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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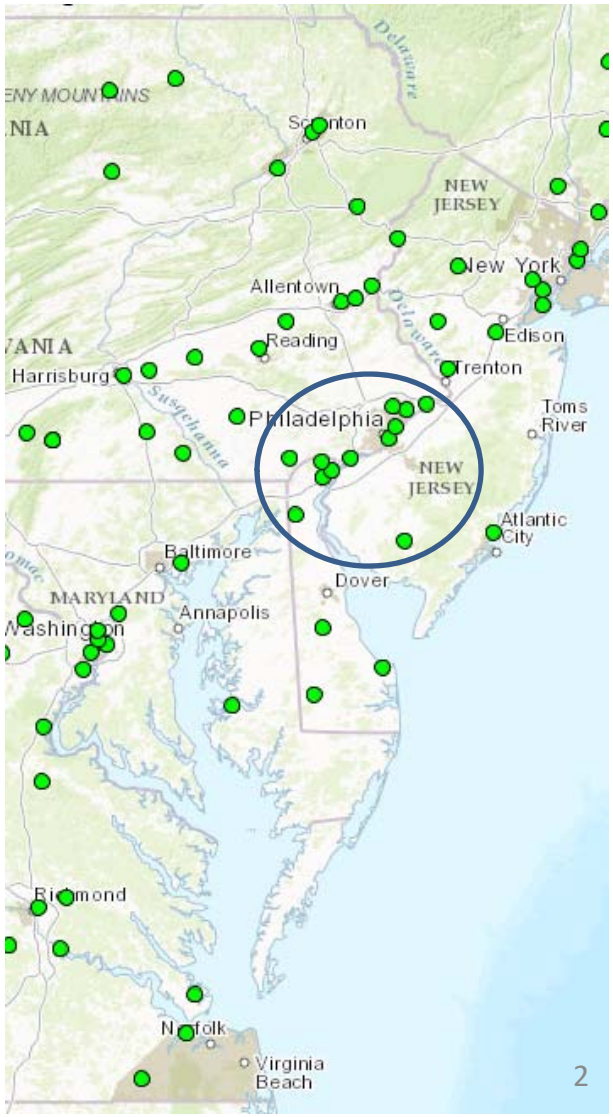
Focus on the Coastal Plain of the Mid-Atlantic

- 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



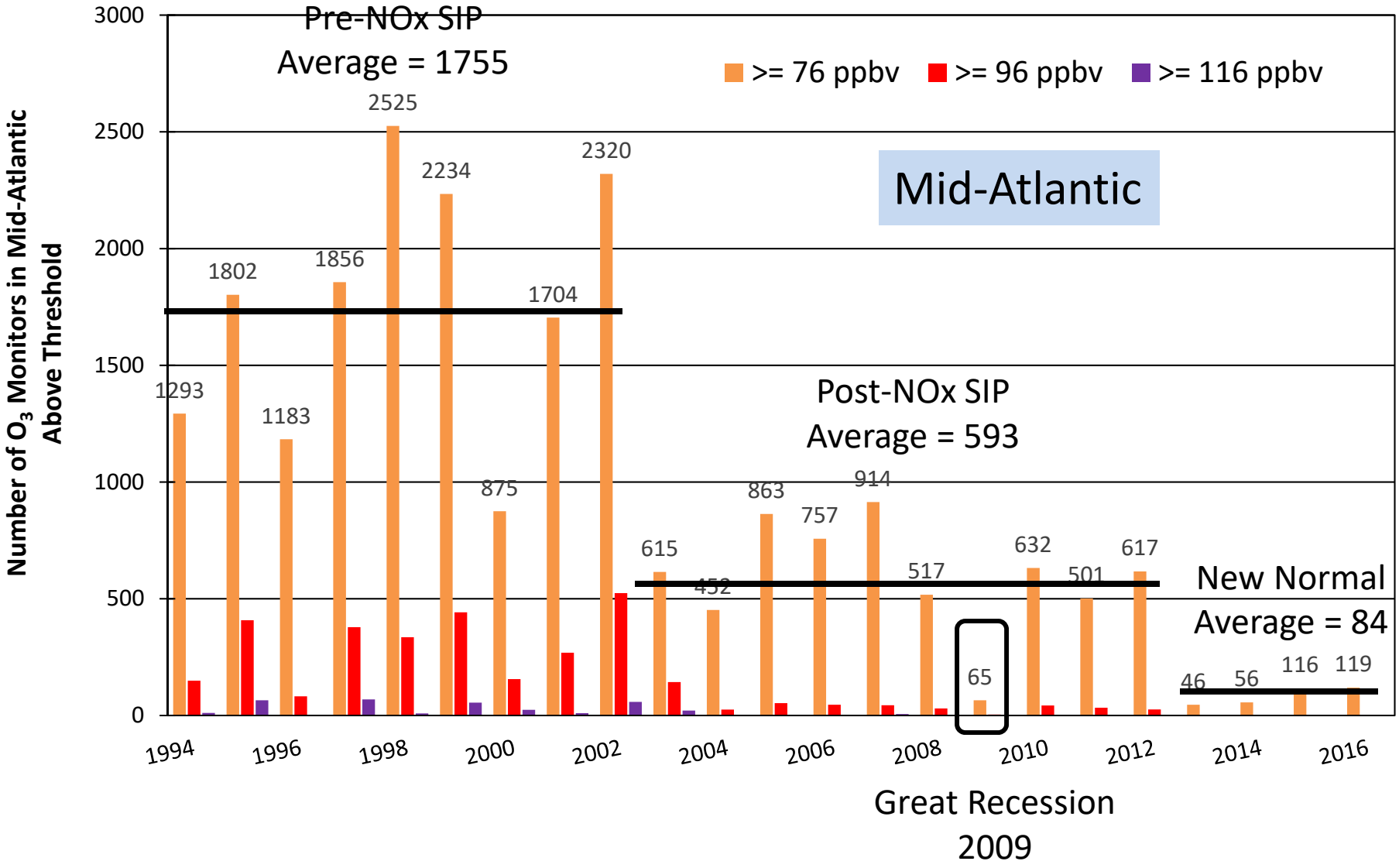
"High" Pollution Days and the NAAQS

- The O_3 and $PM_{2.5}$ 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 O_3 or $PM_{2.5}$ 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 O_3" as days with 8-hour average $O_3 \geq 76$ ppbv
  - "High $PM_{2.5}$" as days with 24-hour average $PM_{2.5} \geq 35$ $\mu g/m^3$

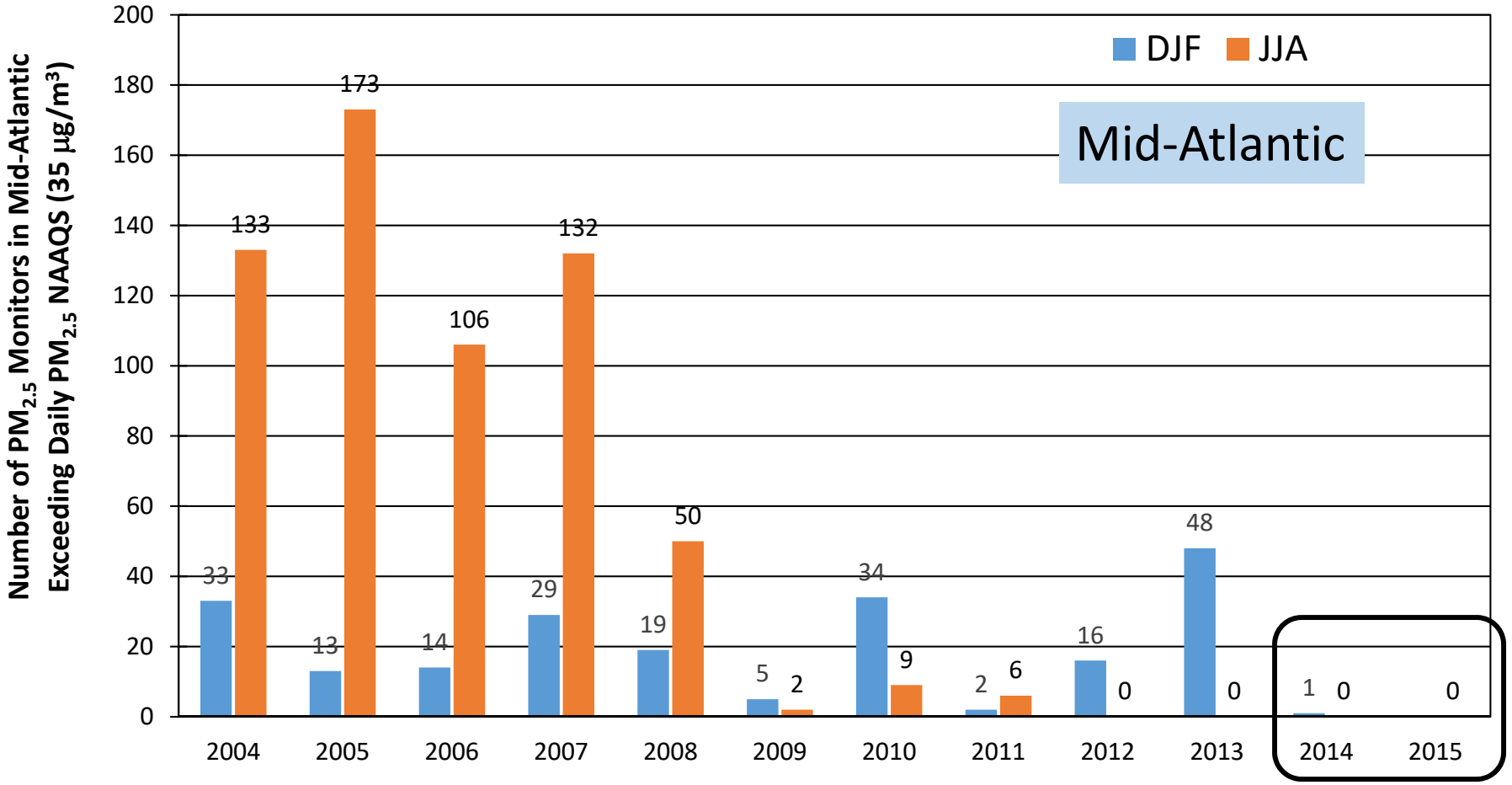
Period	8-Hour O_3 NAAQS (ppbv)
Jul 1997 - Mar 2008	80
Mar 2008 - Oct 2015	75
Oct 2015-	70

Period	24-Hour $PM_{2.5}$ NAAQS ($\mu g/m^3$)
Jul 1997 - Oct 2006	65
Oct 2006-	35

