PM$_{2.5}$ Forecasting: Preliminary Results

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Where is the Ozone Season Summary?


Where was the Ozone?
Where Was the Ozone?

In the Philadelphia metropolitan area, we observed only 7 days with 8-hour $O_3$ concentrations above the Code Orange standard and no Code Red days at all.

$O_3$ forecasts were good. 6 of 7 Code Orange days were correctly forecast. On the missed forecast, the only monitor in the MARAMA region that reached the threshold was Collier’s Mills, NJ.

No “false alarms” of Code Red were issued and only 2 for Code Orange (in one false alarm case, Case Code Red was observed in the Baltimore-Washington area).

Why have we had two very mild $O_3$ seasons in a row?
Temperatures during the summer (JJA) of 2004 were even colder than the summer of 2003.

Light blue areas represent the 5th-33rd percentile of average temperature for the period 1971-2000.
The summer of 2003 was quite wet and almost equaled by the summer of 2004. Note the enhanced rainfall to our west as well.

Dark blue regions represent the 95th percentile for precipitation based on ~ the last 30 years (1971-2000)
The cool and wet weather – not conducive to photochemistry – was driven by a persistent upper level low over the Great Lakes.

Image at right shows the change from normal in upper level height (~ pressure) during the summer of 2004.

The area downwind (east) of low pressure usually experiences unsettled (wet) weather with frequent frontal passages and periodic bursts of maritime tropical air.
While upper level (850 mb) temperatures were not far from normal (right panel), winds varied strongly from normal with unusually strong onshore winds (left panel).

When warm temperatures did occur, they were accompanied by south to southeasterly winds bringing maritime tropical air (clean) to the region.
Instead of O$_3$, PM$_{2.5}$ forecasting will be today’s topic

Routine PM$_{2.5}$ forecasting began in the Philadelphia metropolitan area in October, 2003.

Forecasts are issued on weekdays (Monday-Friday) with a three-day Weekend Outlook issued on Friday valid through Monday. Daily forecasts were issued during the O$_3$ season.

Forecasts are issued to the public as color codes similar to O$_3$, but there is no provision currently for Action Days based on PM$_{2.5}$.

Objective (statistical) forecast tools were provided by MARAMA via a contract with SAI. The forecast tool utilized the Classification and Regression Tree (CART) approach.
Verification of PM$_{2.5}$ Forecasts

Verification of PM$_{2.5}$ forecasts is not a straight forward exercise.

FRM observations require considerable analysis so that QA’d data is only available for October, 2003 through March, 2004. Partial data is available through June, 2004.

Results here are reported through June, 2004 and cover only the Philadelphia area (excluding northern DE and northeast MD) unless otherwise stated.

Forecast results are reported for the 24-hour (weekday) forecasts unless otherwise noted. The objective (CART) forecast tool was only used for those forecasts.
Even when quality assured FRM measurements are available, difficult verification issues remain. Although there are a large number of PM$_{2.5}$ monitors (FRM) in the northeastern US (left panel), the majority report only every third day. The daily FRM monitors (bottom panel) are less numerous. This inconsistency in data collection frequency may introduce problems for accurate verification of forecasts.
When we report mid-Atlantic PM$_{2.5}$ concentrations, the area used in that analysis is shown below.
The question is whether the sample containing the third day collection, with many monitors reporting, can be considered the same, for statistical purposes, as the sample with fewer monitors.

**Problem:** The magnitude of peak PM$_{2.5}$ is affected by the frequency of data collection. Higher peak concentrations are observed on the high frequency (“third day”) collection days.
Results of Statistical Tests on mid-Atlantic PM$_{2.5}$

Daily mean PM$_{2.5}$ concentrations in the mid-Atlantic Corridor are not significantly different for the two samples (every third day and 1-2 day collection).

Maximum PM$_{2.5}$ was significantly different for the third day collection cycle. With more monitors reporting, the range of concentrations was wider and peak concentrations higher. This is likely due to better resolution of the plume of high PM$_{2.5}$.

