2010

Analysis of Atmospheric Boundary Layer Characteristics and the Synoptic-Scale Weather Pattern at the Potosi, WI SLAMS Monitor

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ANALYSIS OF ATMOSPHERIC BOUNDARY LAYER CHARACTERISTICS AND THE SYNOPTIC-SCALE WEATHER PATTERN AT THE POTOSI, WI SLAMS MONITOR

A Thesis

Submitted

In Partial Fulfillment

Of the Requirements for the Designation

University Honors

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This Study by: Sean K. Newlin

Entitled:

Analysis of atmospheric boundary layer characteristics and the synoptic-scale weather pattern at the Potosi, WI SLAMS

has been approved as meeting the thesis requirement for the Designation of University Honors

12-13-2010
Date

Dr. Alan Czarnetzki, Honors Thesis/Project Advisor

12/20/10
Date

Jessica Moon, Director, University Honors Program

ABSTRACT

Boundary layer parameters were analyzed for high impact fine-particulate pollution days for the years 2006 through 2009 in Potosi, Wisconsin. Potosi has seen recent 24-hour $PM_{2.5}$ design values at or near the National Ambient Air Quality Standards (NAAQS) of 35 micrograms per cubic meter. Every sampling date in the years 2006 through 2009 with a 24-hour $PM_{2.5}$ particulate concentration above the year's trend line was studied as were the cleanest 10 days of each year. In particular, composite upper air profiles were constructed using observations from the nearby radiosonde stations, surface and 500mb weather maps were retrieved, the virtual potential temperature profiles were calculated and back trajectories were modeled. The most noticeable relationships between the atmospheric conditions and high fine-particulate concentrations were found to be with the resultant wind direction, temperature inversions at or near the surface and the atmospheric stability as determined by the virtual potential temperature profile. The dirtiest cases studied occurred with resultant wind direction coming largely from the south partnered with a noticeably strong temperature inversion off the surface. The average virtual potential temperature profile for each year studied consistently showed a stable atmosphere with no noticeable mixed layer for the dirtiest days. Therefore, on days with high average $PM_{2.5}$ concentrations, the atmosphere resists vertical mixing and produces greater concentrations at the surface.

1. Introduction

a. History

Ever since man first rubbed two stones together and created fire, anthropogenic particulate matter has been emitted into the atmosphere. However, it was not until the industrial revolution and the wide-spread use of internal combustion engines and coal-fired power plants that the microscopic particles began to cause problems with human health and visibility. Although particulate air pollution can come from natural sources such as volcanic eruptions, forest fires, dust storms and vegetation, pollution sources of greatest concern to regulators are those created by humans i.e., anthropogenic sources. These include industrial sources such as paper mills, power plants and automobiles (Ahrens 2009). Regardless of the source, particulate matter can have a dramatic effect on the health and prosperity of humans.

In fact, it was during the time of rapid expansion of these industries in the 1850's that London first experienced the "stinking fog" that plagued the city for decades after. The dangerous London haze was a mixture of smoke and fog, later given the name smog, which had been blamed for the death of many residents of the city, including one episode in 1911 that claimed the lives of 1,150 people (Ahrens 2009). It was not until 1956 that England enacted air pollution laws. At that time, the Parliament passed the Clean Air Act in response to a 1952 air pollution disaster that killed 4000 people during a 5 day smog episode (Ahrens 2009). According to Godish (2004), Pneumonia was the leading cause of death in a few of these air pollution episodes, and other illnesses such as chest pain, difficulty breathing, cough and irritation of eyes and noses were commonly reported. As industries and economies flourished in Europe and the United States, the consequence of such rapid growth was taking its toll on human lives.

The United States also began to experience the effects of uncontrolled emissions during the industrial revolution. Visibility was the most notable problem in the early 1900's in the United States, but it was not long until the Unites States also saw the negative health effects of pollution. Smog began to appear in Los Angeles just after World War II (Ahrens 2009). An episode in 1948 over Donora, Pennsylvania killed more than 20 people and sickened thousands more (Godish 2004). A number of other episodes were experienced in New York City between 1953 and 1966. The combination of increased pollution-related health issues and the unattractive smog-laced skylines made government action a necessary next step.

The United States developed its own Clean Air Act (CAA) which was signed into law in 1970. Significant amendments in 1977 and 1990 formed the basis for the current CAA. The CAA gave the federal government the power to regulate emissions through enforceable standards for industries and automobiles (Brownell 2007). The CAA led to the establishment of the National Ambient Air Quality Standards (NAAQS), which set limits on six air pollutants considered to be dangerous to public health and welfare. These pollutants are sulfur dioxide, nitrogen dioxide, particulate matter with diameter 2.5 micrometers or less and 10 micrometers or less ($PM_{2.5}$ and PM_{10}), carbon monoxide, ozone and lead.

According to the Environmental Protection Agency (EPA), there are two levels of standards assigned to each pollutant. The first level is known as the primary NAAQS, intended to protect public health, especially for "sensitive" populations such as asthmatics and the elderly. Secondary NAAQS are designed to protect public welfare, such as buildings, crops and visibility, against adverse effects (Brownell 2007). If one or both of these levels are not met at a receptor (a particular location where the concentration is measured), then the area is considered to be in "nonattainment" of the NAAQS and another set of special requirements is issued for the area. The state is required to ensure that the emissions from sources within state lines keep ambient concentrations within the standards set in the NAAQS. This is done with a State Implementation Plan (SIP) that is developed by and for the state and is enforceable once approved by the EPA, which is the government agency in charge of promulgating rules associated with the CAA.

One way a state can demonstrate compliance with the NAAQS is through ambient air monitoring. State and Local Air Monitoring Systems (SLAMS) are networks of ambient air monitors that states can use in their SIPs to demonstrate NAAQS compliance. Wisconsin has a number of SLAMS monitors spread across the state, with one located in Potosi.

The monitor in Potosi measures the concentration of particulate matter with a diameter less than 2.5 micrograms ($PM_{2.5}$), also known as fine-particulate matter. Particulate matter can be either solid or liquid particles that are small enough to be suspended in the air. Particulates can be composed of anything from organic matter to industrial dust to nitrates and sulfates formed in the atmosphere by chemical reactions. The identity of the particulate matter is less important than its concentration. The NAAQS standards for $PM_{2.5}$ have been most recently revised in 2006. $PM_{2.5}$ is unique in that it has both 24-hour and annual standards that states must meet in order to be considered in attainment of the NAAQS. The current primary and secondary NAAQS for $PM_{2.5}$ is 35 ug m^{-3} for the 24-hour standard and 15.0 ug m^{-3} for the annual standard.

The state must meet these standards by verifying that each of its monitoring sites have design values less than or equal to the NAAQS limit. A standard design value is the specific calculation established in the CAA for each pollutant, which results in a concentration used to compare with the NAAQS. According to Brownell, standard design values are used to assess progress towards meeting the NAAQS (2007). Standard design values are calculated annually by the EPA, and if a state's value for a pollutant at a monitor exceeds the NAAQS for that pollutant, the site is considered to be in nonattainment of the NAAQS.

b. Statement of the Problem

A high concentration of particulates can adversely affect visibility as well as human health (Ahrens 2009). The effect on visibility can easily be seen in cities such as Denver, Colorado and Phoenix, Arizona. However, the health of effects of particulates may be more subtle. PM_{10} and $PM_{2.5}$ can both penetrate deep into the lungs and create breathing problems for individuals, especially those with chronic respiratory illnesses. $PM_{2.5}$, however, can be the more dangerous of the two due to its small size, allowing for deeper penetration into the lungs. Also, the smallest particles can consist of toxins and carcinogens, which can have especially dangerous effects on individuals with weak immune systems (as cited in Hains et al 2007).

According to Turner and Schulze (2007), particulates are emitted at an astonishing rate in the Unites states, about 7 million metric tons each year. Industrial processes are responsible for close to 40 percent of particulate emissions (Turner and Schulze 2007). Also, since particulates (especially $PM_{2.5}$) can be suspended in the air for days at a time, it is important to know which industries contribute most to the fine-particulate concentration at a monitor. It is also important to understand the atmospheric characteristics at the monitoring site, because even though the EPA is concerned about emissions, the atmosphere has a vital effect on surface particulate concentrations. An especially stable atmosphere can keep pollutants such as $PM_{2.5}$ from mixing properly with the clean air at higher altitudes. When pollutants can't mix, they tend to stay at the surface and build up in the air (Turner and Schulze 2007). This lack of dilution of the emitted particulates means that concentrations at the surface can increase without an increase in the emissions of local industries.

