Alaska Department of Environmental Conservation

Amendments to:
State Air Quality Control Plan

Vol. III: Appendix III.D.7.04

{Appendix to Volume II. Analysis of Problems, Control Actions; Section III. Area-wide Pollutant Control Program; D. Particulate Matter; 7. Fairbanks North Star Borough PM2.5 Control Plan, Serious Requirements}

Adopted

November 19, 2019

Michael J. Dunleavy
Governor

Jason W. Brune
Commissioner

(This page serves as a placeholder for two-sided copying)

Appendix III.D.7.04

Contents

MEMORANDUM

To: Cindy Heil, Program Manager, Air Non-Point & Mobile Sources Program, Alaska Department of Environmental Conservation

From: Robert Crawford (Rincon Ranch Consulting)
Tom Carlson (Trinity Consultants)

Date: April 20, 2019

RE: Effect of Meteorological Trends on Design Values for Fairbanks and North Pole

Summary and Conclusions

The analysis reported in this memorandum was conducted to determine whether the year-to-year variations in meteorology since 2010 have had a significant effect on the official measures of peak 24-hour average $PM_{2.5}$ concentrations—the yearly 98th percentiles of 24-hour $PM_{2.5}$ and the Design Values (DVs) computed from them. For Fairbanks, based on the NCore monitoring site, the yearly 98th percentiles and DVs have improved (declined) since 2010 and have stayed below the 24-hour $PM_{2.5}$ standard of 35 μg/m^3 for the past two years (the 5-year DV) and the past three years (98th percentile and 3-year DV). For North Pole, based on the Hurst Rd monitoring site, the yearly 98th percentiles and DVs have improved dramatically since 2012, although recent years remain well above the 24-hour standard.

The State Office Building (SOB) monitor was not included in the analysis for Fairbanks because a statistical model of its $PM_{2.5}$ concentrations versus meteorology was not available. The SOB monitor has its own yearly 98th percentiles and DVs, which differ somewhat from those at NCore due to differences in the density and mix of emissions sources. Because of the close proximity of SOB and NCore monitors, they necessarily share the same trends in meteorology and their yearly 98th percentiles and DVs will be affected by meteorology in the same way. The analysis demonstrates that meteorology has not significantly influenced the improvements at the NCore monitor. We can be confident that the same is true at the SOB monitor.

The analysis presented here—how meteorology affects $PM_{2.5}$ concentrations in the Fairbanks North Star Borough—is based on an extension of the methodology developed for that purpose in the Moderate SIP. When the analysis results are used to adjust the yearly 98th percentiles and the DVs to be consistent with the average meteorology over the past decade, none of the conclusions drawn from the official, unadjusted values are changed.

For Fairbanks, the official 98th percentiles for NCore have dropped from 51 and 50 μg/m^3 in 2010 and 2012 to values consistently below 40 μg/m^3 starting in 2013 and to 25 μg/m^3 in 2018. The official 3-year DV values have dropped from 40–45 μg/m^3 in 2012 and 2013 to values below the 24-hour standard in 2016, 2017 and 2018. The official 5-year design values have followed a similar course, dropping to values below the 24-hour standard in 2017 and 2018. Very nearly the same DVs would occur, and exactly the same pattern would be seen over time, if meteorology had not varied.

For North Pole, there is a similar, but much more dramatic trend. There, the official 98th percentiles for Hurst Rd have dropped from 158 μg/m^3 in 2012 to values below 80 μg/m^3 in 2016 and 2017 and to 53 μg/m^3 in 2018. The 3- and 5-year DVs have also dropped from values well above 100 μg/m^3 in the early years to values of 65 μg/m^3 and 89 μg/m^3, respectively, in 2018. Very nearly the same DVs would occur, and exactly the same pattern would be seen over time, if meteorology had not varied.

From these results, it is clear that the year-to-year variation in meteorology is not a primary determinant of trends in the DVs. "Favorable" meteorology is not responsible for the reductions that have occurred since the early years. Instead, control measures (such as the Borough's Wood Stove Change Out Program and the Curtailment Program) and fuel prices have led to lower wintertime emissions and $PM_{2.5}$ concentrations over this period. Note, however, that this analysis was limited to evaluating the effects of meteorological variability and did not attempt to identify the causal factors for the observed trends in the yearly 98th percentiles and DVs.

Background

The analysis presented here uses a variety of data and past analysis to determine the extent to which year-to-year differences in meteorology have influenced the times series for the yearly 98th percentiles and the DVs that are computed from them. It uses methods of statistical analysis to determine the magnitude of variation attributable to meteorology and then applies that to adjust the observed yearly 98th percentiles and DVs to remove the influence of meteorology. This work is an update and extension to a similar analysis reported in Chapter 5 of the 2012 report *Statistical Assessment of* $PM_{2.5}$ *and Meteorology in Fairbanks, Alaska*[1], which developed a 19-winter track record of meteorology in Fairbanks and used it to compare the severity of meteorological conditions occurring during the then-current 2006-2010 design period. This prior analysis was developed for the Moderate SIP to relate $PM_{2.5}$ concentrations to meteorology and was subjected to peer review by specialists in air quality and atmospheric science before being accepted for the SIP.

The 2012 work was conducted at an early stage in development of the Moderate SIP to provide an analytical understanding of the relationship between meteorology and $PM_{2.5}$. The Alert Model, a forecasting model for $PM_{2.5}$ concentrations as a function of meteorology, was subsequently created as an outgrowth of the 2012 work and has been used by air quality personnel at the Borough since 2013 and more recently by personnel at DEC. The current analysis draws heavily on the analysis and algorithms that support the Alert Model to update the 2012 analysis and to examine meteorology trends over the past decade.

Methodology

Approach

The analysis presented here is based on applying a statistical model of $PM_{2.5}$ concentrations in the Borough to a long-term record of hourly meteorology developed from NOAA data sources. The meteorological data used in the analysis are described in the next section. The statistical model of $PM_{2.5}$ concentrations is described in the subsequent section. Once the model is applied to predict $PM_{2.5}$ concentrations, the results are aggregated to a daily basis. Then, a percentile analysis is performed on the 24-hour average $PM_{2.5}$ concentrations to understand how varying meteorology has influenced the determination of the yearly 98th percentiles and the DVs computed from them.

There is an interplay of many meteorological factors in determining the $PM_{2.5}$ concentration that occurs on a given day. In general, there are multiple meteorological conditions—including temperature, wind speed, and inversion strength—that can lead to any given $PM_{2.5}$ level. The variation of meteorology over time leads to varying $PM_{2.5}$ concentrations year-to-year, as do a range of behavioral and programmatic factors that influence the emissions inventory. Examples of the latter include: heating oil prices (which influence the proportions of wood versus fuel oil used in space heating), the efficiency of wood-burning devices (influenced by control

[1] *Statistical Assessment of* $PM_{2.5}$ *and Meteorology in Fairbanks, Alaska*. Prepared for the Alaska Department of Environmental Conservation. Prepared by R. Crawford (Rincon Ranch Consulting) and R. Dulla (Sierra Research). March 2012.

measures such as the Wood Stove Change Out Program), and bans on combustion of solid fuels during periods of high $PM_{2.5}$ concentrations (a short-term switch to fuel oil in dual-fuel households).

The predictive model of $PM_{2.5}$ concentrations is used here to "score" meteorology for its severity by estimating the $PM_{2.5}$ concentration that one would expect from the meteorology under fixed assumptions for the behavioral and programmatic factors that influence the emissions inventory. This approach permits the decoupling of the year-to-year variation in meteorology from the coincident changes in the behavioral and programmatic factors. This has been done by selecting the Alert Model coefficients that represent $PM_{2.5}$ concentrations in the 2017-18 winter. The selection fixes the behavioral and programmatic factors as they existed in that winter and as used (without adjustment or re-calibration) throughout the just-completed 2018-19 winter. Thus, while developed for the 2017-18 winter, the selected set of behavioral and programmatic factors are also applicable to calendar year 2018 and its two separate winter periods (Jan-Mar and Oct-Dec). Thus, the selected set of behavioral and programmatic factors represent a CY2018 Baseline.

When the statistical model is used to predict $PM_{2.5}$ concentrations for the meteorology that occurred in earlier years, one can interpret the $PM_{2.5}$ values as representing the concentrations that would have occurred had the behavioral and programmatic factors been the same as in the CY2018 baseline. Differences between the observed $PM_{2.5}$ concentrations and the predicted $PM_{2.5}$ concentrations represent the influence that differing behavioral and programmatic factors have had over time. The series of predicted $PM_{2.5}$ concentrations can also be used to adjust the observed values to correct for the influence of varying meteorology.