This means that any results of PM$_{2.5}$ forecast verification, based on peak local PM$_{2.5}$ concentrations, must be viewed with some skepticism. But, we move on………………..
PM$_{2.5}$ Forecast Results - Philadelphia

Increasing scatter with increasing concentrations points to key forecast shortcoming.

N = 155

$[\text{PM}_{2.5}]_{\text{obs}} = 4.85 + 0.71[\text{PM}_{2.5}]_{\text{fcst}}$

$r = 0.73$

$r^2 = 0.53$
Forecast Errors - Philadelphia

Next-day forecasts:

N = 153  
(All values in µgm⁻³)

**Forecast:**  16.0 ± 8.1  median = 13.0  
**FRM:**  16.5 ± 8.9  median = 14.5  
**TEOM:**  16.8 ± 8.2  median = 15.2

**Mean Absolute Forecast Error:**  4.7 ± 5.2 µgm⁻³

**Median Absolute Error:**  3.6 µgm⁻³

**rms Error:**  7.0 µgm⁻³

**Improvement over Persistence:**  53%
Forecast Results - Philadelphia

For next day forecasts, the correct color code was issued in 77% of the cases.

Of the missed codes, about half (47%) were cases where the observed PM$_{2.5}$ was in the range of 12-18 µgm$^{-3}$. As a result, ~ 12% of the cases posed large forecast error issues.

Only one Code Orange case was observed during the next day forecast dataset and was forecast moderate.

Four false alarms of Code Orange were issued, two were close calls (observed PM$_{2.5}$ 32.0-39.5 µgm$^{-3}$, two not so close (22-26 µgm$^{-3}$). Clearly, we need better forecast guidance in the high PM$_{2.5}$ cases.
Objective forecast guidance is provided by a statistical method called Classification and Regression Tree (CART). This method groups similar cases (similar weather conditions mainly) into small clusters and assigns a color code based on the average behavior of cases within the cluster.

CART results are adequate. For the Philadelphia area, CART predicted the proper color code on 72% of cases. Consensus forecasts, CART guidance modified by the forecaster, did better, with a 78% correct code rate.

The CART approach did not do well in the high end of the distribution although the sample size is too small right now to reach any conclusions.
CART Background

CART forecasts will cluster cases into Code Orange clusters (or nodes) in two situations:

1. **Hot Cases**: Hot weather is necessary but not sufficient for Code Orange PM$_{2.5}$. $T_{\text{max}} > 33^\circ \text{C}$ accounts for most of the summer season cases but only 26% of “hot” days are Code Orange.

   Within the group of hot cases, Code Orange PM$_{2.5}$ is likely if there is also pre-existing moderate PM$_{2.5}$ and moist air (RH > 55%). Stagnation is not required. This is typically, but not always, a high O$_3$ scenario as well.

2. **Strong Inversion Cases**: The strength of the inversion is based on temperature differences between the surface and 900 mb (~1 km). Within the inversion cases, Code Orange is likely if conditions are also stagnant, moist (RH > 69%) and cool overnight ($T_{\text{min}} < 47 \text{ F}$). Inversions can be based at different levels, and can be “missed” by the algorithm. This occurred in a high PM$_{2.5}$ event in October, 2003.
Because the Camden TEOM was not available for the initial part of the forecast season, we made use of regional TEOM monitors as a measure of local PM$_{2.5}$ in real-time.

