The Air Quality Forecast Rote

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Do You Really Want to See This?

- Forecasts, like sausages, cease to inspire respect in proportion as we know how they are made."
  - First citation, American poet John Godfrey Saxe (1869)
- Often attributed to Otto von Bismarck:
- If you are really interested:
  - How to Make Sausage

Air Quality Forecasting: A High Uncertainty Space

- Observations are Limited in Space and Time
  - This has implications for data assimilation and initialization.
- Forecast Latency Issues
  - Warnings must be posted > 24 hours in advance to allow for public/private emission control efforts to be effective while air quality responds to mesoscale effects on shorter time scales.
- Key Processes Often Not Fully Understood
  - Areas of uncertainty include, for example, secondary particle formation, emissions.
- Year-to-Year Changes in Pollutant Precursors
- Forecast Metrics
  - Key metric (domain peak) poses an Extreme Value challenge.

Rapid Emissions Changes

NO_x and CO Reductions

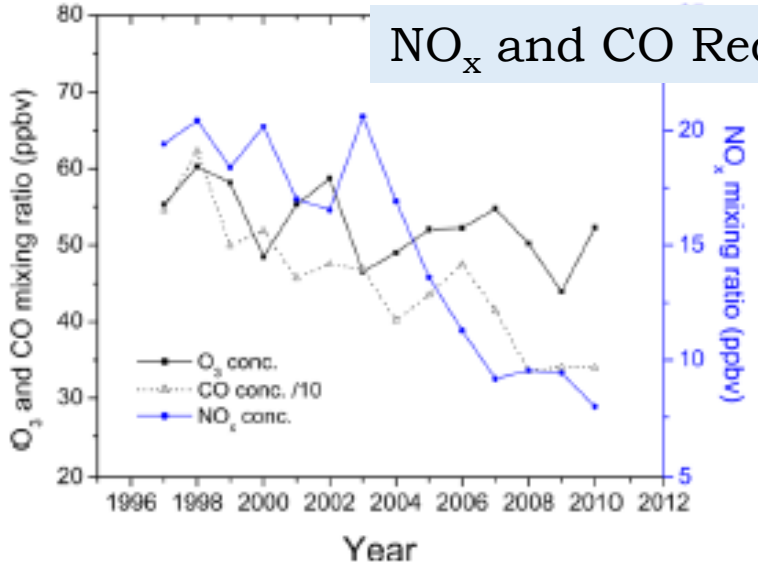
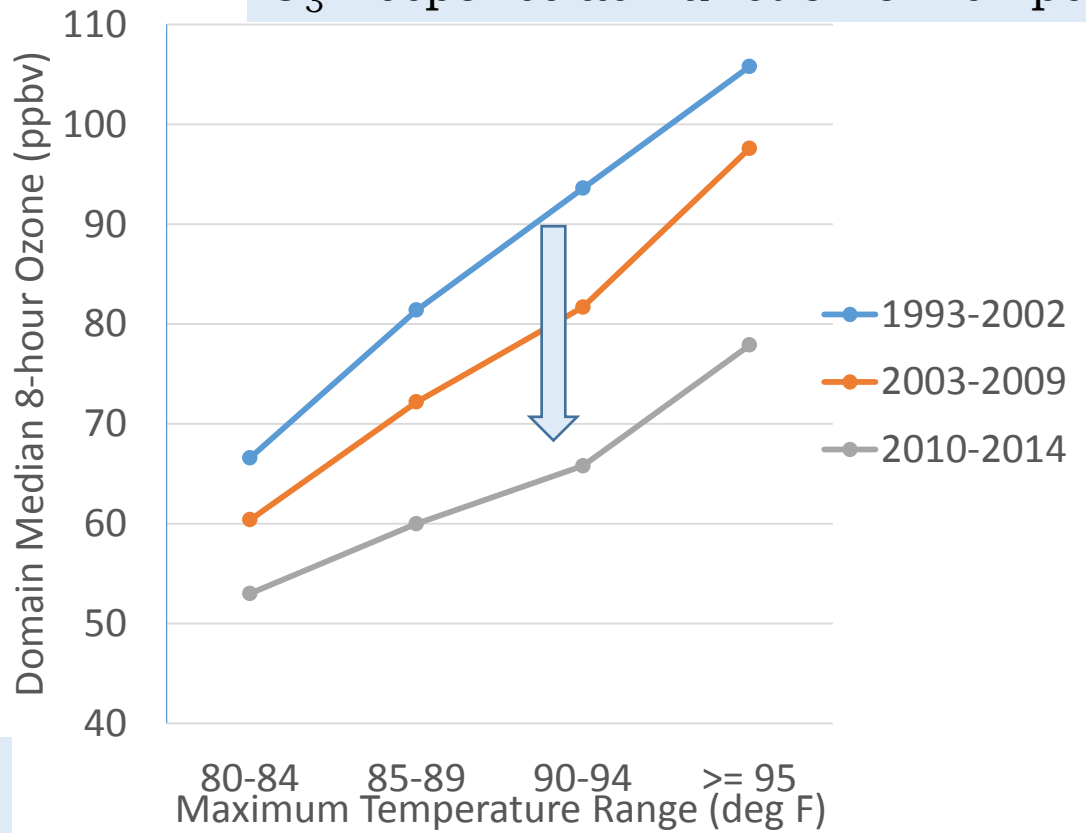


Fig. 3. Long-term trends of ground-level O_3, CO, and NO_x observed in the Baltimore/Washington area in EPA AQS sites (sites shown in Fig. S4 of the Supplement). CO mixing ratios have been scaled by 10 for clarity. To investigate the ozone chemistry, measurements in the afternoon (12:00–18:00 LT) during the ozone seasons were used to calculate annual means.

He, et al., 2013, Trends in emissions and concentrations of air pollutants in the lower troposphere in the Baltimore/Washington airshed from 1997-2011, *Atmos. Chem. Phys.*, **13**, 7859-7874.

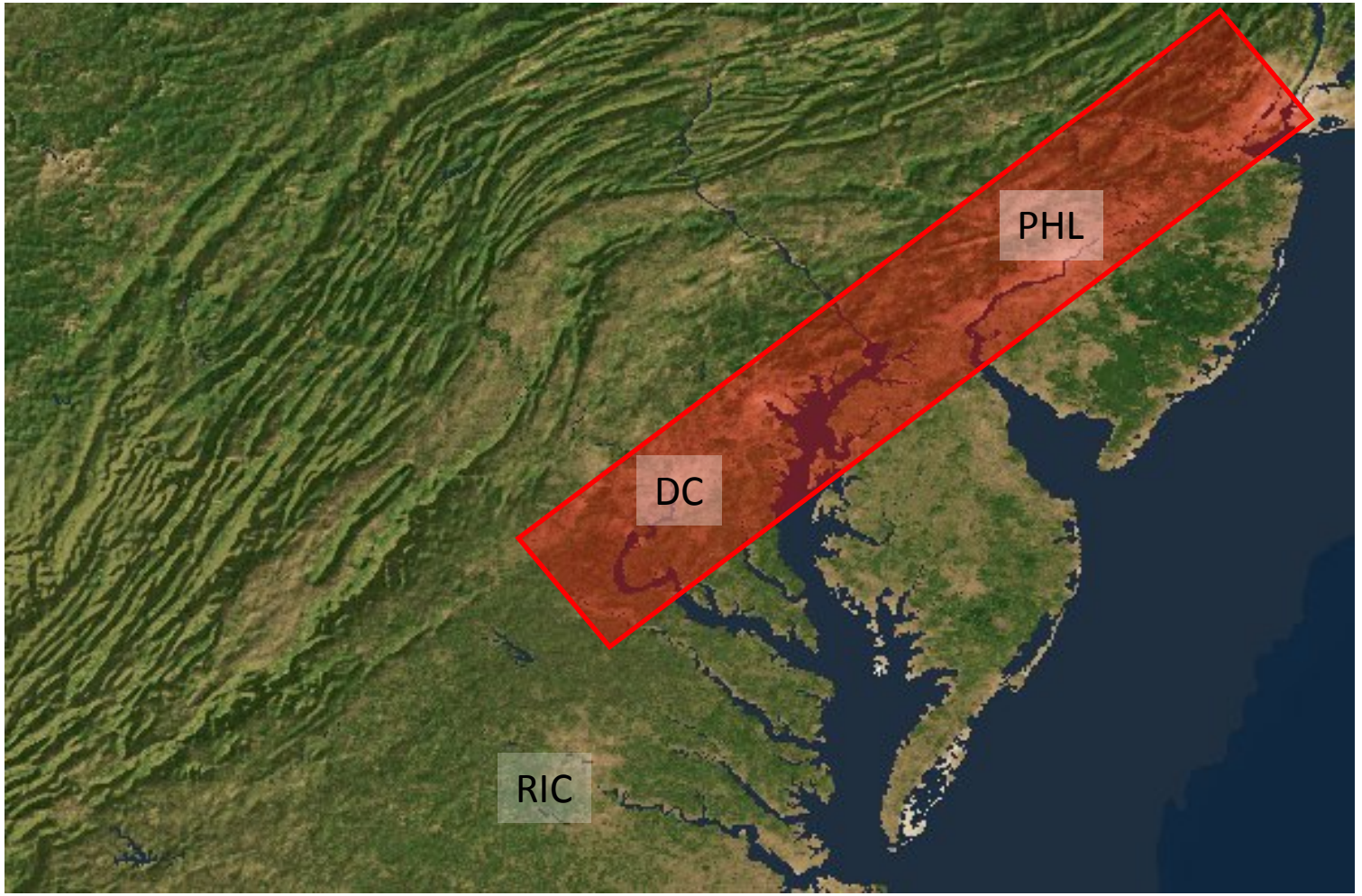
O_3 Response as Function of Temperature



Basic Forecast Principle: "Anchoring and Adjustment"

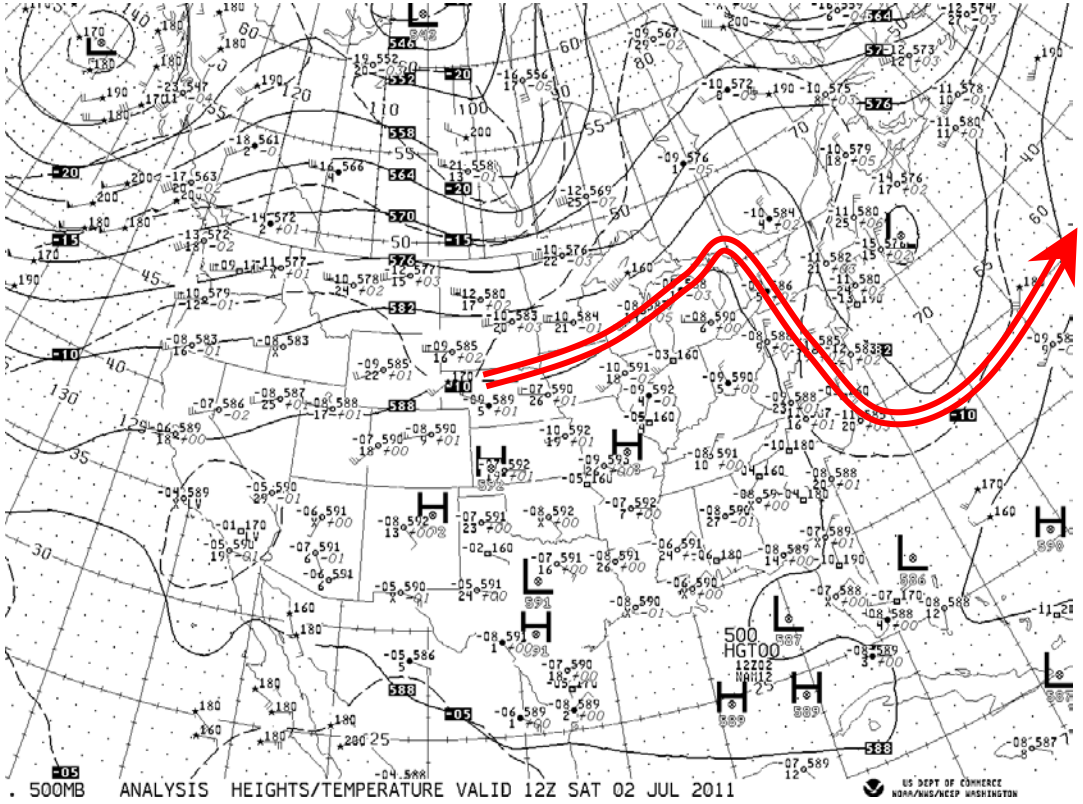
- Poor Man's Bayesian approach: The forecast is anchored by a "first guess" and then adjusted by additional forecast metrics.
- Persistence is typically used as the ***Anchor***.
  - What kind of persistence: Local, regional, transport-specific?
- The ***Adjustments*** are based on:
  - Numerical air quality forecast model guidance.
  - Post-processed model guidance.
  - Statistical guidance (e.g., regression, clustering).
  - Ensembles of guidance (multi-model, multi-method).
  - Factors not fully resolved by coarser resolution AQ numerical models are addressed via heuristics "expert analysis".

