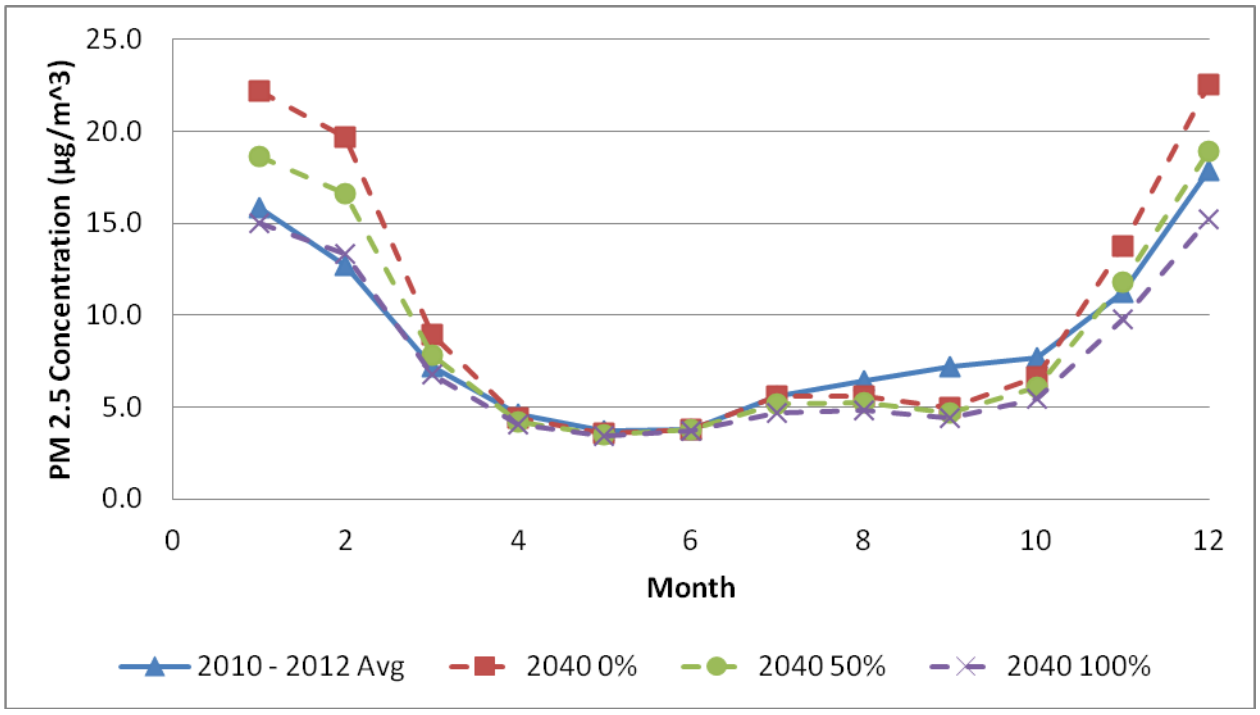

Figure 19: Modeled $PM_{2.5}$ Concentrations for the Year 2040 Control Scenario

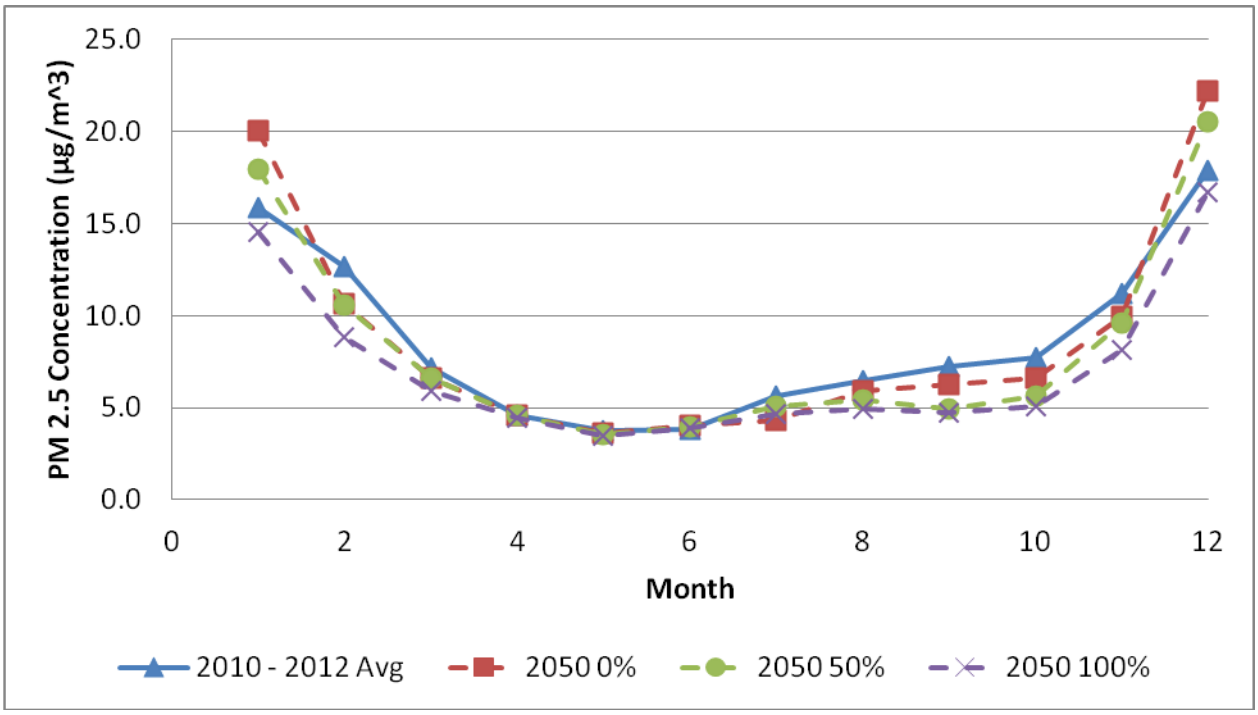

Figure 20: Modeled $PM_{2.5}$ Concentrations for the 2050 Control Scenario

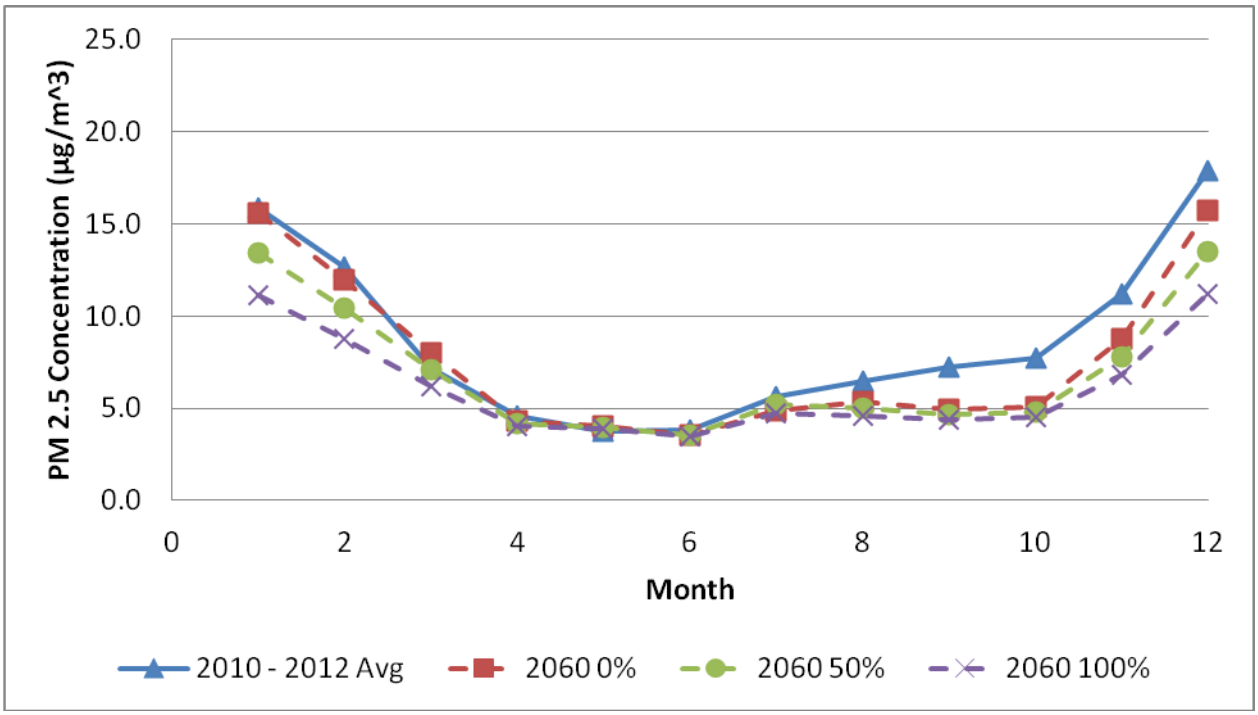

Figure 21: Modeled $PM_{2.5}$ Concentrations for the 2060 Control Scenario

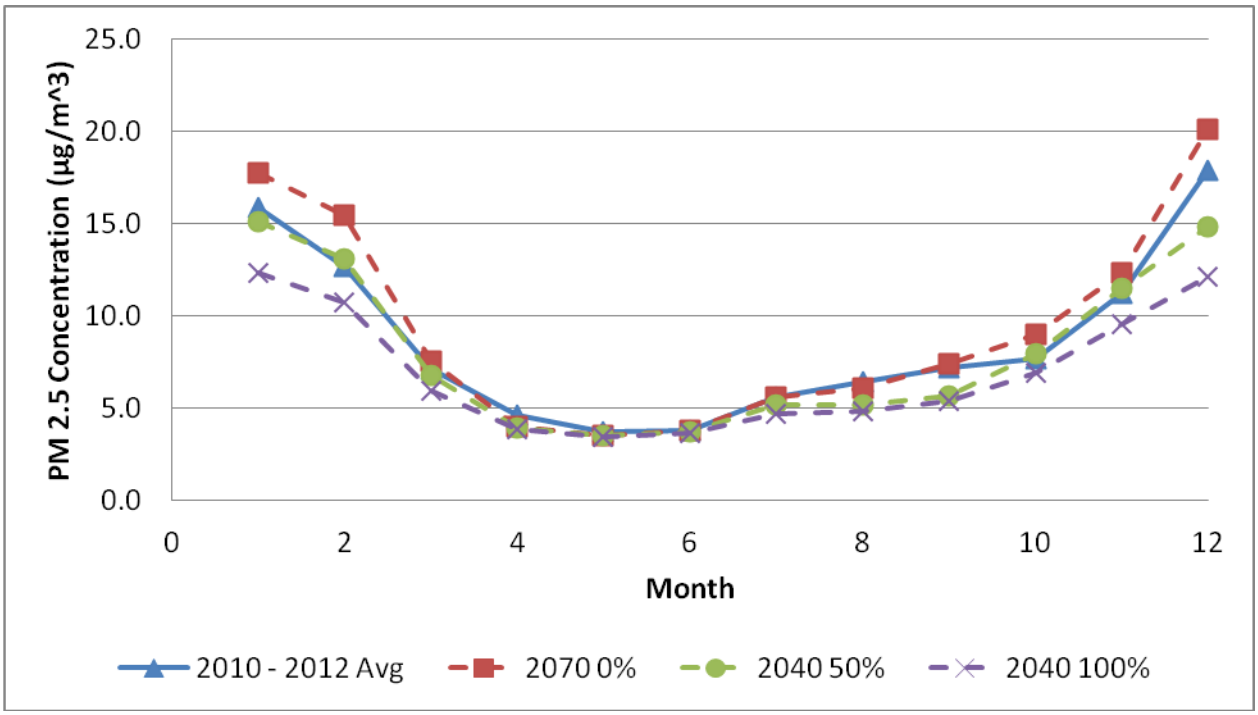

Figure 22: Modeled $PM_{2.5}$ Concentrations for the 2070 Control Scenario

3.4. Comparison to NAAQS Standards

In order to determine the potential risk to human health as a result of modeled concentrations, the annual average and 98th percentile 24-hour concentrations for each modeled year and stove change out percentage were calculated. 0% represents the results of the No Control Scenario. These results are provided in Table XIII, along with the calculated values for the 2010 – 2012 time period and the NAAQS Primary and Secondary standards. All values have units of µg/m^3.

Table XIII: Comparison of Modeled Concentrations to the NAAQS

	Primary Standard	Secondary Standard	2010 - 2012 Avg	2040			2050		
				0%	50%	100%	0%	50%	100%
Annual	12	15	10.52	14.12	10.04	8.51	15.84	11.13	9.36
24-hr	35	-	34.68	48.61	35.85	27.69	52.26	38.48	29.67
	Primary Standard	Secondary Standard	2010 - 2012 Avg	2060			2070		
				0%	50%	100%	0%	50%	100%
Annual	12	15	10.52	10.22	7.57	5.26	10.04	7.46	5.21
24-hr	35	-	34.68	36.04	26.80	15.88	34.25	25.51	15.18

4. Discussion

This section discusses the results generated by the model, and compares them to regulatory standards to determine whether these results would pose a human health risk.

4.1. Effects of Changing Meteorology

Based on the results calculated for the Baseline Scenario, it appears as though changing meteorological conditions will have a slight impact on $PM_{2.5}$ concentrations at the Greeley School receptor. Across all four years that calculations were conducted for, there was a slight increase in wintertime concentrations, but the effect is more pronounced during the later years (2060 and 2070), with concentrations increasing over the average by as much as 5 $\mu g/m^3$ in January and December of 2070.

These effects can be attributed to a reduction in atmospheric mixing, which is the result of several variables. The strongest trends in the NARCCAP data actually show that during the wintertime there is predicted to be a decrease in surface temperature, increase in cloud cover and higher elevation cloud ceiling height. Decreased surface temperature leads to less convective mixing due to thermal activity, while increased cloud cover will block more incoming radiation, leading to the same effect. All of these trends point towards an overall decrease in atmospheric mixing, and therefore a decrease in pollutant dispersion and increase in ground level concentrations during the wintertime.

Conversely, during the summer months, calculated concentrations are decreased. NARCCAP data indicates the opposite trends during the summer months, with an increase in surface temperature and reduced cloud cover (with little change in ceiling height). These trends

lead to an increase in convective mixing, encouraging the dispersion of pollutants released in the area.