In the analysis, a "Winter 96th" metric is developed and compared to the official yearly 98th percentile of $PM_{2.5}$ concentrations. The yearly 98th percentile is the 98th percentile of available FRM measurements for the year once exceptional events[2] (if any) are removed. As the $PM_{2.5}$ problem in the Borough is primarily one of wintertime air pollution caused by $PM_{2.5}$ emissions from space-heating and other devices, the highest concentrations are normally recorded in the winter months (excluding exceptional events). In observations covering a 365-day year, the $PM_{2.5}$ concentration at the 98th percentile will be the one occurring on the 7th highest day. In a six-month winter consisting of 182 days, the same 7th highest day will lie at the 96th percentile of the winter period. Thus, a "Winter 96th" metric was computed from the analysis of the winter period in each year for comparison to the observed 98th percentile of the complete calendar year.

The two metrics for peak $PM_{2.5}$ concentrations are on different bases in terms of time period (annual versus winter) and $PM_{2.5}$ measurement method (FRM versus provisionally-calibrated BAM) and are not necessarily consistent with each other. However, the later presentation of results will demonstrate that a good correspondence exists between the yearly 98th and the Winter 96th percentiles for CY2018. This outcome, which is not a result of calibrating one to the other for 2018, is an indication that the Winter 96th is a closely-comparable analog to the yearly 98th percentile.

Meteorological Data

Winter[3] meteorological data were obtained from NOAA sources to extend the existing historical database (from the prior 2012 work) to cover the period from 2009 through 2018. The data include both surface observations taken at Fairbanks International Airport (FAI) and at Eielson Air Force Base (EIL). The radiosonde soundings that are taken twice-daily at FAI also were obtained to provide information on upper air conditions. The

[2] In the Fairbanks area, exceptional events are most commonly caused by forest wildfires, which can lead to high $PM_{2.5}$ concentrations in summer months.

[3] This work defines "winter" to consist of the months October through March, whether organized as winter periods of 6 consecutive months or on a calendar year basis consisting of the months January through March and October through December of the same year.

primary database used in this work covers the winter months of the 10-year period from 2009 through 2018. Additional, supporting information has been provided by the longer-term database of meteorology conditions from 1989 through 2008 that was developed in the 2012 work.

Surface Conditions

The surface data consist of hourly observations taken at FAI and EIL for barometric pressure, temperature, dew point, wind speed and direction, cloud ceiling, and visibility. Weather conditions are also recorded, including the presence of rain, fog, and snow. National Weather Service (NWS) methods for data collection have changed over the past 30 years and have become increasingly automated with time. In earlier years, surface observations were recorded by human weather observers. Beginning on December 1, 1997, surface observations at FAI were recorded by Automated Surface Observing System (ASOS) equipment and automated weather equipment was in use at both FAI and EIL throughout the 2009 to 2018 period examined here.

The surface data are very complete, with only occasional and scattered outages due to instrument failure. There are normally multiple observations within each hour and the number of hours that are missing entirely is very small. The official readings taken late in the hour were selected to represent the "on the hour" conditions. In cases of missing data, mathematical interpolation over time has been used to fill the gaps and create a continuous record of surface conditions.

Upper Air Soundings

Historically, upper air soundings have been taken with a radiosonde (an instrument package suspended from a balloon) that was manually-tracked by a weather observer to receive reports by radio of temperature, moisture and wind conditions as the radiosonde ascends through the atmosphere. Because of the radiosonde's rapid rise and manual tracking, little data was returned for the air layers very close to the surface. Starting in November 2009, upper air soundings at FAI were taken with a GPS-based radiosonde that permits more reliable collection of data by radio with a greatly improved resolution of atmospheric conditions close to the surface. Over the 2009-2018 period that is the primary focus of this analysis, almost all of the FAI soundings were taken with the GPS radiosonde.

The prior 2012 work noted the change in radiosonde technology in late 2009. Because of the importance of the upper air data in determining the presence and strength of surface temperature inversions, the earlier analysis restricted its attention to the period ending with Winter 2008-2009 to assure internal consistency in the soundings. A statistical model of $PM_{2.5}$ concentrations was developed from the available data to indicate inversion strength.

The present work takes advantage of the improved vertical resolution of the GPS radiosonde, which can make its first return as close at 50m above the surface. The statistical model of $PM_{2.5}$ concentrations used here to "score" meteorology for its severity was derived from a database covering the past 5 years in which all of the sounding data are from the GPS radiosonde. The earlier radiosonde may record similar air temperatures at elevations of 200m or more above the surface, but its absence of information close to the surface will consistently understate the actual strength of surface temperature inversions compared to estimates based on the GPS radiosonde. For this reason, the upper air soundings from the earlier period have not been used in the analysis conducted here, nor has an attempt been made to apply the statistical model to the earlier 1989 to 2008 period.

Although the soundings are taken at FAI, the radiosonde traverses a considerable distance during its rise through the atmosphere. Except for the returns closest to the surface, the temperature, moisture and wind conditions in the soundings can be taken as representative of FAI, EIL and the surrounding area. Based on the methods used in the Alert Model, the analysis adopted the 200m level as the point at which upper air conditions could be taken as representative of both FAI and EIL. Soundings are taken twice daily, but the upper air conditions vary hourly in between. To fill this gap, the soundings are interpolated over time for the 200m level and above. The surface observations for the two airports were then matched to the sounding-based, upper air profiles starting at 200m and mathematical interpolation was used to estimate the conditions in between.

Adjustments for Temperature and Wind Speed

The NOAA weather data and meteorological forecasts pertain to conditions at the FAI and EIL airports, while $PM_{2.5}$ concentrations are driven by conditions at the NCore and Hurst Rd monitors, respectively. In the Alert Model, real-time measurements of temperature and winds are provided by the monitors. $PM_{2.5}$ forecasts are driven by NOAA forecasts for meteorological conditions over the coming 2-3 days and the model contains algorithms to predict temperatures and winds at the monitors from the forecast conditions at the airports.

The algorithms account for a variety of variables based on empirical evidence over recent years. For example, temperature differences between the airports and the monitors are diminished when the area is under low clouds, which limits radiative cooling, and also when wind speeds are elevated, which limits the pooling of cold air and tends to equalize temperatures spatially. Because meteorology is available for long time periods, but meteorological measurements at the monitors are not, the algorithms of the Alert Model were used to adjust the airport temperatures and winds to better reflect conditions at the monitors. No meteorological data from the monitors were used in the analysis.

Under conditions of cold surface temperatures and strong inversions deep in the winter months, true winds—those driven by barometric pressure differentials—are seldom present. Instead, gravity-driven, low-speed drainage flows that originate in the surrounding uplands and mountains are the primary source of air flow to disperse pollutants. The weather stations at FAI and EIL employ anemometers that have limited ability to resolve low wind speeds. The FAI instrument will report "Calm" conditions at speeds below 2.5 knots as will the EIL instrument at speeds below 1 knot. When wind speeds were reported as "Calm" in the NOAA data, a drainage flow algorithm taken from the Alert Model was used to estimate wind speed and direction at the monitors. The algorithms are empirical and based on data for the past 5 years. They are temperature sensitive and predict stronger drainage flows at colder temperatures. The temperature sensitivity is small for the NCore monitor, where drainage flows are limited to speeds of 0.5 m/s or less. The temperature sensitivity is greater at the Hurst Rd monitor, where drainage flows as fast at 1.0 m/s have been recorded at very cold temperatures (-40°C and below).

Once processing of the NOAA data was complete, an hourly database of surface and estimated upper air conditions had been created for Fairbanks (based on FAI) and for North Pole (based on EIL). Temperature and wind conditions had been tailored to better-estimate conditions at the NCore and Hurst Rd monitors and the speed and direction of local drainage flows had been estimated in the hours that "Calm" was reported at the airports.

Predictive Model of $PM_{2.5}$ Concentrations

The daily meteorological conditions over the past 10 years are "scored" for their severity using a statistical model of $PM_{2.5}$ concentrations. That is, the $PM_{2.5}$ concentrations that one would expect each day have been computed from the meteorology under a fixed assumption for the emissions inventory. In the 2012 work, a statistical model was developed for the purpose of relating $PM_{2.5}$ concentrations to meteorology in the Borough. For the present analysis, it has been taken from the Alert Model used by Borough and DEC air quality personnel during the winter to forecast $PM_{2.5}$ concentrations (Borough) and issue Air Quality Alerts (DEC) to the public.