The Potosi monitor is downwind of Dubuque, Iowa. The data from this monitor is approaching the 24-hour NAAQS standard and is close to being in nonattainment. Dubuque has reason to be concerned about which factors are causing concentration values at the monitor to increase, and the degree to which Dubuque's emissions may be responsible.

24-hour $PM_{2.5}$ design values at Potosi have recently been at or near the NAAQS standard of 35 ug m^{-3}. The 24-hour $PM_{2.5}$ design value is calculated as the arithmetic mean of the 98^{th} percentile for the year in question and the two consecutive years prior. The 2009 24-hour design value for PM2.5 in Potosi was 35 ug m^{-3}, leaving Potosi less than a microgram away from exceeding the NAAQS.

If the concentration of fine-particulates continues to increase and the standard is exceeded for a number of consecutive years, then the area will be considered to be in nonattainment of the NAAQS. Local emission sources will then be subject to tighter regulations in accordance with Wisconsin's SIP unless they can convince the EPA that emissions from other states are the primary reason behind their monitor's noncompliance. In this case, the EPA might restrict emissions in neighboring states through the Clean Air Interstate Rule (

c. Purpose

The purpose of this study is to examine the associations between $PM_{2.5}$ concentration at Potosi, Wisconsin and relevant atmospheric conditions. Specifically, this study will examine the conditions that accompanied the most extreme events from the years 2006 – 2009. It hypothesis the atmosphere is quantifiably different on days with high versus low than days of extremely low particulate concentrations.

2. Background and Literature Review

a. Background

The Potosi ambient air monitoring station is located at Potosi High School and is part of Wisconsin's State and Local Air Monitoring System (SLAMS) network. According to the EPA's Model QAPP for the $PM_{2.5}$ SLAMS program (1998), there are approximately 3,500 SLAMS monitors in the United States. The locations and run-schedules are determined by each state's EPA-approved SIP. The Potosi SLAMS monitor runs on a continuous midnight-to-midnight schedule once every three days on average.

$PM_{2.5}$ concentrations can be influenced by a number of factors. Most surprisingly, when looking at pollution episodes seasonally, high fine-particulate concentrations are actually observed most often in the winter and spring (Berge et al 2001). The high concentrations in the winter months are caused by the higher primary emissions mainly due to industrial and domestic heating and the lower depth of the mixing layer (Wehner et al 2008). The low depth of the mixing layer means less dilution by vertical mixing of particulates released near the surface. This, along with horizontal transport, is the primary means of reducing air pollution concentrations (Wallace and Kanaroglou 2009). Without vertical mixing, particulates released at the surface have nowhere to go.

Vertical mixing is also greatly affected by temperature inversions which can "cap" the atmosphere's ability to mix by creating an absolutely stable layer above the surfaces (Stull 1991). Temperature inversions can be caused by warm air advection over the lowest layers in the atmosphere, cooling of the ground by outgoing long-wave radiation, subsidence and fronts (Kukkonennen et al 2005). It can be inferred that a combination of these factors might inhibit vertical mixing enough to greatly decrease the amount of dilution and would, therefore, increase pollution concentrations at the surface.

According to Kukkonen et al (2005) atmospheric chemistry and topography may also have a significant effect on fine-particulate concentrations during episodic conditions. However, neither of these parameters was considered in this study.

b. Inversions

Atmospheric pressure is due to the weight of the air above a given level and, therefore, decreases with height. The air temperature also cools as height increases because the air is farther away from the warm surface of the earth. When a temperature inversion is present, the air temperature in the atmosphere increases with height.

Temperature inversions are signs of an extremely stable atmospheric layer, which will suppress vertical mixing and increase concentrations in a location (Kukkonen et al 2005). Vertical mixing is the most effective means of diluting particulate concentrations at the surface (Wallace and Kanoroglou 2009). If a parcel were to be lifted into an inversion, it would expand and cool and be colder than the air surrounding it. If the lifting force were to cease, the parcel would sink. Surface-based inversions are one type of inversion that has a noticeable effect on mixing. These inversions occur in the late night or early morning hours and usually when skies are clear and the wind is not too strong. Surface radiation cools the ground enough that it becomes cooler than the air above it and an inversion forms (Ahrens 2009). Subsidence inversions are another important type of inversion and last much longer than surface inversions. These occur at high levels in the atmosphere above surface high pressure areas (anticyclones), where air is sinking and warming as it is compressed (Ahrens 2009).

A study by Wallace and Kanaroglou (2009) compared $PM_{2.5}$ concentrations to nighttime and daytime inversion days and also seasonal changes and found that inversions work as a pollutant “multiplier”. Wallace and Kanaroglou obtained their vertical temperature profiles from the Atmospheric Infrared Sounder (AIRS). Daytime inversions were 32% more frequent during the winter, with most occurring in the month of February (Wallace and Kanaroglou 2009). If inversions are expected more in the winter months, than it can also be expected that the atmosphere is more stable in the winter and more air quality problems occur during the colder months.

c. Pollutant Dispersion in the Atmosphere

When particulates are emitted into the atmosphere, from anthropogenic and natural sources, they are affected by the conditions and processes of the atmosphere. These processes act to dilute the pollutant concentrations at a rate dependent on the motions of the atmosphere (Godish 2000). The dispersion of emitted particulates is dependent on four factors: transport, diffusion, transformation and deposition.

1) TRANSPORT

All pollutants emitted into the atmosphere are affected by the wind. According to the *Practical Guide to Atmospheric Dispersion Modeling* by Turner and Schulze (2007), wind can be described as a three-dimensional vector of air in motion relative to the earth's surface. The three dimensions can be separated into two components, the vertical and the horizontal (Turner and Schulze 2007). The horizontal component is typically much larger. The horizontal vector consists of wind direction and speed. Wind speed is a measure of a pollutant's transportation speed and the wind direction determines the pollutant's path (Turner and

Schulze 2007). Wind direction can be used to determine if a pollutant source will contribute to the concentration at a monitoring site.

Wind is caused by an imbalance of heating and cooling. The sun's uneven heating of the surface leads to a heat surplus in the equatorial regions and a heat deficit in the polar regions. This causes heat to flow from the equator to the poles. The Coriolis force deflects the air flow to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This means that the surface flow is generally westerly in the Northern Hemisphere. This is important when studying particulate transport because suspended matter will generally be blown in from the west, (Turner and Schulze 2007). However, in the mid-latitudes air flow is highly variable due to surges of cold air from the north and warm air from the south. This means that wind direction varies frequently, so a study of the relationship between direction and concentration can be valuable. Atmosphere stability and other effects such as rain and topography can have an influence on the effectiveness of air pollutant transportation by wind (as cited in Rozwadowska 2010).

Transported pollutants can increase particulate concentration greatly at a receptor. Long-range transportation sources can be classified as either local (city/state level) or regional and are affected by the movement of air masses (Bergen et al 2001). Relative to Potosi, Dubuque, Iowa may be considered close enough to be classified as a local emissions source, while particulate plumes from farms in western Iowa may be considered regional or long range. Complications can arise when upwind emissions sources are affecting the air quality in a neighboring state. According to Brownell (2007), if a state can prove that its poor air quality is due to interstate transport, the EPA can step in and tighten emissions standards for sources in neighboring states.

2) Diffusion

Random mixing of pollution from higher concentrations to lower concentrations by turbulent processes is known as diffusion, while the numerous chemical reactions that constantly occur in the atmosphere are known as transformation. Both of these processes can work towards increasing or decreasing concentrations in a location. Diffusion decreases concentration where it is initially high, but increases it in surrounding areas.

3) Transformation

Transformation can lead to harmful air pollutants being converted into nonthreatening pollutants and vice versa. The combinations of these processes are very complex and make the study of dispersion difficult.

4) Deposition

Deposition is the transfer of airborne pollutants to the earth's surface. This transfer can occur by impaction with the ground, gravitational settling or removal by rain. Although deposition is an important dispersion process, its effect on the monitor reading at Potosi, were not examined in this project.

d. Modeling Transport

According to Emeis and Schafer (2006), synoptic scale weather has a significant effect on the height of the mixed layer and the vertical mixing of emitted pollutants in the atmosphere. The history of the synoptic-scale meteorological pattern prior to fine particulate pollution episodes can give a description of the pollution's origins (transport) and chemical transformation. An air mass can be characterized by similar temperature and moisture content over a large horizontal area (Ahrens 2009). A direct relationship exists between the history of an air mass and the properties of the aerosols involved in the pollution episode (Wehner et al 2008).

In this study, air mass history is modeled with back trajectories using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model. HYSPLIT can calculate trajectories using gridded meteorological data (Draxler and Rolph 2003). Wehner et al. (2008) presented a study on the relationship between particulates and the history of their air masses in which they used back trajectory models such as HYSPLIT to follow the air mass's history in order to determine the modifications and processes it experienced on its journey.