4.2. Effect of Changes in Temperature Trends

One of the most important predictions made by the NARCCAP data that frames many of the results found during this project is illustrated in Figure 23. This graph has the day of the year plotted along the x-axis with the outdoor surface temperature in degrees Fahrenheit plotted along the y-axis for the years of 2010, 2040, 2050, 2060 and 2070. The most obvious trend is that there is a large increase in temperature during the summer months of approximately 10 degrees in 2040 and 2050, and as large as 25 degrees by 2060 and 2070. However, temperatures during the winter months are actually lower in the years of 2040 and 2050, and do not increase appreciably in 2060 and 2070. When averaged over a yearly time period, there is an overall increase in temperature. However, this does not mean that temperature is increased for every month of the year. In fact, summers are predicted to get hotter while winters are predicted to get colder, meaning that temperature extremes will be exacerbated due to future conditions.

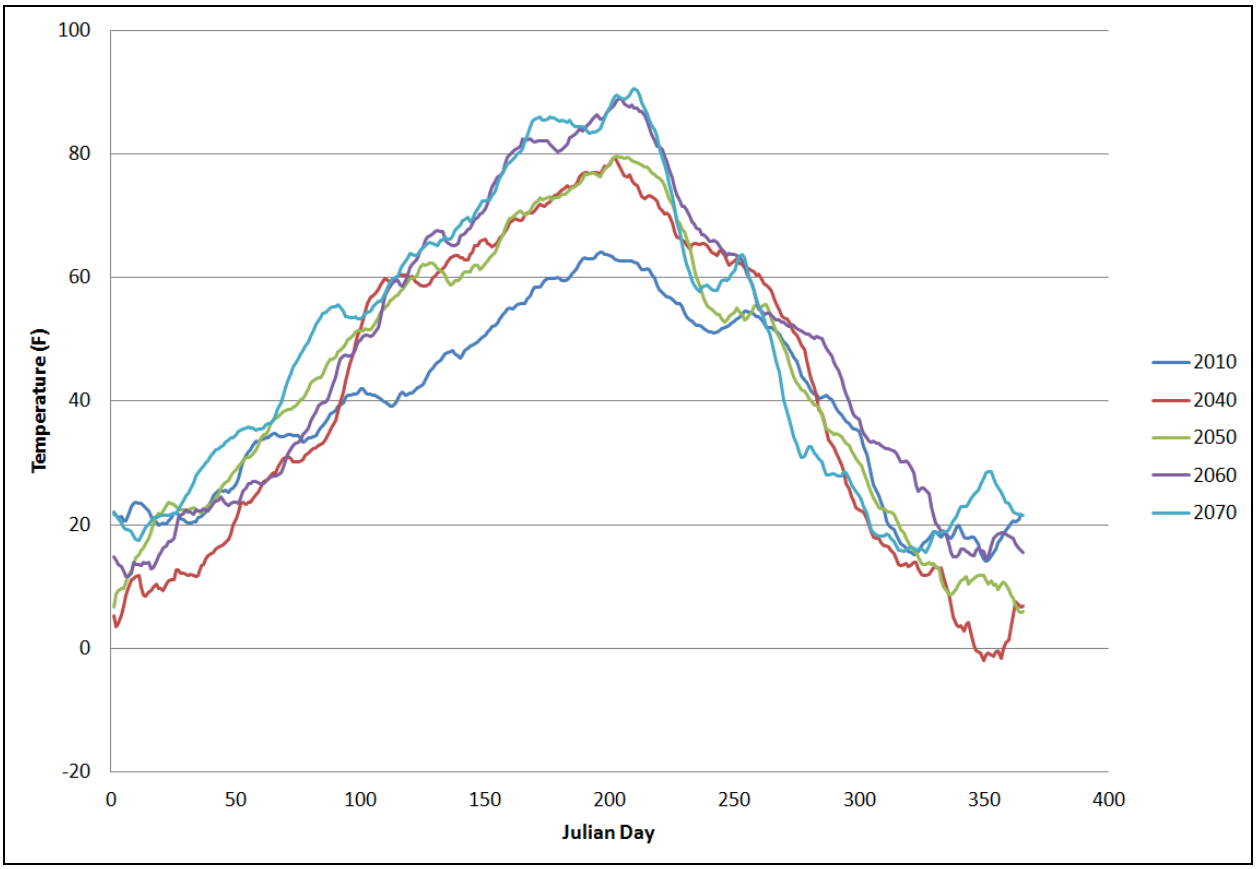

Figure 23: Average Daily Surface Temperature Values for 2010, 2040, 2050, 2060 and 2070

In terms of wood smoke emissions, colder temperatures lead to more energy usage to heat homes, leading to increased emission of $PM_{2.5}$. This is the cause of the increased wintertime concentrations for the years of 2040 and 2050. In 2060, overall warming trends increase wintertime temperatures enough that calculated concentrations are actually below current day levels. While wintertime concentrations in 2070 are actually higher than current concentrations, this effect is mostly due to changes in other meteorological conditions aside from temperature.

4.3. Comparison to NAAQS Standards

The results in Table XIII, located in Section 3.4 show that the model predicts several concentrations exceeding the NAAQS when no control measures are taken. In 2040, the average

annual concentration of 14.12 μg/m^3 exceeded the primary annual standard of 12 μg/m^3 and the 98th percentile of 24-hour concentrations of 48.61 μg/m^3 exceeded the primary 24-hour standard of 35 μg/m^3 by a large margin. In 2050, concentrations were even higher, with both the primary annual and primary 24-hour standards being exceeded with values of 15.84 and 52.26 μg/m^3 respectively. An additional exceedance of the 24-hour NAAQS was predicted in 2060, with a concentration of 36.04 μg/m^3. The modeled result of 2070 was barely below the 24-hour standard with a value of 34.25 μg/m^3.

These values are sufficiently high to warrant remedial action, as these concentrations would likely pose a risk to sensitive populations. To further complicate the issue, these values do not account for additional contributions resulting from the long range transport of particulate pollution from events like forest fires. And, with increasingly strict standards being promulgated by the EPA, standards in the future will almost certainly be stricter than those currently enforced. These results indicate that action will need to be taken in order to reduce $PM_{2.5}$ concentrations in Butte.

While a change out program would alleviate these issues by a significant margin, modeled results indicate that there would still be cause for concern. While the primary and secondary annual standards were predicted to be met for all years with a 50% change out program, the 24-hour standard would still be exceeded in 2040 and 2050 with values of 35.85 μg/m^3 and 38.48 μg/m^3, respectively. Modeled results for the 100% change out scenario indicate that standards would be met for all years. However, as previously mentioned, these results do not account for the activity of forest fires, so future concentrations have the potential to be much higher, especially during the summer months. Other factors, such as increased industrial activity higher than assumed in this model or increased incoming background concentrations could

increase concentrations further. It seems unlikely that standards stricter than those enforced currently would be met in future years.

5. Recommendations

It is important to bear in mind that many assumptions were made during the construction and analysis of this model. Every factor used to predict future concentrations, including meteorological data, source parameters, land use data and other factors is a predicted value. These assumptions are not representative of future conditions, and actual measured concentrations will likely vary significantly from modeled results.

However, these results are valuable as a screening tool to develop strategies to maintain compliance with $PM_{2.5}$ standards. The results of this study imply that actions do need to be taken to reduce future emissions of $PM_{2.5}$ in the area, as changing meteorological conditions will likely exacerbate a problem that already requires a solution.