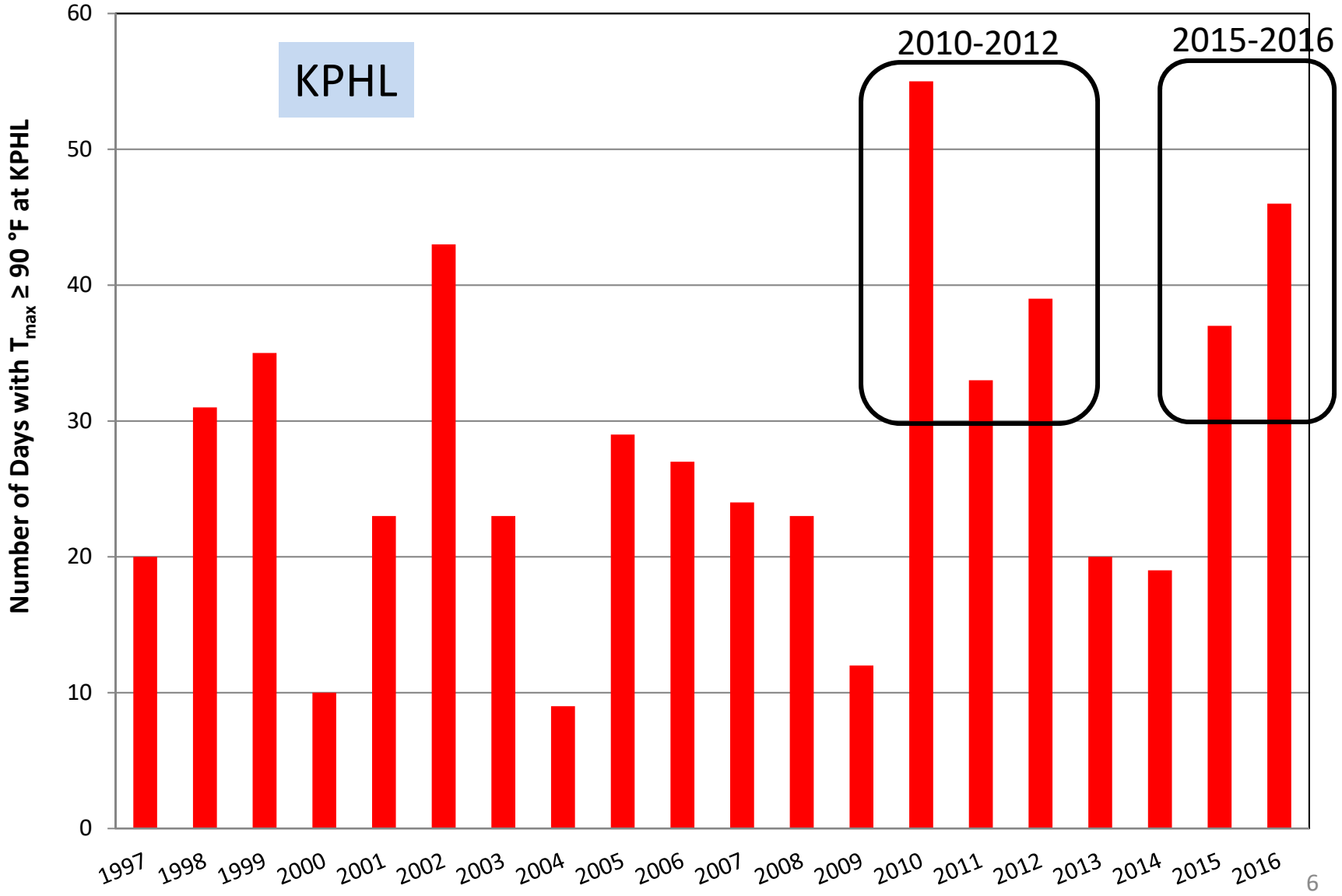
Recent Decreases in O_3 Beginning in 2013



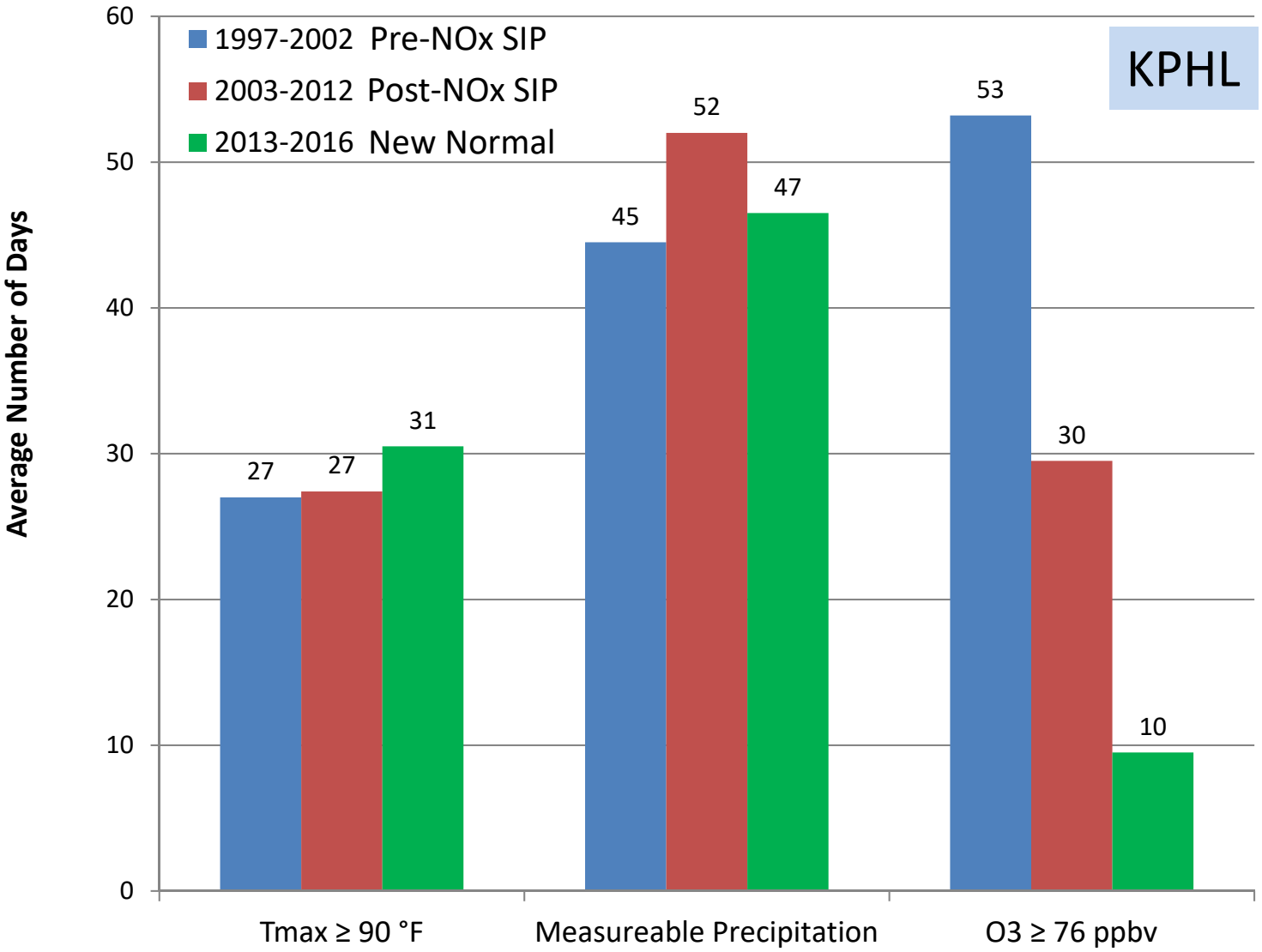
Recent Decreases in $PM_{2.5}$ During Summer (JJA) Beginning in 2009



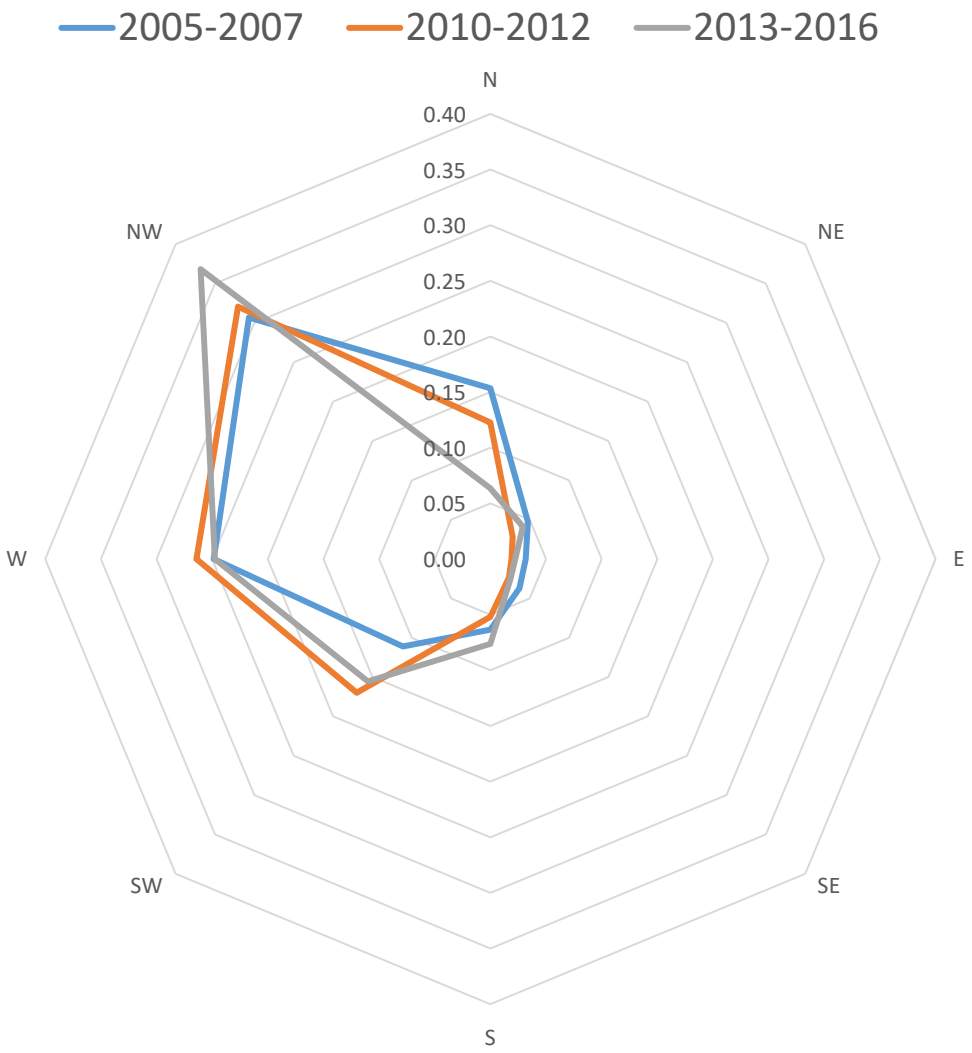
Recent Decreases in O_3 and $PM_{2.5}$ Not Driven Primarily by Fluctuations in Summertime Weather