Another property of air masses that need to be determined is their pressure patterns and advection speed. A higher average advection speed means that the air mass has less time over areas where particulate concentrations are high and/or being emitted more heavily. Slow moving air masses instead accumulate the most particulate mass and are associated with higher concentrations (Wehner et al 2008). Air mass temperature is also an important factor in determining mixing in a location. When a warm air mass moves in above cooler air it produces a very stable atmosphere that allows for little vertical mixing (Ahrens 2009). Pollution episodes are also known to be associated with high pressure areas or a high-pressure ridge which can produce subsidence inversions and cause a stable atmosphere (as cited in Berge et al 2001).

e. Mixed Layer and Virtual Potential Temperature

The mixed layer can be described as the air between the surface and the free atmosphere that is either neutral or unstable enough to mix the air it contains if turbulence occurs. According to R.B. Stull (1991), instability means that small perturbations in the atmosphere grow and air parcels tend not to return to their initial position when displaced. The mixed layer consists of air near is affected by surface forcing such as radiational cooling and the transfer of momentum by the Earth's surface within a time scale of a couple of hours (Turner and Schulze 2007). In the daytime, the mixed layer can often be identified with virtual potential temperature profiles. In the night time on the other hand, the lower atmosphere is more stably stratified and mixing is suppressed (Emeis et al 2006). The depth of this layer over land during the daytime can range from an average of a few hundred meters to a few thousand meters (Turner and Schulze 2007).

The highest concentrations of particulates are usually focused within the mixed layer while the atmosphere above the mixed layer tends to remain relatively clean (Wehner et al 2008). The mixed layer tends to be shallow during the winter months when commercial and industrial heating is highest and more likely to product particulates. This is often why the winter months are usually the worst in terms of air quality (Wehner et al 2008).

The mixed layer is deep when atmospheric conditions allow turbulence to diffuse air to greater heights. Atmospheric turbulence includes swirls, whirls and eddies. Turner and Schulze (2007) wrote that turbulence is "any wind motion on smaller time scales than an hour". This turbulence can be caused by two atmospheric processes, mechanical mixing due to air flow being forcibly deflected by surface features and buoyant effects which force the air to move due to heating and cooling of the air (Turner and Schulze 2007). The more stable the atmosphere, the shallower the mixed layer. In rural areas, such as Potosi, Wisconsin, the mixing height, or top of the mixed layer, is nearly zero around sunrise or just shortly after sunrise and reaches a maximum during the afternoon near the time of maximum temperature (Turner and Schulze 2007).

According to Stull (1991), different strategies should be used to correctly determine the stability in the atmosphere, methods that include local lapse rate and nonlocal parcel movement. Since the analysis of the local lapse rate is done with the vertical temperature profiles and finding inversions and other stable features, a different strategy is needed to determine the nonlocal parcel movement. One way to identify nonlocal parcel movement and thus find depth of the mixed layer is to study the virtual potential temperature profile. Virtual potential temperature is the theoretical temperature that accounts for the effects of pressure and water vapor content on density.. The virtual potential temperature profile can be calculated from radiosonde data at for 1200Z and 0000Z each day of the year. When plotted as a function of height or pressure, the virtual potential temperature can be used to determine the stability of the atmosphere (Czarnetzki 1996).

According to Kunkel et al (1996), the mixed layer is the portion of the virtual potential temperature profile closest to the ground where virtual potential temperature is constant. The mixed layer is capped at the height in the atmosphere where virtual potential temperature increases rapidly with height (Kunkel et al 1996).

If it is determined that the virtual potential temperature profile is unstable or neutral through a surfaced-based layer, then that layer can be designated as the mixed layer and be considered turbulent (Stull 1991). According to Stull (1991), the middle of the mixed layer can be distinguished with a constant virtual potential temperature profile. As shown by an earlier study (Kunkel et al 1996), low mixing heights as evident by a shallow neutral or unstable layer in a virtual potential temperature profile restricts mixing. More importantly, if mixed layer remains consistently shallow throughout the day, then the atmosphere never has a chance to dilute the particulates. Mixed layer depth, on average, reach a maximum between 1000 meters and 2,000 meters by the middle of the day, but an exceptionally stable atmosphere can have mixed layers 500 meters deep or lower (Kunkel et al 1996).

3. Data Collection and Methodology

a. Acquisition and Determination of $PM_{2.5}$ Data

A sequential particulate monitor, sampling for particulate matter with a diameter less than or equal to 2.5 microns, is located at Potosi High School in Potosi, Wisconsin. This monitor is a Partisol Plus 2025. The $PM_{2.5}$ daily concentration data from the monitor were obtained from the Wisconsin DNR website from 1 January 2006 to 30 December 2009. The particulate concentration data were imported into Excel and ordered from highest to lowest concentration. Scatter plots displaying the ordered data from highest to lowest on the x-axis and concentration on the y-axis were constructed for each year (Fig. 1.-4.). The charts were then analyzed to see if a uniform line of increasing concentration would appear. In all years a continuous line was apparent in the data, and the dirtiest cases that departed the line were selected for the study, as were the cleanest 10 cases. As a result of analyzing the graphs, nine dirty cases were selected for 2006, seventeen cases were selected for 2007, nine cases were selected for 2009 and ten dirty cases were selected for 2010. 2007's selection of data presented a problem because of the year's exceptionally high $PM_{2.5}$ concentrations. If the same technique for selecting data was used on 2007 as it was for the other three years, than 2007 would only have four usable days for the study. However, when the limit is drawn for 2007 near the same minimum concentration as the other three years (approximated 22 ug m^{-3}) rather than where the days start to break off of the line, then seventeen cases are included in the study. It was this second selection process that was used for 2007 in this study so that a large enough data set was available for this exceptionally dirty year.

Since the 24-hour standard looks only at the 98^{th}-percentile cases, it is only the top three dirtiest cases a year that are significant. Analyzing the cases with the highest $PM_{2.5}$ concentrations may expose the unique atmospheric conditions that contribute to pollution episodes. Analyzing the ten cleanest cases allowed us to determine the standard atmospheric conditions when particulate pollution was low in order to give us a similar sized data set to the dirty cases.

Each case, along with the two most recent monitoring days both before and after the studied day, was diagramed using a scatter plot. This plot is useful in determining whether or not the day in question was experiencing a pollution episode or if the high concentration recorded by the monitor was an isolated incident. This can be important during the analysis because episodic conditions may have different influencing parameters than merely an isolated incident

b. Radiosonde data and RAOB

The University of Wyoming Department of Atmospheric Science's web interface was used to acquire upper air radiosonde data for three surrounding stations: KDVN (Davenport, Iowa), KGRB (Green Bay, Wisconsin) and KMPX (Chanhassen/Minneapolis, Minnesota). Radiosonde data is collected by sending a free balloon aloft with the radiosonde instrument package attached to it. The radiosonde transmits back to the ground measurements of temperature, relative humidity, wind and pressure via radio. The data were collected for both the 1200 UTC (morning) release on the day of concern and the 0000 UTC (evening) release the same day in order to examine the boundary layer development.

The three observed soundings were used to produce a distance-weighted interpolation to Potosi High School's coordinates of 42.68N -90.68W. The interpolated sounding was then overlaid with the individual soundings from KDVN, KGRB and KMPX in three separate images to compare the interpolated sounding with its contributing components in order to check for feasibility and to see where its features come from.

The resultant thermodynamic profile, or sounding, contained information about pressure, density, temperature and water vapor and was displayed on a Skew-T-LogP chart. This interpolated chart is useful in determining the lapse rates, or the rates at which temperature changes with height, for a number of significant layers in the atmosphere. When the lapse rates in a layer get warmer with height, an inversion in that layer is said to exist. Inversions "cap" the atmosphere because they are characteristically stable and resist vertical motion. The interpolated soundings were qualitatively analyzed for inversions between the surface and around 800 mb.

c. Virtual Potential Temperature

The virtual-potential temperature profiles are highly effective tools in determining the overall stability of the atmosphere and finding the vertical boundaries of a mixed layer. The virtual potential temperature profile was obtained two ways in this study, both involving the interpolated sounding at Potosi. The virtual potential temperature is a pre-calculated parameter when a sounding is opened in the RAOB software used for this study. An interpolated sounding can be exported by RAOB into an Excel-ready CSV file format. The output file, when imported into Excel, contains most of RAOB's observed and calculated sounding data, including pressure, height, temperature, dew point, virtual potential temperature and more. Using the height and virtual potential temperature parameters we were able to create a profile in Excel by plotting height against virtual potential temperature.