A stove change out plan is a necessary first step towards reducing $PM_{2.5}$ emissions. After replacing 50% of inefficient stoves with an EPA certified model, this exercise still predicted concentrations above the NAAQS. After 100% change out, $PM_{2.5}$ standards were met, but only by a small margin without the added burden of forest fire smoke being accounted for. However, these results were obtained assuming that stoves were being replaced with the least efficient EPA approved model available. By requiring stricter standards for replacement stoves, it is likely that much lower concentrations than those predicted by this model are attainable.

Additionally, this model did not account for large scale industrial growth in the area. It is likely that as the population and economy of Butte continue to grow, new facilities will be constructed in the area, many of which will emit $PM_{2.5}$. Any new potential emitters should be required to implement state of the art pollution control devices. Additionally, facility placement will play a major factor in the impact of any new facility. Since the prevailing wind direction in Butte is from the southwest, a facility's impact on concentrations could be greatly reduced by

constructing the facility far south of town, to avoid impacting the areas that already experience high concentrations such as the Greeley School.

While this study developed a methodology for predicting future PM2.5 concentrations, many of the assumptions made could be refined to better improve these results as more information is made available. By incorporating actual industrial source parameters, emissions from such sources could be more accurately modeled. Similarly, by adjusting emissions from wood smoke spatially according to population density, more accurate results could be obtained. As better projections for industrial growth in the Butte area are made available, more accurate predictions of future emissions would be available, and as the details of a wood stove change out program are refined, these results can also be incorporated to determine their benefits.

Since results generated by this study were created using the A2 GHG emissions scenario, which is considered to be the "worst case" for future emissions, it is worth noting that future meteorological conditions may vary by a large margin from those values predicted by the NARCCAP data used (Nakicenovic). By conducting modeling with climate data based on different emission scenarios, a more general idea of potential future concentrations could be created.

6. Conclusion

The model constructed for the purpose of this study was designed to predict future $PM_{2.5}$ concentrations in Butte Montana. Various assumptions went into its construction, including predicted NARCCAP climate values, projected emissions trends and various other variables. After verifying that the model was accurately predicting concentrations based on existing measured concentration values, for the years of 2040, 2050, 2060 and 2070, the model was used to predict $PM_{2.5}$ concentrations.

Based on the results of this study, it appears that there is cause for concern in regards to future $PM_{2.5}$ concentrations in Butte, Montana. Future concentrations did not meet the NAAQS in several years, due to changes in meteorology and increased wintertime emissions from wood burning sources. The year 2050 showed the highest concentrations, with an annual average concentration of 15.84 $\mu g/m^3$ and a 98^{th} percentile 24-hour value of 52.26 $\mu g/m^3$. Even after accounting for reduced emissions as the result of a wood stove change out program, concentrations were sufficiently high that additional control measures are recommended.

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Appendix A: Variables Calculated from Land Use Data

Season	Sector	Albedo	Surface Roughness	Bowen Ratio
Winter	1	0.4275	2.8	0.01
Spring	1	0.167	1.905	0.03
Summer	1	0.175	3.405	0.2
Autumn	1	0.194	3.805	0.05
Winter	2	0.4275	2.8	0.01
Spring	2	0.167	1.905	0.03
Summer	2	0.175	3.405	0.2
Autumn	2	0.194	3.805	0.05
Winter	3	0.4275	2.8	0.15
Spring	3	0.167	1.905	0.3
Summer	3	0.175	3.405	0.3
Autumn	3	0.194	3.805	0.3
Winter	4	0.4275	2.8	1
Spring	4	0.167	1.905	1
Summer	4	0.175	3.405	1
Autumn	4	0.194	3.805	1
Winter	5	0.4275	2.8	1
Spring	5	0.167	1.905	1
Summer	5	0.175	3.405	1
Autumn	5	0.194	3.805	1
Winter	6	0.4275	2.8	1
Spring	6	0.167	1.905	1
Summer	6	0.175	3.405	1
Autumn	6	0.194	3.805	1
Winter	7	0.4275	2.8	1
Spring	7	0.167	1.905	1
Summer	7	0.175	3.405	1
Autumn	7	0.194	3.805	1
Winter	8	0.4275	2.8	0.0001
Spring	8	0.167	1.905	0.0001
Summer	8	0.175	3.405	0.0001
Autumn	8	0.194	3.805	0.0001

Appendix B: AERMOD Input Summary File

AERMOD Model Options

Model Options

Pathway	Keyword	Description	Value
CO	TITLEONE	Project title 1	Butte Montana PM2.5 Concentrations, 2010 - 2012
CO	TITLETWO	Project title 2	
CO	MODELOPT	Model options	DFAULT,CONC
CO	AVERTIME	Averaging times	24,MONTH,ANNUAL
CO	URBANOPT	Urban options	
CO	POLLUTID	Pollutant ID	PM25 H1H
CO	HALFLIFE	Half life	
CO	DCAYCOEF	Decay coefficient	
CO	FLAGPOLE	Flagpole receptor heights	
CO	RUNORNOT	Run or Not	RUN
CO	EVENTFIL	Event file	F
CO	SAVEFILE	Save file	T
CO	INITFILE	Initialization file	
CO	MULTYEAR	Multiple year option	N/A
CO	DEBUGOPT	Debug options	N/A
CO	ERRORFIL	Error file	T
SO	ELEVUNIT	Elevation units	METERS
SO	EMISUNIT	Emission units	N/A
RE	ELEVUNIT	Elevation units	METERS
ME	SURFFILE	Surface met file	F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.SFC
ME	PROFFILE	Profile met file	F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.PFL
ME	SURFDATA	Surf met data info.	24144 2010
ME	UAIRDATA	U-Air met data info.	24143 2010
ME	SITEDATA	On-site met data info.	

ME	PROFBASE	Elev. above MSL	1692
ME	STARTEND	Start-end met dates	
ME	WDROTATE	Wind dir. rot. adjust.	
ME	WINDCATS	Wind speed cat. max.	10,12.5,15,17.5,20
ME	SCIMBYHR	SCIM sample params	
EV	DAYTABLE	Print summary opt.	N/A
OU	EVENTOUT	Output info. level	N/A
OU	DAYTABLE	Print summary opt.	Table(2,2) / /item /value /MONTH

Source Parameter Tables

All Sources

Source ID / Pollutant ID	Source Type	Description	UTM		Elev.	Emiss. Rate	Emiss. Units	Release Height
			East (m)	North (m)	(m)			(m)
REC_SILI	POINT		369020	5091951	1669	0.2159	(g/s)	65
BASINCRE	POINT		381780	5087373	1723	0.0189	(g/s)	65
MTRESOUR	POINT		383568	5095907	1680	1.3074	(g/s)	20
WOODSMOK	AREAPOLY	Smoke from residential wood combustion	379507	5097053	1852.85	6.6694E-08	(g/s-m**2)	0
FUGIDUST	AREAPOLY	Fugitive Dust	382439	5099915	1923.85	2.94295E-07	(g/s-m**2)	0

Point Sources

Source ID / Pollutant ID	Description	UTM		Elev.	Emiss. Rate	Stack Height	Stack Temp	Stack Velocity	Stack Diameter
		East (m)	North (m)	(m)	(g/s)	(m)	(K)	(m/s)	(m)
REC_SILI		369020	5091951	1669	0.2159	65	0	0.001	1
BASINCRE		381780	5087373	1723	0.0189	65	0	0.001	1
MTRESOUR		383568	5095907	1680	1.3074	20	0	0.001	1