Example Case: Mid-Atlantic US
July 1-3, 2011

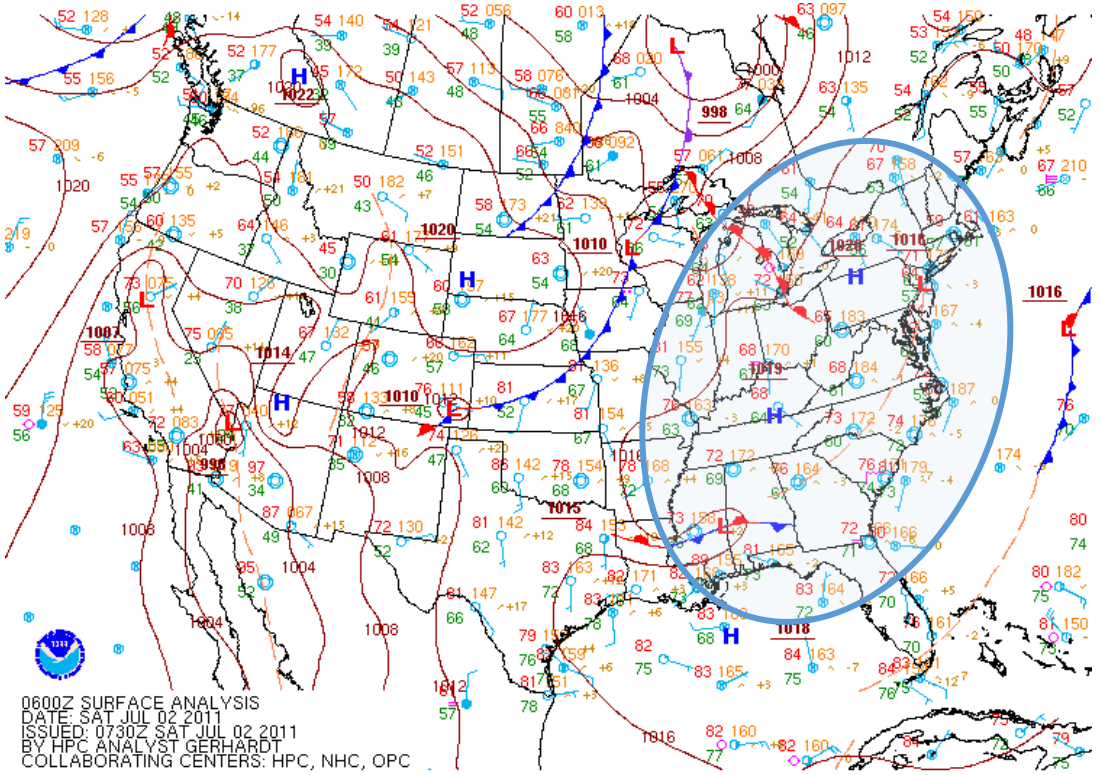


This area is characterized by a band of high emissions along the I-95 Corridor (red rectangle), complex terrain with higher elevations to the west, and a coastal plain, with embayments, to the south and east.

“Standard” Poor AQ Synoptic Pattern



500 mb Height Analysis, 1200 UTC, July 2



NCEP Surface Analysis, 0600 UTC, July 2

Operational AQ Forecasting Rote

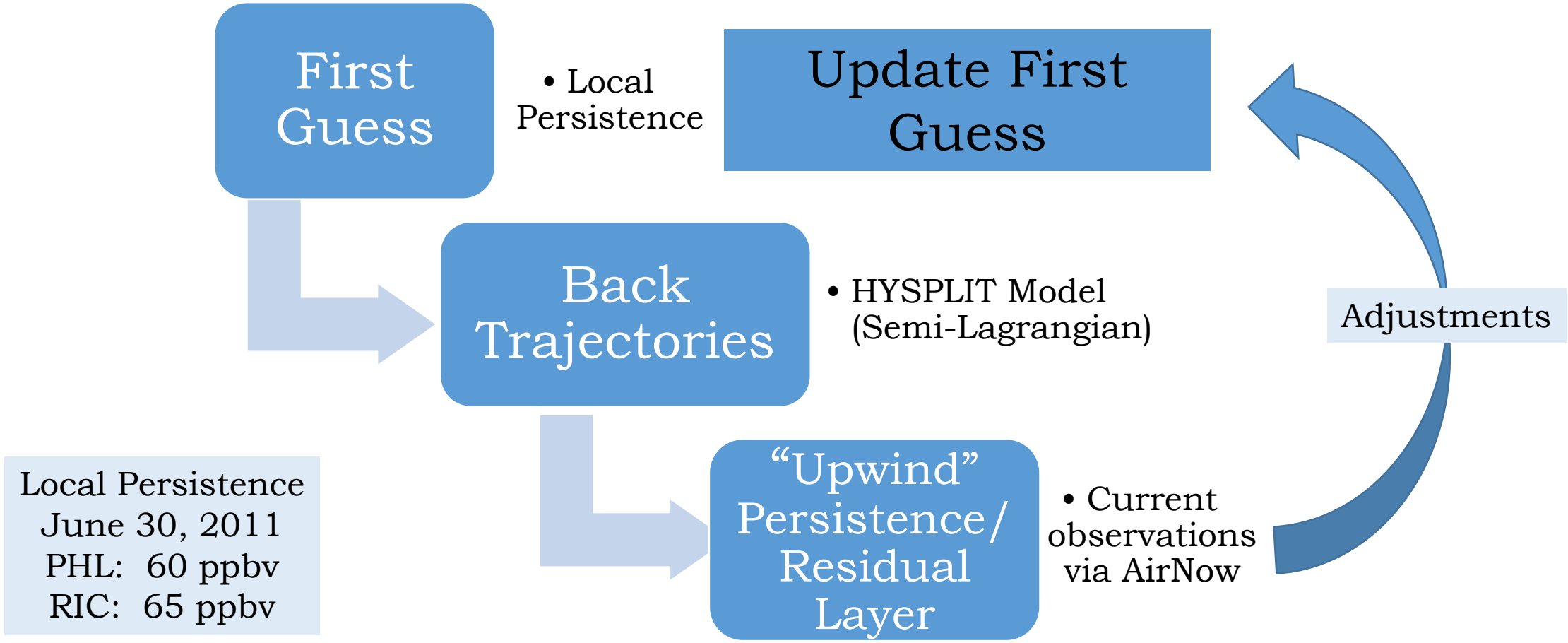
Persistence: Local and Transport

Numerical Model Guidance

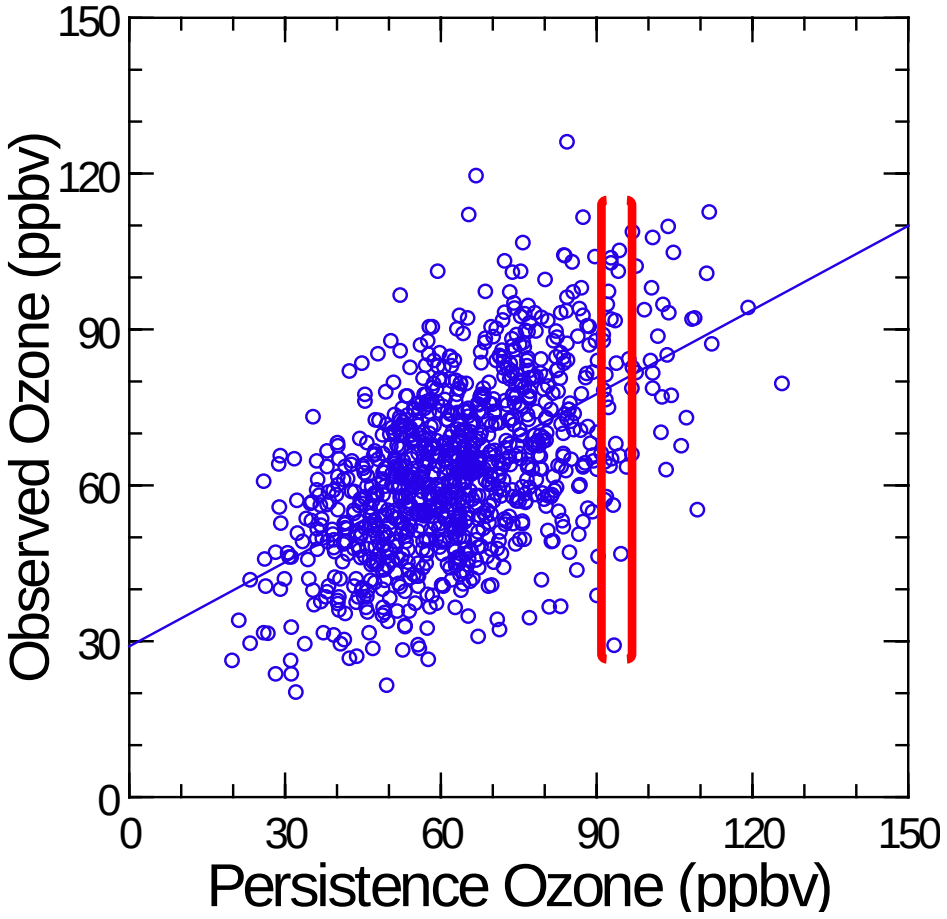
Post-Processed Model Guidance
Statistical and Ensemble Guidance

Heuristics and “Unresolved” Effects

First Guess is Local Persistence, First Adjustment is "Transport" Persistence



Local Persistence O_3 in the Philadelphia Area (JJA, 2004-2014)



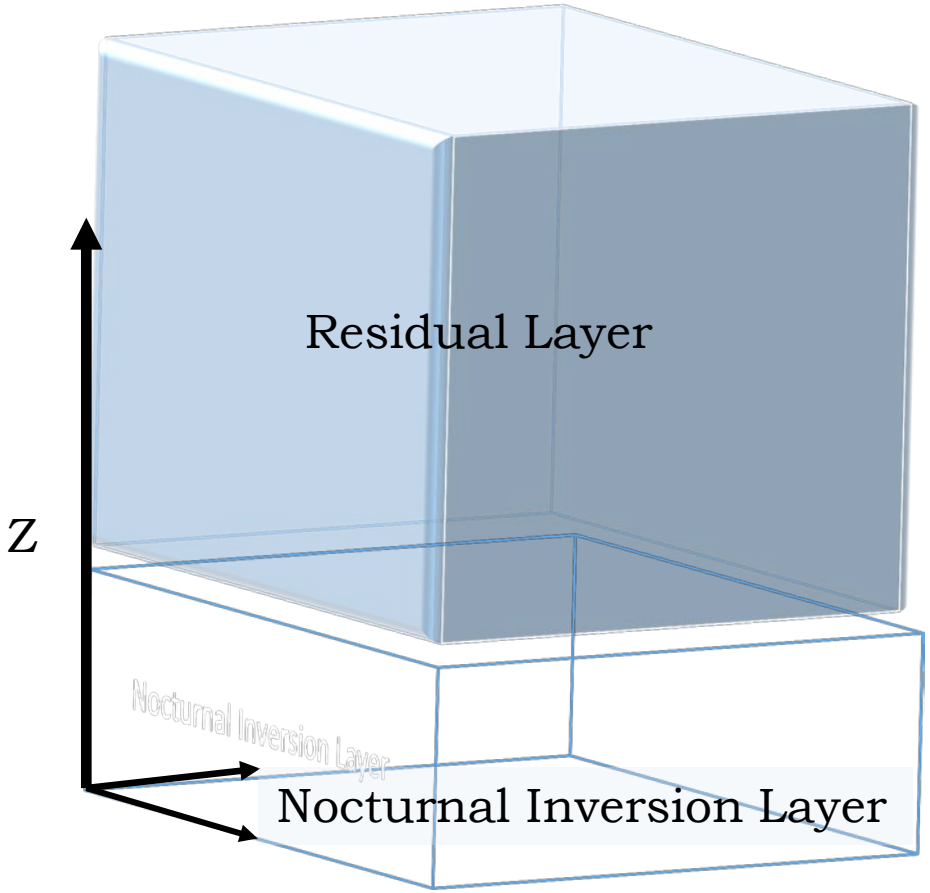
$r = 0.54$
$r^2 = 0.29$,
Best Fit Linear:
$[O_3]_{obs} = 29.0 + 0.54*[O_3]_{lag}$

$PM_{2.5}$ persistence is roughly similar in summer but weaker in other seasons.

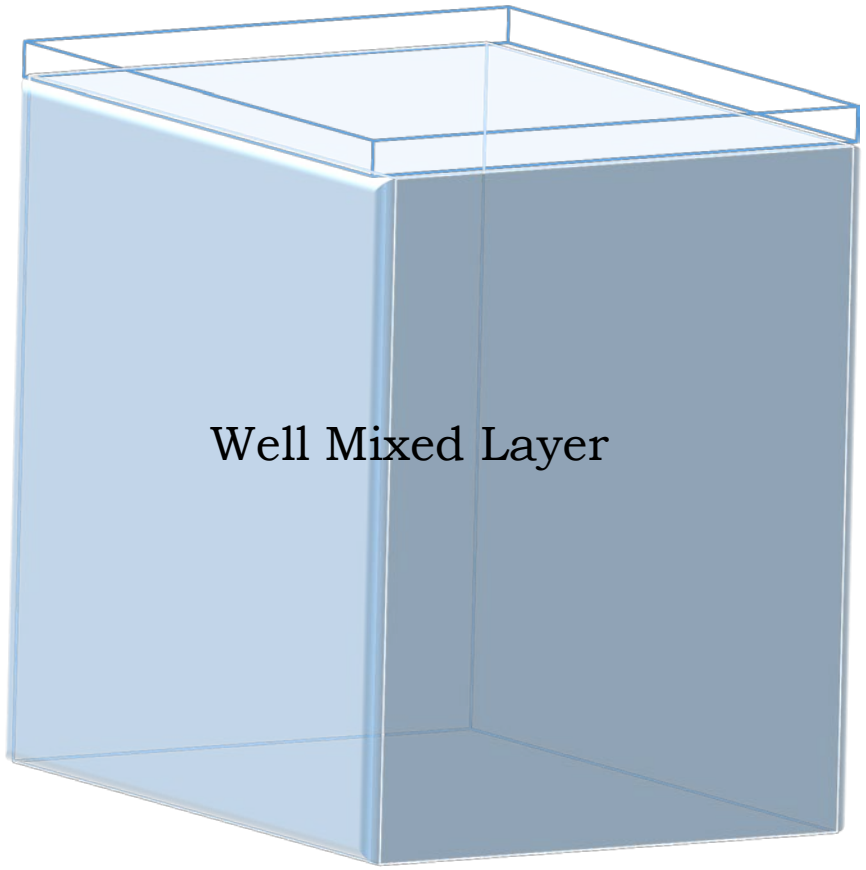
PHL $PM_{2.5}$ Persistence by Season		
	r	r^2
Summer (JJA)	0.57	0.32
Winter (DJF)	0.40	0.16

Transport Persistence: What's in Your Residual Layer?