Average virtual potential temperature profiles were also calculated using an Excel spreadsheet. 0000 UTC and 1200 UTC profiles were created by averaging the virtual potential temperature at each height for the dirtiest and the cleanest cases for each year. The two profiles were plotted on the same chart, along with the cleanest and dirtiest profiles. The process was done for each year in order to standardize the information and make comparison of each year's cases easier.

d. Air Mass History

According to a study by Wehner et al. (2005), back trajectories are useful when tracing the path of an air mass and to help gain understanding of the processes and transformations the particles went through during transportation. The back trajectories for Potosi were calculated using NOAA's HYSLIT on-line trajectory model with the Model Vertical Velocity vertical motion calculation method chosen. Models were run for a 24 hour duration ending at 1200 UTC on the studied day and also at either 1700 UTC or 1800 UTC depending on the day of the year (12pm local time) to show the change, if any, during the transition from the residual layer to a developed mixed layer. The trajectory runs used an arrival time of 12:00pm local time because this time was the midpoint of Potosi's sampling period. Each model was run for three terminating-heights: 10, 500 and 1000 meters. Additional models were run with higher terminating-heights if the mixed layer exceeded 1000 meters in height. Analyses of the back trajectories were done by noting the trajectory length, which is directly proportional to mean transportation speed (Wehner et al 2005).

e. Surface Weather Observations

1) TEMPERATURE

To study the association between average temperature and high particulate concentrations, a relative frequency histogram was made for the compiled 44 dirty cases and another for the 40 total clean cases. The average temperature was compiled from the local climatic data available for the Dubuque, IA National Weather Service observation station. The data were separated into eight bins that were designated with ten degree ranges starting from a 1 – 10 degree Fahrenheit range bin and going to a 71-80 degree bin. The bins were then tallied and divided by the entire number of days to obtain the relative frequency. The same analysis was done for the clean cases to give the best possible chart for overall comparison.

2) Relative Humidity

Average Relative humidity was studied by also developing two relative frequency histogram charts compiled from the 44 dirty cases and the 40 total clean cases. The average relative humidity for each day was taken from the local climatic data for Dubuque. The data for relative humidity were separated into five range bins. The five bins were labeled in ten-percent increments, starting with a 51-60% bin and ending with a 91-100% bin. The same analysis was done for the clean cases to make sure the charts were consistent for comparison.

3) Wind Direction

Two histograms displaying relative frequency of the eight primary resultant wind directions (N, NE, E, SE, S, SW, W, NW) were created for the 44 dirty cases and the 40 total clean cases. The data for the resultant wind directions were taken from the local climatic data for Dubuque. Again, eight bins were designated for the resultant wind direction of each day. Each bin was reserved for a 45 degree slice of the total 360 degree polar coordinate grid. North was considered to be any resultant wind that fell between 337.5 degrees and 22.5 degrees, Northeast was considered be any resultant wind that fell between 22.5 degrees and 112.5 degrees etc. The total number in each bin was then divided by the number of total dirty cases to obtain the relative frequency for each direction. The same analysis was done for the 40 clean cases.

4. Results

a. Virtual Potential Temperature Profiles.

Average virtual potential temperature profiles were compiled for the selected dirty and cases clean cases. Each year had consistent virtual potential temperature profiles that supported a stable atmosphere in the mornings for both the dirty and the clean cases. The afternoon soundings seemed to show the most significant results. The dirtiest cases kept a stable virtual potential temperature profile throughout the afternoon sounding, with no clear mixed layer. The cleanest cases often saw a dramatic deepening in the size of the mixed layer, in most cases averaging close to 1000 meters in the afternoon.

1) 2006 PROFILES

The 1200 UTC morning virtual potential temperature profiles from the 2006 interpolated radiosonde data for Potosi, Wisconsin were a unique group of profiles among the four years that were studied. Unlike the other three years, the morning average clean profile was colder throughout the first 2000 meters than the average profile of the dirtiest nine days. It would be expected that the virtual potential temperatures are warmer in the clean cases than they are in the dirty cases because most of the dirty cases occur in the winter months, when temperatures are colder. However, as can be seen in Fig 5a., the average cleanest profile is colder in the morning. All four 2006 1200 UTC profiles, the two averages and the two extremes, were considerably stable throughout the profile length. There is strong evidence that a nocturnal boundary layer is still present in the morning sounding and that the residual layer is very stable. The most extreme clean case of 2006 also has evidence of a stable nocturnal boundary layer near the surface, but its residual layer is actually fairly well mixed up to 1400 meters.

The 0000 UTC afternoon average virtual potential temperature profiles for 2006 are very typical and have the expected appearance, as seen in Fig 5b. The average profile for the dirtiest 9 cases remains very stable with no evidence of a mixed layer throughout the profile. There was slight warming at the surface in the average profile for the dirty cases, overcoming the extremely stable nocturnal boundary layer but never quite becoming neutral or unstable anywhere in the profile. 2006 was unique as well in that the average clean afternoon profile was colder than the average dirty afternoon profile, meaning the air at higher heights was colder or had less moisture in the clean cases than the dirty. On the other hand, the average virtual potential temperature profile for the cleanest 10 cases of 2006 became much more neutral. The average clean case had a mixed layer around 1000 meters deep, giving ample space for particulate emissions to be diluted by cleaner air at higher heights. The extreme cleanest case had a very well defined and much deeper mixed layer, reaching around 1200 meters high, while the extreme dirtiest case had a much more stable profile than the average for 2006's dirtiest cases.

2) 2007 PROFILES

2007 was difficult to examine at first because the selection process left only four dirty cases to analyze. Since the selection process was altered to eventually include 17 total dirty cases for 2007, the average virtual potential temperature profiles for 2007 include an extra average profile, one for the dirtiest four cases and one for the dirtiest seventeen cases. Aside from the extra profile, the results were as expected. As seen in Fig. 6a., the 1200 UTC profiles in 2007 showed a stable atmosphere for all five average profiles. The average profile for the dirtiest cases (both the dirtiest four and dirtiest seventeen) were much colder than the average profile of the cleanest ten cases. The average virtual potential temperature profile for the dirtiest four cases was nearly identical in slope to the average profile for the dirtiest seventeen cases, but shifted about five degrees colder at the surface. The average profile for the cleanest 10 cases at 1200 UTC was also stable with a well-defined nocturnal boundary layer near the surface. The nocturnal boundary layer for the cleanest cases, however, was much shallower than the average for the dirtiest. Again, the extreme cleanest case had evidence of a very stable and shallow nocturnal boundary layer, but these cases kept a well mixed residual layer throughout the nighttime hours.

The 2007 0000 UTC average virtual potential temperature profiles had the structure that was expected. The average profile for the cleanest 10 cases had a very well defined and deep mixed layer, as evident by the upright structure of the profile. As in Fig. 6b., the mixed layer for the cleanest cases was about 1000 meters deep and the entire profile was on the warm side of the average dirtiest profile. The extreme cleanest case had another well defined mixed layer that was around 1000 meters deep. The average profile for the dirty cases was almost completely stable throughout the first 2000 meters, although it can be argued a very shallow mixed layer may have been present near the surface.

3) 2008 PROFILES

The average virtual potential temperature profiles at Potosi in 2008 were good examples of the relationship between atmospheric mixing and virtual potential temperature. The 0000 UTC morning average profiles (Fig. 7a.) had similar overall structure in 2008 as in the other years. The average profile for the dirtiest eight cases was consistently stable, with a sharp inversion near the surface signifying the nocturnal boundary layer. The stable nocturnal boundary layer's depth in the dirtiest case can be interpreted as about 180 meters to 400 meters. This deeper depth of the nocturnal boundary layer means that the surface has to warm up significantly during the day before mixing would be expected. The cleanest 10 cases have an average profile that is continuously warmer than the dirtiest cases. The clean average profile has a very shallow nocturnal boundary layer and a less sloped structure higher up, meaning the atmosphere has to overcome less resistance to begin mixing.

The afternoon 0000 UTC virtual potential temperature profiles (Fig. 7b.) for the dirtiest eight cases kept a stable profile into the evening. There is no obvious mixed layer present at any height, although again one might argue there could have been a very shallow mixed layer near the surface. The dirtiest case's average profile remains colder than the cleanest at every height. The cleanest cases average profile has a very similar structure to the other years, with a 1000 meter deep mixed layer. The extreme clean case has an exceptionally deep mixed layer that extends off the charts and above 2000 meters deep.

4) 2009 PROFILES

The 2009 average virtual potential temperature profiles kept a typical and expected structure for the morning 0000 UTC sounding. The dirty average cases in Fig. 8a had a gentle, upward sloping curve from the surface, making it difficult to define the boundaries of the stable nocturnal boundary layer. The average profile for the dirtiest cases is much colder than the cleanest average profile. Again, the average of the cleanest ten days shows a shallow nocturnal boundary and a steep upward slope to 2000 meters. The extreme dirtiest case was unique compared to the other years because it already had a defined mixed layer, although it was only a shallow 200 meters deep.