The Alert Model was first used by the Borough during Winter 2012-13 to provide forecasts of $PM_{2.5}$ concentrations in Fairbanks and, later, in North Pole. The model works in near-real time, collecting information from the local monitors on an hourly basis and from NOAA sources throughout the day. The readings for $PM_{2.5}$ concentrations are those posted by DEC's Envista system based on measurements taken by BAM instruments at the monitor locations. The hourly $PM_{2.5}$ values are raw BAM readings that have been provisionally calibrated to the FRM scale. The provisional calibration is based on the empirical relationship between BAM and FRM readings in the prior calendar year. It is updated annually, but it always lags the real-time data by a full year.

The hourly $PM_{2.5}$ data reported by Envista are the information available to Borough and State air quality staff during each winter. As such, the statistical model of $PM_{2.5}$ calibrations is calibrated to predict the Envista values. Thus, the (unofficial) $PM_{2.5}$ values predicted by the model are not the same, and not necessarily comparable to, the (official) FRM measurements that are taken throughout the year. However, the analysis results demonstrate that the unofficial $PM_{2.5}$ values are useful analogs to the official FRM values for purposes of analyses such as conducted here.

At present, the Alert Model is configured to report and forecast $PM_{2.5}$ concentrations for the NCore monitor in Fairbanks and the Hurst Rd monitor in North Pole. The statistical models for these two monitors are used in the analysis to score the severity of meteorology. While the Alert Model originally used the SOB monitor for Fairbanks, it was dropped from the model when the NCore monitor came into operation. As the SOB statistical model has not been used or maintained since that time, the SOB monitor was not included in the analysis for Fairbanks. The SOB monitor has its own yearly 98th percentiles and DVs, which differ from those at NCore due to a somewhat different density and mix of emissions sources.

Although SOB was not included in the analysis, the trends in meteorology over time and the effects on the yearly 98th percentiles and DVs will be essentially the same as that for NCore. The two monitors are located in close proximity to each other and share very similar (if not identical) conditions for surface temperature, wind and weather events such as snow and ice fog. Upper air conditions will be nearly identical since these conditions extend across the entire area at elevations of 200m or more (to exclude surface effects). Thus, the strength of the surface inversion will be very nearly the same at the two monitor sites. There is no evidence in the analysis that "favorable" meteorology has influenced the improvements at the NCore monitor in recent years. We can be confident that the same is true at the SOB monitor.

Model Structure

The mathematical structure of the predictive model for $PM_{2.5}$ concentrations is given in Eq. 1 below. The model form differs slightly between the NCore and Hurst Rd monitors, as is noted below, and each monitor is represented by its own set of coefficients. The empirical coefficients are indicated in **bold.** The underlying data include the $PM_{2.5}$ concentrations, temperatures and wind speeds measured at the monitors and a large number of additional meteorological variables measured at the nearby airports[4]. Each variable represents a lagging 4-hour average ending in the current hour "h".

Indices are: i = a sequential index for the 4-hr periods

h = hour of the day ending the 4-hr period (for diurnal pattern)

m = winter month (October-March)

w = specific winter (for coefficients varying over time)

[4] The additional meteorological variables for the NCore monitor are taken at Fairbanks International Airport (FAI), while the additional variables for the Hurst Rd monitor are taken at Eielson Air Force Base (EIL).

δ = dummy variable (e.g., $\delta(w)$ indicates the dummy variable for winter w)

$$
\begin{aligned}
PM_{2.5}(i, h, m, w) = \; & \mathbf{ZeroPt} + \textstyle\sum_m [\, \mathbf{S_m} * \delta(m) \,] \\
& + \{\; \mathbf{F_{LAG}} * PM_{2.5}(i-1, h, w) \; + \\
& \quad \mathbf{A_w} * [\, 1 + \mathbf{C(h)} * \delta(h) \,] * \exp(\, \mathbf{T_w} * Temp(i) \,) \;/\; \exp(\, \mathbf{M1} * Met1(i) \,) \\
& \quad \} \\
& * \; WSpd(i)^{\mathbf{D}} \\
& * \; (\, 1 + \mathbf{D_{SNOW}} * IsSnowing(i) \,) \\
& * \; \exp(\, \mathbf{D_{ICEFOG}} * K_{EXT}(Temp(i)) / 0.000243 \,) \qquad \text{(Eq. 1)}
\end{aligned}
$$

The model is estimated using a non-linear regression procedure and data from the past 3 to 5 winters. The empirical coefficients have been updated annually as new experience is gained.

The model structure follows a "box model" approach in which, conceptually, $PM_{2.5}$ concentrations are computed as the total $PM_{2.5}$ emitted into a box divided by the volume of the box. The box's surface area equals the area of influence surrounding the monitor, while its vertical height is determined by the strength of the surface inversion. Pollutants are assumed to be evenly mixed within the box. In this, a portion of the prior period's concentrations may carry forward into the current period, horizontal dispersal of pollutants by winds will reduce concentrations, while the presence of snow or ice fog will reduce concentrations by lifting the base of the inversion to the top of the snow or ice fog layer.

The terms in the equation represent the following behavioral and meteorological drivers to $PM_{2.5}$ concentrations:

- **ZeroPt** and $\mathbf{S_m}$ are intercept terms overall and for the individual winter months (Oct-Mar)
- The coefficient $\mathbf{F_{LAG}}$ denotes the fraction of the $PM_{2.5}$ concentration from the prior (non-overlapping) 4-hour period that carries over to the current 4-hour period.
- The term $\mathbf{A_w} * [\, 1 + \mathbf{C(h)} * \delta(h) \,] * \exp(\, \mathbf{T_w} * Temp(i) \,)$ is the numerator of the box model. It represents the sensitivity of current-period concentrations to ambient temperature (a surrogate for the space-heating emissions rate) along with a fixed, diurnal profile of concentrations. The coefficients $\mathbf{A_w}$ and $\mathbf{T_w}$ are specific to each winter.

  At the NCore monitor, the numerator in the box model is the sum of two different $\mathbf{A_w} * [\, 1 + \mathbf{C(h)} * \delta(h) \,] * \exp(\, \mathbf{T_w} * Temp(i) \,)$ terms to reflect the empirical determination that the diurnal profile has two separate components with differing temperature sensitivities. At the Hurst Rd monitor, the numerator is a single term of the form $\mathbf{A_w} * [\, 1 + \mathbf{C(h)} * \delta(h) \,] * \exp(\, \mathbf{T_w} * Temp(i) \,)$ in which the diurnal profile reflects a classic space-heating pattern of rising concentrations starting in late afternoon that reach a peak at/near midnight before falling through the overnight hours and remaining low during the day.

  The term $\exp(\, \mathbf{M1} * Met1(i) \,)$ is the denominator of the box model. Met1 is a multivariate metric constructed through Principal Component Analysis to measure the strength of the surface temperature inversion. Table 1 itemizes its constituent meteorological variables. The empirical coefficient **M1** gives the inversion strength on an index-like, dimensionless scale that ranges from about -4.5 (convective conditions) to +4.5 (strong inversion). **M1**=0 denotes the average inversion strength encountered during the winter months.
- The term $(\, 1 + \mathbf{D_{SNOW}} * IsSnowing(i) \,)$ represents the reduction in $PM_{2.5}$ concentrations due to the presence of snow in the current period (denoted by IsSnowing(i) = 1). The effect of snow on

concentrations should vary with the density of the snow layer. Thus, the empirical coefficient $\mathbf{D_{SNOW}}$ reflects the effect of an "average" snow.

- The term exp($\mathbf{D_{ICEFOG}}$ * K_{ext}(Temp(i)) / 0.000243) represents the reduction in $PM_{2.5}$ concentrations due to the presence of ice fog. Ice fog is a phenomenon that is common in the Borough but seldom seen outside the Arctic. Further, ice fog is not recorded by automated weather stations[5] and is not forecast by weather models. Thus, the K_{EXT} variable has been constructed from algorithms in the scientific literature to estimate the number density of small ice particles at a given ambient temperature and their resulting effect on atmospheric extinction and the air temperature profile near the surface. This term should be interpreted as an estimate of the expected effect of ice fog on $PM_{2.5}$ concentration through the theoretical K_{EXT} variable and the empirical coefficient $\mathbf{D_{ICEFOG}}$.

