The Impact of Recent Decreases in $O_3$ and PM$_{2.5}$ on Air Quality Forecasting in the Mid-Atlantic Region

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2016 MARAMA Air Quality Monitoring Workshop
December 6-8, 2016
Focus on the Coastal Plain of the Mid-Atlantic

• Analysis of monitor data trends from subset of entire Mid-Atlantic
  – All of NJ and DE; PA, MD, and VA east of I-81
  – Area bounded by the Atlantic Ocean and Appalachian Mountains

• Includes urbanized I-95 Corridor:
  – Highest population density
  – Characterized by poorest regional air quality (in general)

• Influenced by mesoscale weather features:
  – Appalachian lee troughs
  – Sea/Bay breezes
  – Summertime weak frontal boundaries

• Metropolitan trends analysis of Greater Philadelphia Area (PHL):
  – Encompasses Philadelphia-Wilmington Non-Attainment Area
“High” Pollution Days and the NAAQS

- The O₃ and PM₂.₅ National Ambient Air Quality Standards (NAAQS) have changed through the years, and so has our definition of “high” or “poor” air quality days.
- We often refer to “exceedance days” or days when O₃ or PM₂.₅ exceeded the daily NAAQS.
- This gets confusing when we look at air quality over a long period (1994-2016).
- So for this presentation, we define:
  - “High O₃” as days with 8-hour average O₃ ≥ 76 ppbv
  - “High PM₂.₅” as days with 24-hour average PM₂.₅ ≥ 35 µg/m³

<table>
<thead>
<tr>
<th>Period</th>
<th>8-Hour O₃ NAAQS (ppbv)</th>
<th>Period</th>
<th>24-Hour PM₂.₅ NAAQS (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 2015-</td>
<td>70</td>
<td></td>
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</table>
Recent Decreases in O₃ Beginning in 2013

Pre-NOx SIP
Average = 1755

Post-NOx SIP
Average = 593

New Normal
Average = 84

Great Recession 2009

Mid-Atlantic

Number of O₃ Monitors in Mid-Atlantic Above Threshold

> 76 ppbv
> 96 ppbv
> 116 ppbv

Pre-NOx SIP Average = 1755
Post-NOx SIP Average = 593
New Normal Average = 84
Recent Decreases in PM$_{2.5}$ During Summer (JJA) Beginning in 2009

Number of PM$_{2.5}$ Monitors in Mid-Atlantic Exceeding Daily PM$_{2.5}$ NAAQS (35 µg/m$^3$)

- DJF
- JJA

Mid-Atlantic

<table>
<thead>
<tr>
<th>Year</th>
<th>DJF</th>
<th>JJA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>33</td>
<td>133</td>
</tr>
<tr>
<td>2005</td>
<td>13</td>
<td>173</td>
</tr>
<tr>
<td>2006</td>
<td>14</td>
<td>106</td>
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<td>2007</td>
<td>29</td>
<td>132</td>
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<tr>
<td>2008</td>
<td>19</td>
<td>50</td>
</tr>
<tr>
<td>2009</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>2010</td>
<td>34</td>
<td>9</td>
</tr>
<tr>
<td>2011</td>
<td>2</td>
<td>6</td>
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<tr>
<td>2012</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>2013</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>2014</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Recent Decreases in O₃ and PM₂.₅ Not Driven Primarily by Fluctuations in Summertime Weather

Number of Days with $T_{max} \geq 90$ °F at KPHL
Temperature and Precipitation vs. High O₃
May 1 to Sept 30

Average Number of Days

<table>
<thead>
<tr>
<th>Condition</th>
<th>1997-2002 Pre-NOx SIP</th>
<th>2003-2012 Post-NOx SIP</th>
<th>2013-2016 New Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmax ≥ 90 °F</td>
<td>27</td>
<td>27</td>
<td>31</td>
</tr>
<tr>
<td>Measureable Precipitation</td>
<td>45</td>
<td>52</td>
<td>47</td>
</tr>
<tr>
<td>O3 ≥ 76 ppbv</td>
<td>53</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

KPHL
Wind Rose for 850 mb Winds (12 UTC) at KIAD for Tmax ≥ 84 °F at KPHL, May 1 to Sept 30

Overall wind direction distribution on hot days is similar for post-NOx SIP period (2005-2007 and 2010-2012) and new normal period (2013-2016)
Composite Mean 850 mb Vector Winds During “Heat Waves” in PHL