The afternoon, 0000Z, soundings were not as typical in 2009 as the other three years. The average profile (Fig. 8b) for the dirty cases still remained stable throughout the entire structure so there was not much evidence that mixing was occurring in the atmosphere during those cases. However, the average profile for the cleanest ten cases only had a defined mixed layer up to 600 meters deep, which was shallower than the other years. The extreme clean case in 2009 also had an unusually shallow mixed layer, reaching only to as high as about 500 meters. This would not appear to allow as much mixing as the other three years. However, since the cleanest case already had a defined mixed layer in the morning sounding, it is likely that the atmosphere had been continuously mixing throughout the day.

b. Temperature Inversions

The 1200 UTC meteorological thermodynamic profiles in the dirty cases were characterized by strong temperature inversions starting between the surface to 850 mb. The 0000 UTC profiles had strong inversions between the surface and 850 mb and were also characterized by near-isothermal layers in the middle altitudes. Although there were cases where the surface inversion strengthened between the 1200 UTC and 0000 UTC soundings, it was more common to observe the surface temperature inversion weaken between the morning and afternoon sounding and move aloft from near the surface to closer to 850 mb. The elevated inversions in the afternoon soundings were most likely the result of subsidence in the atmosphere and increased temperatures near the surface.

The 1200 UTC thermodynamic soundings for the clean cases also contained profiles with strong surface inversions and especially frequent subsidence inversions, although cases with surface inversions were less common than in the dirty cases. However, by the time the 0000 UTC sounding was taken, the surface inversions often completely decayed leaving a sounding with no capping inversions.

The biggest difference is that clean cases' inversions tended to decay before the afternoon radiosonde sounding, leaving an atmosphere much more susceptible to mixing. The morning inversions in both the dirty and clean cases are likely due to the overnight development of the nocturnal boundary layer, or the stable layer from the surface to as high as 200 meters that forms as radiational cooling brings surface temperatures down.

c. Surface Weather Observations

1) Wind Direction

The dirty cases were analyzed for resultant wind speed and direction using a wind rose compiled from each year's selected days as well as using a histogram, Figs. 9a.-b., displaying relative frequency of resultant wind direction for the total number of dirty cases (44 total cases). The dominant resultant wind direction, as apparent from the relative frequency histogram, during high particulate concentration days was from directions that include a southerly component. Winds purely from the south were the most common, with approximately 40 percent of the total dirty cases having south winds. However, when southeast and southwest winds are also included, close to 60 percent of the total dirty cases had resultant wind directions from a southerly component.

Histograms were also made for the four years of compiled clean case data, a total of 40 days. Winds from the northwest were predominant with a total of 30 percent of the cases coming from that direction. However, when combined with its two adjacent wind directions, north and west, 60 percent of the cases could have been represented by three of the eight directions.

The wind roses that were compiled for the dirty and clean cases for each year were useful in confirming the results in the histograms. The wind roses also separate the results by year to give the opportunity for further comparisons. The results of the wind roses are consistent with the results of the histogram in that the dominant winds during dirty cases were from the south, southwest and southeast while the clean cases more often have resultant winds from the northwest, north and west.

2. Relative Humidity

The average 24-hour relative humidity at the surface also revealed a definitive difference between the dirty and clean cases. Relative frequency histograms, Figs 10a.-b., were created with the total number of dirty cases. The dirty cases most often had an average relative humidity of greater than 80%. Over 65% of dirty cases had an average relative humidity over 80% while only 20% of clean cases had an average relative humidity that high. The histogram of the cleanest cases showed that 60% of all the clean cases studied had an average relative humidity of 70% or less while only 5% of dirty cases had an average relative humidity less than or equal to 70%.

3) Temperature

Relative frequency histograms were made for average daily temperature. The histogram for average daily temperature (Figs. 11a.-b.) for the dirty cases was much more evenly distributed among the bins than were wind direction or average relative humidity. Half of the dirty cases had an average temperature under 30 degrees Fahrenheit. The peak in the dirty cases could be seen around the freezing point, as 30 percent of the cases fell in the range of 21-30 degrees. The cleanest cases had a nearly oppositely distributed histogram. Only 7% of the clean cases had average temperatures below freezing. Instead, about 50% of the clean cases fell within two range bins, the 41-50 degree range bin and the 51-60 degree range bin.

d. HYSPLIT Back Trajectories

The 24-hour back trajectory runs for the dirty and clean cases were done for 1200 UTC and 1700 UTC/1800 UTC. The dirty cases saw trajectories that were consistent from 1200 UTC to 1700 UTC/1800 UTC and confirmed our findings from the resultant wind directions by tracing the source of the air from the south for most of the dirty cases. The trajectories in the dirty cases were of medium length, meaning that the transport speed was neither extremely slow nor extremely fast. However, the surface trajectories, which were run 10 meters from ground level, were much shorter. This meant that the transport speed at the surface could have been considered slow, allowing the air time to accumulate fine-particulates. The air ending at Potosi at the 500 meters and 1000 meters started at lower heights or near the surface so it was clear the motion of the air at those levels was ascending, while the surface air started and remained at the surface.

The clean cases had much faster transport speeds with the longer back trajectories. The directions of the trajectories also confirmed the resultant wind speeds in the surface observations. The surface back trajectories were also shorter than the upper air trajectories, but the transport speed was faster relative to the dirty cases. The air in the clean cases had a descending rather than ascending trend at greater attitude, meaning the air that ended at Potosi started at higher heights. The surface air tended to remain at the surface during the entire trajectory.

5. Conclusions

This study has examined atmospheric conditions associated with the days of extreme high fine-particulate concentrations from 2006-2009 at the Potosi, Wisconsin monitor. This study has shown that there are significant quantifiable differences in the atmosphere during days of high fine-particulate concentrations. The differences in atmospheric conditions between days of high fine-particulate concentrations and days of low fine-particulate concentrations mean that the atmosphere is a primary factor that determines surface particulate concentrations.

The most significant association is between mixed layer depth and high-fine particulate concentrations. Using virtual potential temperature profiles to determine the mixed layer depth, an obvious relationship can be observed between an extremely shallow or non-existent mixed layer and days of high fine-particulate concentration. The average virtual potential temperature profile for the dirtiest cases for each year showed an exceptionally stable atmosphere throughout the entire length of the profile. The stable atmosphere resists turbulent mixing and traps the particulates near the surface. Without dilution, concentrations at the surface can build up rapidly.

Similar explanations are behind the relationship between temperature inversions and high fine-particulate concentrations. Strong temperature inversions were present in all of the dirty cases and remained at or near the surface throughout the day. The clean cases also commonly had morning temperature inversions near the surface, but those inversions deteriorated by the evening in almost all cases. This again tends to support the notion that the dirtiest cases analyzed had exceptionally stable atmospheres that greatly impaired vertical mixing of emitted particulates.

Resultant wind from the south, temperatures near freezing and high relative humidity are also positively associated with high fine-particulate concentrations. Resultant winds from the south are the most common among dirty cases. Since the majority of high-particulate pollution days occur in the winter months, it is less common to see winds from the south. However, in the case of the dirtiest days, over 60% of the cases have a resultant wind with a southerly component. This would support a concept that high concentrations are associated with extreme events and unusual atmospheric conditions.

Temperatures near freezing fit better with the notion that air pollution episodes are most common in the winter, since winter brings colder temperatures to the Midwest. It is also possible that this association could be due to chemical processes in the atmosphere that occur near freezing temperatures. Further study on these chemical transformations should be done to confirm their effect on fine-particulate concentrations in the winter months. Average relative humidity is a more difficult association to explain. Dirty cases most often experience high average relative humidity in the cases that were studied. High average relative humidity is often associated with stable conditions. This might point out that average relative humidity and high particulate concentrations have a secondary relationship.

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Figure Captions

Fig. 1. Scatter plot displaying the ordered ranking, from highest concentration to lowest concentration for the year 2006. The yellow line represents the cutoff point for the selection of the dirty cases in the study.

Fig. 2. Scatter plot displaying the ordered ranking, from highest concentration to lowest concentration for the year 2007. The yellow line represents the cutoff point for the selection of the dirty cases in the study.

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Fig. 10. Relative frequency histograms of the average relative humidity for the 44 total dirty cases studied, Fig. 10a, and the 40 total clean cases studied, Fig. 10b.

Fig. 11. Relative frequency histograms of the average temperature for the 44 total dirty cases studied, Fig. 11a., and the 40 total clean cases studied, Fig. 11b.