Table 1. Meteorological Variables used to Define Met1 Variable Measuring Surface Inversion Strength

Variable	Description
CEIL	Cloud ceiling, hundreds of feet
VIS	Horizontal visibility, miles
ALTM	Station pressure, in Hg
PWater	Precipitable water, inches
MixHt	Height of mixed layer, meters
MixLapse	Temperature lapse rate within mixed layer, ^{o}C/m
MixWSpd	Wind speed in mixed layer, m/sec
CapWSpd	Wind speed at top of mixed layer, m/sec
CapBRN	Bulk Richardson Number at top of mixed layer, dimensionless
dT050	Temperature difference surface to 50 m, ^{o}C
dT100	Temperature difference surface to 100 m, ^{0}C
dT200	Temperature difference surface to 200 m, ^{0}C
dT300	Temperature difference surface to 300 m, ^{0}C
dT500	Temperature difference surface to 500 m, ^{0}C

Note: this list includes three variables that are recorded in surface observations (CEIL, VIS, ALTM) and eleven others that are constructed from the combination of surface observations and upper air soundings.

The predictive model was applied in this analysis to estimate the $PM_{2.5}$ concentrations for each non-overlapping 4-hour period of each winter day over the past 10 years. The six non-overlapping periods that constitute each

[5] The weather stations report the presence of fog or mist in the area, but do not differentiate between the presence of water fog (water aerosols) and ice fog (ice particles). Weather observers follow the same procedure when recording manual observations.

day were combined to estimate the 24-hr average $PM_{2.5}$ concentration. The resulting values become the primary data for the trend analysis.

Impact of Meteorology on $PM_{2.5}$ Concentrations

Fairbanks Area

Figure 1 presents the trend in peak 24-hour $PM_{2.5}$ concentrations at the NCore monitor over the past 10 years. The blue diamonds are the 98th percentiles for each year as calculated from the FRM data[6] and used in the determination of 3- and 5-year DVs. The red circles are the estimated Winter 96th percentiles as calculated from statistical model's predicted daily $PM_{2.5}$ concentrations. The latter assumes a constant emissions inventory representing the set of behavioral and programmatic factors that existed as of CY2018. As no effort was made to "calibrate" the predicted values to the FRM, the good correspondence in 2018 between the official yearly 98th and the unofficial Winter 96th percentiles is evidence that the Winter 96th is a closely-comparable analog and should be a reliable indicator of the influence of meteorology over time.

The variation from year to year in the Winter 96th percentiles (calculated in this analysis) is due solely to the variation of meteorology. The Winter 96th has varied from a high of 33.4 μg/m^3 in 2014 to a low of 27.2 μg/m^3 in 2018. The variation up and down over time appears to be cyclic without evidence of a consistent upward or downward linear trend. The Winter 96th averages 30.6 μg/m^3 over the 10-year period from 2009 to 2018, with a 95th confidence interval of ±4.2 μg/m^3 (or ±13%) as indicated by the dotted red lines. This is the extent to which year-to-year variations in meteorology have perturbed the official yearly 98th percentiles.

In comparison, the yearly 98th percentiles for Fairbanks were 51 and 50 μg/m^3 for 2010 and 2012, respectively, and have ranged between 30 and 40 μg/m^3 in all but one of the other years. The lowest yearly 98th values are close to or within the range of Winter 96th values estimated in the analysis, with the 2018 value of 25 μg/m^3 being the only one below the range.

The values for the Winter 96th percentile can be used to adjust the official yearly 98th percentiles to remove the effects of meteorology and re-state them on a basis of constant meteorology equal to the average for the 2009-2018 period. This is done by finding the ratio between the Winter 96th percentile for a given year and its average value for the period, then dividing the yearly 98th values by that ratio. For example, 2014 had the most severe meteorology as indicated by its 33.4/30.6 = 1.092 ratio. Thus, the yearly 98th percentile for 2014 is adjusted downward to 31.6/1.092 = 29 μg/m^3 on a constant meteorology basis.

Figure 2 shows the result of the adjustment process for Fairbanks. The blue diamonds are now the yearly 98th percentiles adjusted to constant 2009-2018 meteorology and the red line is the average Winter 96th value for the 2009-2018 period. Once year-to-year variations in meteorology are controlled, the four earliest years (2010-2013) all fall above the red line representing the average, while the past five years (2014-2018) vary around the line. The met-adjusted data indicate that the observed reductions in yearly 98th percentiles since 2010 are not the result of more favorable meteorology but, instead, indicate real progress in reducing $PM_{2.5}$ concentrations through a combination of control measures (such as the Borough's Wood Stove Change Out Program and the Curtailment Program) and wood use shifts caused by lower heating oil prices in recent years.

[6] Daily FRM sampling began on May 25, 2017 at NCore and on January 1, 2017 at SOB. Prior to these dates, FRM sampling was conducted on a 1-in-3 day basis. While daily sampling will record all high-concentration events (barring equipment failure, etc.), 1-in-3 sampling leads to a statistical estimate of peak $PM_{2.5}$ concentrations, rather than an enumeration. The use of 1-in-3 sampling in the earlier period introduces additional, random variation in the yearly 98th percentiles, but otherwise has no effect on the comparisons made here.

Figure 1. Fairbanks: Trend in Peak 24-Hour $PM_{2.5}$ Concentrations under Actual Meteorology

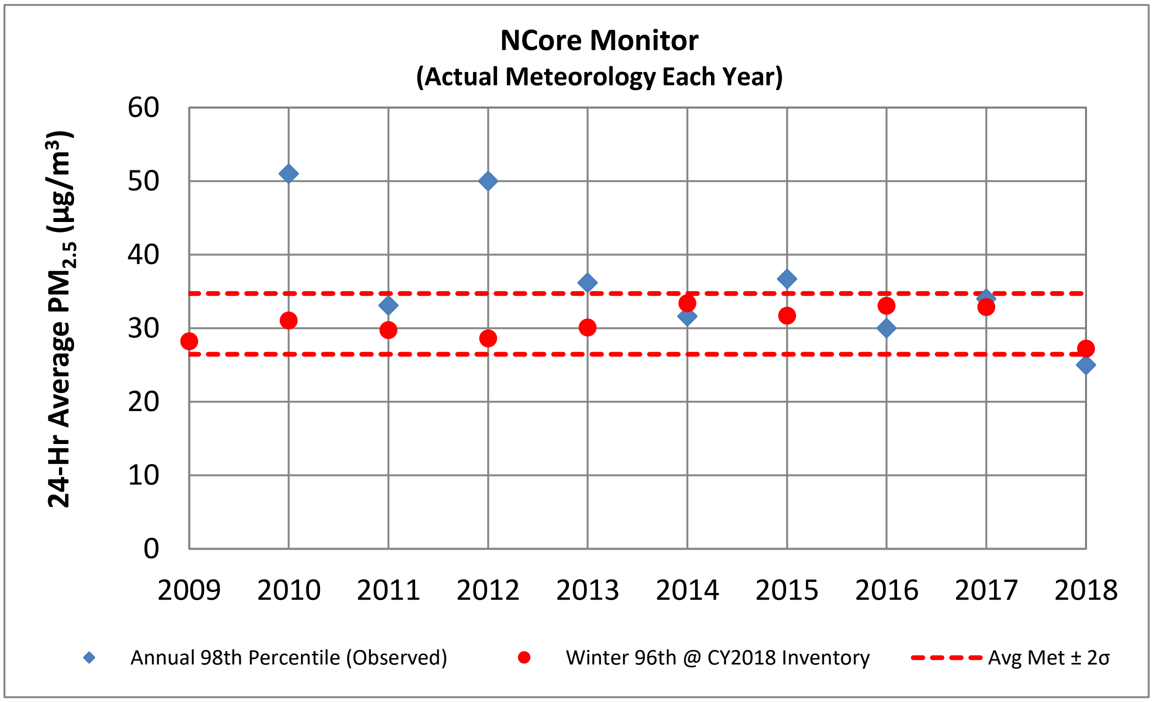
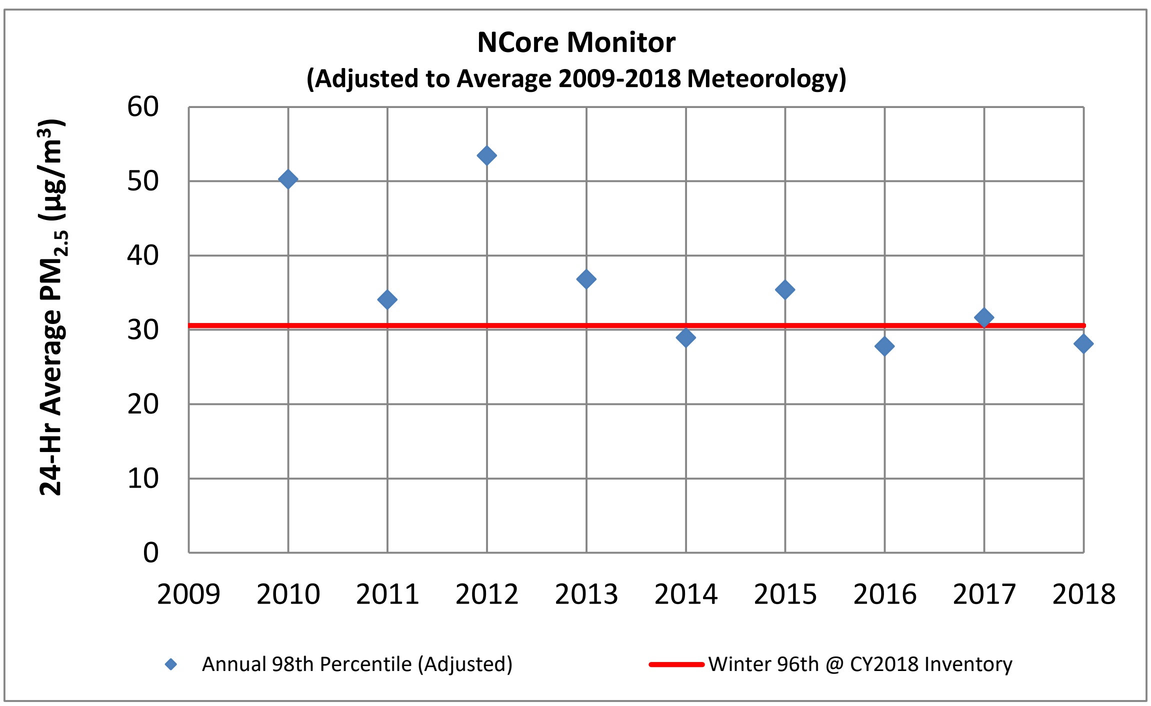