Temperature and Precipitation vs. High O_3 May 1 to Sept 30



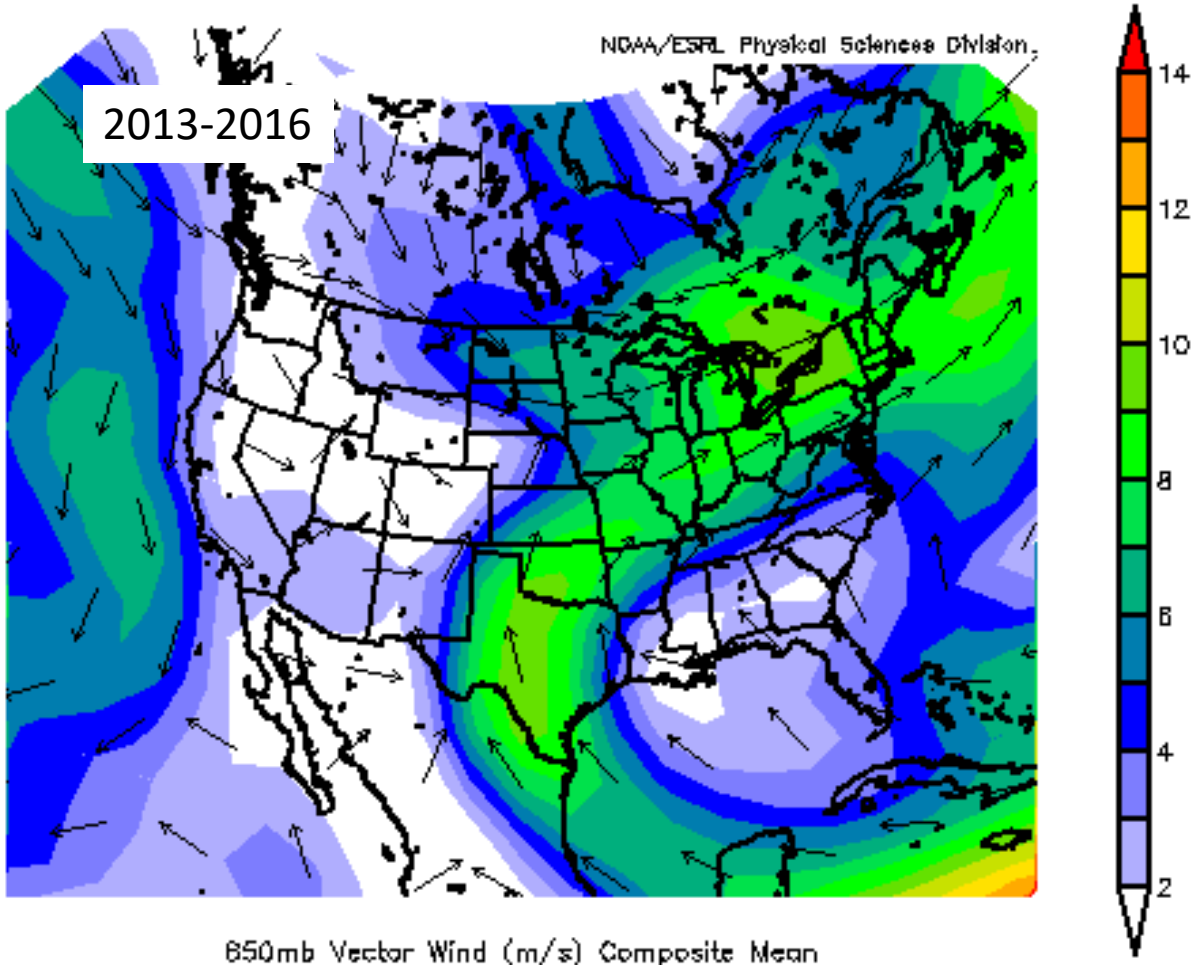
Wind Rose for 850 mb Winds (12 UTC) at KIAD for Tmax ≥ 84 °F at KPHL, May 1 to Sept 30



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 $T_{max} \geq 90$ °F at KPHL

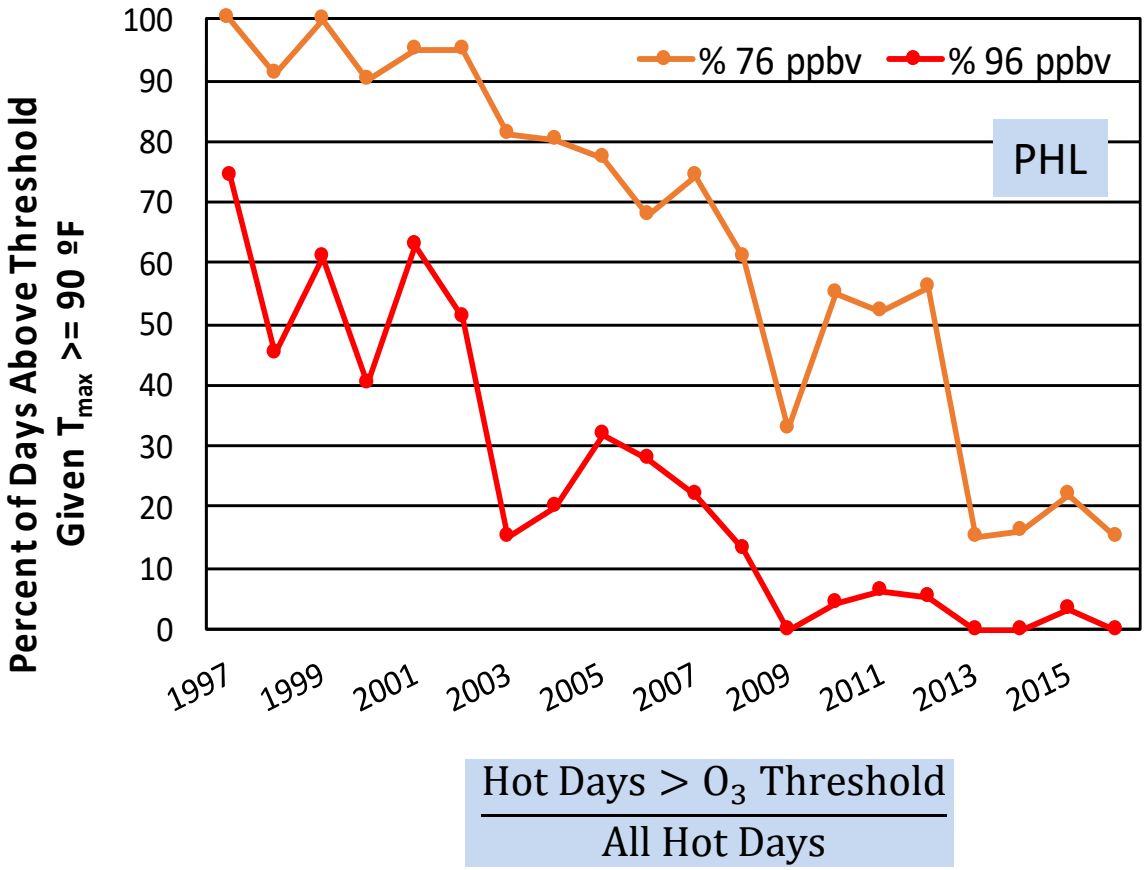


Transport aloft at 850 mb is similar – westerly from Ohio River Valley – with similar westward extension of Bermuda High for heat waves during post-NOx SIP period and new normal period

Summary of Recent Decreases in O_3 and Summertime $PM_{2.5}$ in the Mid-Atlantic

- Observed daily peak decreases across Mid-Atlantic:
  - Beginning in 2013 for O_3
  - Beginning in 2009 for $PM_{2.5}$
- 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 O_3 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 NO_x and SO_2
- Important implications for air quality forecasting in region

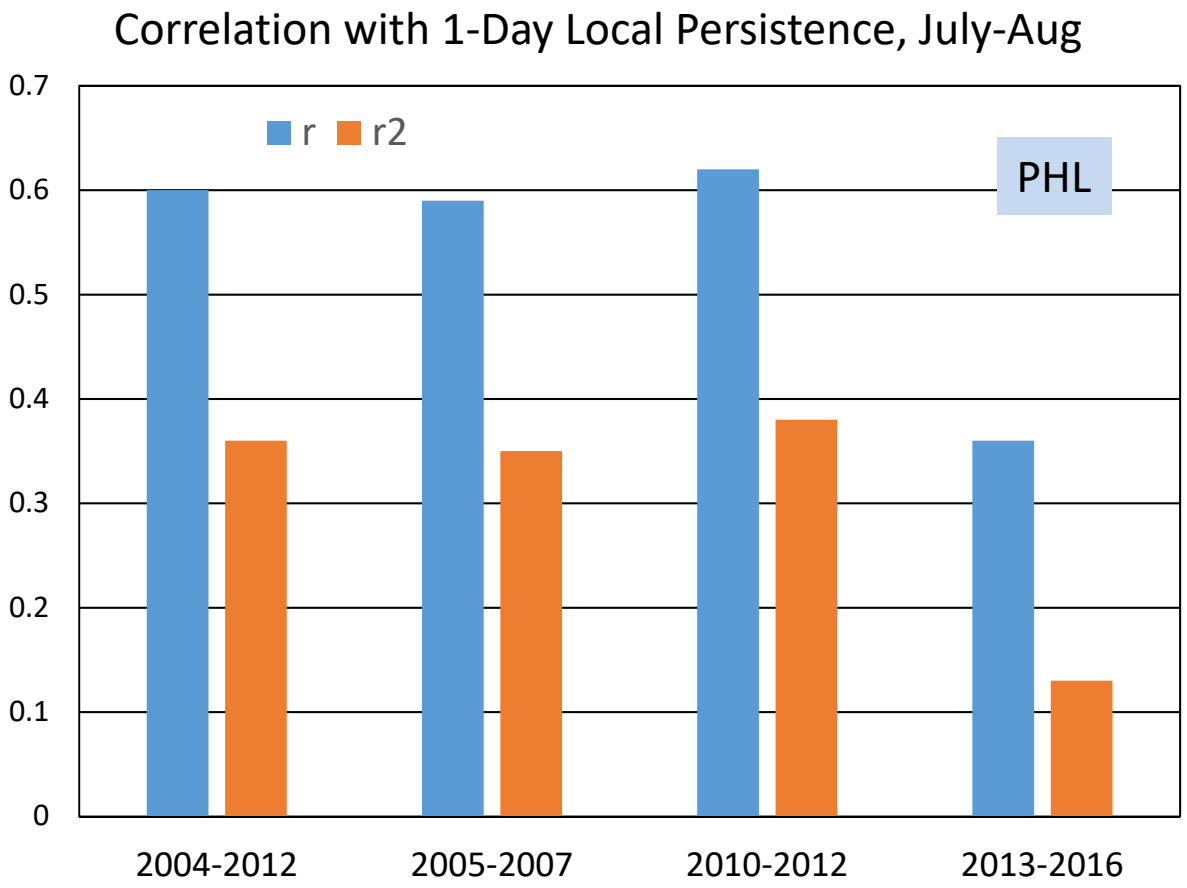
Hot Weather (T_{max} ≥ 90°F) Is No Longer Correlated with High O_3 Days