Figures

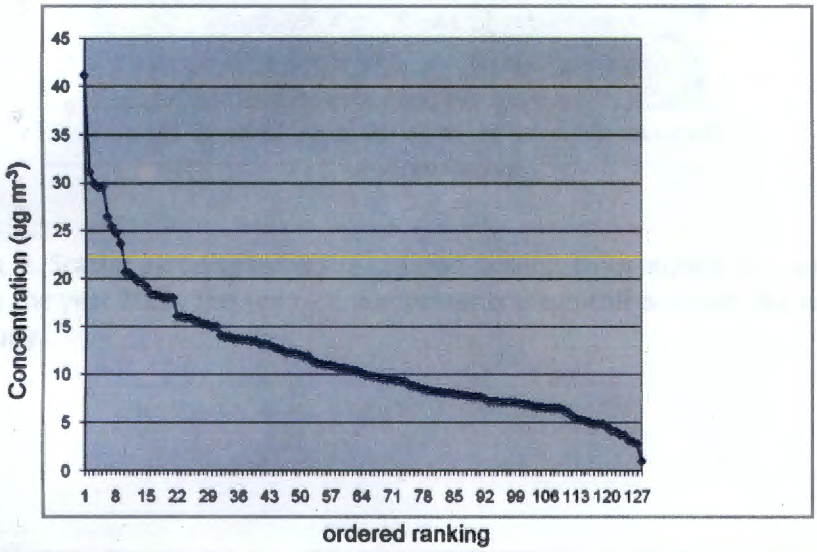


Fig. 1. Scatter plot displaying the ordered ranking, from highest concentration to lowest concentration for the year 2006. The yellow line represents the cutoff point for the selection of the dirty cases in the study.

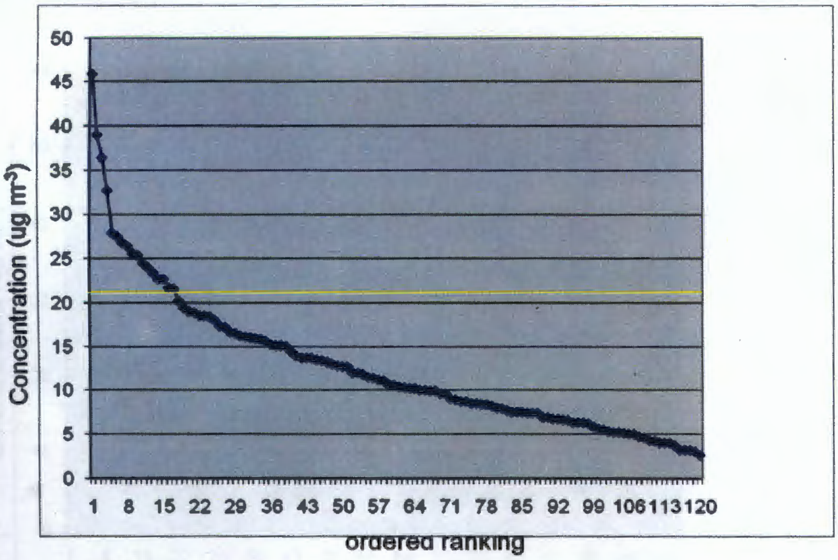


Fig. 2. Scatter plot displaying the ordered ranking, from highest concentration to lowest concentration for the year 2007. The yellow line represents the cutoff point for the selection of the dirty cases in the study.

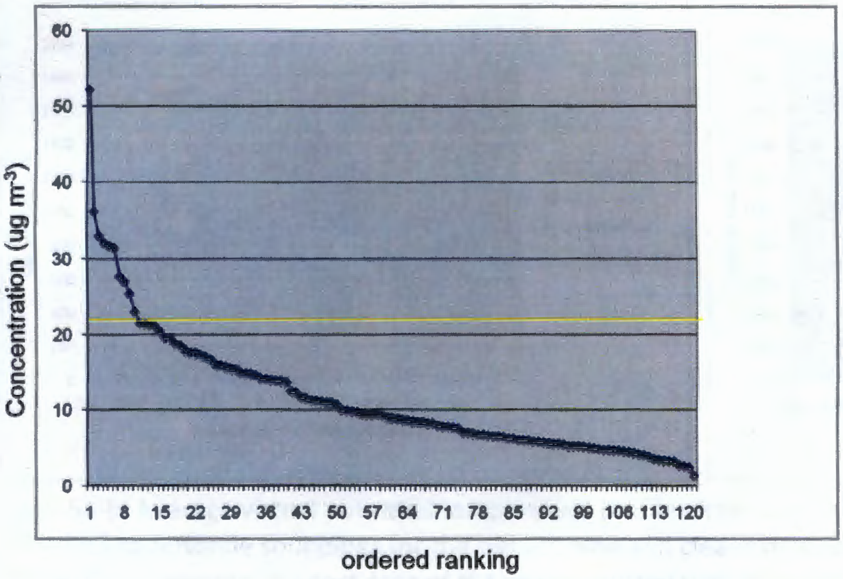


Fig. 3. Scatter plot displaying the ordered ranking, from highest concentration to lowest concentration for the year 2008. The yellow line represents the cutoff point for the selection of the dirty cases in the study.

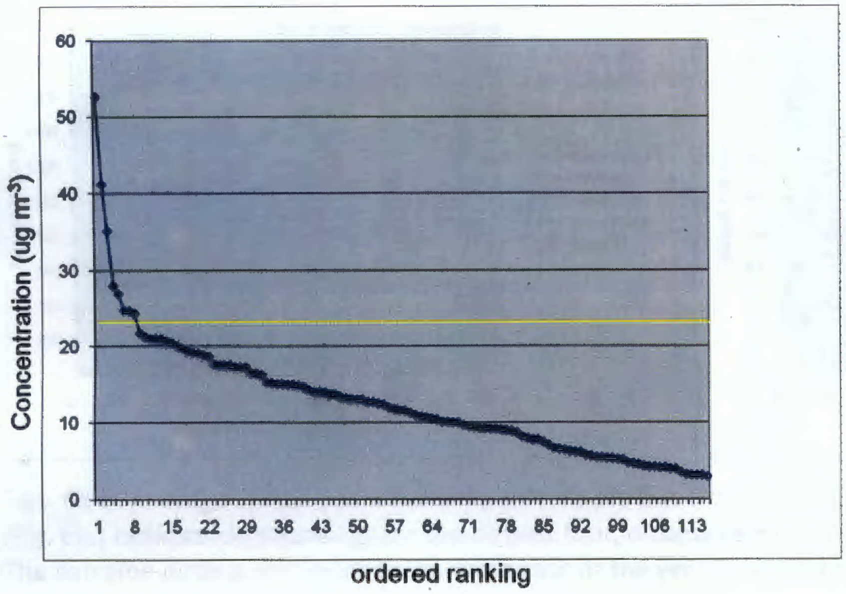
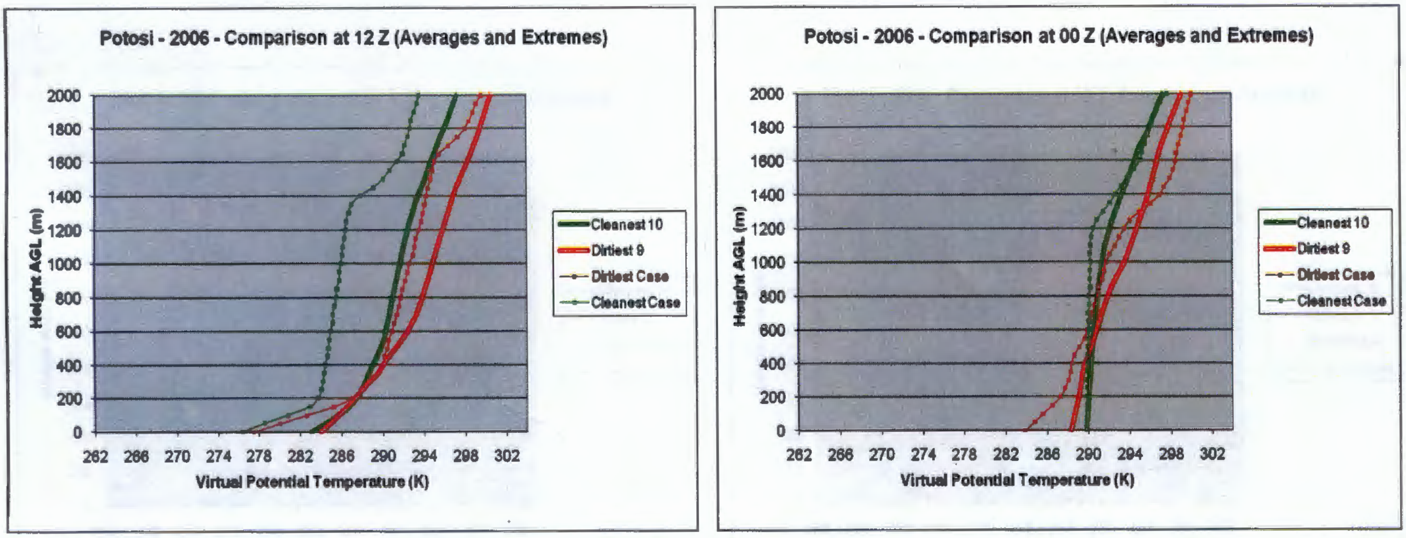
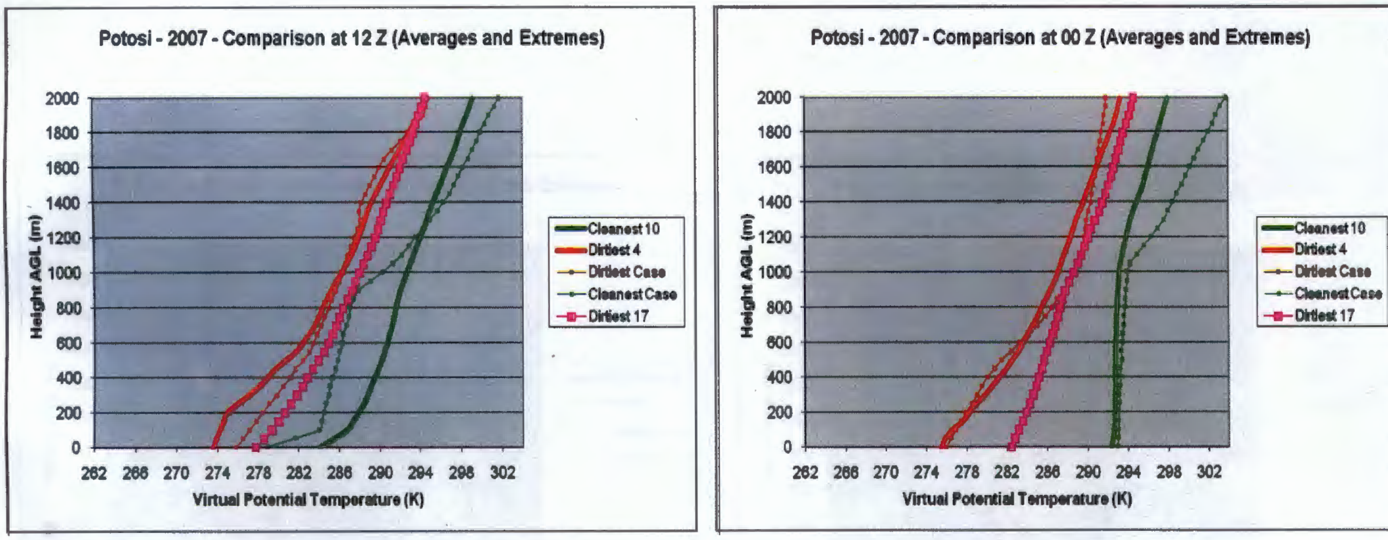