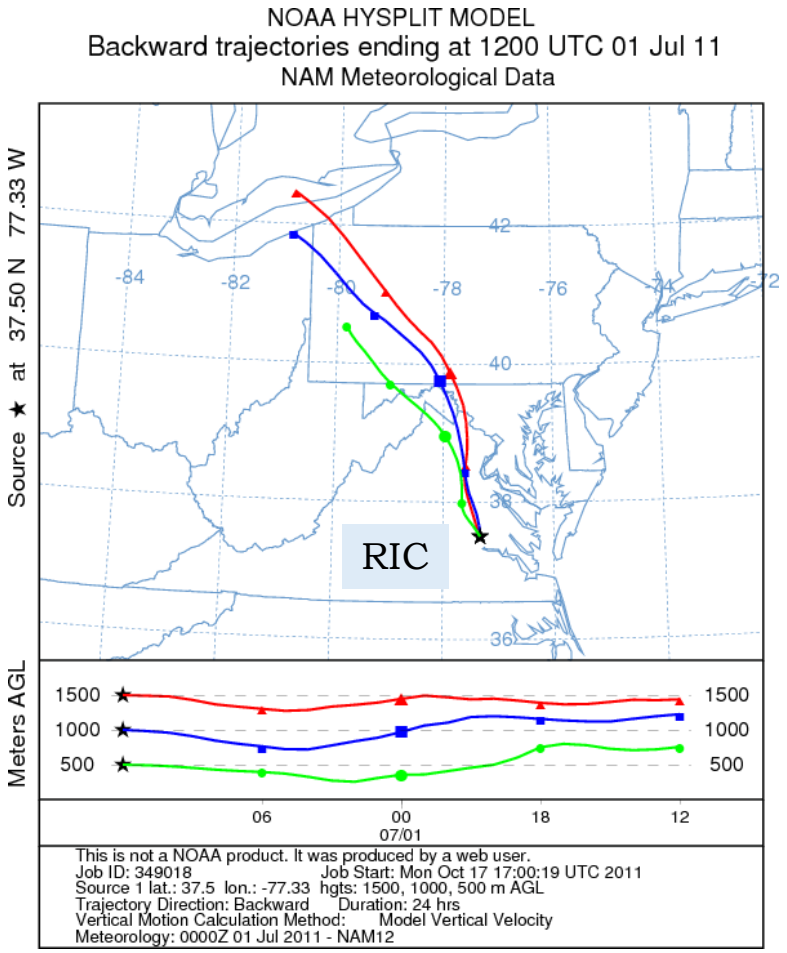
Sun Rise

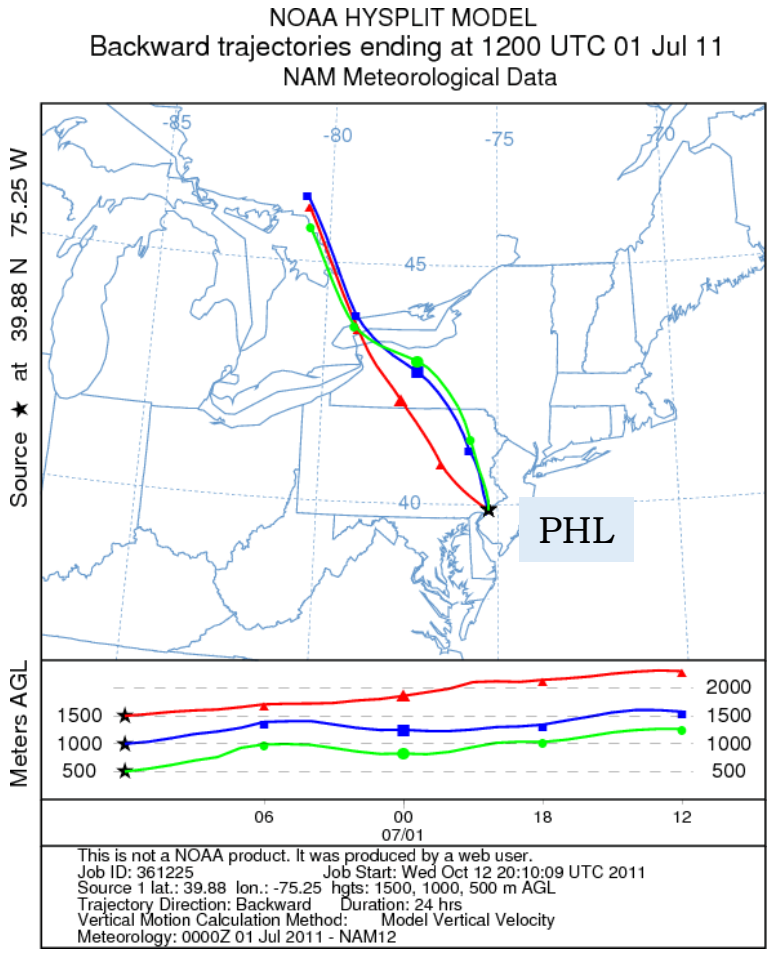


Afternoon



Example of Transport Persistence Analysis: Forecast Back Trajectories for 1200 UTC, July 1 for RIC (left) and PHL (right).

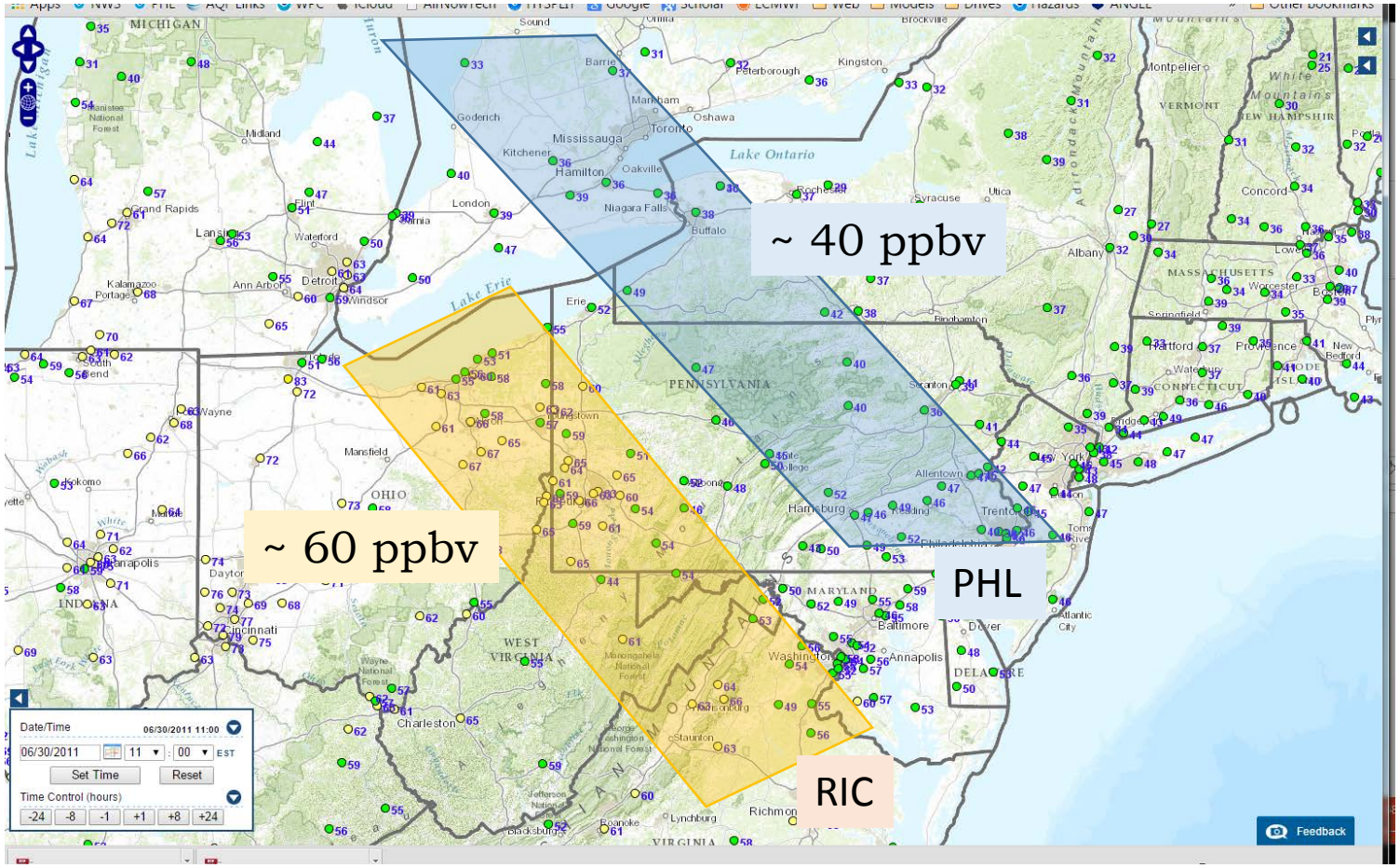




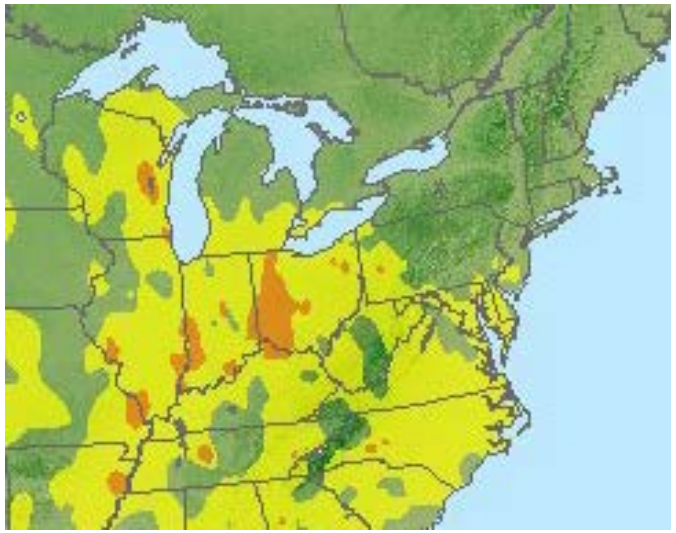
HYSPLIT Model

24-hour back trajectories terminating at 500 m (green), 1000 m (blue)and 1500 m (red) AGL, 1200 UTC, July 1.

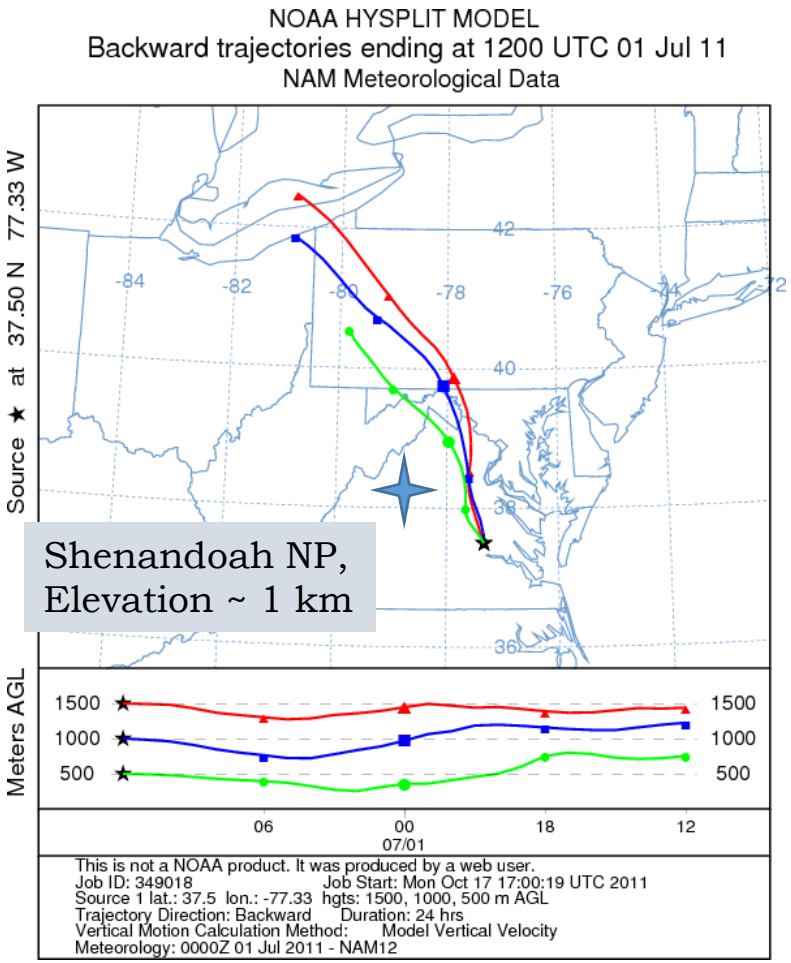
Real-Time O_3 Observations via AirNow:
1700 UTC on June 30