Polygon Area Sources

Source ID / Pollutant ID	Description	UTM		Elev.	Emiss. Rate	Release Height	Vertices	Init. Vert. Dim.
		East (m)	North (m)	(m)	(g/s-m**2)	(m)	#	(m)
WOODSMOK	Smoke from residential wood combustion	379507	5097053	1852.85	6.6694E-08	0	8	0
FUGIDUST	Fugitive Dust	382439	5099915	1923.85	2.94295E-07	0	12	0

Appendix C: Table of Heating Degree Days and $PM_{2.5}$ Emission Rates due to Wood Burning

2010 - 2012 Heating Degree Days and Emission Rates							
		HDD					
Month	Days	2010	2011	2012	Average	Emission Factor	Emission Rate (g/s)
Jan	31	1504	1264	1262	1343	1.76	1.17E-07
Feb	28	1176	1400	993	1190	1.56	1.04E-07
Mar	31	1036	1062	872	990	1.29	8.63E-08
Apr	30	862	786	689	779	1.02	6.79E-08
May	31	523	537	607	556	0.73	4.85E-08
Jun	30	313	360	317	330	0.43	2.88E-08
Jul	31	136	137	138	137	0.18	1.19E-08
Aug	31	185	228	200	204	0.27	1.78E-08
Sep	30	381	426	375	394	0.52	3.44E-08
Oct	31	913	630	781	775	1.01	6.76E-08
Nov	30	1050	1207	1066	1108	1.45	9.66E-08
Dec	31	1436	1305	1373	1371	1.79	1.20E-07

2040, 2050, 2060 and 2070 Heating Degree Days and Emission Rates									
		HDD				Emission Rate (g/s)			
Month	Days	2040	2050	2060	2070	2040	2050	2060	2070
Jan	31	1826	1687	1656	1386	1.59E-07	1.47E-07	1.44E-07	1.21E-07
Feb	28	1532	1249	1254	1132	1.34E-07	1.09E-07	1.09E-07	9.87E-08
Mar	31	1241	991	1232	923	1.08E-07	8.64E-08	1.07E-07	8.05E-08
Apr	30	706	570	624	535	6.16E-08	4.97E-08	5.44E-08	4.67E-08
May	31	498	485	442	465	4.34E-08	4.23E-08	3.85E-08	4.06E-08
Jun	30	254	241	212	214	2.22E-08	2.10E-08	1.85E-08	1.87E-08
Jul	31	125	122	109	107	1.09E-08	1.06E-08	9.51E-09	9.33E-09
Aug	31	170	173	143	139	1.48E-08	1.51E-08	1.25E-08	1.21E-08
Sep	30	386	402	374	364	3.37E-08	3.51E-08	3.26E-08	3.17E-08
Oct	31	812	844	742	756	7.08E-08	7.36E-08	6.47E-08	6.59E-08
Nov	30	1239	1067	774	1196	1.08E-07	9.31E-08	6.75E-08	1.04E-07
Dec	31	1783	1594	1376	1302	1.55E-07	1.39E-07	1.20E-07	1.14E-07

Appendix D: Change Log of Area Source Adjustment

Trial 1		
Point #	**Latitude (°N)**	**Longitude (°W)**
1	46.0253	112.5504
2	46.004	112.5582
3	45.9734	112.5234
4	45.956	112.5117
5	45.9632	112.4756
6	46.0032	112.4905
7	46.012	112.5238
8	46.0259	112.548

Trial 2		
Point #	**Latitude (°N)**	**Longitude (°W)**
1	46.0253	112.5504
2	46.004	112.5582
3	45.9807	112.5501
4	45.9825	112.4862
5	46.0032	112.4905
6	46.012	112.5238
7	46.025	112.548

Trial 3		
Point #	**Latitude (°N)**	**Longitude (°W)**
1	46.0156	112.5377
2	45.996	112.5386
3	45.9878	112.4872
4	46.0042	112.4952
5	46.0152	112.5321

Trial 4		
Point #	**Latitude (°N)**	**Longitude (°W)**
1	46.0164	112.5566
2	46.0042	112.5577
3	45.9803	112.4998
4	45.9816	112.4879
5	45.9962	112.4486
6	46.0037	112.4962
7	46.0055	112.5209
8	46.0165	112.5326

Appendix E: AERMOD Files

BREEZE AERMOD Model Results

Max. Annual (3 YEARS) Results of Pollutant: PM25 (ug/m**3)

Group ID	High	Avg. Conc.	UTM		Elev.	Hill Ht.	Flag Ht.	Rec. Type	Grid ID
			East (m)	North (m)	(m)	(m)	(m)		
ALL	1ST	7.51637	383760.00	5095433.00	1678.00	2507.60	0.00	DC	
	2ND	0.00000	0.00	0.00	0.00	0.00	0.00		
	3RD	0.00000	0.00	0.00	0.00	0.00	0.00		
	4TH	0.00000	0.00	0.00	0.00	0.00	0.00		
	5TH	0.00000	0.00	0.00	0.00	0.00	0.00		
	6TH	0.00000	0.00	0.00	0.00	0.00	0.00		
	7TH	0.00000	0.00	0.00	0.00	0.00	0.00		
	8TH	0.00000	0.00	0.00	0.00	0.00	0.00		
	9TH	0.00000	0.00	0.00	0.00	0.00	0.00		
	10TH	0.00000	0.00	0.00	0.00	0.00	0.00		

Highest Results of Pollutant: PM25

Avg. Per.	Grp ID	High	Type	Val	Units	Date	UTM		Elev.	Hill Ht.	Flag Ht.	Rec. Type	Grid ID
						YYMMDDHH	East (m)	North (m)	(m)	(m)	(m)		
MONTH	ALL	1ST	Avg. Conc.	16.78638c	ug/m**3	11123124	383760.00	5095433.00	1678.00	2507.60	0.00	DC	

Summary of Total Messages

#	Message Type
0	Fatal Error Message(s)
6	Warning Message(s)
10021	Informational Message(s)
26304	Hours Were Processed
168	Calm Hours Identified
9853	Missing Hours Identified (37.46 Percent)

Error & Warning Messages

Msg. Type	Pathway	Ref. #	Description
WARNING	CO	W276	Special proc for 1h-NO2/SO2 24hPM25 NAAQS disabled PM25 H1H
WARNING	CO	W276	Special proc for 1h-NO2/SO2 24hPM25 NAAQS disabled PM25 H1H
WARNING	CO	W363	Multiyr 24h/Ann PM25 processing not applicable for SAVEFILE
WARNING	OU	W540	No RECTABLE/MAXTABLE/DAYTABLE for Average Period 024-HR
WARNING	OU	W190	Incompatible Option Used With SAVEFILE or INITFILE DAYTABLE
WARNING	MX	W496	Total precipitation in SURFFILE is zero (0.0) with WetDepos