Heat wave: 3 or more consecutive days with $T_{\text{max}} \geq 90$ °F at KPHL

Transport aloft at 850 mb is similar – westerly from Ohio River Valley – with similar westward extension of Bermuda High for heat waves during post-NOx SIP period and new normal period.
Summary of Recent Decreases in O₃ and Summertime PM₂.₅ in the Mid-Atlantic

• Observed daily peak decreases across Mid-Atlantic:
  – Beginning in 2013 for O₃
  – Beginning in 2009 for PM₂.₅

• New, lower baseline for peak air quality across region
  – Analogous to “step-down” beginning in 2003 after implementation of NOₓ SIP rule
  – Same scale as temporary drop in O₃ observed during Great Recession year of 2009

• Fluctuations in summertime weather in 2013-2016 do not appear to be primary driver of recent decreases
  – Proven by hotter than average summers of 2015 and especially 2016

• Main driver is continued regional reductions in precursor emissions, specifically NOₓ and SO₂

• Important implications for air quality forecasting in region
Hot Weather \((T_{max} \geq 90° F)\) Is No Longer Correlated with High \(O_3\) Days

- In pre- and post-NOx SIP periods, most (50-100%) hot days were high \(O_3\) days
- In new normal period, most hot days are not high \(O_3\) days
  - Only 15% of hot days in 2016 were high \(O_3\) days
  - Aug 2016: only 3 \(O_3\) exceedances in PHL despite hottest Aug on record!
- Temperature threshold for high \(O_3\) still exists, but it is trending lower
  - Used to be ~ 85 °F
  - Now ~ 80 °F
Local Persistence Has Become Less Reliable for Predicting High O₃

- Much less (~50%) correlation with local persistence in new normal period (2013-2016)
- Fewer multi-day high O₃ events, more single day “spikes”
- Increasing incidence of high O₃ day (Code Orange) immediately following a Code Green day
  - Rare in pre-2013 period
  - Indicates very localized, rapid increase in O₃
Growing Importance of Stagnation for High $O_3$

- Much shorter back trajectories (~half as long) in new normal period compared to pre- and post-NOx SIP periods
- Much less emphasis on westerly transport from Ohio River Valley
- Local recirculation and stagnation now play more important role in high $O_3$ cases for Mid-Atlantic
Back Trajectory Comparison, 24-hr, 1000 m AGL, 96th Percentile O₃ Days in PHL

82% of trajectories ≤ 400 km  2013-2016
Expert Forecast Skill for O$_3$ Exceedance Days in
PHL Deteriorated 2013-2014

- Post-NOx SIP period:
  - High hit rate (0.72)
  - Low false alarm rate (0.28)

- 2013-2014
  - Low hit rate (0.29)
  - High false alarm rate (0.77)

- 2015-2016: leveling off, forecasters compensating for implications of precursor emissions changes

- Note that 2009 Great Recession year had low hit rate/high false alarm rate, similar to 2015-2016
Skill Scores for NOAA O₃ Model/NAQFC Also Deteriorated during 2013-2016

2007-2012 vs 2013-2016

76 ppbv threshold

Skill Score Measures

False Alarm

Hit

0.38

0.59

0.77

0.39

PHL
Increase in Seasonal Drift of NOAA O₃ Model

Since its inception, NOAA model (CMAQ) has shown seasonal drift in forecast bias:
- Large over-prediction July thru September

Magnitude of over-prediction has increased in new normal period (2013-2016)

Numerical models are struggling with effects of recent decreases in precursor emissions!
Example: 2016 NOAA Model Guidance for PHL

- Very high false alarm rate
  - 13 false alarms!!! Especially poor in July and August
- Low hit rate
  - Correctly identified only 5 exceedance days out of 14 total (71 ppbv threshold)
  - Missed first 5 exceedance days
- Strong model bias:
  - Under-predicted May-June
  - Over-predicted July-Sept

<table>
<thead>
<tr>
<th>NOAA Model</th>
<th>Late May to mid June</th>
<th>Late June thru Sept</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hits</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>False Alarms</td>
<td>1</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Missed</td>
<td>5</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>
Status of Statistical O₃ Models