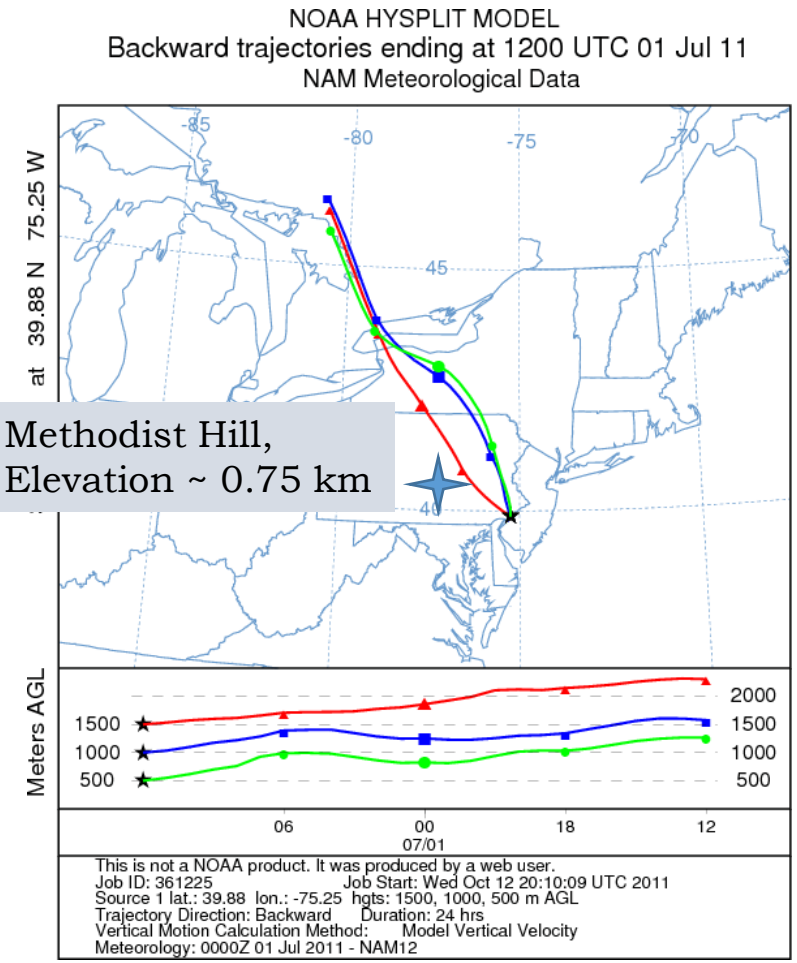


Peak O_3 for June 30

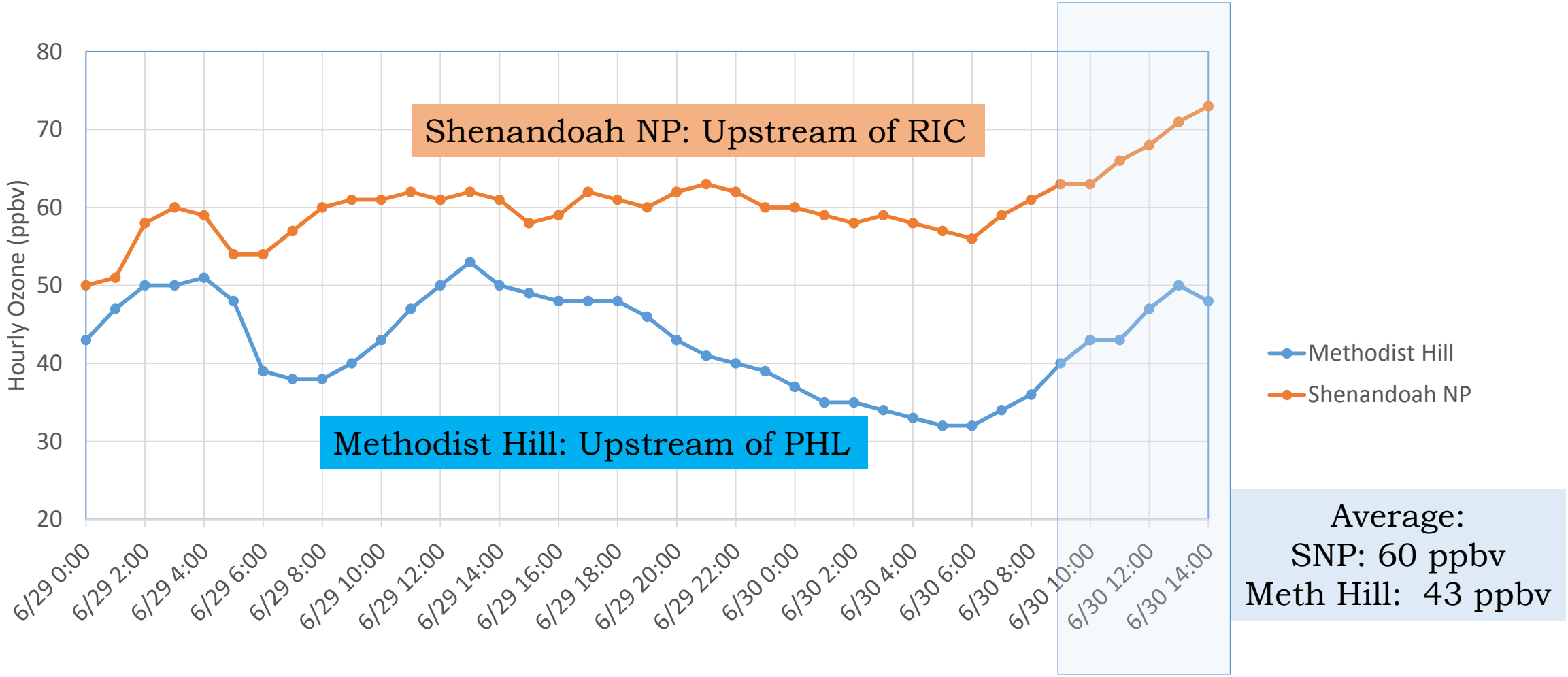


Regional Scale Persistence Can be Estimated by High Elevation Rural "Sentinel" Monitors:





High Elevation Ozone Monitors

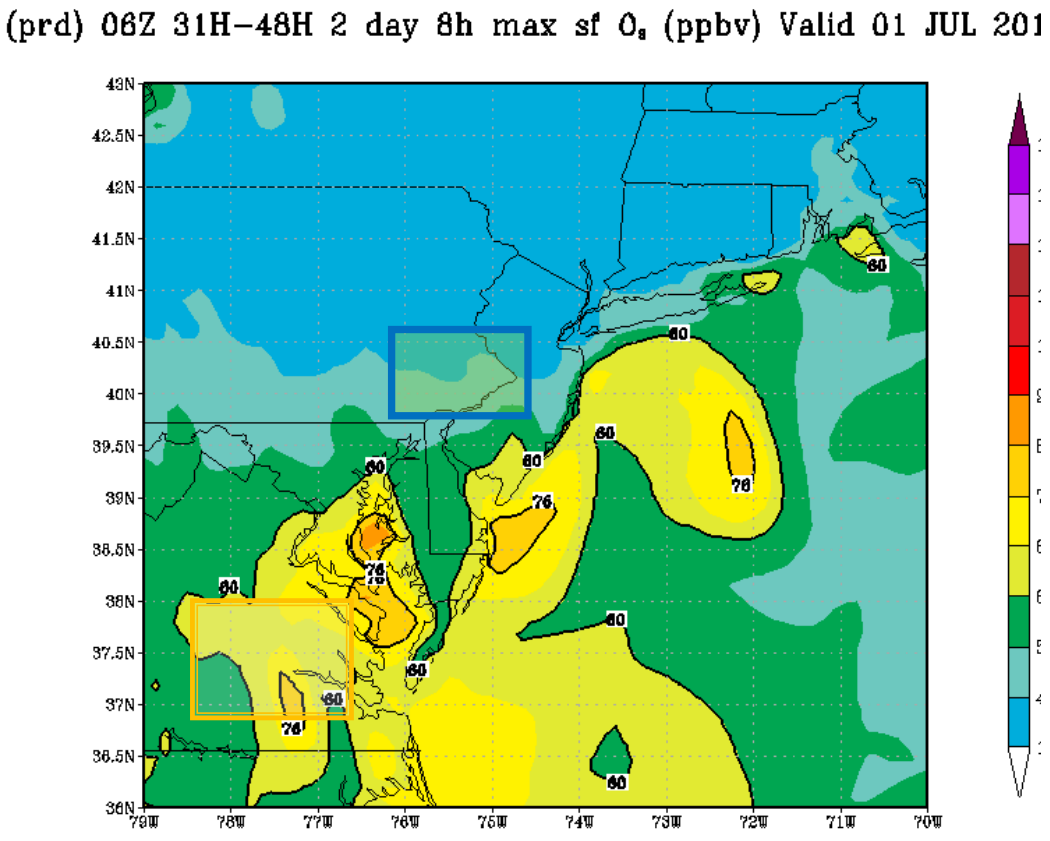


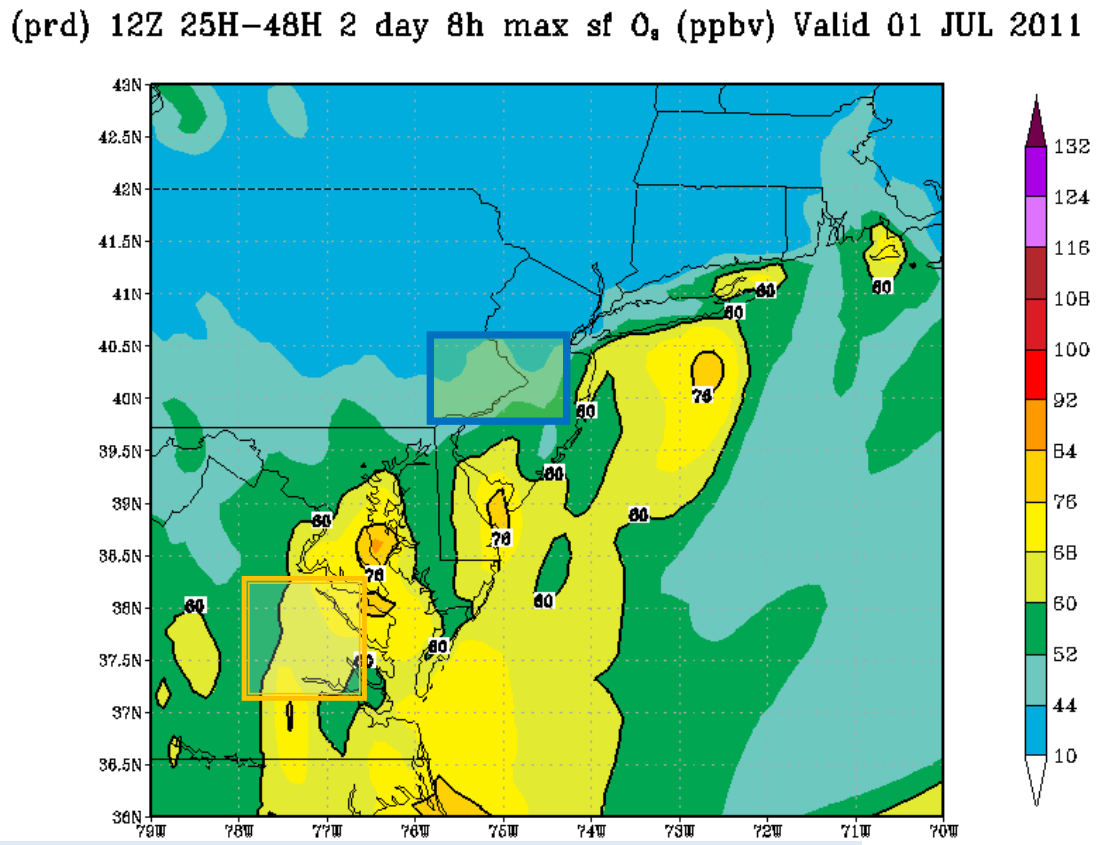
Average:
SNP: 60 ppbv
Meth Hill: 43 ppbv

Numerical AQ Model Guidance

- NAQC (NOAA/EMC)
  - NAM + CMAQ
- Baron Meteorological Services (2 versions)
  - MM5 + CMAQ/MAQSIP-RT
- North Carolina Department of Environment and Natural Resources, Division of Air Quality (4 versions)
  - WRF + CMAQ
- Multi-Model Ensemble: Models vary by emissions, physics, dynamic core. Note that nearly all numerical models in operational use in US are coupled CTMs.

NAQC Forecast Guidance for July 1:
0600 UTC Run June 30 (left), 1200 UTC Run (right)



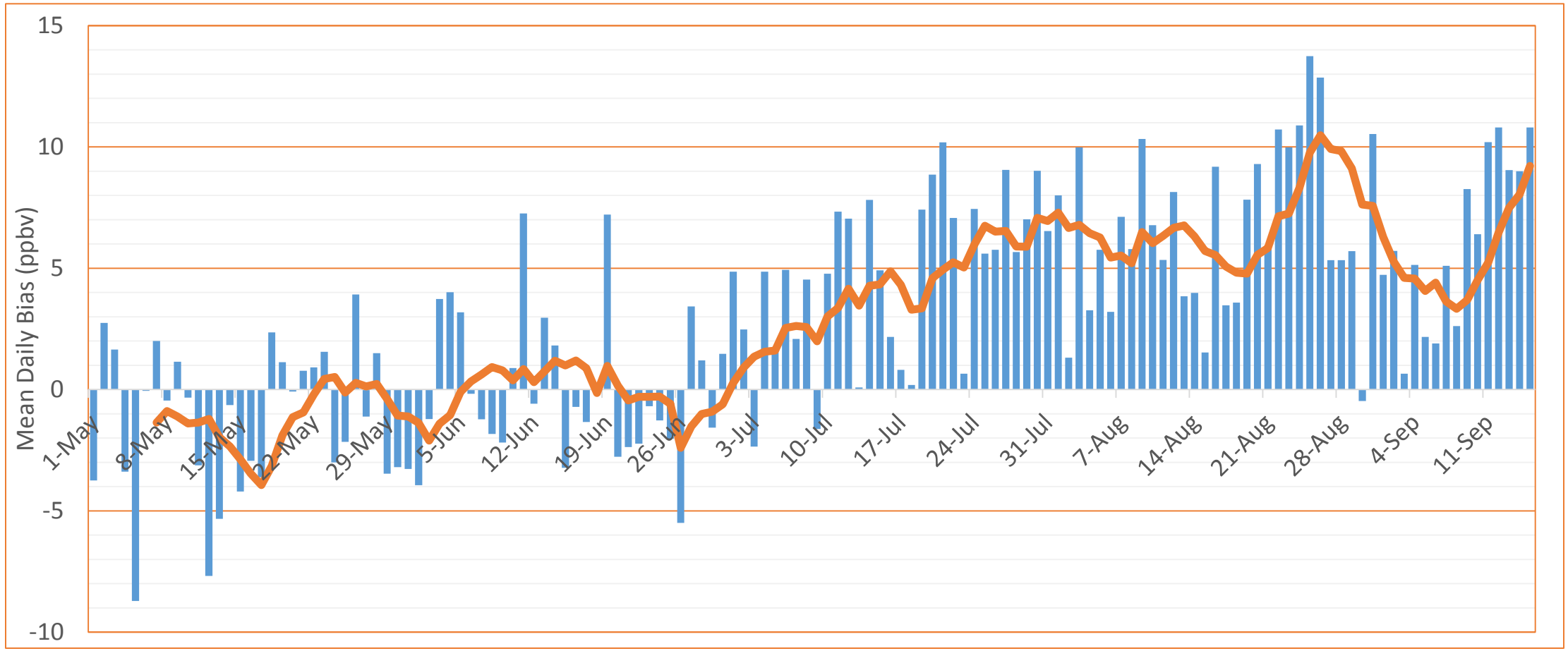


Range of Numerical Model Guidance: PHL [62, 72], RIC [68, 80],
Standard Ensemble for PHL: 67 ppbv