Peak concentrations were determined from these monitors:

- Old Town, MD
- Killens Pond, DE
- Arendtsville, PA
- New Brunswick, NJ
- Annandale, VA
- McMillan, DC

### TEOM vs. FRM

<table>
<thead>
<tr>
<th></th>
<th>15.7 ± 7.7 µgm$^{-3}$</th>
<th>15.5 ± 7.6 µgm$^{-3}$</th>
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<tbody>
<tr>
<td>PHL FRM Maximum (microg/m$^3$)</td>
<td>50</td>
<td>50</td>
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**TEOM**

15.7 ± 7.7 µgm$^{-3}$

**FRM**

15.5 ± 7.6 µgm$^{-3}$

\[
[\text{PM}_{2.5}]_{\text{FRM}} = 3.72 + 0.74[\text{PM}_{2.5}]_{\text{TEOM}}
\]

**Note:** Bias increases to -2.7 µgm$^{-3}$ for “third day” cases.
Camden TEOM Results

The Camden TEOM, once online, was consistent with FRM observations

\[ n = 117 \]

\[ \text{[PM}_{2.5}\text{]}_{\text{FRM}} = 6.84 + 0.63\text{[PM}_{2.5}\text{]}_{\text{TEOM}} \]

\[ r = 0.73 \]

\[ r^2 = 0.53 \]
Summer Season PM$_{2.5}$ Episodes

Summer season PM$_{2.5}$ episodes tend to occur in concert with high O$_3$ episodes although there are exceptions.

Regional PM$_{2.5}$ is a significant fraction of local PM$_{2.5}$ during these episodes.

The transport pattern associated with high PM$_{2.5}$ is roughly similar to O$_3$.

The timing of peak PM$_{2.5}$ during an episode is often significantly different than peak O$_3$ and tends to be sensitive both to transport regimes and to available low level moisture.
Summer Season PM$_{2.5}$ Concentrations are Correlated with Peak 8-hour O$_3$

Results at right shown for the Baltimore metropolitan area for 1999-2002

[PM$_{2.5}$$] = 0.29[O_3] - 2.8
Regional PM$_{2.5}$ is a Significant Fraction of Local Peak PM$_{2.5}$

The diurnal two-peak ("rush hour") pattern is not present during the highest 90$^{th}$ percentile cases. This has implications for the magnitude of regional impacts on local PM$_{2.5}$. 
Transport Patterns for High PM$_{2.5}$ Cases are Quite Similar to High O$_3$ Cases

Data from the 1999 NEOPS field program in Philadelphia shows that the transport pattern associated with high PM$_{2.5}$ concentrations (left panel) is similar to that for the highest O$_3$ cases (1999-2001).
Summer season PM$_{2.5}$ in the mid-Atlantic Corridor is dominated by sulfate.

With large sulfate sources locally and west of the Appalachians, we expect both stagnant and westerly transport patterns to favor high PM$_{2.5}$ concentrations.

Data from Fort Meade, courtesy Antony Chen, UMCP
PM$_{2.5}$ and O$_3$ episodes share common weather features, but the timing of maximum concentrations for each pollutant differ both on the daily and episodic scale. Here is an example from 2003.
O₃ concentrations fall on June 28 as convection develops ahead of a frontal boundary. PM₂.₅ drops only after the front passes.
Summer Season $O_3$ and PM$_{2.5}$ Episode
June 26-28, 2001

Large scale weather features consistent with “standard” $O_3$ episode. Broad upper level ridge with surface high pressure centered west of PHL.
Code Red $\text{O}_3$ is observed early in the episode on June 26 (left panel) in stagnant weather conditions (right panel).
Onset of High $O_3$

Profiler from Fort Meade shows variable winds through depth of boundary layer
Hourly PM$_{2.5}$ measurement from Old Town (right panel) show concentrations falling during the mid-day hours when downward mixing is at its peak. The regional load is only $\sim 10$ µgm$^{-3}$.
O$_3$ Concentrations Remain High on June 27, PM$_{2.5}$ Rises to the Upper Moderate Range