AERMOD Input File

```
** BREEZE AERMOD
** Trinity Consultants
** VERSION  7.9

CO STARTING
CO TITLEONE  Butte Montana PM2.5 Concentrations, 2010 - 2012
CO MODELOPT  DFAULT  CONC
CO RUNORNOT  RUN
CO AVERTIME  24  MONTH  ANNUAL
CO POLLUTID  PM25 H1H
CO SAVEFILE  TMP.FIL
CO ERRORFIL  ERRORS.LST
CO FINISHED

SO STARTING
SO ELEVUNIT  METERS
SO LOCATION  WOODSMOK  AREAPOLY  379507  5097053  1852.85
** SRCDESCR  Smoke from residential wood combustion
SO LOCATION  FUGIDUST  AREAPOLY  382439  5099915  1923.85
** SRCDESCR  Fugitive Dust
SO LOCATION  REC_SILI  POINT     369020  5091951  1669
SO LOCATION  BASINCRE  POINT     381780  5087373  1723
SO LOCATION  MTRESOUR  POINT     383568  5095907  1680
SO SRCPARAM  WOODSMOK  6.6694E-08  0  8  0
SO SRCPARAM  FUGIDUST  2.94295E-07  0  12  0
SO SRCPARAM  REC_SILI  0.2159  65  0  0.001  1
SO SRCPARAM  BASINCRE  0.0189  65  0  0.001  1
SO SRCPARAM  MTRESOUR  1.3074  20  0  0.001  1
SO AREAVERT  WOODSMOK  379507.0 5097053.0  379396.0 5095689.0
SO AREAVERT  WOODSMOK  383822.0 5092947.0  384750.0 5093078.0
SO AREAVERT  WOODSMOK  384728.0 5094707.0  384151.0 5095547.0
SO AREAVERT  WOODSMOK  382248.0 5095787.0  381360.0 5097027.0
SO AREAVERT  FUGIDUST  382439.0 5099915.0  382034.0 5097199.0
SO AREAVERT  FUGIDUST  383335.0 5097856.0  384138.0 5096884.0
SO AREAVERT  FUGIDUST  383917.0 5096327.0  385571.0 5094741.0
SO AREAVERT  FUGIDUST  386366.0 5095470.0  386314.0 5097172.0
SO AREAVERT  FUGIDUST  385090.0 5098602.0  384769.0 5100281.0
SO AREAVERT  FUGIDUST  383956.0 5099008.0  383421.0 5098944.0
SO EMISFACT  WOODSMOK  MONTH  1.76 1.56 1.29 1.02 .73 .43 .18 .27 .52 1.01 1.45 1.79
SO EMISFACT  FUGIDUST  WSPEED  0  0.085635401  0.251648983  0.493849322
SO EMISFACT  FUGIDUST  WSPEED  0.812236418  1
SO PARTDIAM  WOODSMOK  2.5
SO MASSFRAX  WOODSMOK  1
SO PARTDENS  WOODSMOK  1.3
SO PARTDIAM  FUGIDUST  2.5
SO MASSFRAX  FUGIDUST  1
SO PARTDENS  FUGIDUST  1.3
SO PARTDIAM  REC_SILI  2.5
SO MASSFRAX  REC_SILI  1
SO PARTDENS  REC_SILI  1.3
SO PARTDIAM  BASINCRE  2.5
SO MASSFRAX  BASINCRE  1
SO PARTDENS  BASINCRE  1.3
SO PARTDIAM  MTRESOUR  2.5
SO MASSFRAX  MTRESOUR  1
SO PARTDENS  MTRESOUR  1.3
SO SRCGROUP  ALL
SO FINISHED

RE STARTING
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RE ELEVUNIT  METERS
RE DISCCART  383760  5095433  1678  2507.6
** RCPDESCR  Greeley
RE FINISHED

ME STARTING
ME SURFFILE  "F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.SFC"
** SURFFILE  "F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.SFC"
ME PROFFILE  "F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.PFL"
** PROFFILE  "F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.PFL"
ME SURFDATA  24144 2010
ME UAIRDATA  24143 2010
ME PROFBASE  1692  METERS
ME WINDCATS  10  12.5  15  17.5  20
ME FINISHED

OU STARTING
OU RECTABLE  MONTH  FIRST
OU FILEFORM  FIX
OU SUMMFILE  SUMMARYFILE.SUM
OU MAXTABLE  MONTH  1
OU DAYTABLE   MONTH
OU PLOTFILE  MONTH  ALL  FIRST  ALL`MONTH`FIRST.plt  10000
OU POSTFILE  24  ALL  UNFORM  ALL`24.bin  10001
OU FINISHED

** **************************************************************************
** It is recommended that the user not edit any data below this line
** **************************************************************************


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5081225.3  374169.3  5095113.3  383848.5  5094923.3  383587.1  5081035.4
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5081035.4  383848.5  5094923.3  393527.7  5094748.6  393288.2  5080860.6
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5095113.3  374453.0  5109001.5  384110.4  5108811.6  383848.5  5094923.3
** AMPTYPE  DEM
** AMPDATUM  0
** AMPZONE  12
** AMPHEMISPHERE  N
** HILLBOUN  375220.1 5084019.3 392162.1 5108427.2

** PROJECTION  UTM
** DATUM  NAS-C
** UNITS  METER
** ZONE  12
** HEMISPHERE  N
** ORIGINLON  0
** ORIGINLAT  0
** PARALLEL1  0
** PARALLEL2  0
** AZIMUTH  0
** SCALEFACT  0
** FALSEEAST  0
** FALSENORTH  0

** PRCNTFIL  1  0  98
** POSTFMT  UNFORM
** TEMPLATE USERDEFINED
** AERMODEXE  AERMOD_BREEZE_14134.EXE
** AERMAPEXE  AERMAP_EPA_11103.EXE
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AERMOD Summary File

```
 *** AERMOD - VERSION  14134 ***   ***  Butte Montana PM2.5 Concentrations, 2010 - 2012

***        04/16/15

 *** AERMET - VERSION  14134 ***   ***
***        17:58:06

PAGE   1
 **MODELOPTs:   RegDFAULT CONC      ELEV      DRYDPLT   WETDPLT

                                          ***     MODEL SETUP OPTIONS SUMMARY       ***
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - -

 **Model Is Setup For Calculation of Average CONCentration Values.

   --  DEPOSITION LOGIC  --
 **NO GAS DEPOSITION Data Provided.
 **PARTICLE DEPOSITION Data Provided.
 **Model Uses DRY DEPLETION.     DDPLETE  =  T
 **Model Uses WET DEPLETION.     WETDPLT  =  T

 **Model Uses RURAL Dispersion Only.

 **Model Uses Regulatory DEFAULT Options:
        1. Stack-tip Downwash.
        2. Model Accounts for ELEVated Terrain Effects.
        3. Use Calms Processing Routine.
        4. Use Missing Data Processing Routine.
        5. No Exponential Decay.

 **Other Options Specified:
        CCVR_Sub - Meteorological data includes CCVR substitutions
        TEMP_Sub - Meteorological data includes TEMP substitutions

 **Model Assumes No FLAGPOLE Receptor Heights.

 **The User Specified a Pollutant Type of:  PM25

 **NOTE: Special processing requirements applicable for the 24-hour PM2.5 NAAQS have been
disabled!!!
        High ranked 24-hour values are NOT averaged across the number of years modeled,
and
        complete years of data are NOT required.