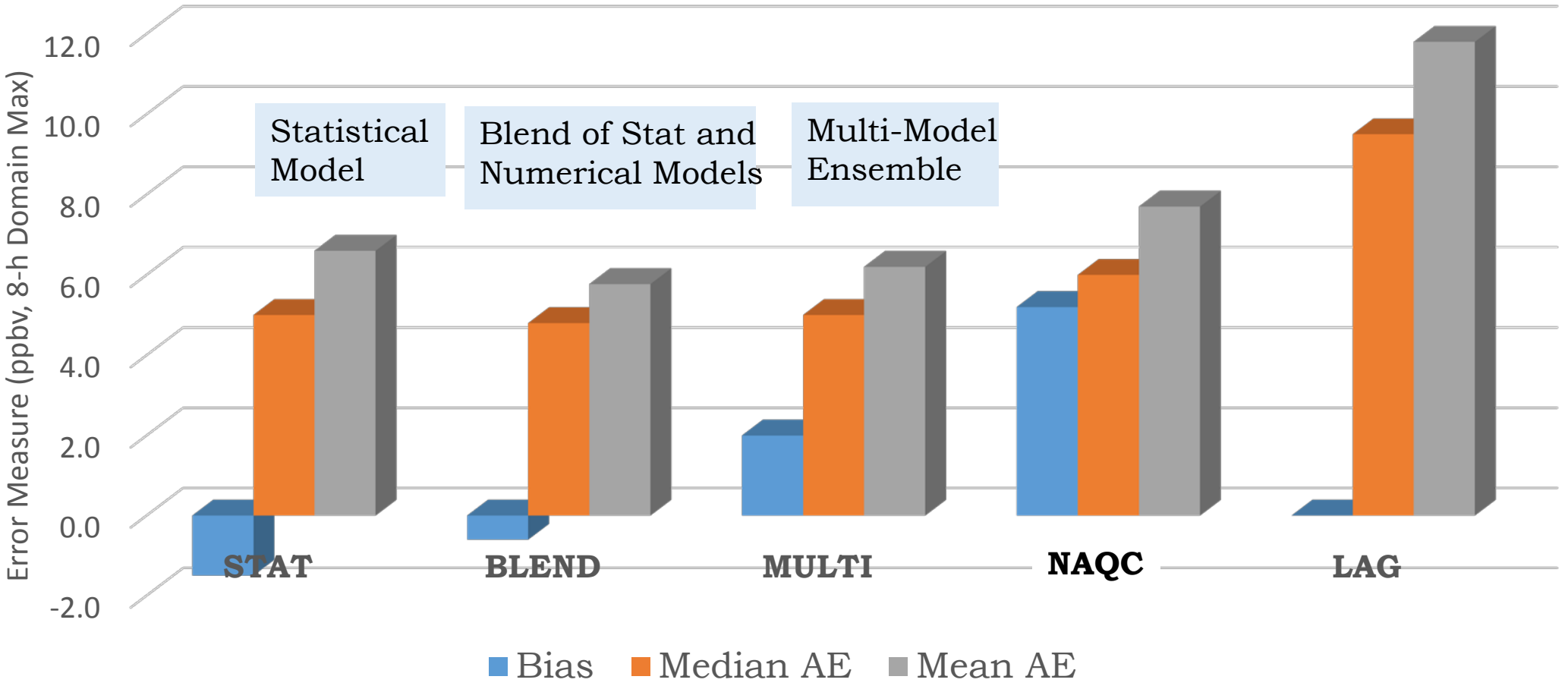
Model Guidance Post-Processing

- Raw Model Guidance
  - Running Bias and/or Seasonal Drift Corrections.
  - 2015: EMC KF/Analog Bias Corrections for $PM_{2.5}$
    - See, Djalalova, I, Monache, L.D. and Wilczak, J. **2015**, *Atmos. Environ.*, in press.
    - Preliminary results (PHL, Summer 2015) reduced bias by 43%, decreased MAE by 21%.
- Statistical Guidance: Variety of methods using model guidance and meteorological variables as predictors.
- Multi-Model and Multi-Method Ensembles.

Example of Seasonal Drift (PHL Forecast Area) NAQC Model Bias (2007-2013)



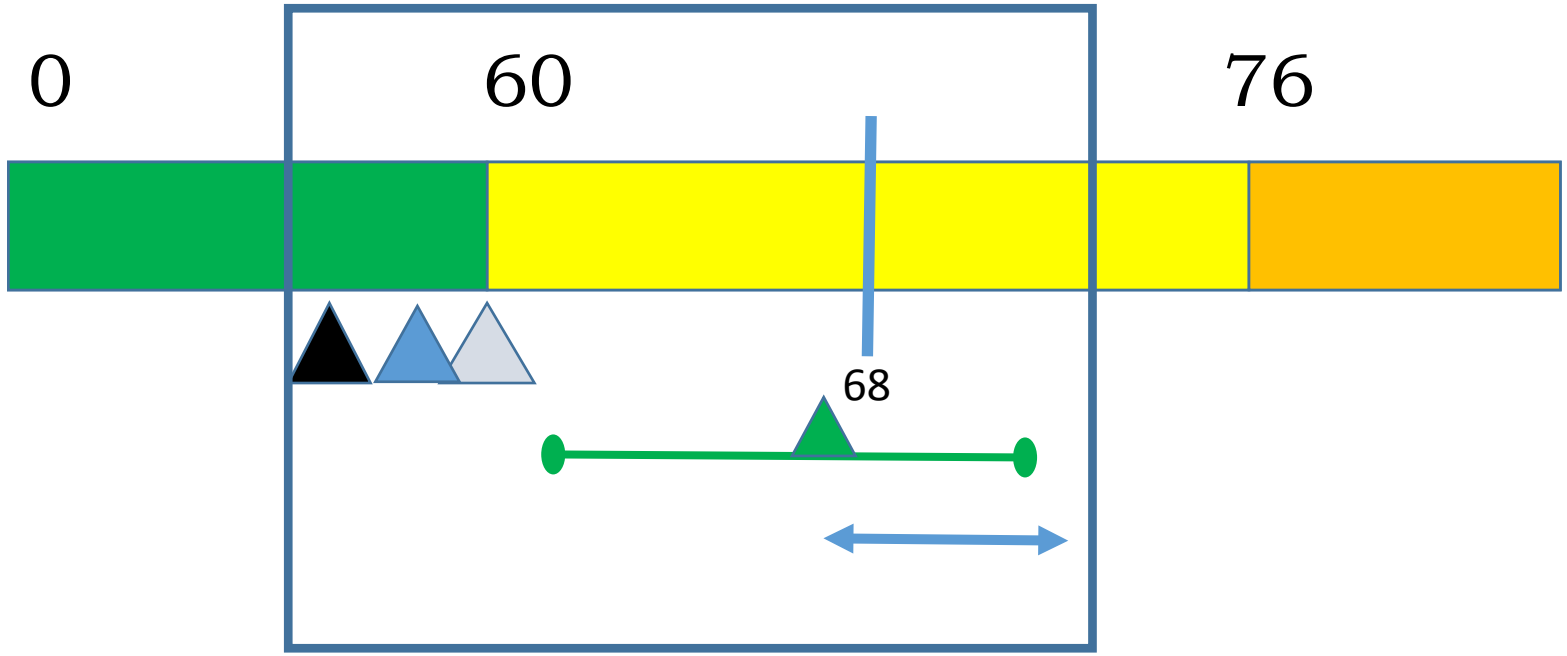
Error Measures in PHL (JJA, 2015)
Peak Domain 8-Hour Average O_3



Statistical Guidance for PHL on July 1

- Standard linear regression (for this example, July 1, 2011 statistical guidance is backcast from the current operational regression model). Heavily weighted to T_{max}, wind speed, sky cover, persistence.
  - 75 ppbv but over-prediction bias ~ +6 ppbv.
- Simple cluster including "air mass relevant" variables: T_d, T_{850}, wind direction, NAQC forecast.
  - N = 9, Median: 66 ppbv, Mean: 65 $\pm$ 8 ppbv; 1 of 9 cases reached warning threshold.

PHL: Anchoring and Adjustment



Local Persistence

Adjusted Transport Persistence (k ~ 1.2)