$$\frac{\text{Hot Days} > O_3 \text{ Threshold}}{\text{All Hot Days}}$$

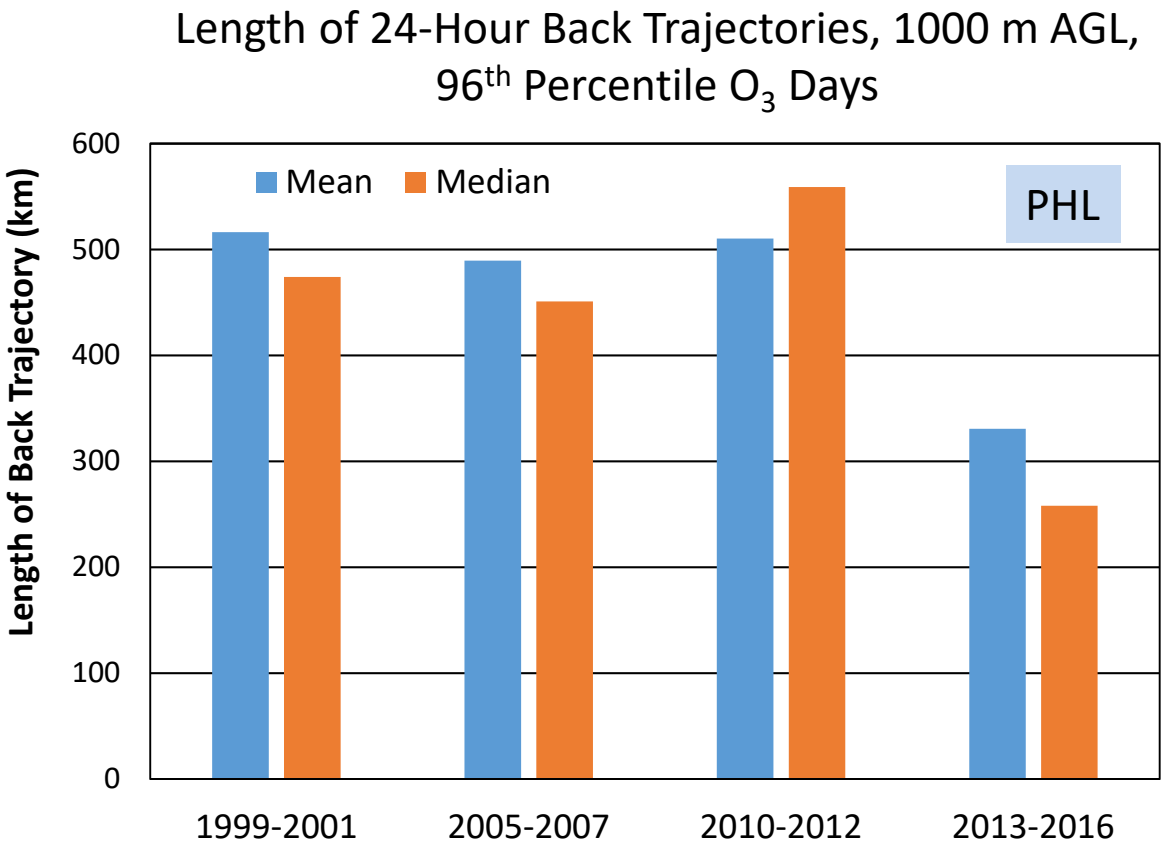
- In pre- and post-NOx SIP periods, most (50-100%) hot days were high O_3 days
- In new normal period, most hot days are <u>not</u> high O_3 days
  - Only 15% of hot days in 2016 were high O_3 days
  - Aug 2016: only 3 O_3 exceedances in PHL despite hottest Aug on record!
- Temperature threshold for 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 O_3



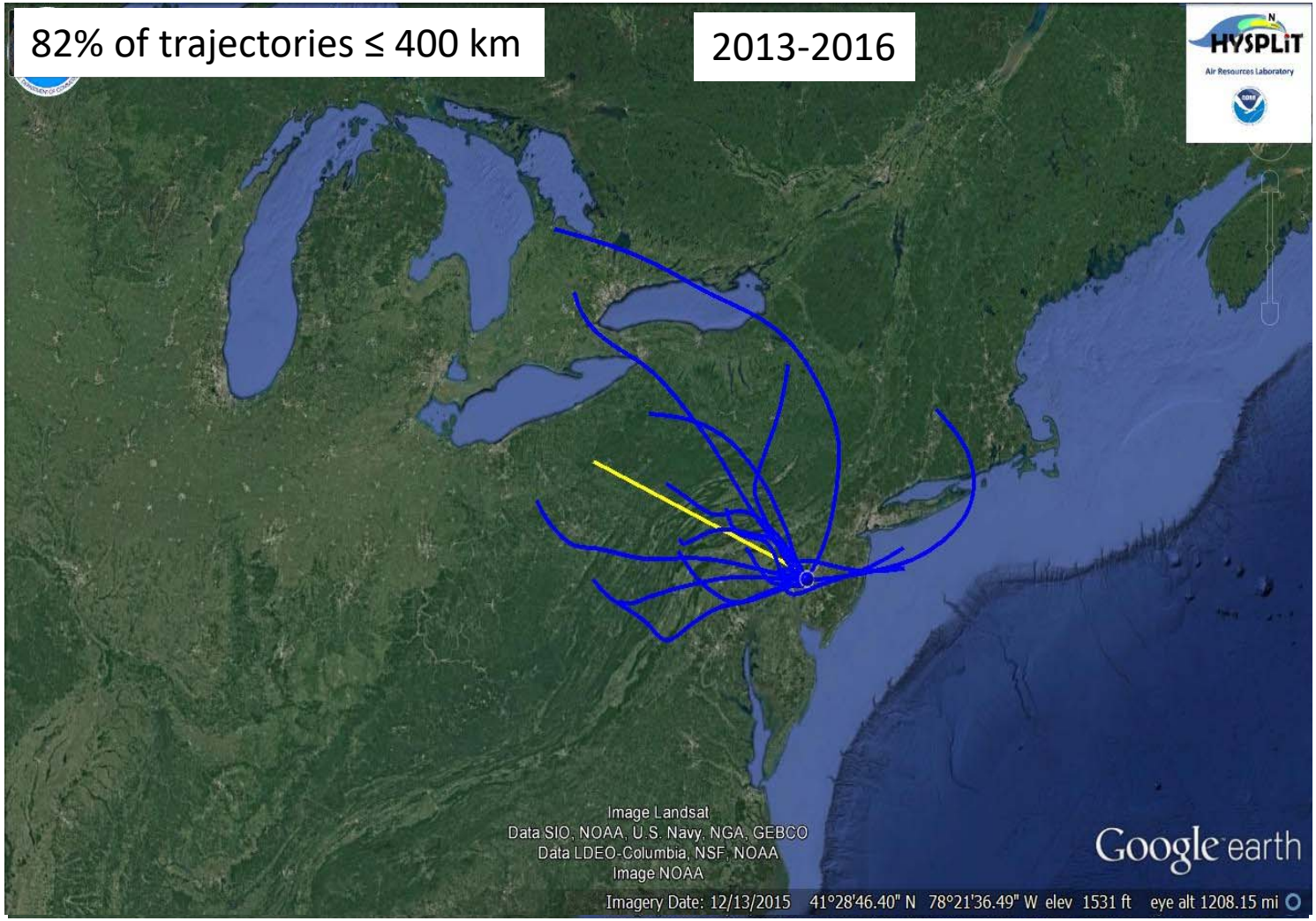
- Much less (~50%) correlation with local persistence in new normal period (2013-2016)
- Fewer multi-day high O_3 events, more single day "spikes"
- Increasing incidence of high O_3 day (Code Orange) immediately following a Code Green day
  - Rare in pre-2013 period
  - Indicates very localized, rapid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

Growing Importance of Stagnation for High O_3

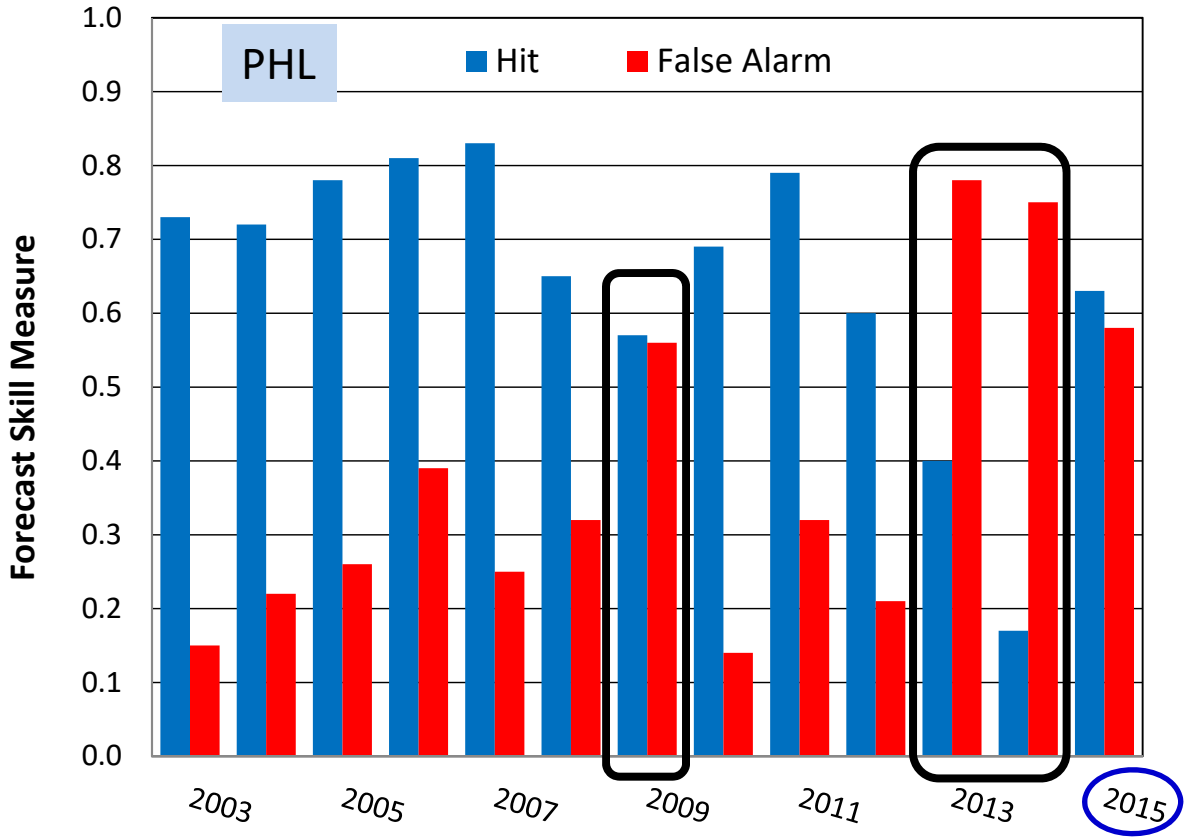


- Much shorter back trajectories (~half as long) in new normal period compared to pre- and post-NOx SIP periods
- Much less emphasis on westerly transport from Ohio River Valley
- Local recirculation and stagnation now play more important role in high O_3 cases for Mid-Atlantic

