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Top-down and bottom-up emissions forecasting for dynamic air quality management

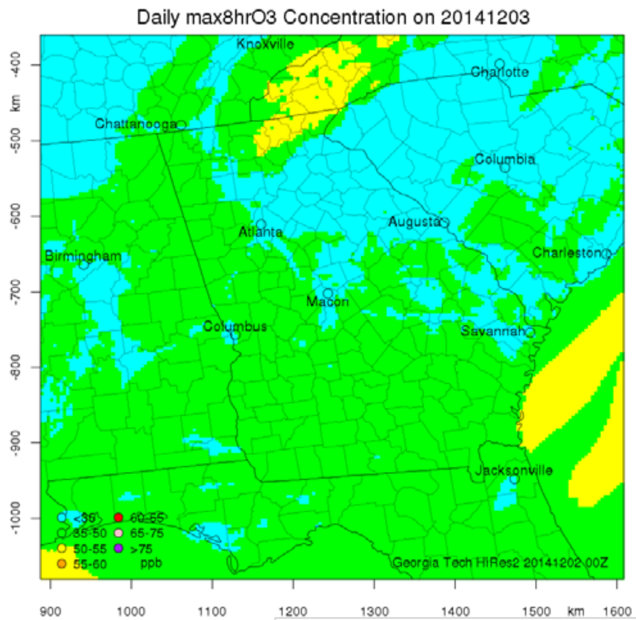
IWAQFR 2015
College Park, MD
September 1, 2015

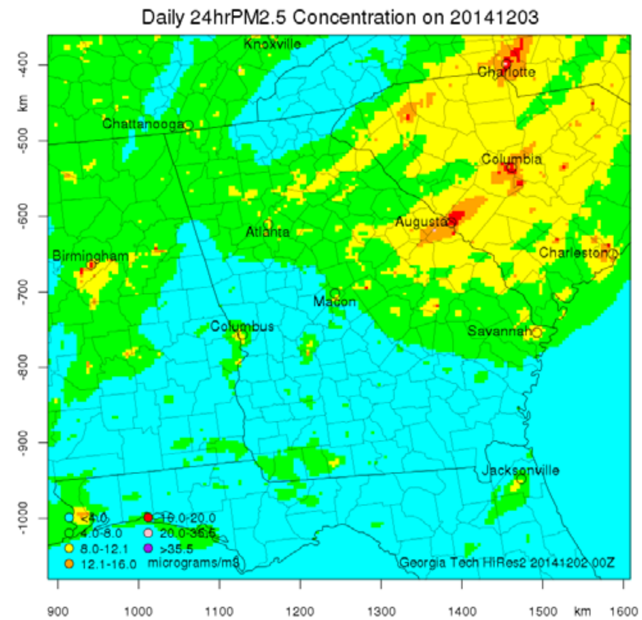
Motivation and Objective

- Motivation:
  - Air quality models provide the backbone of regional and national air quality forecasting systems.
  - Improved AQM forecasting performance is desired.
    - Emissions are uncertain and they change with time.
  - Forecasts of source specific air quality impacts are potentially useful for dynamic air quality management.

- Objective:
  - Provide information that can better assist air quality management
    - Improve air quality forecasting accuracy using near real time measurements (gases, PM, AOD and PM composition) through dynamic adjustment of emissions
    - Forecast source impacts in addition to air quality

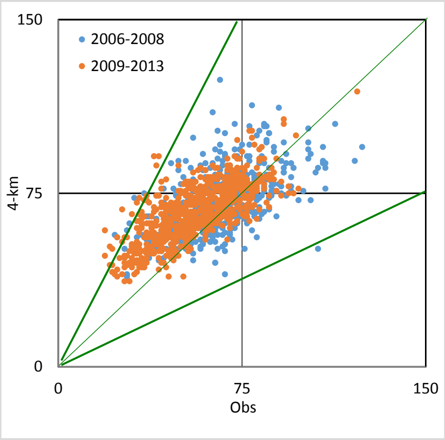
Hi-Res air quality forecasting system has been operational since 2006.