 **Model Calculates  2 Short Term Average(s) of:  24-HR  MONTH
     and Calculates ANNUAL Averages

 **This Run Includes:      5 Source(s);       1 Source Group(s); and       1 Receptor(s)

 **Model Set To Continue RUNning After the Setup Testing.

 **The AERMET Input Meteorological Data Version Date:  14134

 **Output Options Selected:
         Model Outputs Tables of ANNUAL Averages by Receptor
         Model Outputs Tables of Highest Short Term Values by Receptor (RECTABLE Keyword)
         Model Outputs Tables of Overall Maximum Short Term Values (MAXTABLE Keyword)
         Model Outputs Tables of Concurrent Short Term Values by Receptor for Each Day
Processed (DAYTABLE Keyword)
         Model Outputs External File(s) of Concurrent Values for Postprocessing (POSTFILE
Keyword)
```

```
         Model Outputs External File(s) of High Values for Plotting (PLOTFILE Keyword)
         Model Outputs Separate Summary File of High Ranked Values (SUMMFILE Keyword)

 **NOTE:  The Following Flags May Appear Following CONC Values:  c for Calm Hours
                                                                 m for Missing Hours
                                                                 b for Both Calm and
Missing Hours

 **Misc. Inputs:  Base Elev. for Pot. Temp. Profile (m MSL) =  1692.00 ;  Decay Coef. =
0.000     ;  Rot. Angle =     0.0
                  Emission Units = GRAMS/SEC                                ;  Emission
Rate Unit Factor =   0.10000E+07
                  Output Units   = MICROGRAMS/M**3

 **Approximate Storage Requirements of Model =      3.5 MB of RAM.

 **Input Runstream File:          AERMOD.INP
 **Output Print File:             AERMOD.OUT

 **File for Saving Result Arrays: TMP.FIL
 **Detailed Error/Message File:   ERRORS.LST
 **File for Summary of Results:   SUMMARYFILE.SUM

 *** AERMOD - VERSION  14134 ***   ***  Butte Montana PM2.5 Concentrations, 2010 - 2012
***        04/16/15
 *** AERMET - VERSION  14134 ***   ***
***        17:58:06

PAGE   2
 **MODELOPTs:   RegDFAULT CONC      ELEV      DRYDPLT   WETDPLT

                                            *** METEOROLOGICAL DAYS SELECTED FOR PROCESSING
***
                                                               (1=YES; 0=NO)

            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1
1 1 1  1 1 1 1 1 1 1 1 1 1
            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1
1 1 1  1 1 1 1 1 1 1 1 1 1
            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1
1 1 1  1 1 1 1 1 1 1 1 1 1
            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1
1 1 1  1 1 1 1 1 1 1 1 1 1
            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1
1 1 1  1 1 1 1 1 1 1 1 1 1
            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1
1 1 1  1 1 1 1 1 1 1 1 1 1
            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1
1 1 1  1 1 1 1 1 1 1 1 1 1
            1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1

                NOTE:  METEOROLOGICAL DATA ACTUALLY PROCESSED WILL ALSO DEPEND ON WHAT IS
INCLUDED IN THE DATA FILE.



                                  *** UPPER BOUND OF FIRST THROUGH FIFTH WIND SPEED
CATEGORIES ***
                                                            (METERS/SEC)

                                                10.00,  12.50,  15.00,  17.50,  20.00,

 *** AERMOD - VERSION  14134 ***   ***  Butte Montana PM2.5 Concentrations, 2010 - 2012
***        04/16/15
```

```
 *** AERMET - VERSION  14134 ***   ***
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PAGE   3
 **MODELOPTs:   RegDFAULT CONC      ELEV      DRYDPLT   WETDPLT

                                    *** UP TO THE FIRST 24 HOURS OF METEOROLOGICAL DATA ***

   Surface file:   F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.SFC
Met Version:  14134
   Profile file:   F:\METDAT~1\BERTMO~1\OUTPUTS\2010-2012.PFL
   Surface format: FREE
   Profile format: FREE
   Surface station no.:    24144                 Upper air station no.:    24143
                 Name: UNKNOWN                                   Name: UNKNOWN
                 Year:   2010                                    Year:   2010

 First 24 hours of scalar data
 YR MO DY HR     H0     U*     W*  DT/DZ ZICNV ZIMCH  M-O LEN  Z0 BOWEN  ALB  REF WS   WD
HT  REF TA  HT IPCOD PRATE  RH SFCP CCVR
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - -
 10 01 01 01   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  101.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 02   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50   98.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 03   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  104.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 04   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  103.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 05   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  103.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 06   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  102.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 07   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  105.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 08   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  103.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 09   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50   97.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 10   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  101.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 11   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  104.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 12   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50   96.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 13   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  103.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 14   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50   99.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 15   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 1.00    1.50  102.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 16   -3.8  0.071 -9.000 -9.000 -999.   46.      7.6 0.15 2.80 0.85    1.50  104.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 17   -2.8  0.011 -9.000 -9.000 -999.   66.     20.9 0.15 2.80 0.63    1.50  101.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 18   18.1  0.173  0.380  0.005   95.  172.    -22.3 0.15 2.80 0.54    1.50   97.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 19   38.1  0.184  0.612  0.005  272.  190.    -12.9 0.15 2.80 0.50    1.50  104.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 20   45.2  0.188  0.960  0.005  615.  195.    -11.5 0.15 2.80 0.49    1.50   97.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 21   38.6  0.185  0.999  0.005  809.  191.    -12.8 0.15 2.80 0.50    1.50  100.
10.  272.0   2.  0  -9.00  999.  879.  6
```

```
 10 01 01 22   19.1  0.173  0.803  0.005  848.  173.    -21.3 0.15 2.80 0.54    1.50  102.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 23   -2.8  0.101 -9.000 -9.000 -999.   79.     29.0 0.15 2.80 0.62    1.50  100.
10.  272.0   2.  0  -9.00  999.  879.  6
 10 01 01 24   -0.4  0.017 -9.000 -9.000 -999.   20.      1.2 0.00 2.80 0.83    1.00  350.
10.  270.9   2.  0  -9.00  999.  879.  7


 First hour of profile data
 YR MO DY HR HEIGHT F  WDIR    WSPD AMB_TMP sigmaA  sigmaW  sigmaV
 10 01 01 01   10.0 1  101.    1.50   272.1   99.0  -99.00  -99.00

 F indicates top of profile (=1) or below (=0)

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 **MODELOPTs:   RegDFAULT CONC      ELEV      DRYDPLT   WETDPLT

                                  *** THE SUMMARY OF MAXIMUM ANNUAL RESULTS AVERAGED OVER
3 YEARS ***


                                   ** CONC OF PM25     IN MICROGRAMS/M**3
**


NETWORK
GROUP ID                       AVERAGE CONC                RECEPTOR  (XR, YR, ZELEV, ZHILL,
ZFLAG)  OF TYPE  GRID-ID
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - -

ALL       1ST HIGHEST VALUE IS       7.51637 AT (  383760.00,  5095433.00,  1678.00,
2507.60,    0.00)  DC
          2ND HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
          3RD HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
          4TH HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
          5TH HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
          6TH HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
          7TH HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
          8TH HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
          9TH HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)
         10TH HIGHEST VALUE IS       0.00000 AT (       0.00,        0.00,     0.00,
0.00,    0.00)


 *** RECEPTOR TYPES:  GC = GRIDCART
                      GP = GRIDPOLR
                      DC = DISCCART
                      DP = DISCPOLR