Back Trajectory Comparison, 24-hr, 1000 m AGL, 96th Percentile O_3 Days in PHL



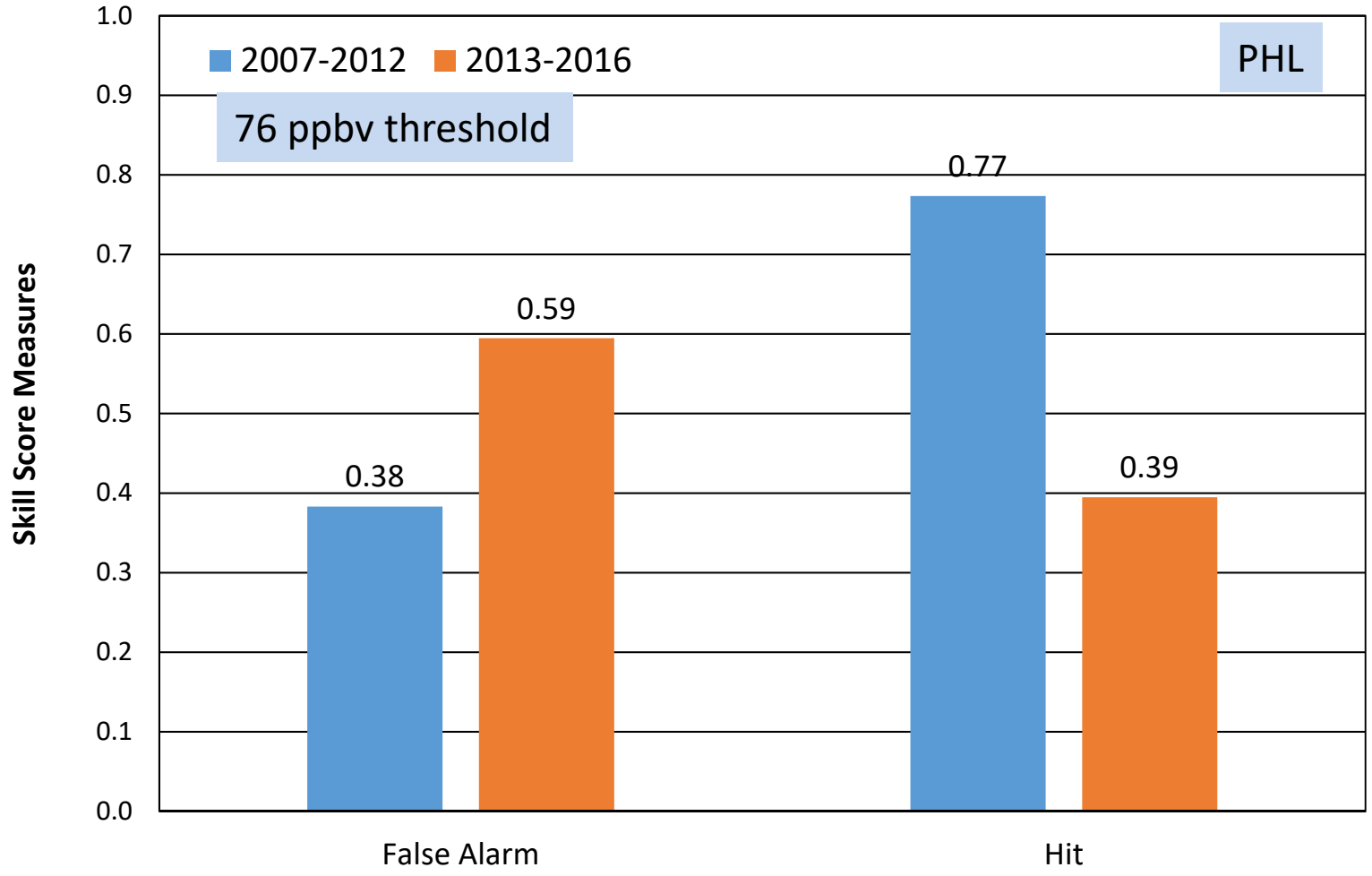
Expert Forecast Skill for O_3 Exceedance Days in PHL Deteriorated 2013-2014



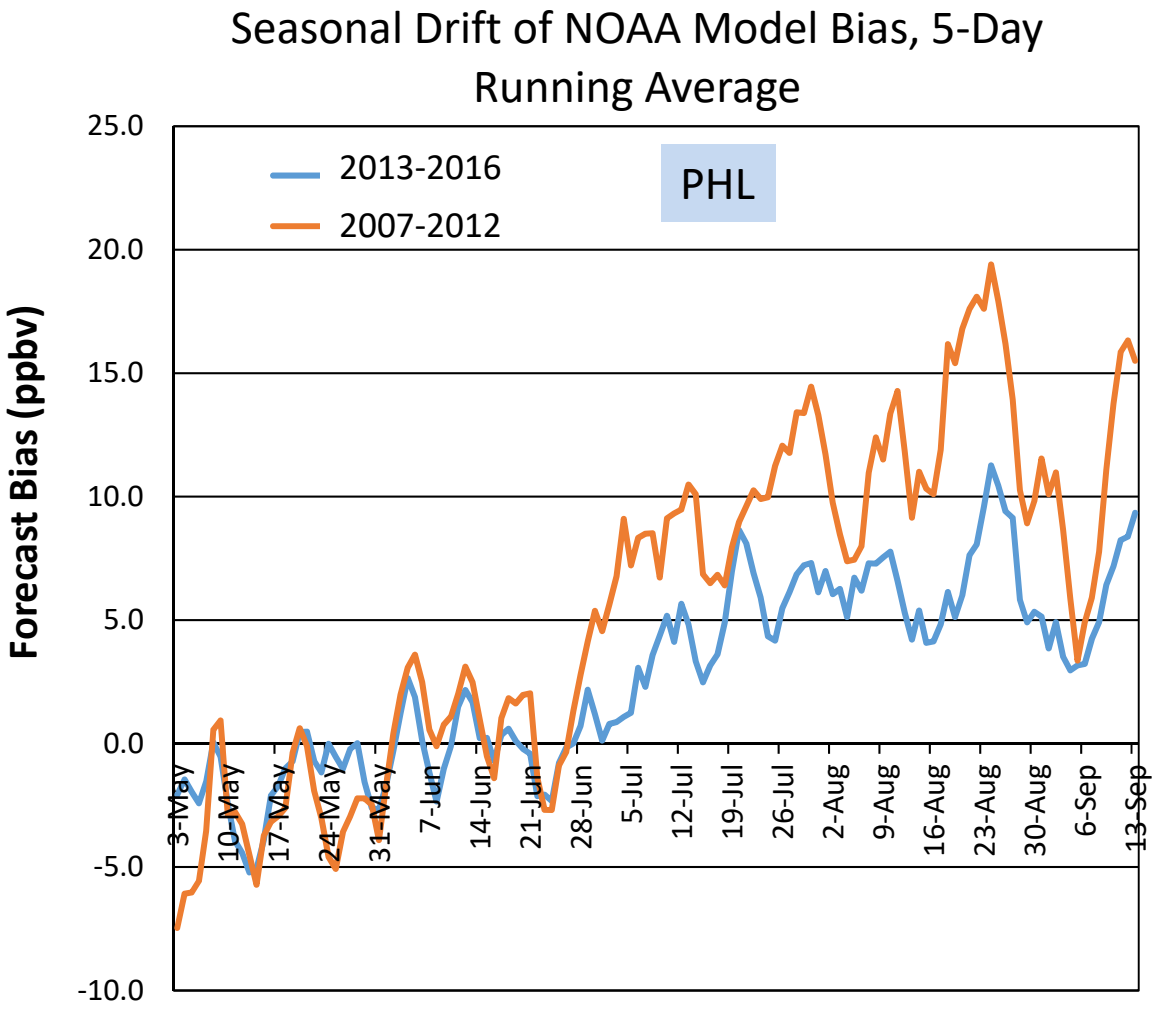
Best False Alarm rate (red) = 0
Best Hit rate (blue) = 1
76 ppbv threshold

- 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 O_3 Model/NAQFC Also Deteriorated during 2013-2016



Increase in Seasonal Drift of NOAA O_3 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

NOAA Model	Late May to mid June	Late June thru Sept	TOTAL
Hits	1	4	5
False Alarms	1	12	13
Missed	5	4	9