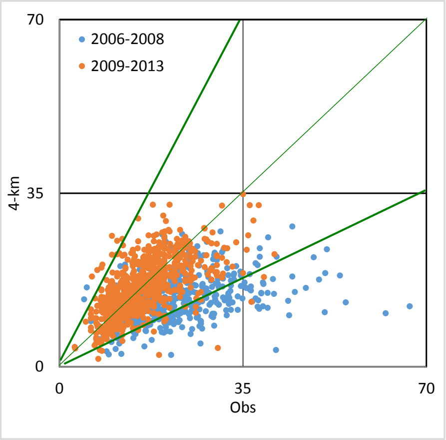
Ozone

MNB	20%
MNE	25%



$PM_{2.5}$

MNB	-10%
MNE	32%

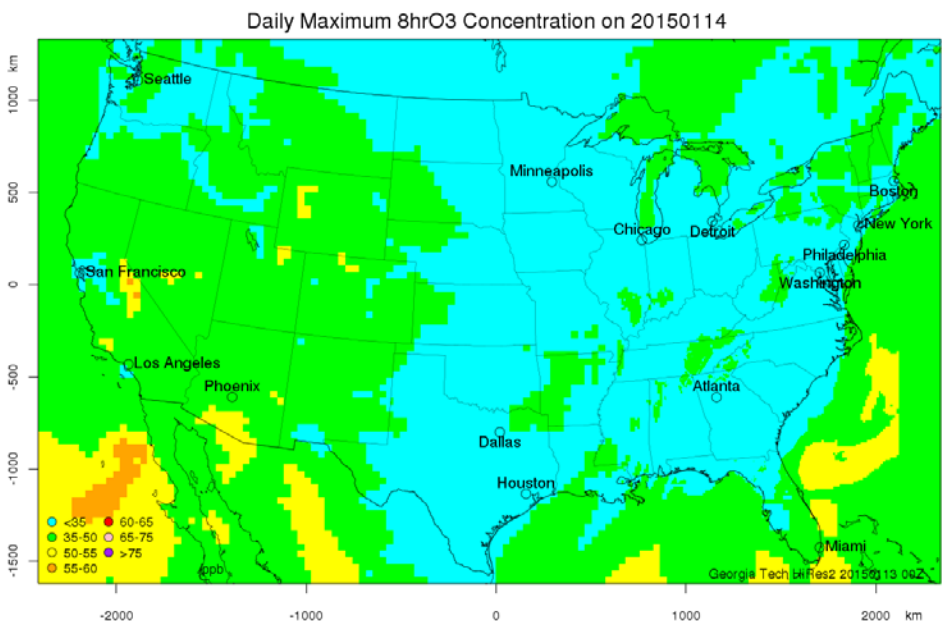


Last year, Hi-Res was updated with the latest versions of its components.

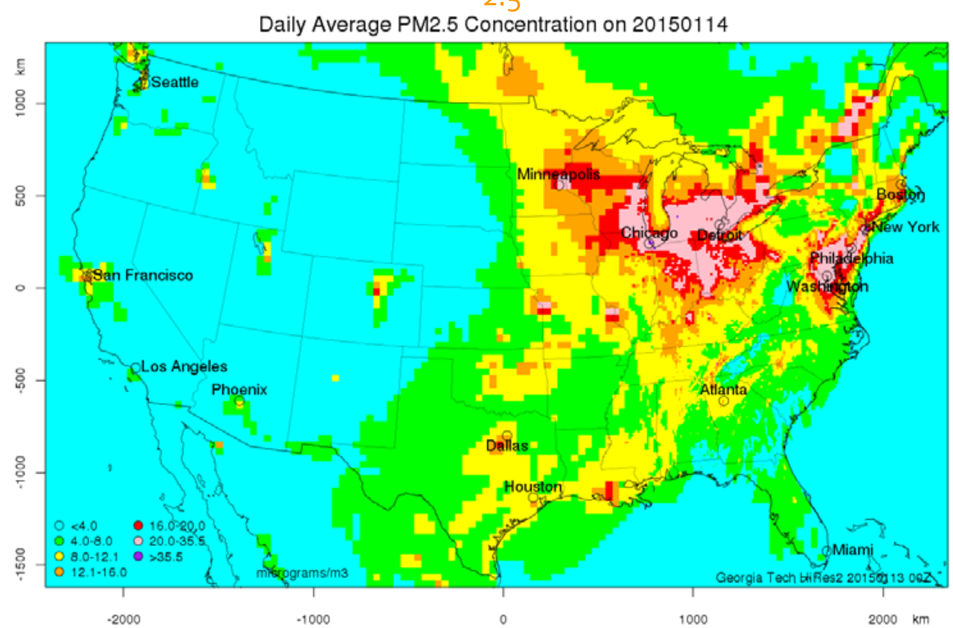
- 2011 NEI base emissions
- WRF3.6.1 and CMAQv5.02
- 72-hour forecasts
- 4-km resolution in/around Georgia
  - 12-km for most of Eastern states
  - 36-km for the rest of CONUS

Hi-Res2
since December, 2014
(https://forecast.ce.gatech.edu)