Figure 2. Fairbanks: Trends in Peak 24-Hour $PM_{2.5}$ Values Adjusted to Constant Meteorology



Compliance determinations are based on DVs that reflect a running average of recent values for the yearly 98th percentile of concentrations. The leftmost columns in Table 2 summarize the current set of yearly 98th percentiles and DVs for the NCore monitor, based on actual meteorology, while the rightmost columns summarize values that are calculated when the actual yearly 98th percentiles are adjusted to constant meteorology. Both 3-year and 5-year average DVs are shown. As can be seen, the met-adjusted 3-yr DVs differ from the official values only to a small extent: ±1 μg/m^3 in most years and by a maximum of ±2 μg/m^3 in two years. The met-adjusted 5-year DVs also differ by ±1 μg/m^3 in most years and by a maximum of ±2 μg/m^3 in two years.

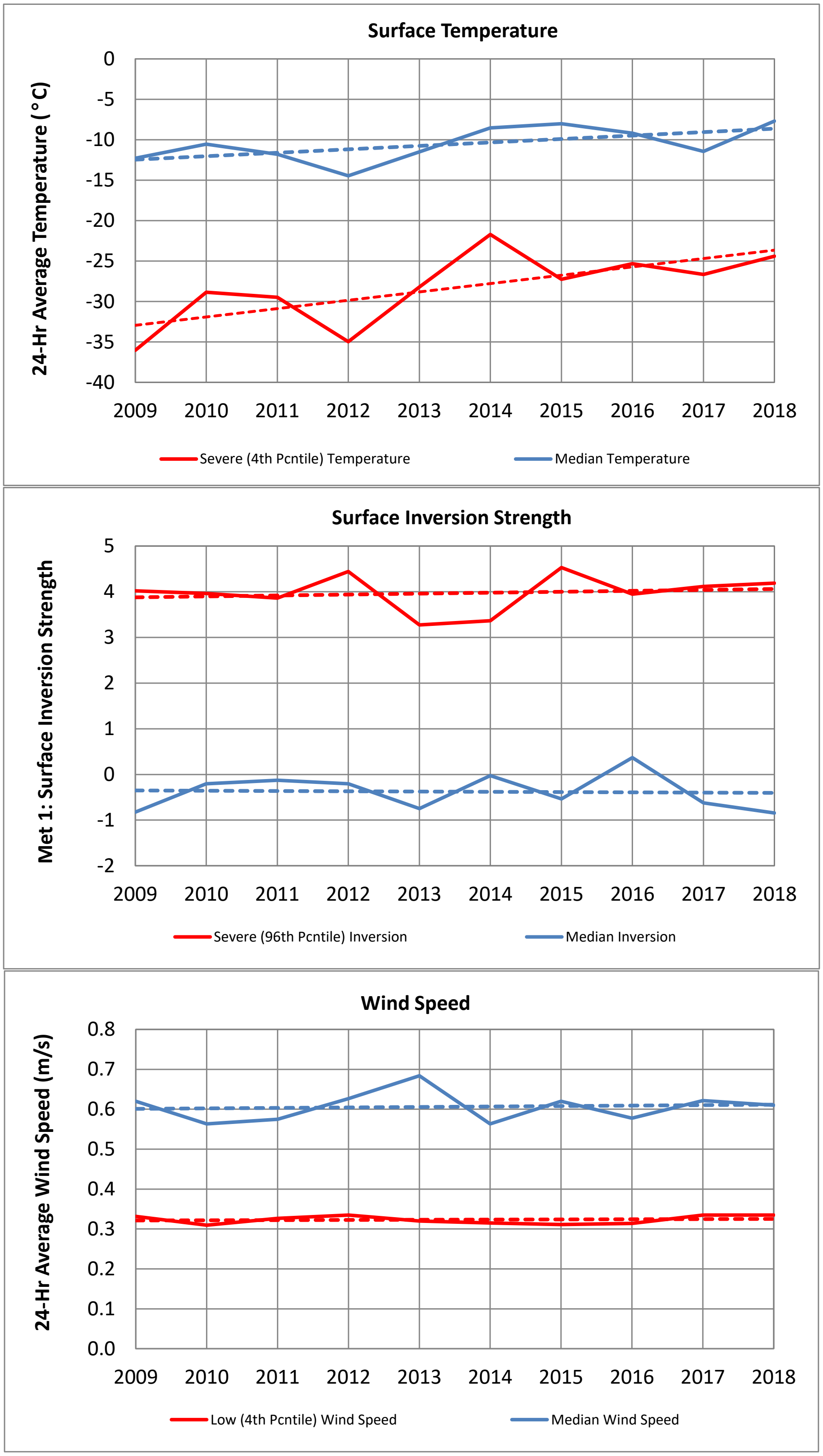
The met-adjusted 3-year DVs indicate that NCore has been below the 24-hour $PM_{2.5}$ standard of 35 μg/m^3 in the past four years, but above it in the years before. The met-adjusted 5-year DVs indicate that the NCore monitor has been below the standard in the past two years (2017 and 2018), but above the standard in the years before that (2014 through 2016). This is a nearly identical assessment to that given by the official 5-year DVs.

Table 2. Fairbanks: Comparison of NCore Yearly 98th Percentiles and Design Values as Observed and as Adjusted to Constant Meteorology

	As Observed (Actual Meteorology)				Adjusted to Average Meteorology (2009-2018)		
	yearly 98th Percentile	3-Year Design Value	5-Year Design Value		yearly 98th Percentile	3-Year Design Value	5-Year Design Value
2009							
2010	51				50		
2011	33				34		
2012	50	45			53	46	
2013	36	40			37	41	
2014	32	39	40		29	40	41
2015	37	35	38		35	34	38
2016	30	33	37		28	31	36
2017	34	34	34		32	32	32
2018	25	30	32		28	29	30

While the severity of meteorology depends on the interplay of a number of meteorological variables, insight can be gained examining trends in the three chief meteorological drivers. Figure 3 shows these trends for Fairbanks. The top graph shows trends over time for the median (50th percentile) daily-average temperature in winter months and for severely-cold (4th percentile) daily-average temperatures each winter. The middle graph shows the trends for the Met1 measure of the surface inversion strength, both on a median basis and for severe inversions (the 96th percentile) each winter. The bottom graph shows the trends for daily-average wind speed during the winter, both median and the 4th percentile. While defined as 4th percentiles (low values) or 96th percentiles (high values) to correspond to the Winter 96th percentile for $PM_{2.5}$ concentrations, there is no intent to imply that any <u>one</u> of these met variables is sufficient on its own to cause concentrations to reach the 96th percentile level.