Status of Statistical O_3 Models

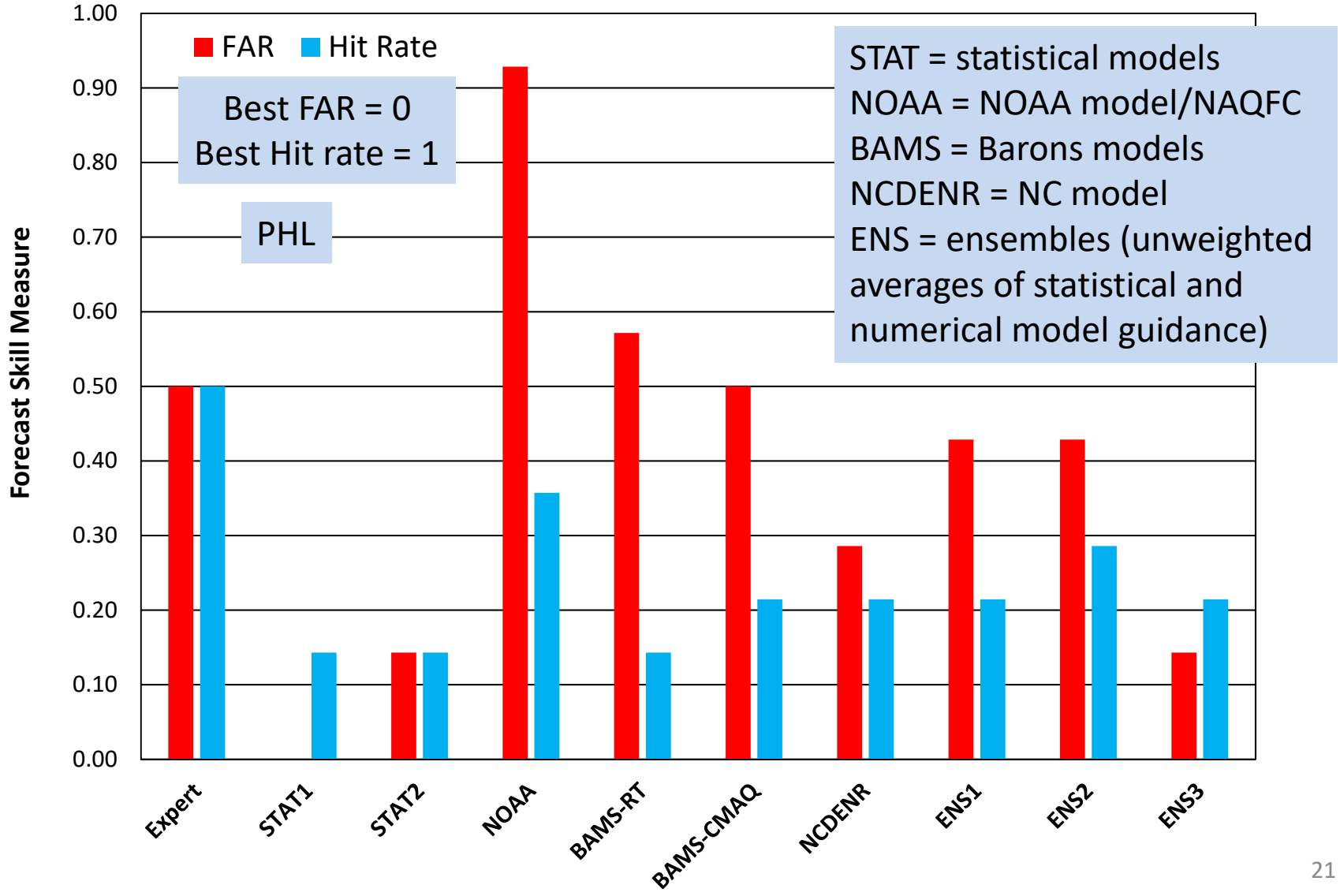
- Backbone of O_3 forecast guidance prior to NOx SIP Rule
- Historically, very useful due to strong relationship b/w high O_3 and T_{max} (hot weather)
  - Used predictor variables such as temperature, humidity, wind speed, O_3 persistence, SZA or Julian day
- Discontinued use of statistical models ~ 2008 in PHL
  - Models trained on data from prior to 2003 no longer skillful due to O_3 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 O_3 beginning in 2013 was "real"
- Updated models were shown to have poor skill in 2015
  - No help in identifying O_3 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_{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_{max} and local persistence means statistical models now have very limited usefulness for Mid-Atlantic

Skill for 2016 O_3 Exceedance Days in PHL

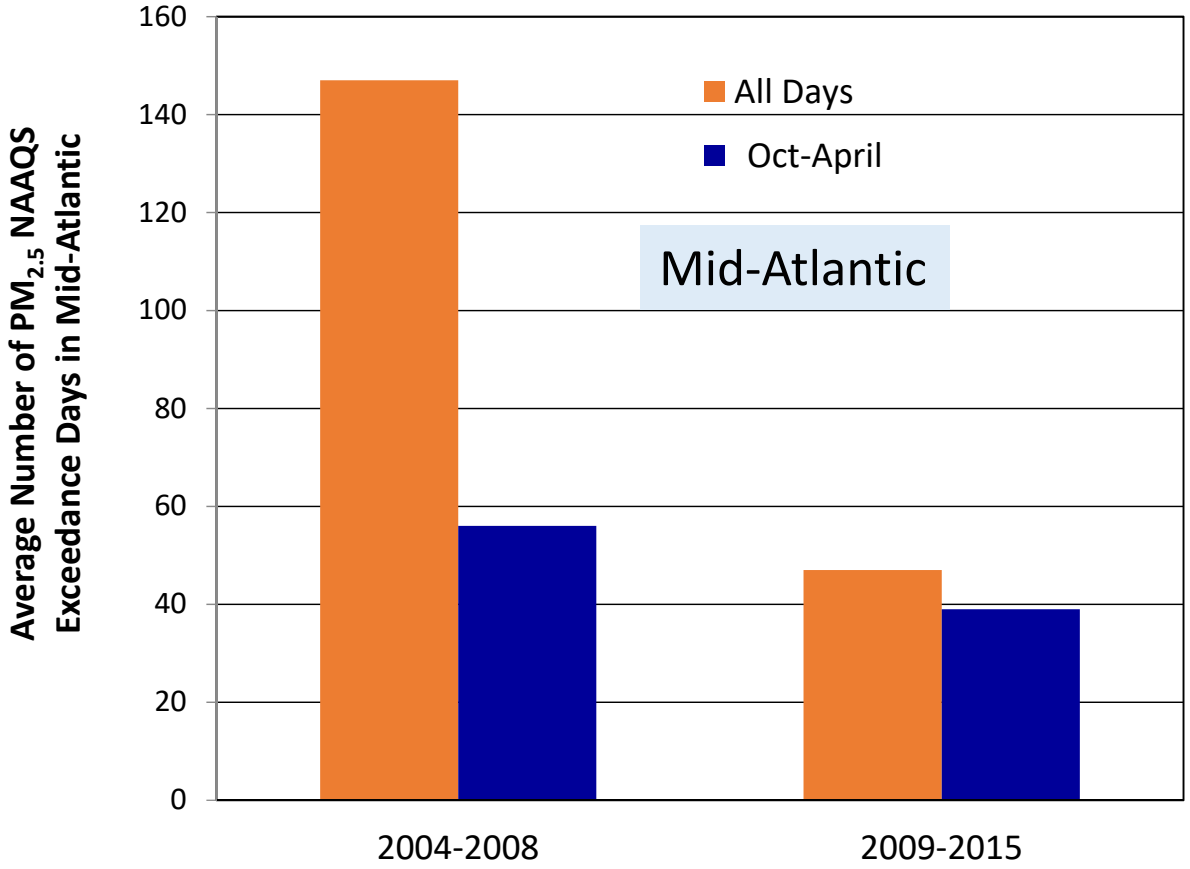
(71 ppbv threshold for exceedances)



Summary: O_3 Forecasting

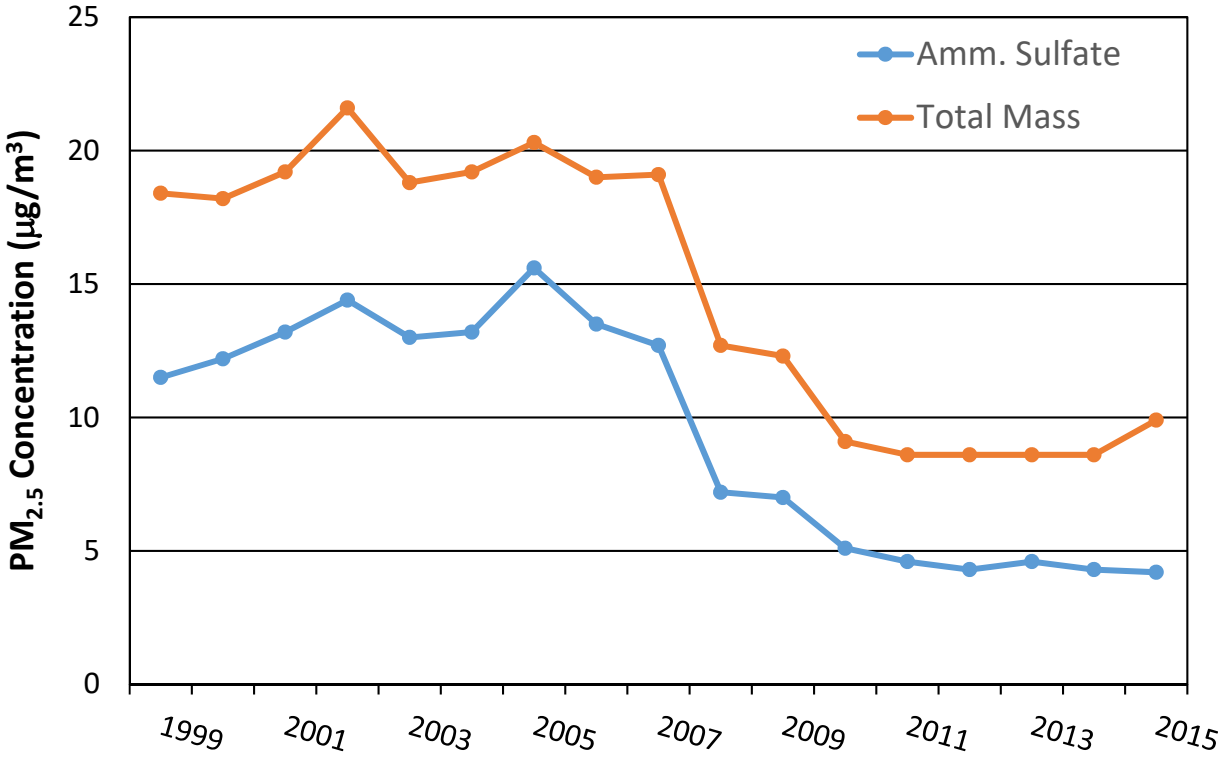
- Forecasters can no longer rely on standard conceptual model for O_3 forecasting in Mid-Atlantic
  - Historical strong association of high O_3 with hot weather, high persistence O_3, and westerly regional scale transport has weakened *considerably*
- High O_3 days increasingly associated with quasi-stagnant conditions, making *mesoscale* weather features more important
- Forecast skill for high O_3 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 O_3 models, including NOAA/NAQFC, showed similar deterioration in forecast skill
  - Utility of statistical models now limited because surface temperature and local O_3 persistence are no longer strong statistical predictors
- Essentially, all of our historical O_3 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