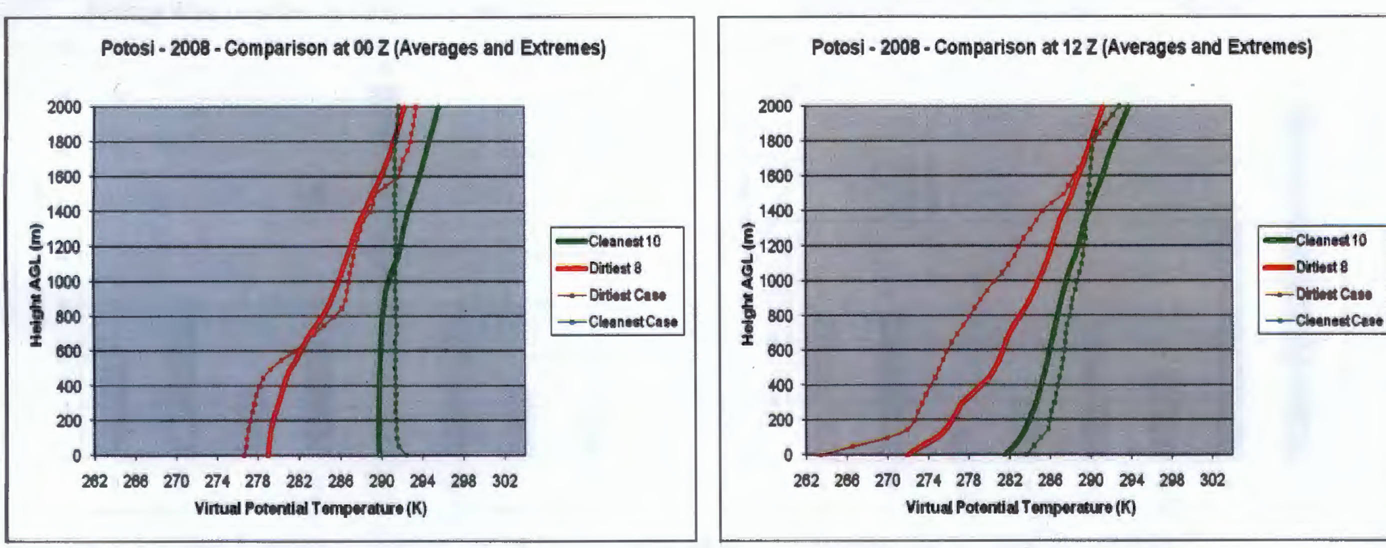
Fig. 4. Scatter plot displaying the ordered ranking, from highest concentration to lowest concentration for the year 2009. The yellow line represents the cutoff point for the selection of the dirty cases in the study.



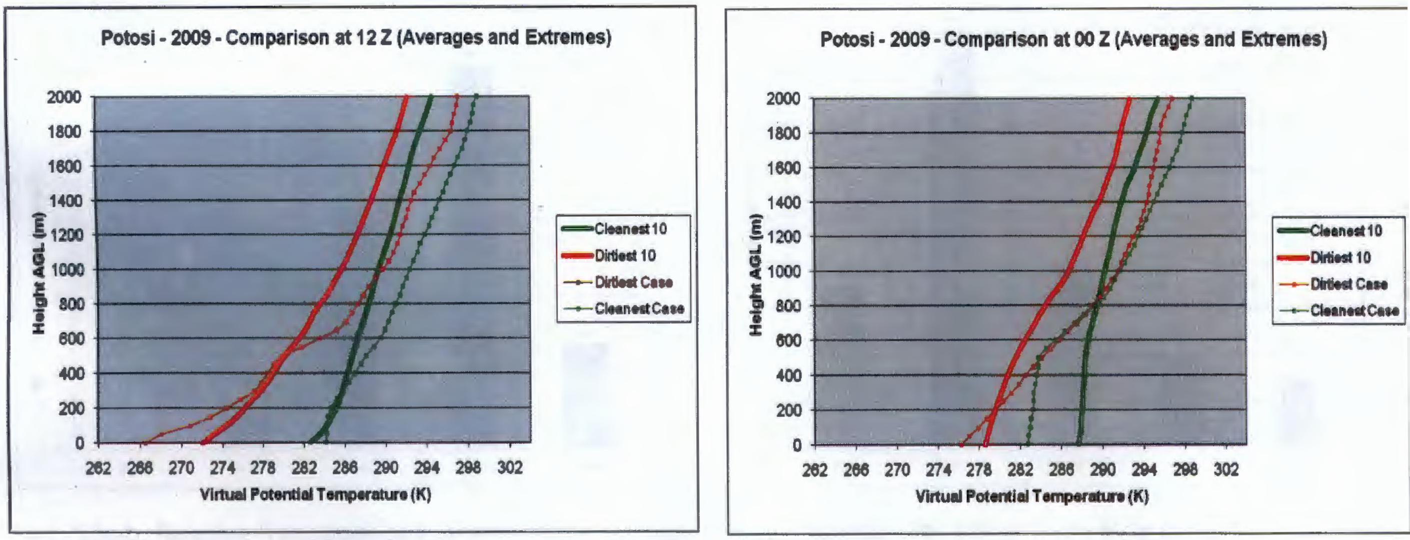
Figs. 5a-b. Average virtual potential temperature profiles from the 1200 UTC (Fig. 5a.) and 0000 UTC (Fig. 5b.) radiosonde soundings for the dirtiest nine and cleanest ten cases of 2006. The extreme dirtiest and extreme cleanest case of the year is plotted with the averages for both the morning and evening charts.