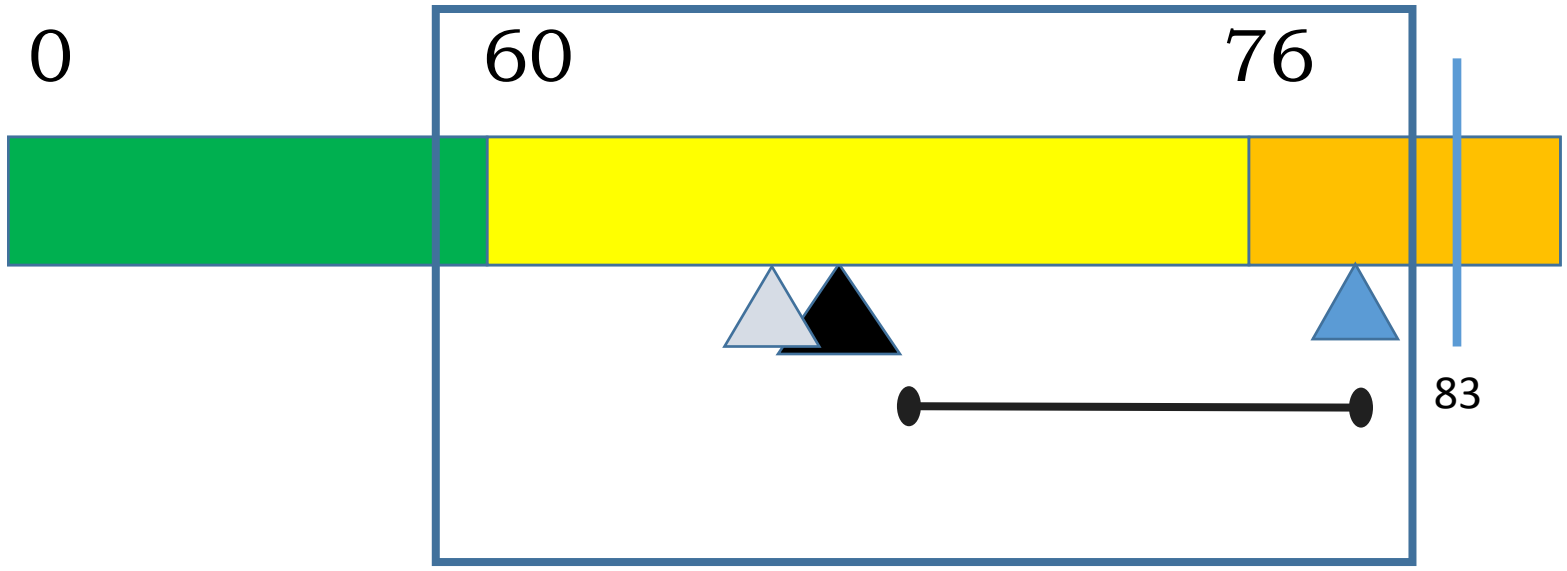
Transport Persistence

Range of AQ Models

AQ Model Ensemble

Range of Statistical Models

RIC: Anchoring and Adjustment



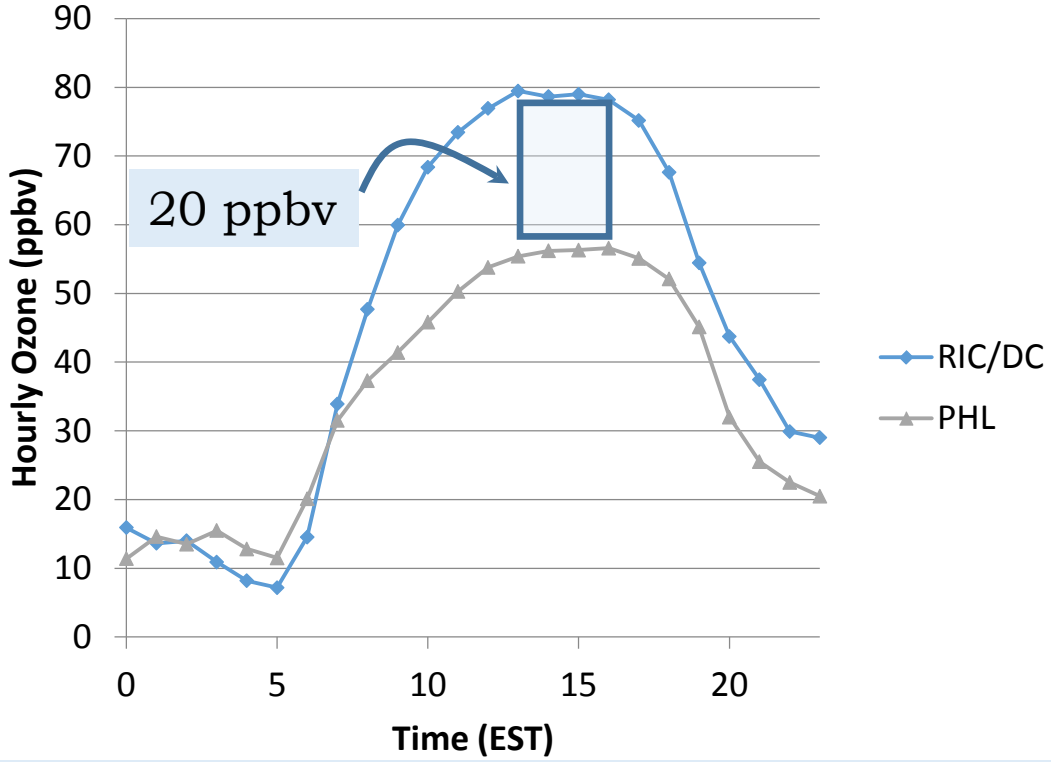
Local Persistence

Transport Persistence

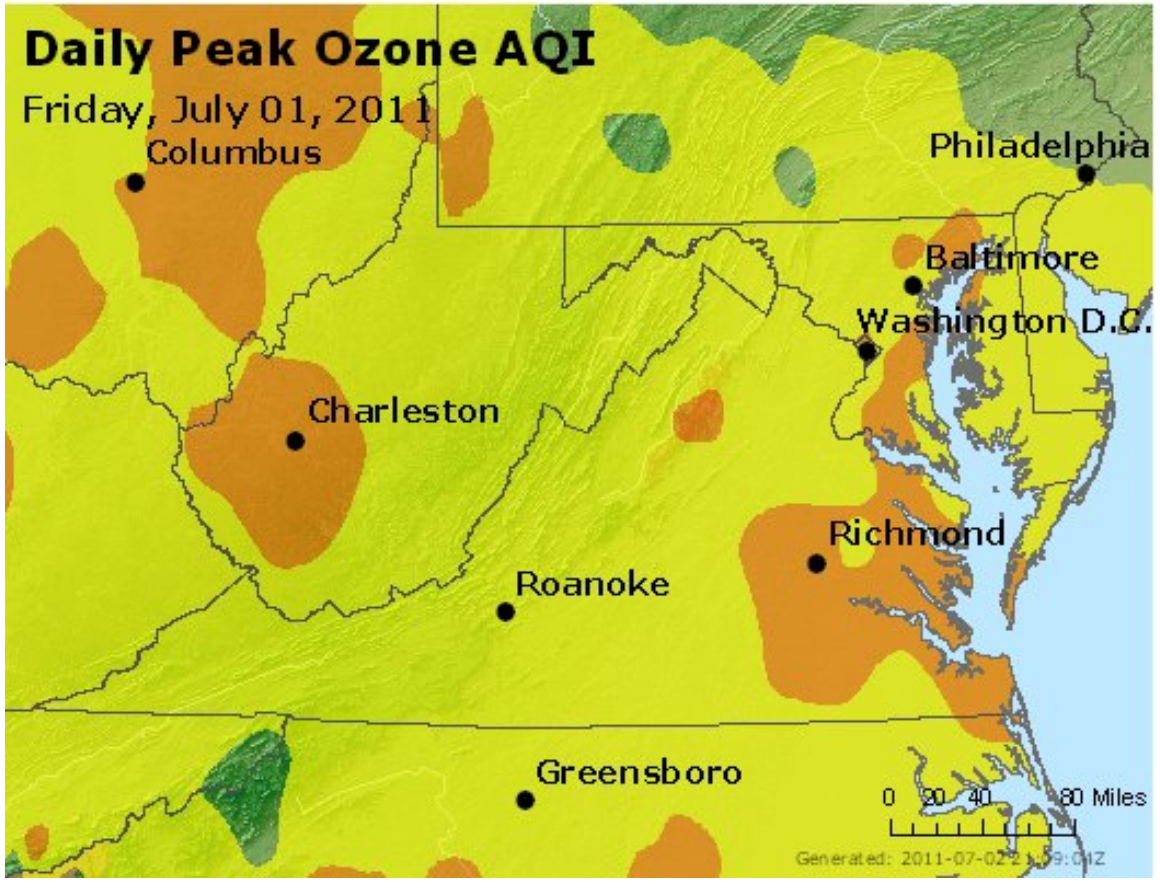
Adjusted Transport Persistence

Range of Numerical Models

Result on July 1: Strong Intra-Regional Gradient in O_3 Impact of O_3 Transport in the Residual Layer



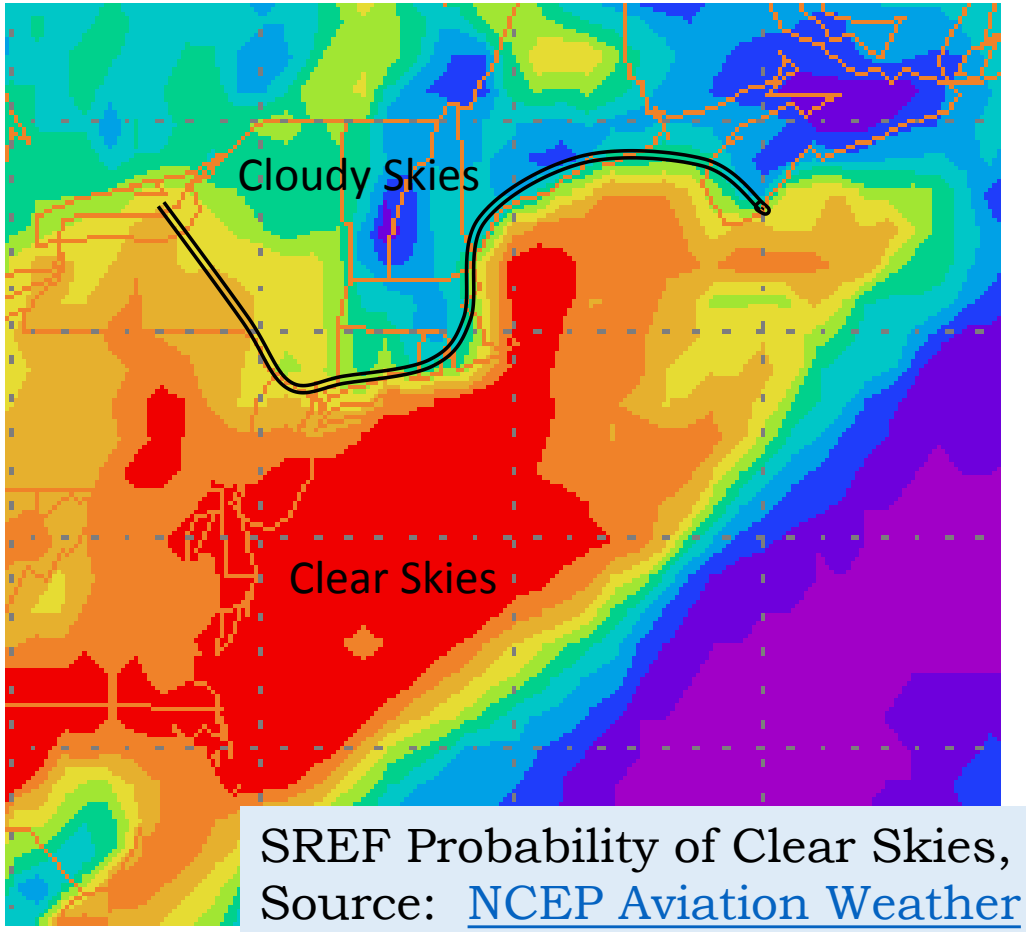
Average hourly O_3 for monitors south of DC including RIC (RIC/DC) and monitors in PHL.



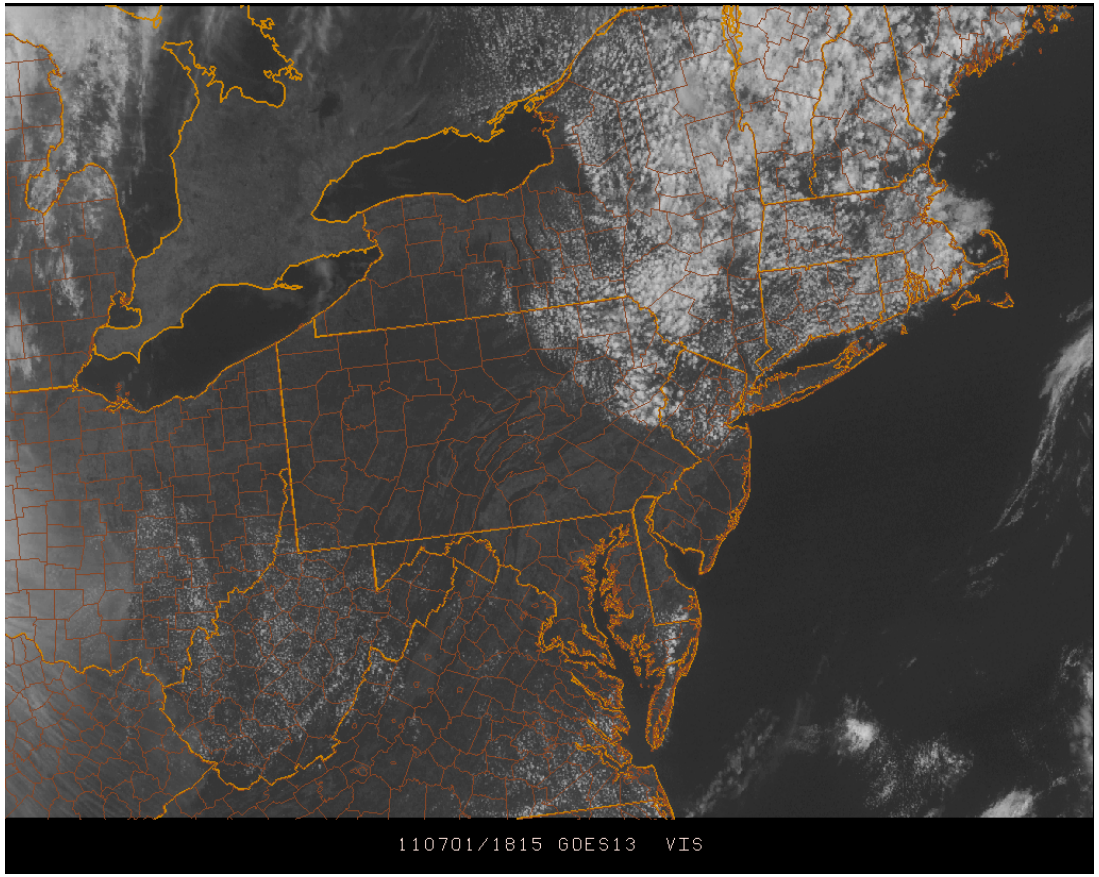
Heuristics (Meatball Meteorology)

- What Features are not Fully Resolved by Models?
- Mesoscale Effects
  - Local Circulations, e.g., bay and sea breezes.
  - Timing of Cloud Cover, Precipitation and Convection.
  - CTMs usually coarser scale than met model.
- Unusual Events
  - Snow Cover (winter season $PM_{2.5}$)
  - Wildfire Smoke (summer season O_3 and $PM_{2.5}$)

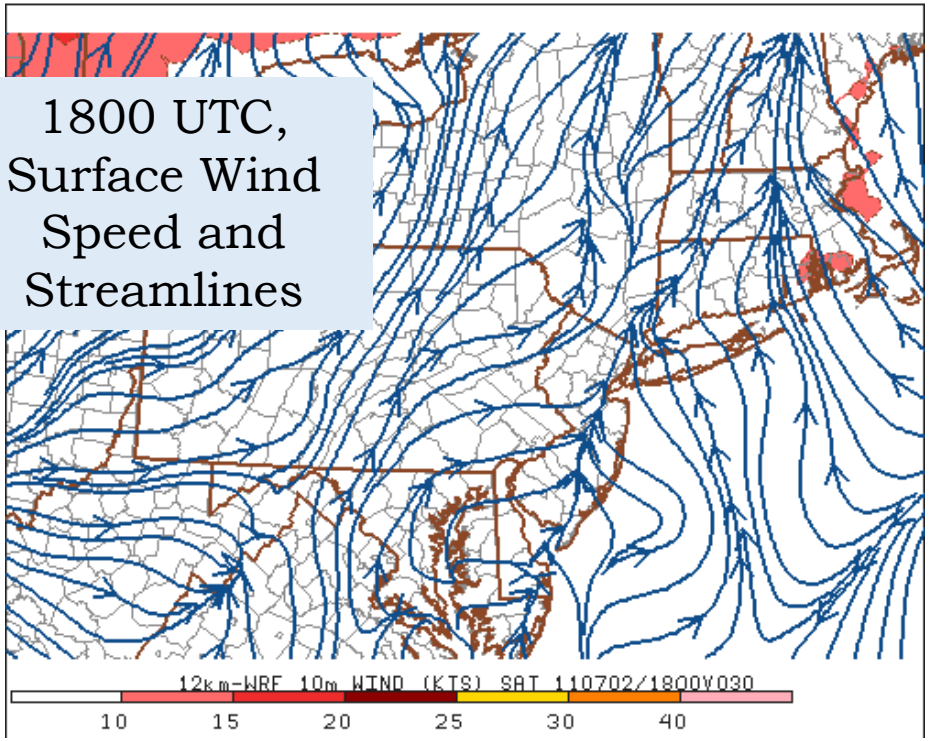
July 1: Impact of Mesoscale Phenomena (Cloud Cover)