Surface high pressure (left) remains stalled in place. Western O$_3$ monitors (right) show a rising regional O$_3$ load (60-80 ppbv).
On June 28 a weak disturbance crosses the northern mid-Atlantic. As the disturbance passes to the north, winds increase and veer northerly. A subtle difference but critical for $O_3$ concentrations.
$O_3$ concentrations fall regionwide as stagnation ends
On June 28, the PM$_{2.5}$ diurnal pattern changes abruptly (left panel) with enhanced PM$_{2.5}$ during the afternoon hours. Regional PM$_{2.5}$ load increases from ~ 25 to 45 µg/m$^3$. 
The peak of an $O_3$ episode generally occurs with a ridge solidly in place over the eastern US and the highest moisture (shaded oval) located well west of the region.
As high pressure drifts east and allows Gulf of Mexico moisture to spread over the eastern US, PM$_{2.5}$ concentrations increase and remain high. Processing of gases to particles is very efficient in a moist air mass and the transport pattern assures a large supply of sulfur compounds.
Previous research has shown that, in the winter season, sulfur compounds form a smaller fraction of total PM$_{2.5}$ in the eastern United States.

Lower insolation and humidity during winter months depress both homogeneous and heterogeneous reactions that produce secondary sulfate particles.

Particulate nitrate production, however, is favored under cool, moist conditions and makes up a larger fraction of total PM$_{2.5}$.

In the mid-Atlantic region, the ratio of nitrate to sulfate is very low (0.1 or less) in the summer months but is significantly higher in the winter months (0.5 or greater) – IMPROVE data.
Winter PM$_{2.5}$ Episodes Have a Different Diurnal Pattern

Old Town, Maryland (1999-2002)

The diurnal pattern at Old Town for winter season cases is different from the overall 90$^{th}$ percentile cases. The higher morning and slightly lower mid-day concentrations suggest a stronger local scale contribution.
Winter season high PM$_{2.5}$ events tend to occur in weather patterns favoring stagnant near-surface winds, increasing moisture and a strong low level inversion.
Winter Season Episodes Characterized by Strong Inversion and Re-circulation with Increasing Moisture

The morning sounding (left panel) shows a remarkably strong low level inversion with a plume of moisture evident in the lower levels as well.
PM$_{2.5}$ Concentrations are High Region Wide

PM$_{2.5}$ concentrations are high region-wide and continue on the following day with the onset of fog and rain.
Winter Season Event: February 9-10, 2000

Surface pattern similar to previous case. Again, high pressure overhead, coupled with an area of low pressure developing offshore. Offshore low adds moisture and enhances re-circulation effects.
Winter Season Event – February, 2000

The combination of westerly transport, with re-circulation late (left panel) and strong low level inversions (right panel) lead to high PM2.5.
Again, the key features include a developing offshore low that provides re-circulation and increased moisture.
Similar pattern with offshore low driving recirculation. In this case, however, inversion weaker so statistical forecast fails.
PM$_{2.5}$ Episode: October 8-10, 2003
Peak Concentration Occur with Recirculation

**October 9**
PHL PM$_{2.5}$ rises further to 39 $\mu$gm$^{-3}$

**October 10**
PHL PM$_{2.5}$ to 41 $\mu$gm$^{-3}$, regional TEOMs in the 28-46 $\mu$gm$^{-3}$ range.
1. PM$_{2.5}$ forecasts are reasonably accurate:
   - 77% correct code
   - ~ 12% bad forecasts

2. Range of error of forecasts is ~ 5 µgm$^{-3}$.

3. But, can’t completely trust forecast verification statistics based on peak concentrations due to FRM data frequency issues.

4. TEOM data is good enough to support operational forecasts.

5. Forecast skill in the high end of the observed distribution is not known due to paucity of high PM$_{2.5}$ cases so far.
6. Summer season PM$_{2.5}$ episodes occur generally in concert with O$_3$ episodes. Both pollutants thrive under similar weather scenarios. However, the timing or phasing of episodes can vary. PM$_{2.5}$ events frequently begin and end later.

7. Winter season PM$_{2.5}$ events may be more affected by local conditions with strong inversions and stagnation or re-circulation a critical issue.

8. Wider deployment of continuous monitors will help forecasting although siting and monitor characteristics pose challenges to use in forecasting.