 *** AERMOD - VERSION  14134 ***   ***  Butte Montana PM2.5 Concentrations, 2010 - 2012
***        04/16/15
```

```
 *** AERMET - VERSION  14134 ***   ***
***        17:58:06

PAGE   5
 **MODELOPTs:   RegDFAULT CONC      ELEV      DRYDPLT   WETDPLT

                                              *** THE SUMMARY OF HIGHEST MONTH RESULTS
***


                                     ** CONC OF PM25     IN MICROGRAMS/M**3
**

                                                        DATE
NETWORK
GROUP ID                           AVERAGE CONC     (YYMMDDHH)             RECEPTOR  (XR,
YR, ZELEV, ZHILL, ZFLAG)    OF TYPE  GRID-ID
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
- - - - - - - - - - - - - - - - - - -

ALL      HIGH   1ST HIGH VALUE IS      16.78638c ON 11123124: AT (  383760.00,  5095433.00,
1678.00,  2507.60,    0.00)  DC


 *** RECEPTOR TYPES:  GC = GRIDCART
                      GP = GRIDPOLR
                      DC = DISCCART
                      DP = DISCPOLR

 *** AERMOD - VERSION  14134 ***   ***  Butte Montana PM2.5 Concentrations, 2010 - 2012
***        04/16/15
 *** AERMET - VERSION  14134 ***   ***
***        17:58:06

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 **MODELOPTs:   RegDFAULT CONC      ELEV      DRYDPLT   WETDPLT

 *** Message Summary : AERMOD Model Execution ***

  --------- Summary of Total Messages --------

 A Total of            0 Fatal Error Message(s)
 A Total of            6 Warning Message(s)
 A Total of        10021 Informational Message(s)

 A Total of        26304 Hours Were Processed

 A Total of          168 Calm Hours Identified

 A Total of         9853 Missing Hours Identified ( 37.46 Percent)

 CAUTION!:  Number of Missing Hours Exceeds 10 Percent of Total!
            Data May Not Be Acceptable for Regulatory Applications.
            See Section 5.3.2 of "Meteorological Monitoring Guidance
            for Regulatory Modeling Applications" (EPA-454/R-99-005).

 Met Data File Includes       0.00 Millimeters (     0.000 Inches) of Precipitation


    ******** FATAL ERROR MESSAGES ********
               ***  NONE  ***


    ********   WARNING MESSAGES   ********
```

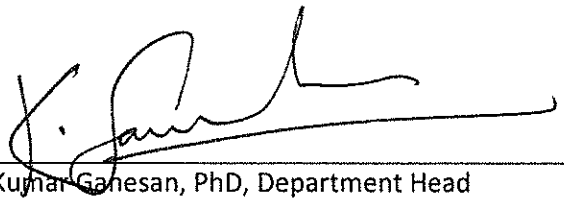
```
 CO W276      70       POLLID: Special proc for 1h-NO2/SO2 24hPM25 NAAQS disabled     PM25
H1H
 CO W276      17       POLLID: Special proc for 1h-NO2/SO2 24hPM25 NAAQS disabled     PM25
H1H
 CO W363      20       COCARD: Multiyr 24h/Ann PM25 processing not applicable for
SAVEFILE
 OU W540      92        OUTQA: No RECTABLE/MAXTABLE/DAYTABLE for Average Period
024-HR
 OU W190      92        OUTQA: Incompatible Option Used With SAVEFILE or INITFILE
DAYTABLE
 MX W496   26305         MAIN: Total precipitation in SURFFILE is zero (0.0) with
WetDepos
```

Appendix F: Results of Control Scenario

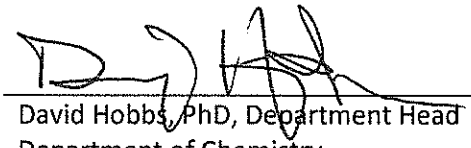
2040					2050			
	Monthly $PM_{2.5}$ Concentration (µg/m^3)				Monthly $PM_{2.5}$ Concentration (µg/m^3)			
Month	2010 - 2012 Avg	0% Replaced	50% Replaced	100% Replaced	2010 - 2012 Avg	0% Replaced	50% Replaced	100% Replaced
Jan	15.9	22.2	18.66	15	15.9	20.0	17.97	14.5
Feb	12.7	19.7	16.59	13.3	12.7	10.7	10.6	8.8
Mar	7.2	8.9	7.85	6.79	7.2	6.6	6.63	5.9
Apr	4.6	4.4	4.22	4.06	4.6	4.6	4.61	4.4
May	3.7	3.6	3.5	3.45	3.7	3.6	3.54	3.5
Jun	3.8	3.8	3.74	3.68	3.8	4.0	3.93	3.9
Jul	5.6	5.6	5.18	4.71	5.6	4.3	5.11	4.7
Aug	6.4	5.6	5.22	4.84	6.4	5.9	5.44	4.9
Sep	7.2	4.9	4.66	4.39	7.2	6.3	4.96	4.7
Oct	7.7	6.6	6.06	5.46	7.7	6.6	5.6	5.1
Nov	11.2	13.7	11.8	9.78	11.2	10.0	9.59	8.2
Dec	17.9	22.5	18.92	15.2	17.9	22.2	20.49	16.7
2060					**2070**			
	Monthly $PM_{2.5}$ Concentration (µg/m^3)				Monthly $PM_{2.5}$ Concentration (µg/m^3)			
Month	2010 - 2012 Avg	0% Replaced	50% Replaced	100% Replaced	2010 - 2012 Avg	0% Replaced	50% Replaced	100% Replaced
Jan	15.9	15.6	13.4	11.1	15.9	17.8	15.1	12.4
Feb	12.7	12.0	10.4	8.7	12.7	15.5	13.1	10.7
Mar	7.2	8.0	7.1	6.2	7.2	7.5	6.8	6.0
Apr	4.6	4.3	4.2	4.0	4.6	4.0	3.9	3.8
May	3.7	4.0	4.0	3.9	3.7	3.6	3.5	3.5
Jun	3.8	3.6	3.6	3.5	3.8	3.8	3.7	3.7
Jul	5.6	4.9	5.2	4.7	5.6	5.6	5.2	4.7
Aug	6.4	5.4	5.0	4.6	6.4	6.1	5.2	4.8
Sep	7.2	5.0	4.7	4.4	7.2	7.4	5.7	5.4
Oct	7.7	5.1	4.8	4.5	7.7	9.0	8.0	6.9
Nov	11.2	8.7	7.8	6.8	11.2	12.3	11.5	9.5
Dec	17.9	15.7	13.5	11.2	17.9	20.1	14.9	12.1

SIGNATURE PAGE

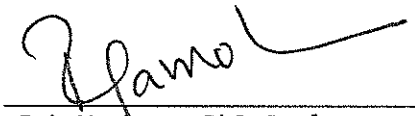
This is to certify that the thesis prepared by Christopher Atherly entitled "Impact of a Changing Climate on Fine Particulate Concentrations in Butte, Montana" has been examined and approved for acceptance by the Department of Environmental Engineering, Montana Tech of The University of Montana, on this 5th day of May, 2015.



Kumar Ganesan, PhD, Department Head
Department of Environmental Engineering
Chair, Examination Committee



David Hobbs, PhD, Department Head
Department of Chemistry
Member, Examination Committee



Raja Nagisetty, PhD, Professor
Department of Environmental Engineering
Member, Examination Committee