Figure 3. Fairbanks: Meteorological Drivers of $PM_{2.5}$ Concentrations



The graphs demonstrate that surface temperatures have changed the most over the past 10 years. Median temperatures have warmed by 4°C over the past 10 years and the severely-cold temperatures have warmed by 5°C, both as estimated from the trend lines in the graph. Surface inversion strengths (as measured by Met1) have held constant over time, both for the median and for strong inversions, and the same is true for wind speeds. The upward trends in surface temperatures are consistent with the widely-noted warming of Arctic regions that has occurred in recent years and with the longer-term trend that will be documented later in this report. The more-rapid rate of increase for severely-cold temperatures is believed to be influenced by both overall warming and by a reduced frequency at which the very coldest temperatures occur.

North Pole Area

Figure 4 shows the trend in peak annual $PM_{2.5}$ concentrations at the Hurst Rd monitor over the past 10 years. The blue diamonds give the official yearly 98th percentiles[7] and the red circles give the estimated Winter 96th percentiles from the statistical model predictions. As for Fairbanks, there is a close correspondence between the official yearly 98th and the unofficial Winter 96th percentiles for 2018. (In Figure 4, the yearly 98th percentile value for 2018 is nearly hidden under that for the Winter 96th percentile.)

For North Pole, the Winter 96th has varied from a high of 61.3 μg/m³ in 2014 to a low of 46.5 μg/m³ in 2013. The most recent five years have been somewhat more severe on average than the first five years and have additional year-to-year fluctuation superimposed. The Winter 96th averages 53.6 μg/m³ over the 10-year period from 2009 to 2018, with a 95th confidence interval of ±9.2 μg/m³ (or ±17%) as indicated by the dotted red lines. The ±17% range year-to-year indicates somewhat greater variability than for Fairbanks (±13%) and is the extent to which year-to-year variation in meteorology has perturbed the 98th percentiles and DVs.

In comparison, the official yearly 98th percentiles for North Pole are historically much higher and have fallen rapidly over time. The yearly 98th values were above 100 μg/m³ for 2012 through 2015 but have been below 80 μg/m³ since 2016. Only the 2018 value is within the expected range[8] based on meteorology (the ±95th confidence interval indicated by the red lines); the 2016-2017 values, although much lower than before, are outside the range. These comparisons indicate that real and dramatic reductions have been achieved in North Pole through a combination of control measures (such as the Borough's Wood Stove Change Out Program and the Curtailment Program) and wood use shifts caused by lower heating oil prices. The comparisons are confirmed when the yearly 98th percentiles for North Pole are adjusted to constant meteorology.

Figure 5 shows the trends in peak $PM_{2.5}$ concentrations for North Pole after they are adjusted to constant-meteorology using the same process as for Fairbanks. The blue diamonds are the yearly 98th percentiles adjusted to constant 2009-2018 meteorology and the red line is the average Winter 96th value for the 2009-2018 period. Once the year-to-year variations in meteorology are controlled, all six of the past years lie above the value expected at constant meteorology (the red line).

Without question, the observed reductions in yearly 98th percentile values since 2012 are not simply the result of more favorable meteorology. While this analysis has not attempted to attribute the observed reductions to causal factors, the potential factors include: 1) decreased wood use in response to cheaper heating oil prices; 2) the Borough's Wood Stove Change Out Program, which began in July 2010; and 3) the solid-fuel burning appliance Curtailment Program, which started in Winter 2015-16.

[7] Daily FRM sampling began at the Hurst Rd monitor on July 1, 2017. Prior to this date, FRM sampling was conducted on a 1-in-3 day basis. While daily sampling will, in principle, record all high-concentration events, 1-in-3 sampling leads to a statistical estimate of peak $PM_{2.5}$ concentrations. This introduces additional, random variation in the yearly 98th percentiles, but otherwise has no effect on the comparisons made here.

[8] This is necessarily true because the expected range is based on the CY2018 emissions inventory and the 2018 values must fall within the range.

Figure 4. North Pole: Trends in Peak 24-Hour $PM_{2.5}$ Concentrations under Actual Meteorology

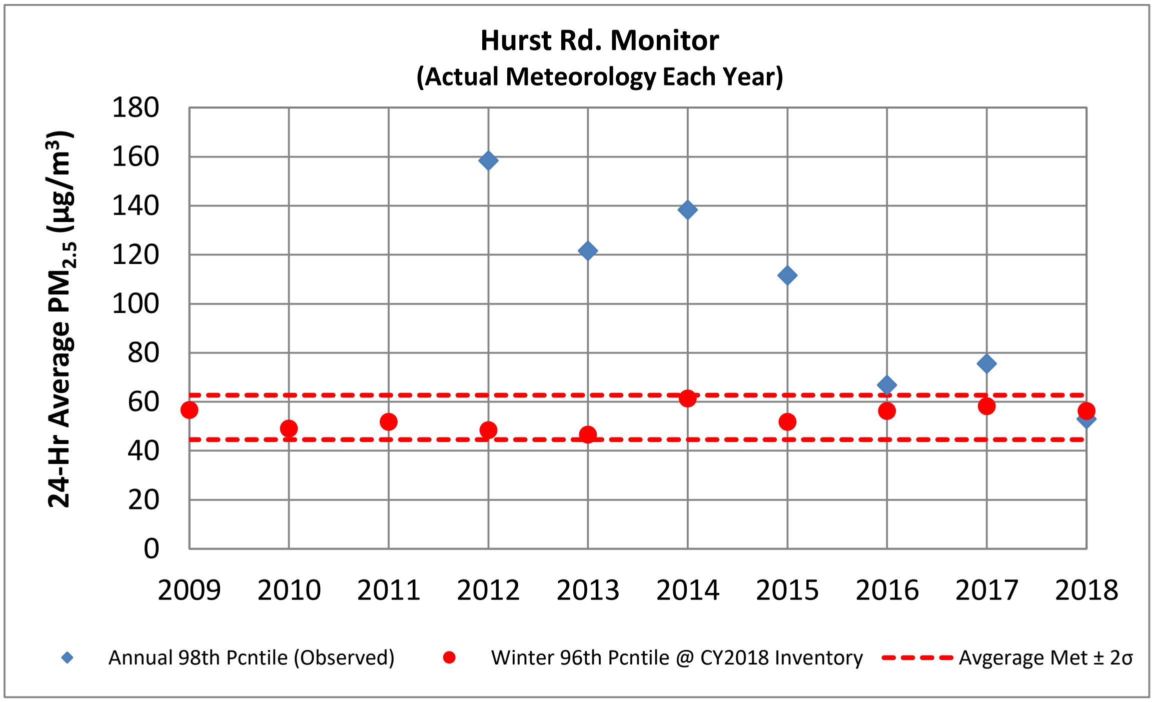


Figure 3. North Pole: Trends in Peak 24-Hour $PM_{2.5}$ Values Adjusted to Constant Meteorology