• Backbone of O₃ forecast guidance prior to NOx SIP Rule
• Historically, very useful due to strong relationship b/w high O₃ and T_max (hot weather)
  – Used predictor variables such as temperature, humidity, wind speed, O₃ persistence, SZA or Julian day
• Discontinued use of statistical models ~ 2008 in PHL
  – Models trained on data from prior to 2003 no longer skillful due to O₃ reductions associated with NOx SIP Rule
• REU student updated statistical models in 2014, but used training data from 2004-2013 and 2007-2013
  – We weren’t sure yet that recent decrease in observed O₃ beginning in 2013 was “real”
• Updated models were shown to have poor skill in 2015
  – No help in identifying O₃ exceedance days
New Statistical Models for 2016

- After 3 years of historically low O$_3$ observations, we realized that another “step-down” in O$_3$ precursor emissions had likely occurred.
- Developed new set of statistical models trained on data from 2013-2015
  - Only 3 years of data: not ideal, but worth a try
- 2 models for PHL, 1 for DE
  - $T_{\text{max}}$
  - RH (15-21 UTC)
  - Surface wind speed (03-12 UTC)
  - SNP (regional) O$_3$ persistence, local O$_3$ persistence
  - 12 UTC NAQFC guidance, “lag” NAQFC guidance
- Result: very poor forecast skill (hit rate < 0.15)
- Conclusion: recent decoupling of high O$_3$ from $T_{\text{max}}$ and local persistence means statistical models now have very limited usefulness for Mid-Atlantic
Skill for 2016 O₃ Exceedance Days in PHL
(71 ppbv threshold for exceedances)

Best FAR = 0
Best Hit rate = 1

STAT = statistical models
NOAA = NOAA model/NAQFC
BAMS = Barons models
NCDENR = NC model
ENS = ensembles (unweighted averages of statistical and numerical model guidance)
Summary: O₃ Forecasting

- Forecasts can no longer rely on standard conceptual model for O₃ forecasting in Mid-Atlantic
  - Historical strong association of high O₃ with hot weather, high persistence O₃, and westerly regional scale transport has weakened considerably
- High O₃ days increasingly associated with quasi-stagnant conditions, making *mesoscale* weather features more important
- Forecast skill for high O₃ days deteriorated 2013-2016
  - Expert forecasts had spike in false alarms, drop in hits for 2013-2014, leveled off in 2015-2016 (calibrating and adjusting to new NAAQS)
  - Numerical O₃ models, including NOAA/NAQFC, showed similar deterioration in forecast skill
  - Utility of statistical models now limited because surface temperature and local O₃ persistence are no longer strong statistical predictors
- Essentially, all of our historical O₃ forecasting tools are now unreliable. What’s next? Need more accurate mesoscale models, both weather and air quality.
High PM$_{2.5}$ Days Have Essentially Disappeared from the Summer Season

- Prior to 2009, two peaks in PM$_{2.5}$ per year:
  - Summer (sulfate)
  - Winter (nitrate)
- Summer peak has disappeared!!
- Easier for forecasters!

![Graph showing decrease in PM$_{2.5}$ exceedance days from 2004-2008 to 2009-2015.](image)

<table>
<thead>
<tr>
<th>Year</th>
<th>All Days</th>
<th>Oct-April</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-2008</td>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td>2009-2015</td>
<td>50</td>
<td>30</td>
</tr>
</tbody>
</table>
IMPROVE Monitor at Shenandoah National Park, 80th Percentile PM$_{2.5}$ Days

- Ammonium sulfate, derived from SO$_2$ emissions, used to comprise $\sim$60-75% of total mass of regional PM$_{2.5}$
- Due to Acid Rain Rule regulations, reductions in SO$_2$ emissions led to big drop in sulfate component of PM$_{2.5}$ and thus total mass of highest PM$_{2.5}$ days beginning in 2009
PM$_{2.5}$ Exceedances Are Now Rare Locally and Regionally
New PM$_{2.5}$ Forecast Tool: NOAA Bias Correction

- NOAA/NAQFC PM$_{2.5}$ model (CMAQ) has known seasonal bias:
  - Under-predicts in summer (carbon aerosols)
  - Over-predicts in winter (unspecified aerosols)

- Post-process model output to correct for known bias using work of Djalalova et al., Atmos. Env., May 2015
  - Post-processing using historical analogs of hourly Kalman-filtered model output