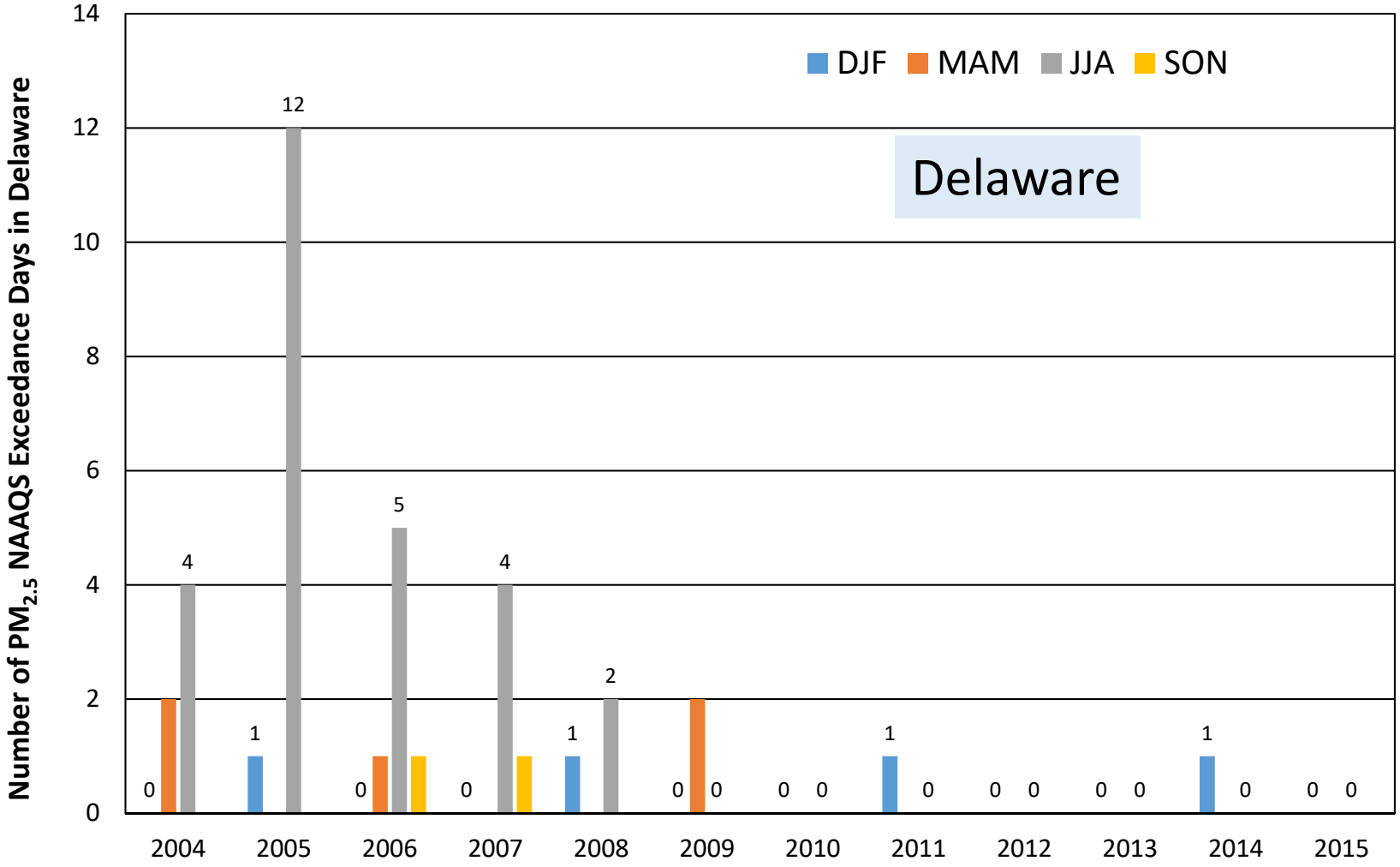
- Prior to 2009, two peaks in $PM_{2.5}$ per year:
  - Summer (sulfate)
  - Winter (nitrate)
- Summer peak has disappeared!!
- Easier for forecasters!

IMPROVE Monitor at Shenandoah National Park, 80th Percentile $PM_{2.5}$ Days

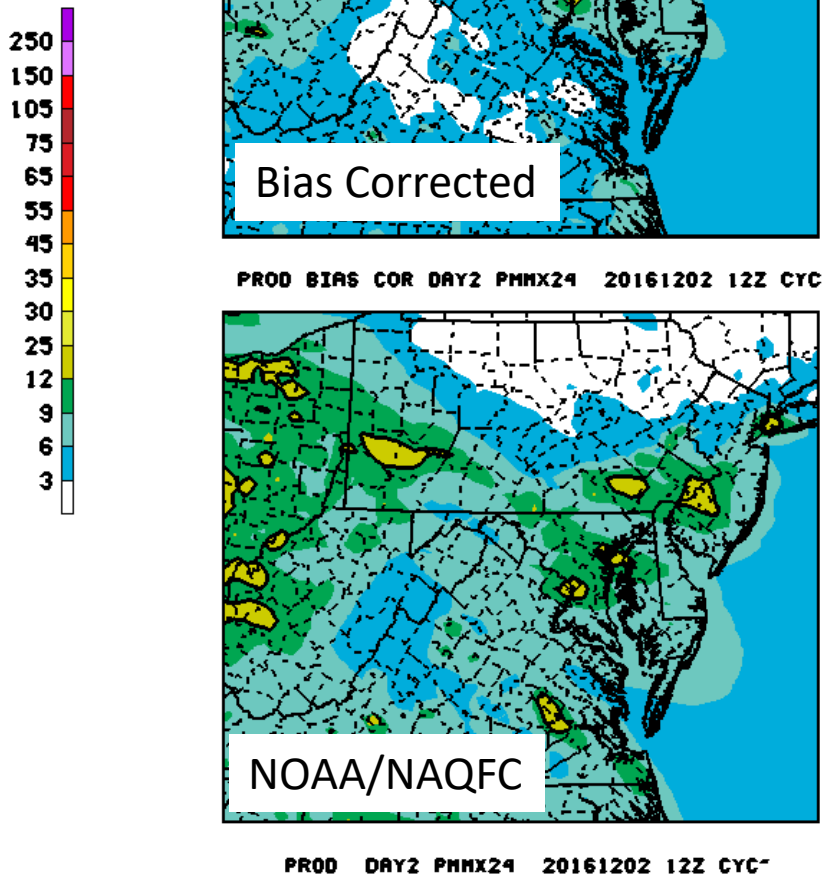


- Ammonium sulfate, derived from SO_2 emissions, used to comprise ~60-75% of total mass of regional $PM_{2.5}$
- Due to Acid Rain Rule regulations, reductions in SO_2 emissions led to big drop in sulfate component of $PM_{2.5}$ and thus total mass of highest $PM_{2.5}$ days beginning in 2009