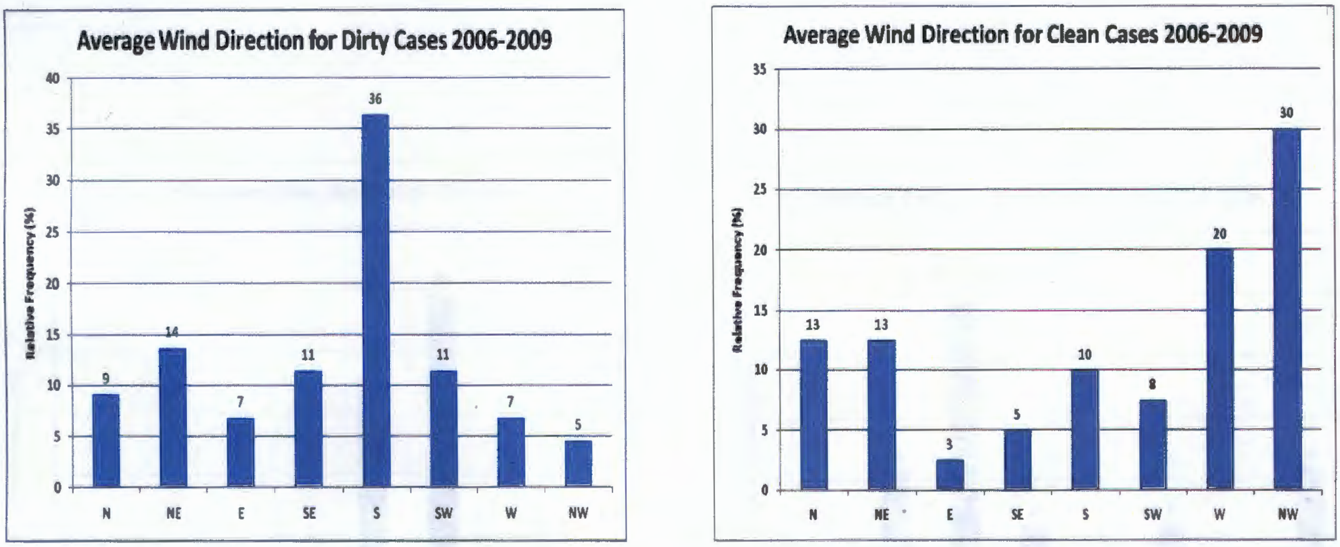
Figs. 6a-b. Average virtual potential temperature profiles from the 1200 UTC (Fig. 6a.) and 0000 UTC (Fig. 6b.) radiosonde soundings for the dirtiest four, dirtiest seventeen and cleanest ten cases of 2007. The extreme dirtiest and extreme cleanest case of the year is plotted with the averages for both the morning and evening charts.



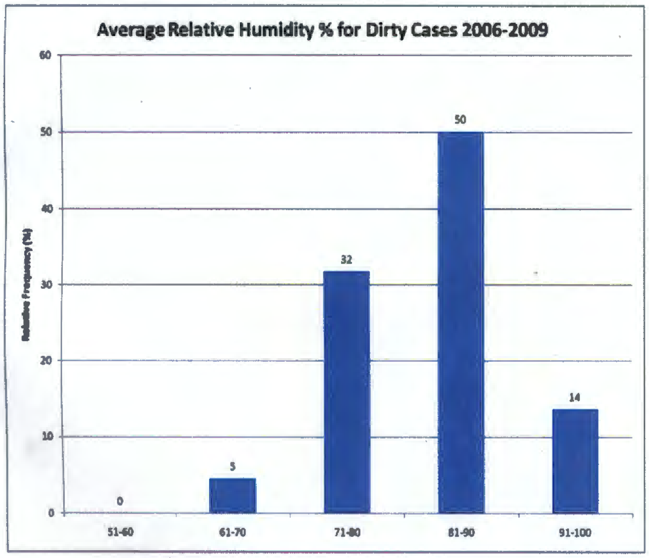
Figs. 7a-b. Average virtual potential temperature profiles from the 1200 UTC (Fig. 7a.) and 0000 UTC (Fig. 7b.) radiosonde soundings for the dirtiest eight and cleanest ten cases of 2006. The extreme dirtiest and extreme cleanest case of the year is plotted with the averages for both the morning and evening charts.

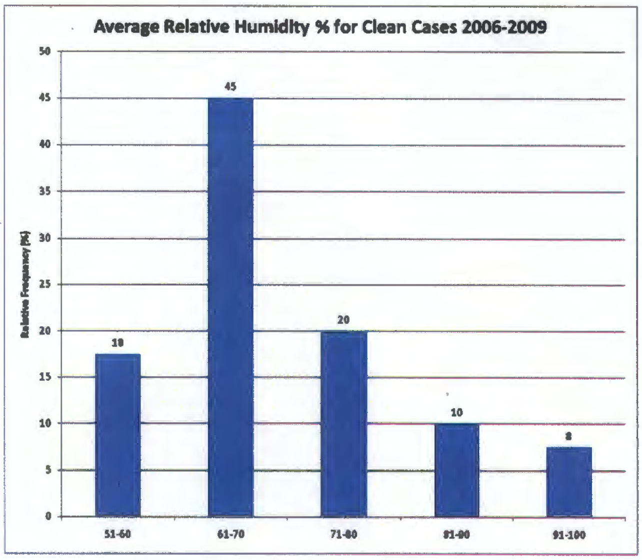


Figs. 8a-b. Average virtual potential temperature profiles from the 1200 UTC (Fig. 8a.) and 0000 UTC (Fig. 8b.) radiosonde soundings for the dirtiest tem and cleanest ten cases of 2006. The extreme dirtiest and extreme cleanest case of the year is plotted with the averages for both the morning and evening charts.

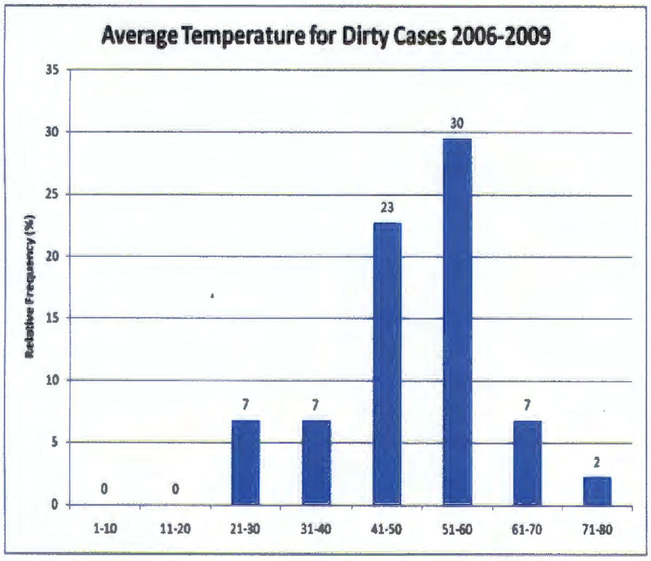


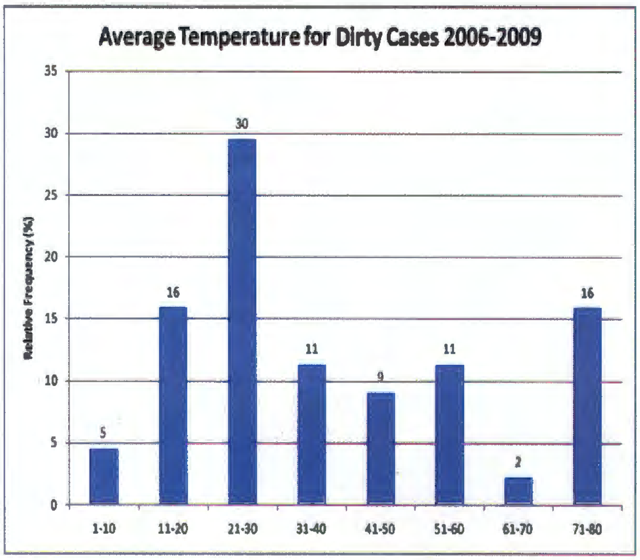
Figs. 9a-b. Relative frequency histograms of the average wind direction for the 44 total dirty cases studied, Fig. 9a., and the 40 total clean cases studied, Fig. 9b.





Figs. 10a-b. Relative frequency histograms of the average relative humidity for the 44 total dirty cases studied, Fig. 10a, and the 40 total clean cases studied, Fig. 10b.





Figs. 11a-b. Relative frequency histograms of the average temperature for the 44 total dirty cases studied, Fig. 11a., and the 40 total clean cases studied, Fig. 11b.