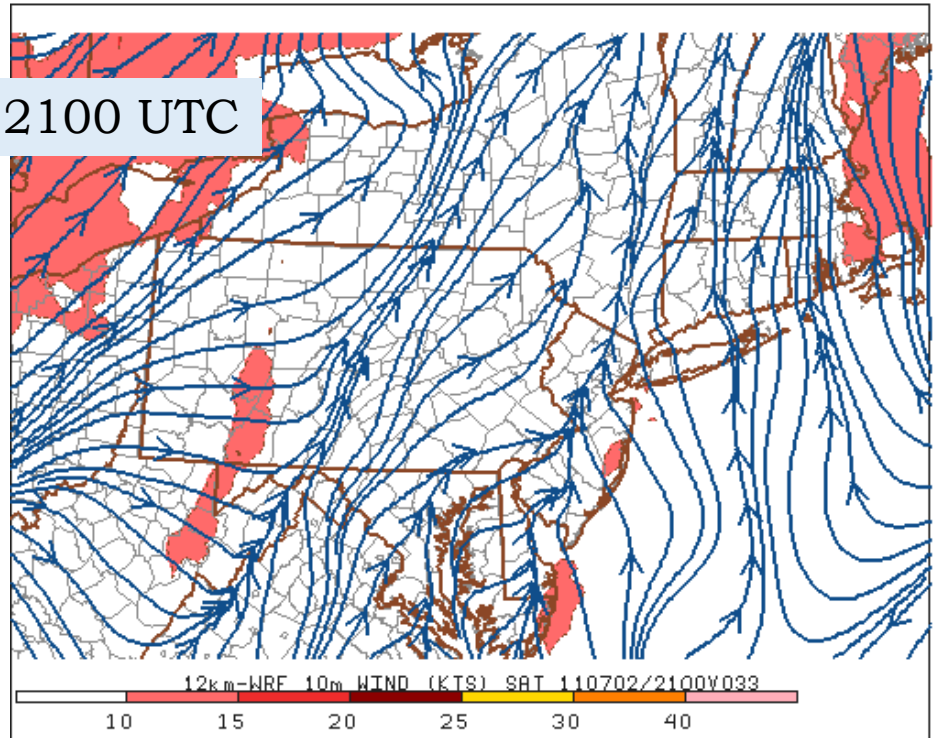


SREF Probability of Clear Skies,
Source: NCEP Aviation Weather



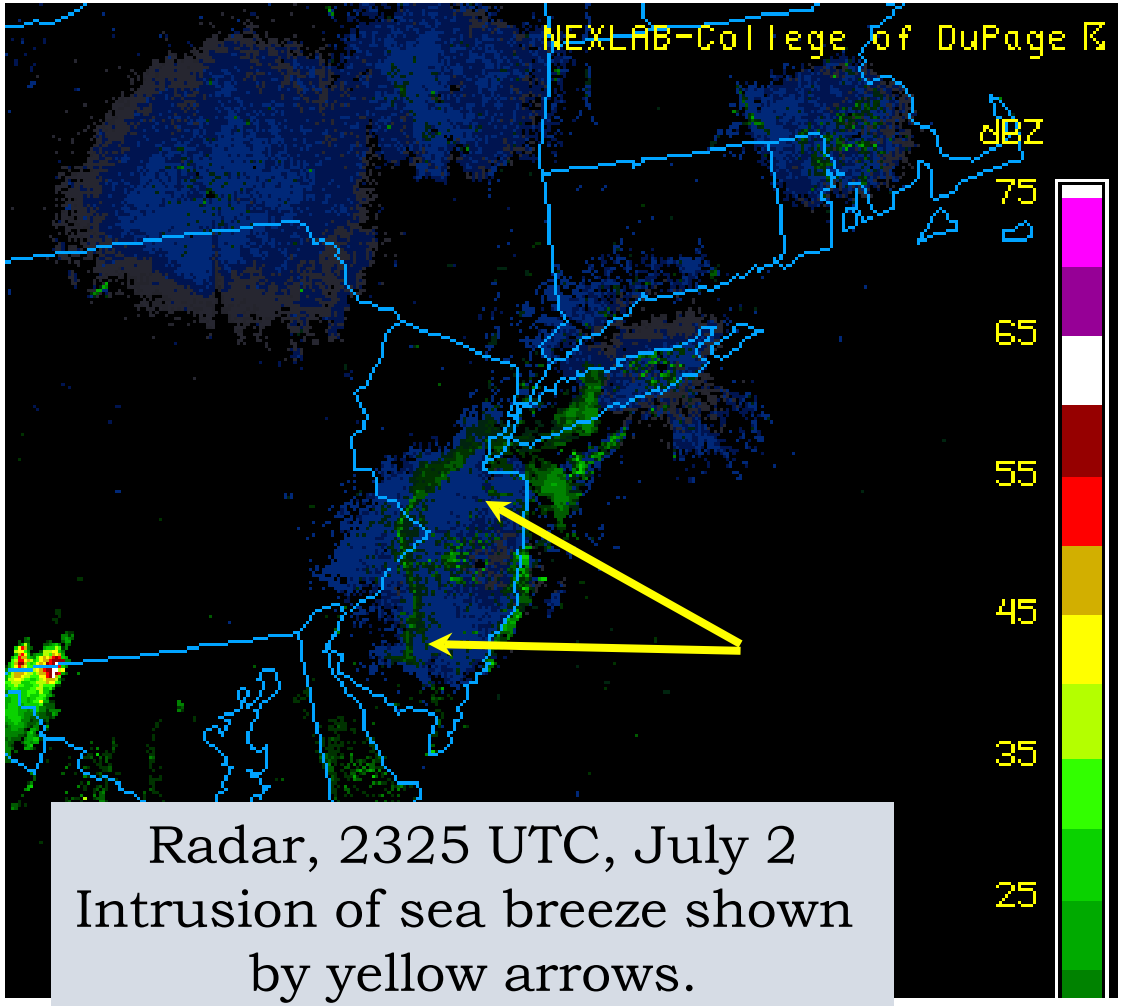
July 2: Impact of Mesoscale Phenomena: (Sea Breeze)



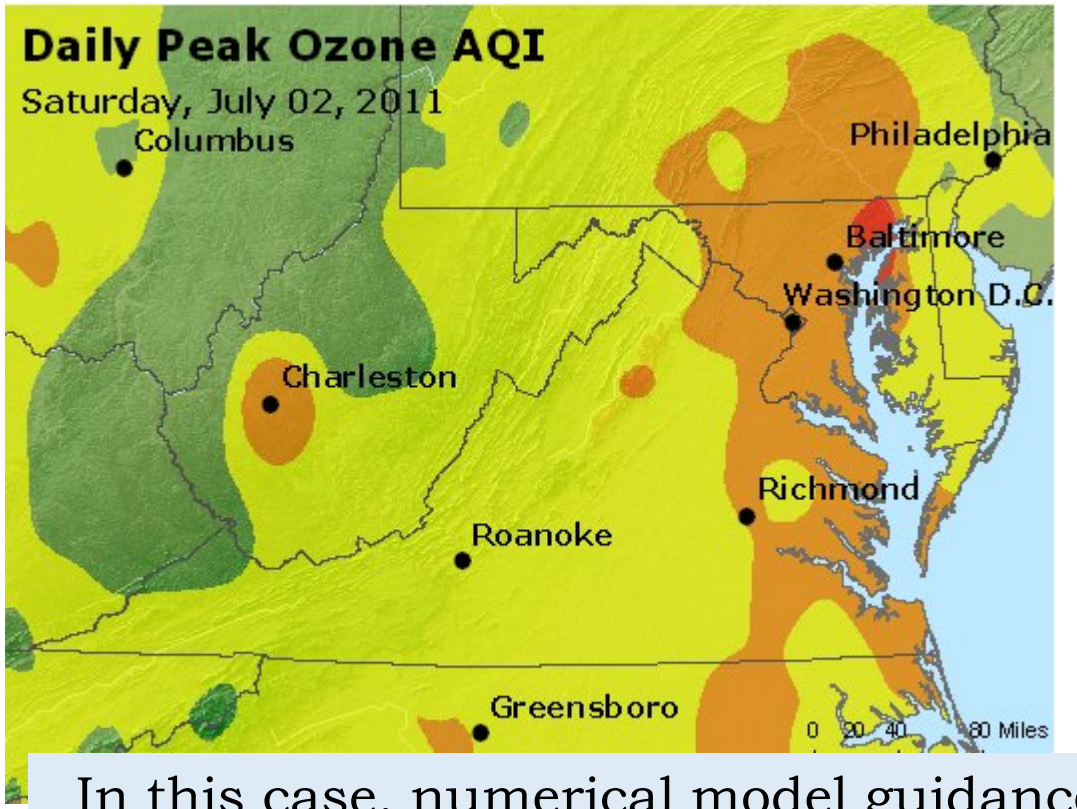


Finer scale weather model (12 km WRF at this time) predicts strong sea breeze in NJ, weak sea breeze in Delmarva Peninsula with hint of bay breeze north of Baltimore.

July 2: Impact of Mesoscale Phenomena (Sea Breeze)

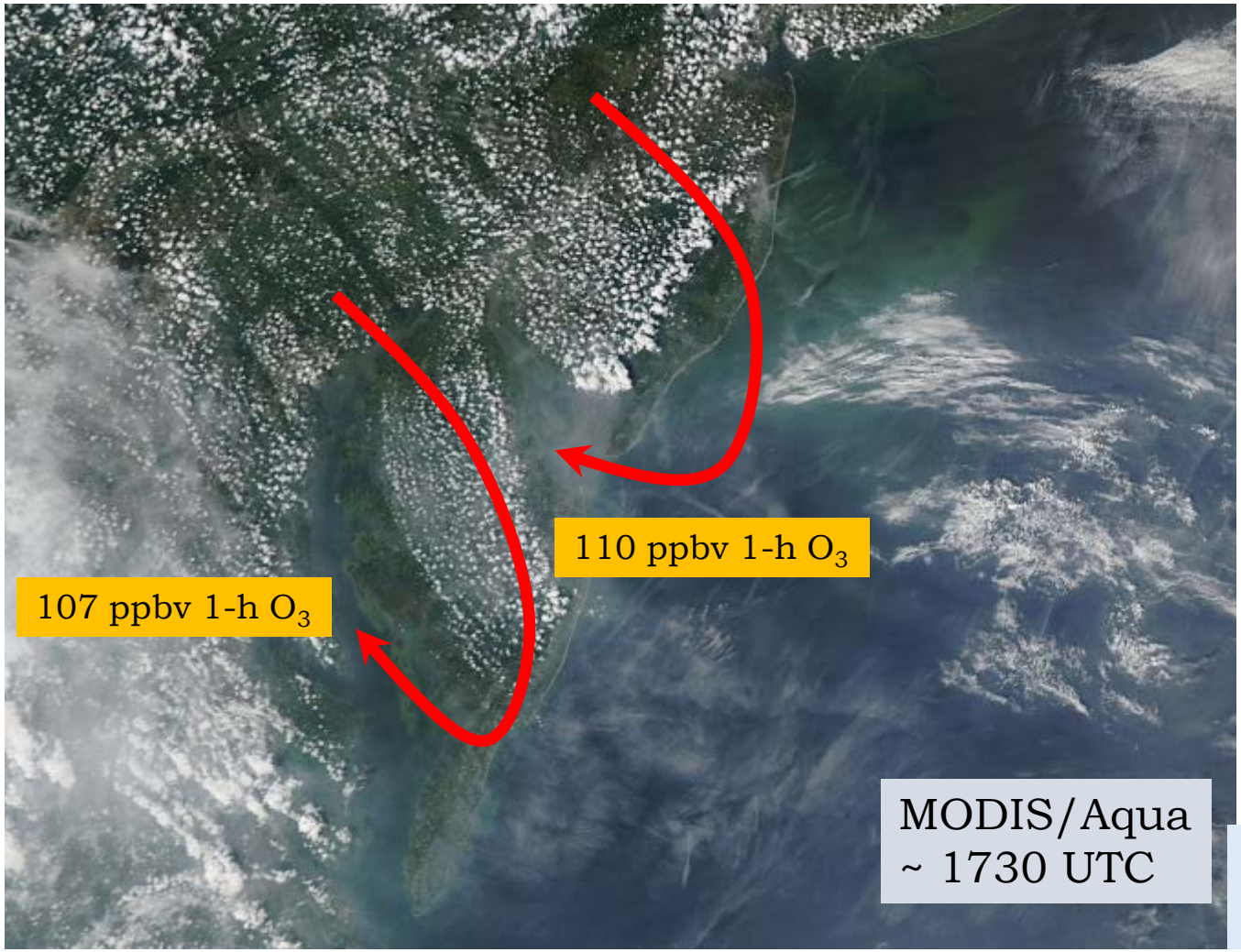


Radar, 2325 UTC, July 2
Intrusion of sea breeze shown by yellow arrows.

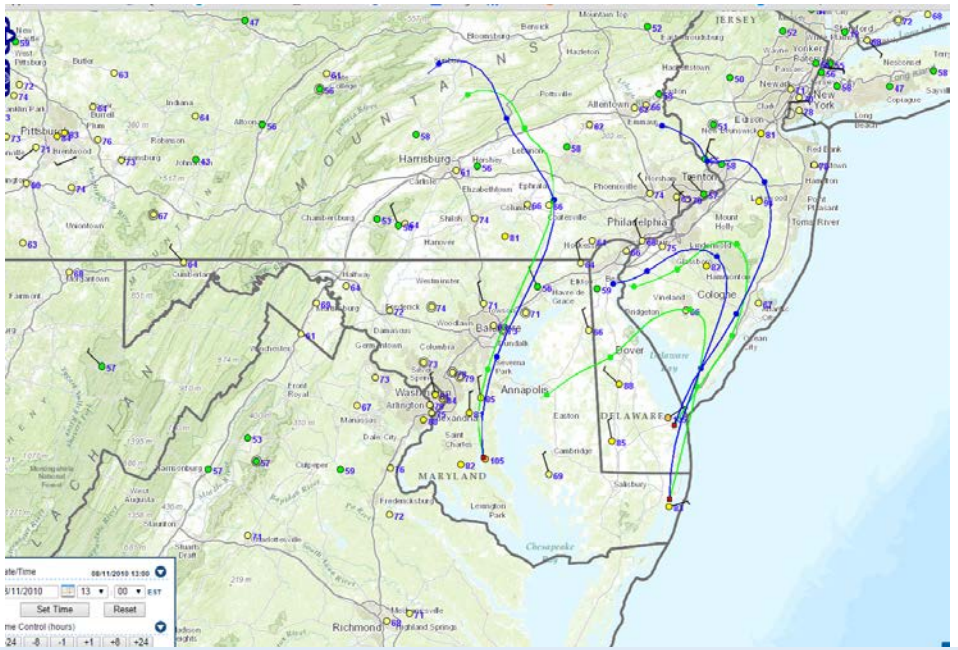


In this case, numerical model guidance was not in agreement, nor consistent.