$PM_{2.5}$ Exceedances Are Now Rare Locally and Regionally

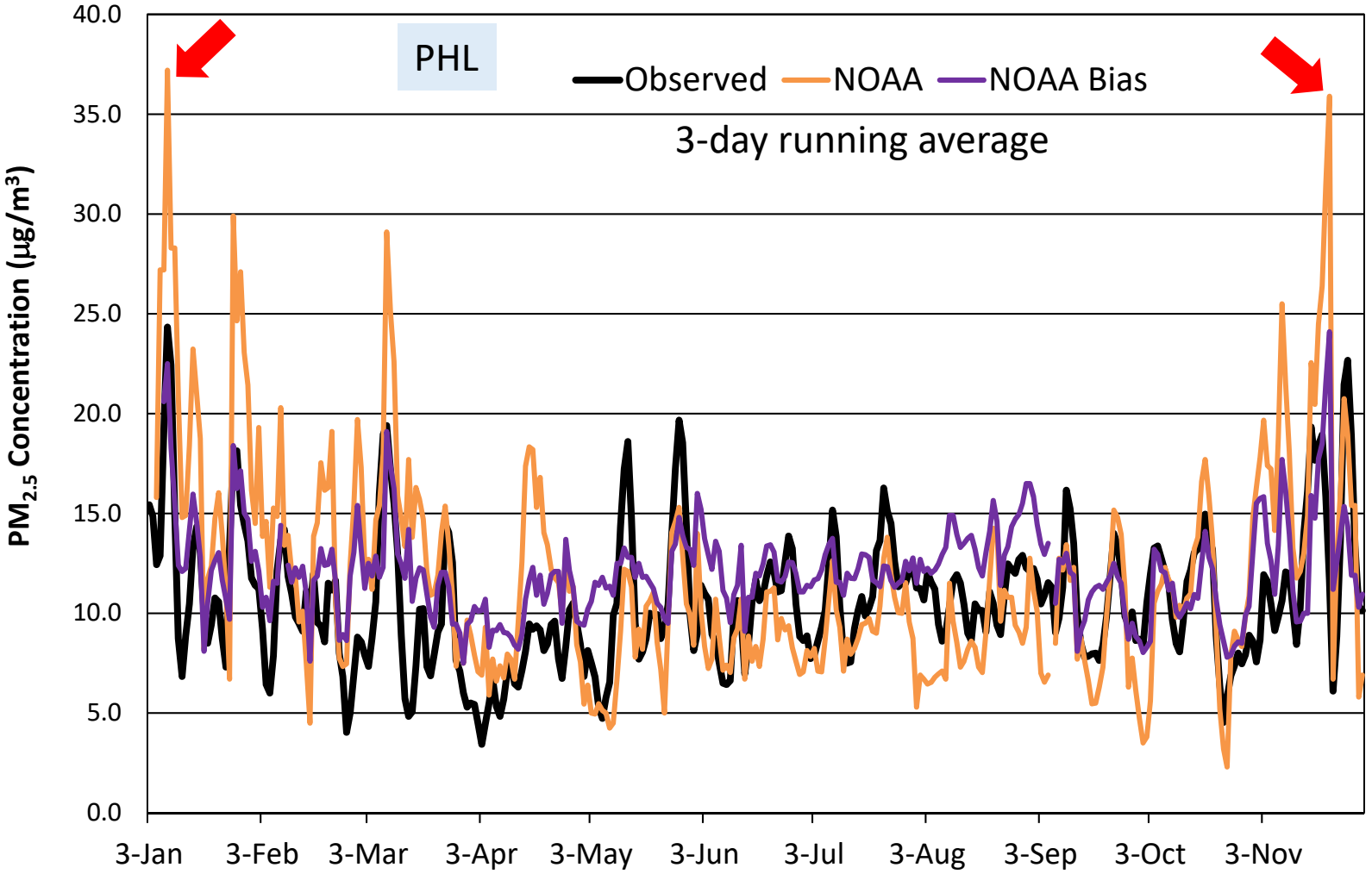


New $PM_{2.5}$ Forecast Tool: NOAA Bias Correction



- 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



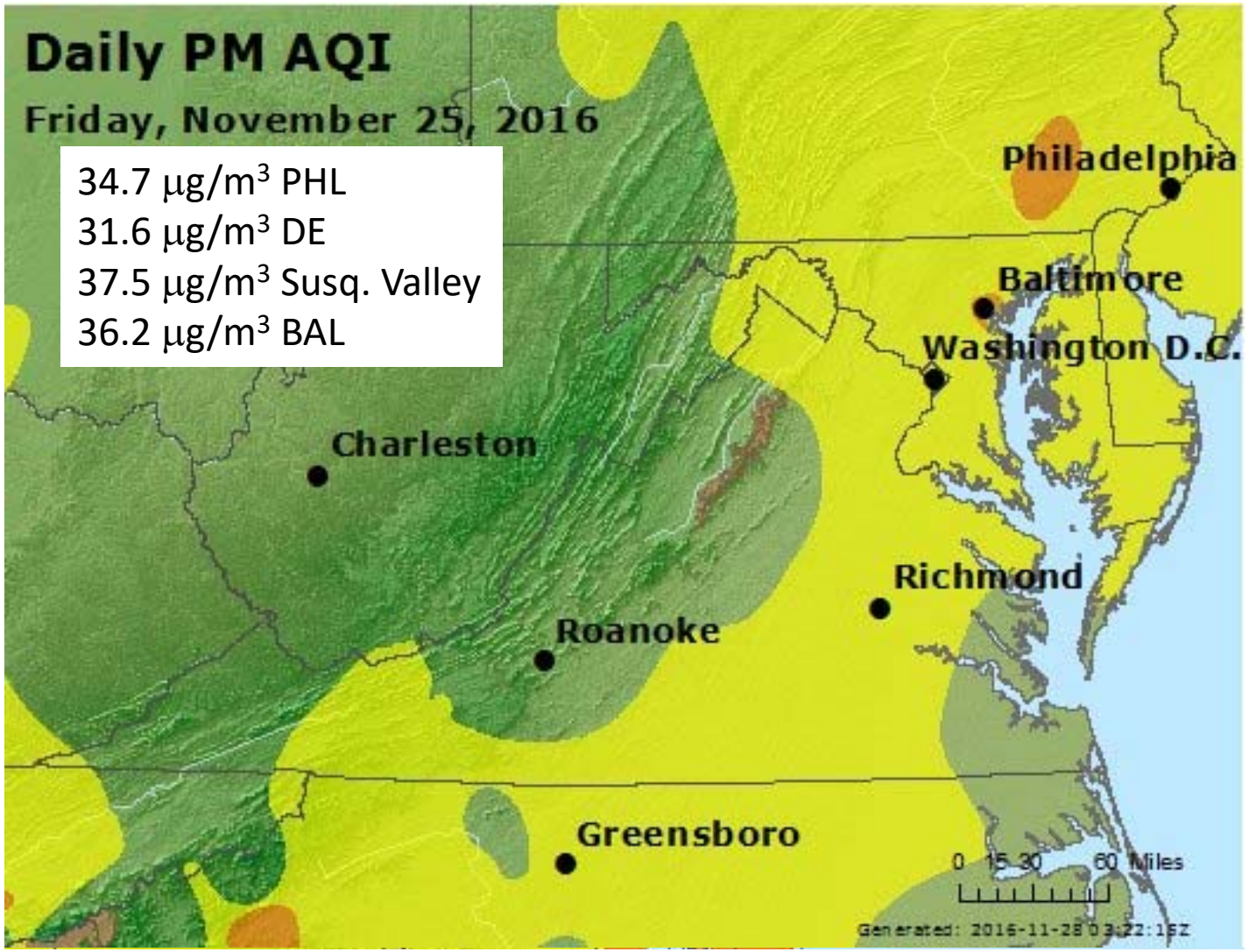
Summary: $PM_{2.5}$ Forecasting

- 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 $\mu g/m^3$ for PHL/ILG in 2016)

Often Difficult to Forecast Impacts of Smoke

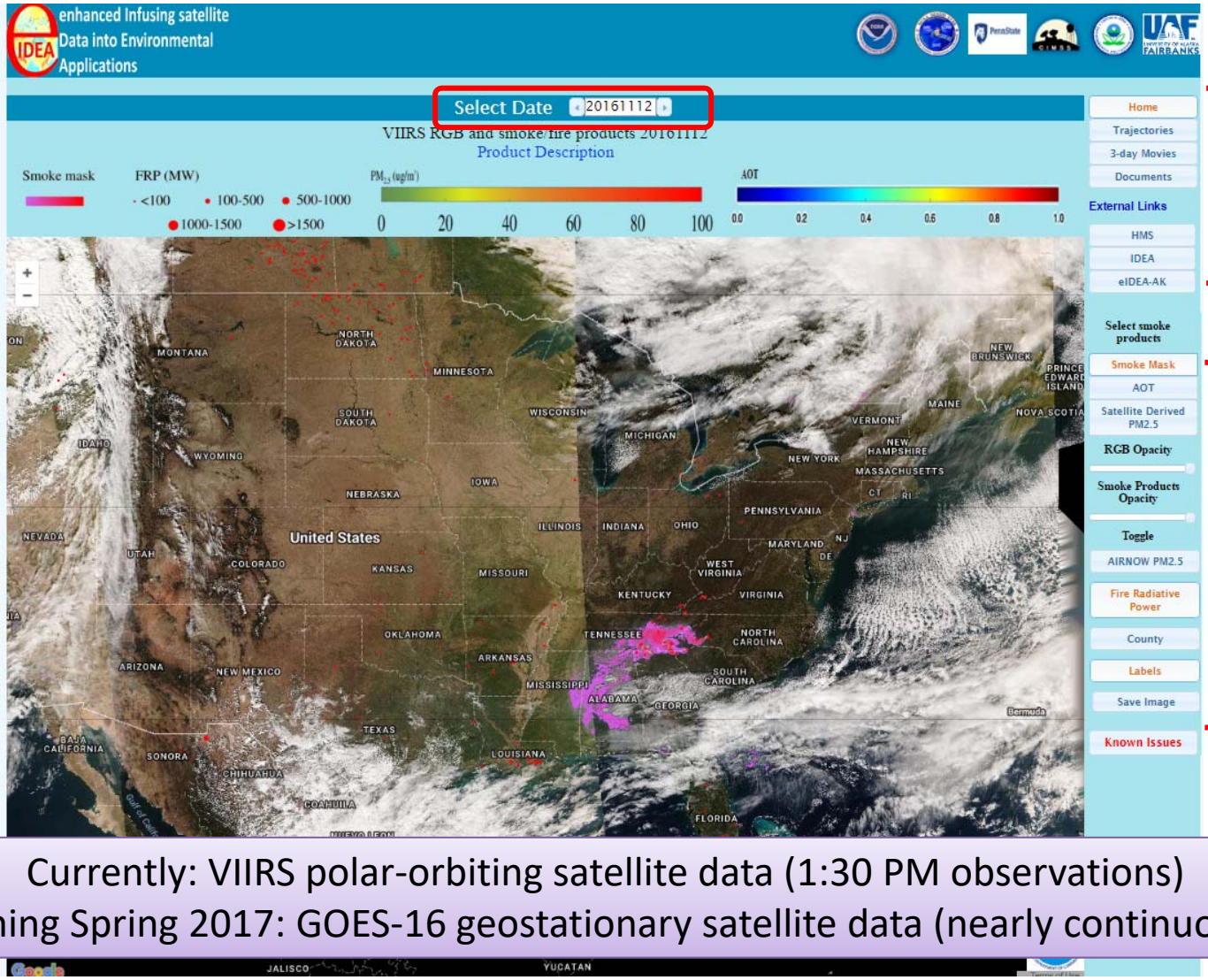
- Smoke from major wildfires can be transported long distances, sometimes 100s of km downwind, at varying altitudes
- Wildfires are becoming more common due to widespread droughts across U.S. (e.g., California, Southeastern U.S.)
- Smoke is an issue for air quality because it contains O_3 and $PM_{2.5}$ precursors (NO_x and hydrocarbons) and primary $PM_{2.5}$
- In new normal period, some of the highest O_3 and summer $PM_{2.5}$ cases have been associated with transported smoke
- Most of our forecast tools are not skillful for predicting impacts of transported smoke
  - Numerical O_3 and $PM_{2.5}$ 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



eIDEA Website: New Tool for NRT Fire & Smoke Satellite Imagery

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



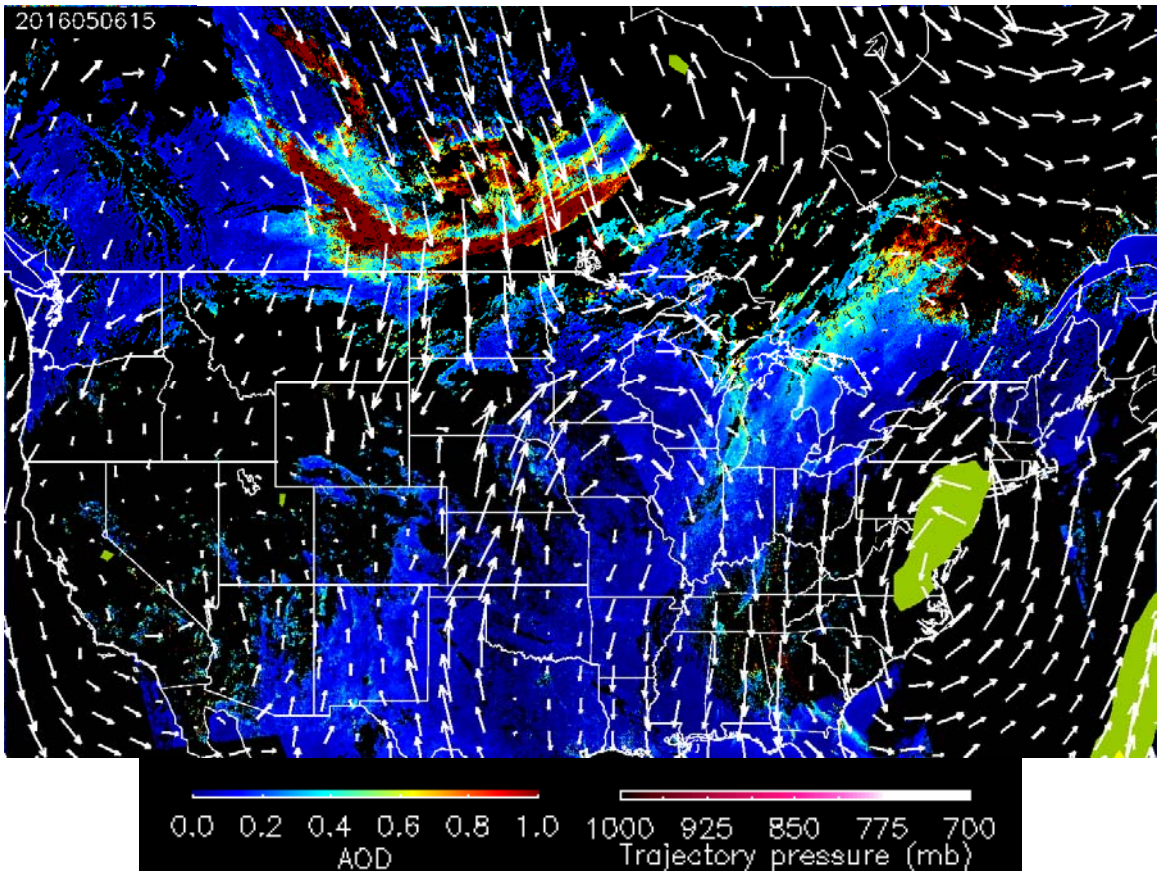
animations and external links

main product overlay buttons

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?

VIIRS Aerosol Trajectories
Initiated 12 UTC, May 6, 2016



- 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?

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- Matt Brown (2016)