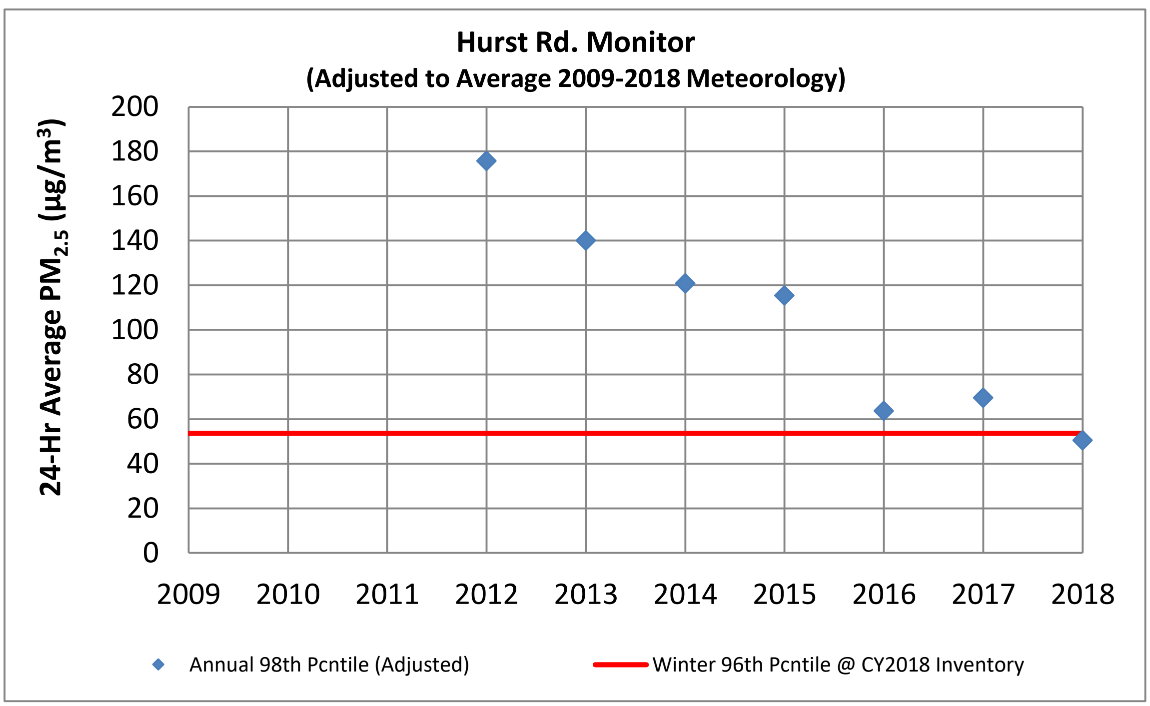


Table 3 summarizes the yearly 98th percentiles and DVs for North Pole in comparison to the values that are calculated when the observed 98th percentiles are adjusted to constant meteorology. The differences in the 3-year DVs between the as-observed and met-adjusted bases range from ±1 μg/m³ up to a maximum of ±6 μg/m³, but all of the differences are small in comparison to the DVs themselves. The 5-year DVs differ by a maximum of ±5 μg/m³. The met-adjusted DVs indicate that North Pole, while still well above the 24-hour $PM_{2.5}$ standard of 35 μg/m³, has made dramatic progress since 2014. This is the same assessment that is given by the official DVs.

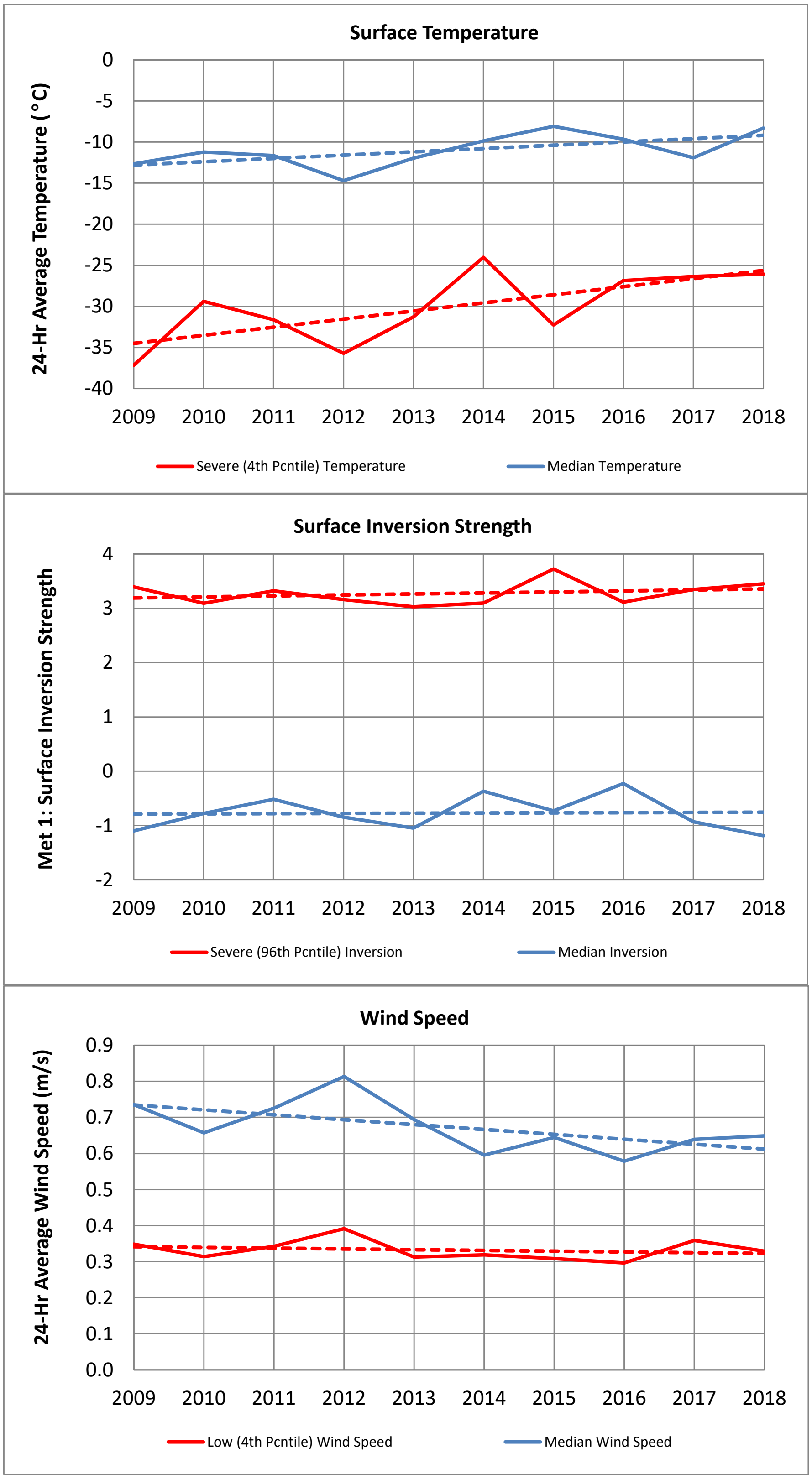
Table 3. North Pole: Comparison of Hurst Rd Yearly 98th Percentiles and Design Values as Observed and as Adjusted to Constant Meteorology

	As Observed (Actual Meteorology)				Adjusted to Average Meteorology (2009-2018)		
	yearly 98th Percentile	3-Year Design Value	5-Year Design Value		yearly 98th Percentile	3-Year Design Value	5-Year Design Value
2009							
2010							
2011							
2012	158				176		
2013	122				140		
2014	138	140			121	146	
2015	112	124			115	125	
2016	67	106	119		64	100	123
2017	76	85	103		70	83	102
2018	53	65	89		51	61	84

Figure 6 shows the trends over time in the three chief meteorological drivers of $PM_{2.5}$ concentrations at the Hurst Rd monitor. As for Fairbanks, the graphs demonstrate that surface temperatures have changed the most over the past 10 years. Median temperatures have warmed by 4°C over the past 10 years, the same as in Fairbanks, and the severely-cold temperatures have warmed by twice as much, as estimated from the trend lines in the graph. The observed temperatures at the cold end of the distribution (the 4th percentile) may appear to make a step change between the first five and the last five years, but as will be seen later, the changes in the past 10 years are actually a part of the longer-term trend in temperatures over the past 30 years.

Surface inversion strengths as measured by the Met1 variable have been constant over time, both for the median inversion and for strong inversions, as was seen for Fairbanks. There is a slight trend toward lower wind speeds for North Pole, which were estimated for the monitor locations using the drainage flow algorithms from the Alert Model. The algorithms are sensitive to the surface temperature and will estimate slightly lower speeds as the temperature warms.

Figure 4. North Pole: Meteorological Drivers of $PM_{2.5}$ Concentrations



Discussion

The preceding results demonstrate that meteorology has played a relatively small role in the yearly 98th percentiles and the 3- and 5-year DVs determined for Fairbanks (NCore monitor) and North Pole (Hurst Rd monitor). Year-to-year variations in meteorology over the past 10 years are enough to cause the yearly 98th percentiles to vary by ±13% in Fairbanks and ±17% in North Pole (95th confidence range) but without any consistent upward or downward trend. For Fairbanks, this range of variation is not nearly enough to explain the significant drop in the yearly 98th percentiles since 2010, while for North Pole the range of variation is actually small in comparison to the dramatic reductions that have occurred since 2012.