Ozone



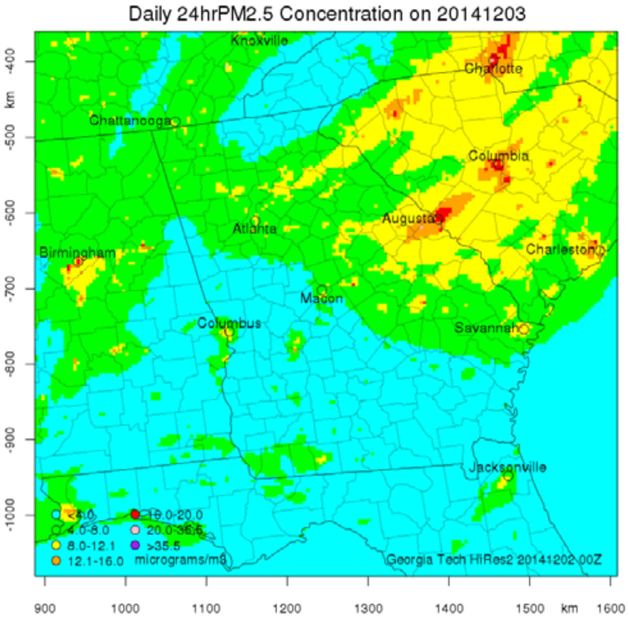
$PM_{2.5}$



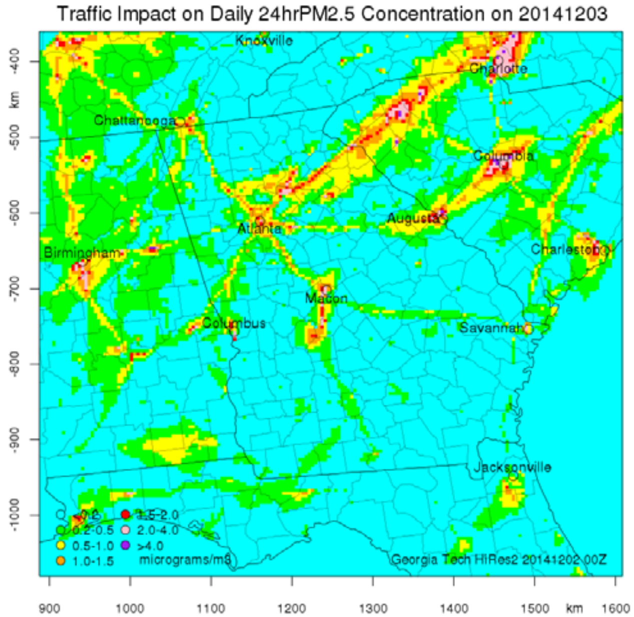
But the most distinctive feature of Hi-Res2 is source impact forecasting.

- Using the Decoupled Direct Method, DDM-3D, Hi-Res2 is forecasting traffic, power plant and prescribed burn emission impacts on O_3 and $PM_{2.5}$.