The Sea Breeze Giveth and the Sea Breeze Taketh Away

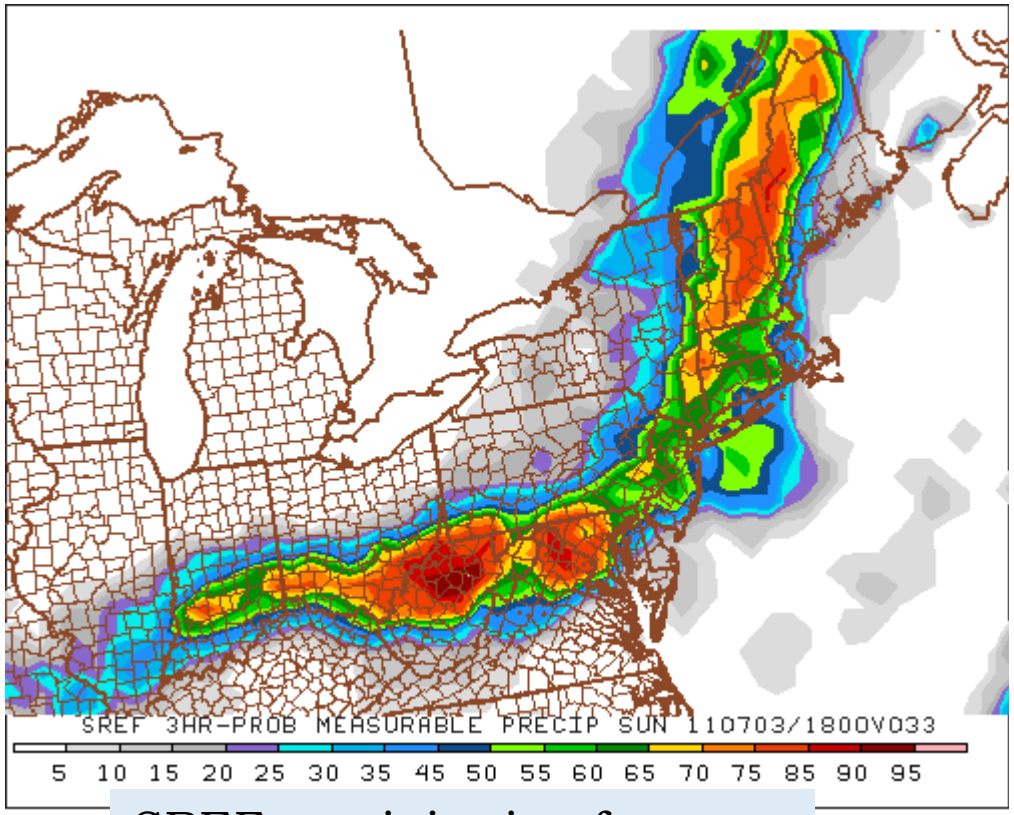


In this case (August 11, 2010) sea breeze re-circulated the previous day's polluted air mass.

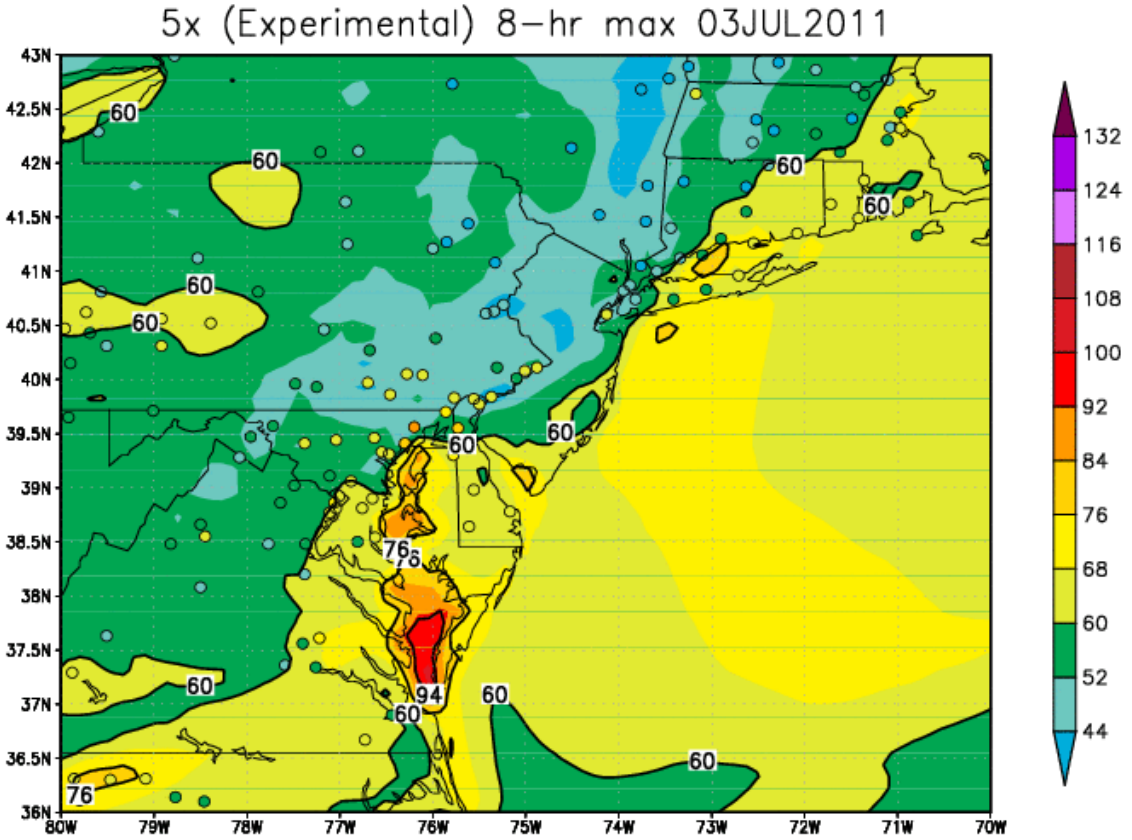


HYSPLIT back trajectories superimposed on AirNow observations

July 3: Impact of Mesoscale Phenomena (Convection)

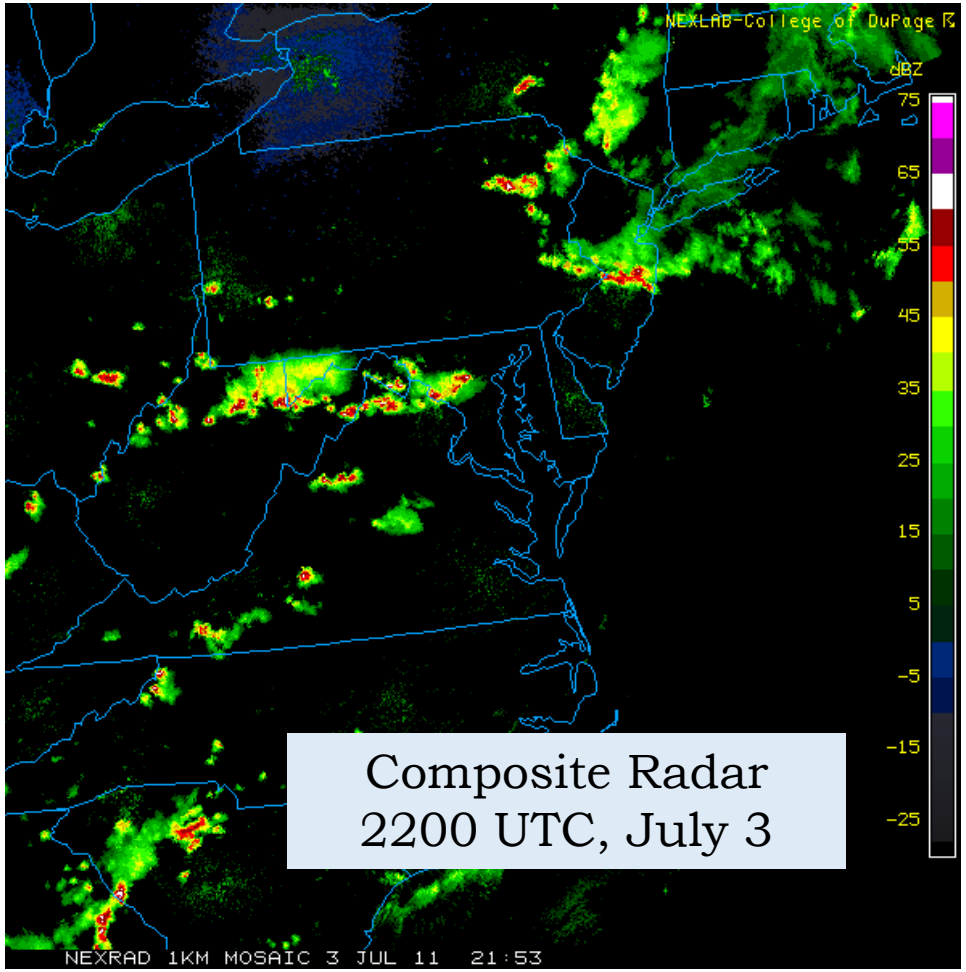


SREF precipitation forecast for 1800 UTC, July 3

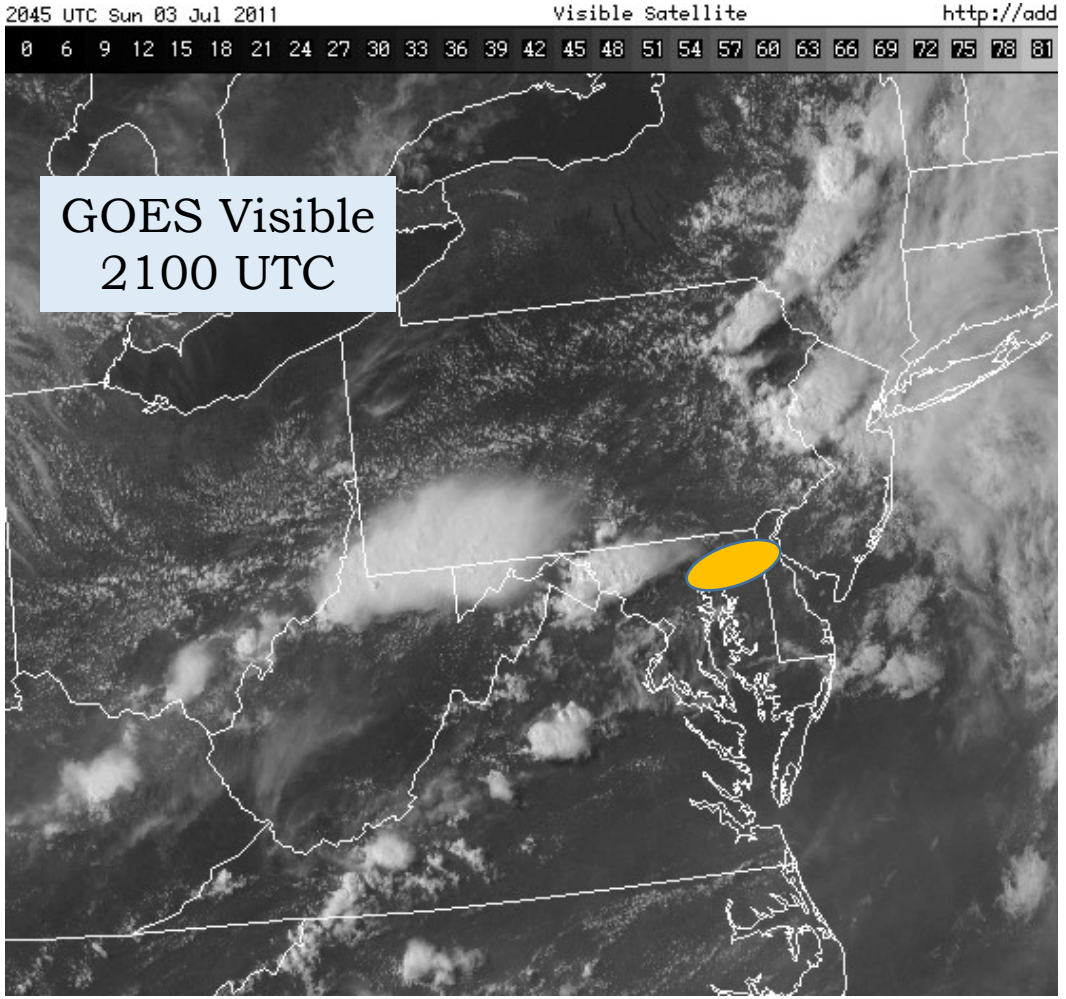


NAQC Forecast Guidance for July 3

July 3: Impact of Mesoscale Phenomena: (Convection)



Composite Radar
2200 UTC, July 3



GOES Visible
2100 UTC

Operational AQ Forecasting Rote

Persistence: Local and Transport

Numerical Model Guidance

Post-Processed Model Guidance
Statistical and Ensemble Guidance

Heuristics and “Unresolved” Effects

Things We Would Like

- Higher resolution in-line or strongly coupled CTMs.
  - Air quality events increasingly driven by mesoscale.
- Fine particle ($PM_{2.5}$) numerical guidance is critical.
  - Few statistical alternatives, particularly in winter season.
- Post-processed guidance for both O_3 and $PM_{2.5}$
- Methods for diagnosing residual layer pollutants.
- Continue efforts to ease access to model output (US).
  - Forecaster community is diverse and non-hierarchial.
- Assimilation of emissions (“top down”).
  - Useful in multi-day intra-regional events. We realize this is a tall order.