When the results of the analysis are used to adjust the yearly 98th percentiles and the 3- and 5-year DVs to be consistent with the average meteorological severity over the past decade, none of the conclusions drawn from the official, unadjusted values are changed. For Fairbanks, the official 98th percentiles at NCore have dropped from 51 and 50 $\mu g/m^3$ in 2010 and 2012, respectively, to values below the 24-hour $PM_{2.5}$ standard of 35 $\mu g/m^3$ in 2016, 2017 and 2018. The official 3- and 5-year DV values have dropped from values of 40 $\mu g/m^3$ or more in the early years to values below 35 $\mu g/m^3$ in 2016, 2017 and 2018 (3-year DV) and 2017 and 2018 (5-year DV). Very nearly the same DVs would have been determined, and exactly the same pattern over time would be seen, if meteorology had not varied.

There is a similar, but much more dramatic, outcome for North Pole. There, the official 98th percentiles have dropped from 158 $\mu g/m^3$ in 2012 to values below 80 $\mu g/m^3$ in 2016 and 2017 and to 53 $\mu g/m^3$ in 2018. The 3- and 5-year DVs also drop from values well above 100 $\mu g/m^3$ in the early years to values of 65 and 89 $\mu g/m^3$, respectively, in 2018. Very nearly the same DVs would have been determined, and exactly the same pattern over time would be seen, if meteorology had not varied.

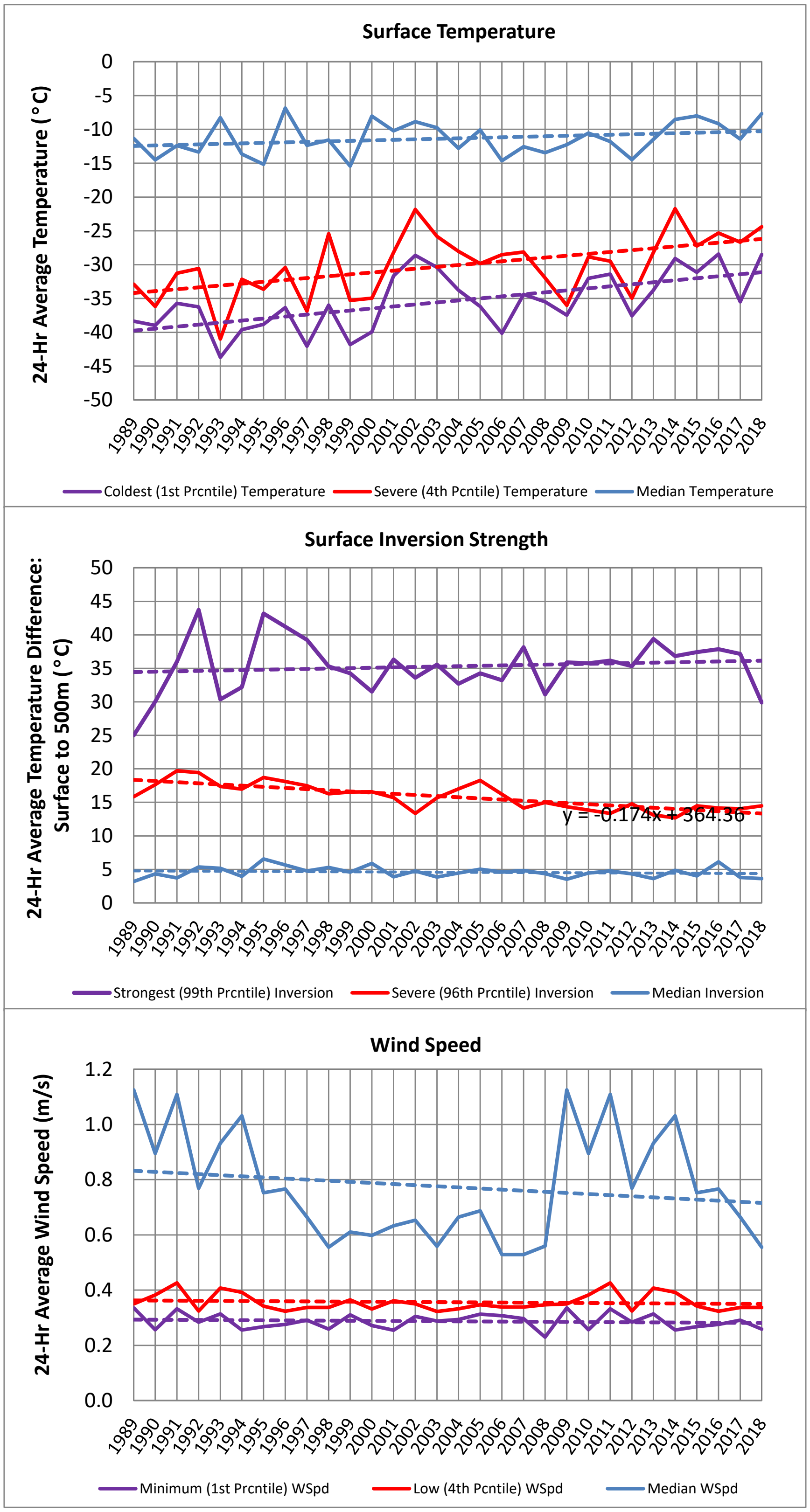
From the results of the analysis, it is clear that year-to-year variations in meteorology are not a primary determinant of trends in the DVs and are not responsible for the reduction in DVs that has occurred over time. Instead, control measures (such as the Borough's Wood Stove Change Out Program and the Curtailment Program) and wood use shifts triggered by heating oil prices have led to lower emissions over this period.

The meteorological trends observed in this analysis are consistent with the qualitative observations of Borough air quality staff on how the weather has changed over the past 10 years. Specifically, they report that winter temperatures are generally milder than in the decades before. But very cold temperatures can still occur accompanied by very strong surface inversions, just as in earlier decades. However, the occurrence of severe conditions is less frequent than before and, when it does occur, the episodes do not last as long. This assessment by Borough staff is supported and amplified by recent, independent work on long-term trends in Alaska meteorology by the Alaska Center for Climate Assessment and Policy[9].

The analysis conducted for this report includes the long-term baseline of meteorology for the FAI airport that was developed in the 2012 work for the Moderate SIP. While not used in this analysis to score meteorology for severity, it does provide an assessment of how the key meteorological drivers of $PM_{2.5}$ concentrations have changed over the last 30 years. Figure 7 shows these trends for Fairbanks based on the meteorology at FAI with the surface temperatures and winds adjusted to better estimate conditions at the NCore monitoring site. In this, the worst-case conditions (1st or 99th percentiles) have been added to the severe conditions (4th or 96th percentiles) and median conditions found in the earlier Figures 3 and 6. The surface inversion strength is measured as the temperature difference between the surface and 500m to permit use of the older radiosonde data with its reduced resolution of conditions very near the surface in comparison to GPS radiosonde that came into use in late 2009.

[9] Thoman, R. *Fairbanks' Changing Environment: Planning for the Future*. Presented to the Alaska Sustainability Commission by the Alaska Center for Climate Assessment and Policy. March 13, 2019.

Figure 7. Long-term Trends in Meteorological Drivers of $PM_{2.5}$ Concentrations in Fairbanks



The most striking trend in the figure is the consistent, long-term warming of surface temperatures. Median winter temperatures have trended upward through the period, but the warming is most evident for the colder temperatures that occur. The coldest (1st percentile) temperature has warmed by 9°C since 1989 and the severe (4th percentile) temperature has warmed by 8°C. The trends for surface temperatures over the past decade are simply a continuation of the longer-term trends.

The Borough experiences the strongest surface inversions of any city in the United States and this has not changed much over the past 30 years. The strongest inversions (1st percentile) have not changed in strength over time nor has there been appreciable change in the median inversion strength. The severe inversion strength (96th percentile) has weakened (warmed) by 5°C since 1989 as estimated by these data. These trends support the assessment given by Borough personnel—that historically severe conditions still occur, but less frequently than before and in episodes that do not last as long.

The trends for wind speed add little to this picture. On a median basis, wind speeds show a modest downward trend in the data. However, there have been a number of changes in measurement methods over the past 30 years and it is difficult to assess the internal consistency of the data. True, pressure-driven winds are seldom present when $PM_{2.5}$ concentrations are elevated in the winter. Instead, gravity-driven drainage flows provide the predominant source of air flow in these conditions. Drainage flows during otherwise calm conditions were estimated for this analysis from algorithms developed for the Alert Model. The values estimated for the minimum (1st percentile) and low (4th percentile) wind speeds change very little over the period.

State planning efforts for the Serious SIP have taken place within the context of a long-term warming trend in Fairbanks and the surrounding Arctic region. The meteorology that has occurred in the past 10 years reflects a continuation of these long-term trends and is neither aberrant nor unusual in this context.

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