- Compares “today’s” model output with recent analog days to correct bias

- NOAA bias correction available to forecasters as text and graphics files, Jan 1, 2016 to present
2016 PHL Observed PM$_{2.5}$ Compared to NOAA Model and NOAA Bias Corrected Guidance

3-day running average
Summary: PM$_{2.5}$ Forecasting

- Summer season peak in PM$_{2.5}$ has disappeared in Mid-Atlantic
  - Downward trend began in 2009
  - Due to continued reductions in regional SO$_2$ emissions
  - Easier for forecasters! One less thing to worry about

- Winter peak due to local nitrate continues
  - Winter PM$_{2.5}$ in the Mid-Atlantic is dominated by conversion of NO$_x$ (from combustion sources) to nitrate
  - Possible hint of downward trend in number of wintertime PM$_{2.5}$ exceedances in 2014-2015 (will need a few more years to verify)

- New Bias Correction to NOAA model guidance
  - Helps to correct known seasonal biases in CMAQ model
  - Not yet full year of data, but already guidance is useful, especially in winter months

- In general, highest summer PM$_{2.5}$ concentrations in Mid-Atlantic now associated with transported smoke from wildfires (e.g., 20s µg/m$^3$ for PHL/ILG in 2016)
Often Difficult to Forecast Impacts of Smoke

- Smoke from major wildfires can be transported long distances, sometimes 100s of km downwind, at varying altitudes.
- Wildfires are becoming more common due to widespread droughts across U.S. (e.g., California, Southeastern U.S.)
- Smoke is an issue for air quality because it contains O₃ and PM₂.₅ precursors (NOₓ and hydrocarbons) and primary PM₂.₅.
- In new normal period, some of the highest O₃ and summer PM₂.₅ cases have been associated with transported smoke.
- Most of our forecast tools are not skillful for predicting impacts of transported smoke:
  - Numerical O₃ and PM₂.₅ models: currently don’t include transported smoke in boundary conditions.
- Satellite aerosol products help to track transport of smoke plumes and to predict whether smoke will mix to surface.
Recent Examples of Transported Smoke Impacting Local Air Quality in the Mid-Atlantic

Daily PM AQI
Friday, November 25, 2016

34.7 μg/m³ PHL
31.6 μg/m³ DE
37.5 μg/m³ Susq. Valley
36.2 μg/m³ BAL
eIDEA Website: New Tool for NRT Fire & Smoke Satellite Imagery

http://www.star.nesdis.noaa.gov/smcd/spb/aq/eidea/

Currently: VIIRS polar-orbiting satellite data (1:30 PM observations)
Coming Spring 2017: GOES-16 geostationary satellite data (nearly continuous!)
VIIRS Aerosol Trajectories: Will Smoke Mix to Surface?

• Trajectories: transport of smoke plumes in next 48 hours
• Areas of high AOT (>0.4) used as starting locations
• Trajectories initialized at 50, 100, 150, and 200 mb above surface
• Trajectories run in 3-hr steps using output from NAM 12 UTC run:
  • Pink: near surface
  • White: away from surface
• 850 mb wind vectors (white)
• 3-hr accumulated precipitation (yellow)
Moving Forward: What do “Bad” Air Quality Days Look Like in the Mid-Atlantic?

• **O$_3$ (summer):**
  – Hot and sunny, limited afternoon convection, light surface winds (same as before)
  – Growing importance of stagnation and mesoscale features (recirculation, sea and bay breezes, weak frontal boundaries, Appalachian lee trough, timing and extent of convection)

• **PM$_{2.5}$ (winter):**
  – High humidity, strong surface inversion/limited vertical mixing, light surface winds (stagnation)

• **Growing importance of wildfires for transporting O$_3$ and PM$_{2.5}$ precursors and primary PM$_{2.5}$ into Mid-Atlantic**

• **Pressure is on numerical air quality models as primary forecasting tools in new emissions regime**
  – Resolution of mesoscale winds, PBL height, land/surface moisture
  – Include smoke in lateral boundary conditions?
Acknowledgements

Funding for air quality forecasts and supporting research is provided by:

- Pennsylvania Department of Environmental Protection
- Delaware Department of Natural Resources and Environmental Control

Thanks to our recent summer forecasting interns and researchers:

- Ali Catena and Lexie Herdt (2014)
- Matt Brown (2016)