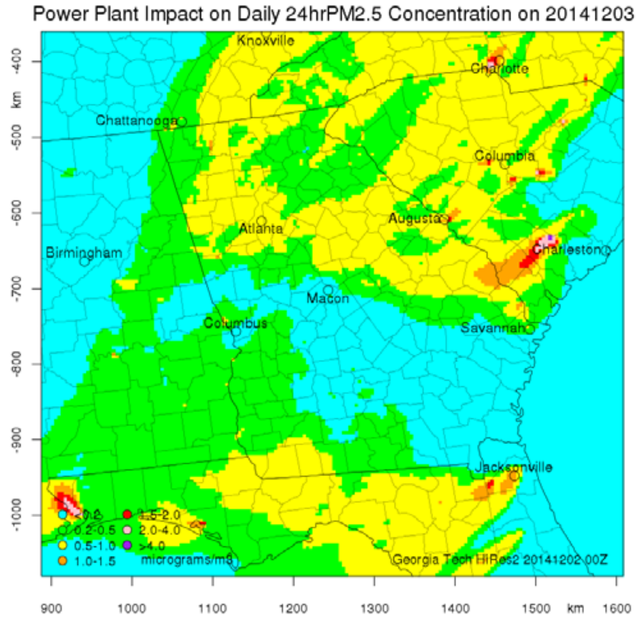
$PM_{2.5}$



Traffic Contribution

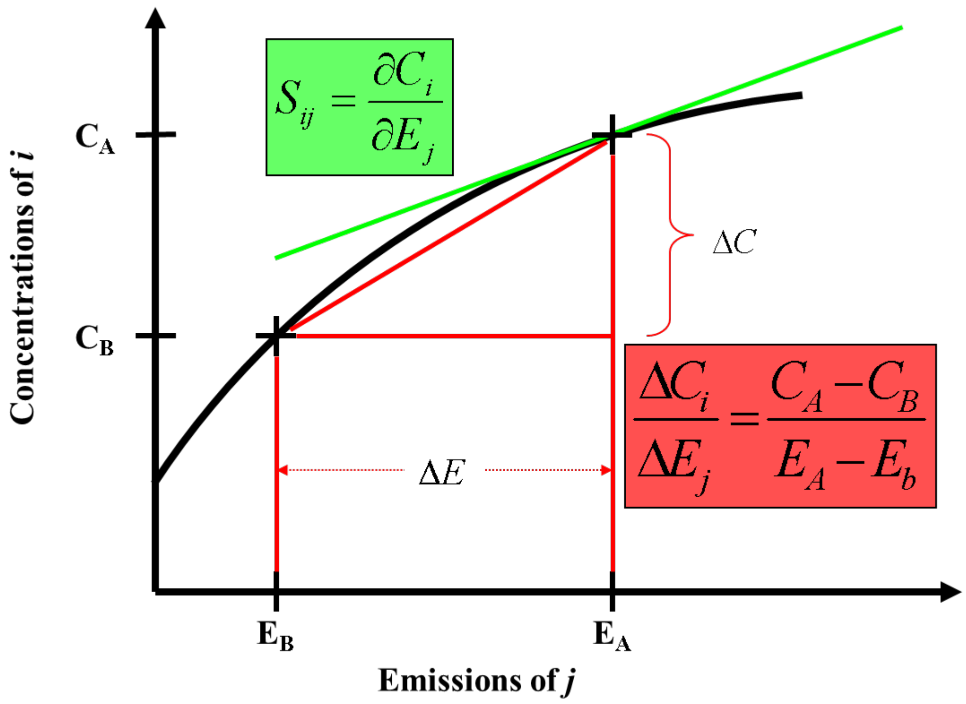


Power Plant Contribution



(The scales for $PM_{2.5}$ and the contributions are different)

With DDM-3D, impacts are calculated independently from concentrations using emission sensitivities.



- Sensitivity is the local change in pollutant concentration due to a change in emissions.
- Impacts can be approximated as:

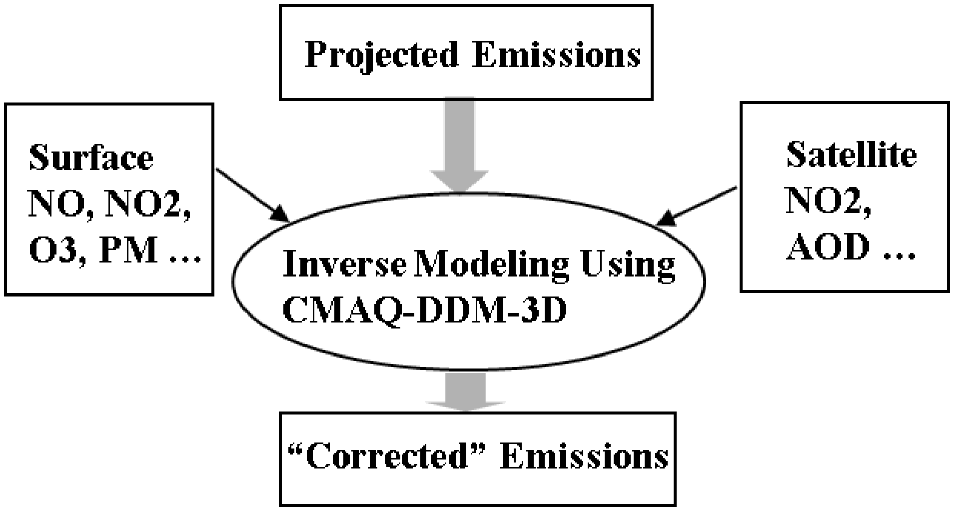
$$\Delta C_i \approx S_{ij}^{(1)} \Delta E_j$$

- Since we are using first order DDM, impacts can be erroneous for large ΔE.

Top-down methods for tracking changes in emissions

Emission sensitivities are used along with air quality observations to adjust emissions.

- An auto-correction system for traffic and power plant emissions utilizing near real-time satellite and surface observations



- Minimizes the differences between forecasted and observed concentrations
- Minimal adjustment to source emissions
- Currently utilizes $PM_{2.5}$ measurements at ~20 sites in Georgia
- Soon with MODIS C6 AOD

The inverse modeling approach for adjusting emissions is an optimization problem.

- Solve for the Adjustment Factors, R_j, that minimize χ^2

DDM-3D calculated sensitivity of concentration *i* to source *j* emissions

emission adjustment ratio

$$\chi^2 = \sum_{i=1}^{N} \left[\frac{\left(c_i^{obs} - c_i^{sim} - \sum_{j=1}^{J} S_{i,j} (R_j - 1) \right)^2}{\sigma_{C_i^{obs}}^2} \right] + \Gamma \sum_{j=1}^{J} \frac{(\ln R_j)^2}{\sigma_{\ln R_j}^2}$$

weigh
t

χ_{Ci}^2

Remaining Error

χ_{Rj}^2

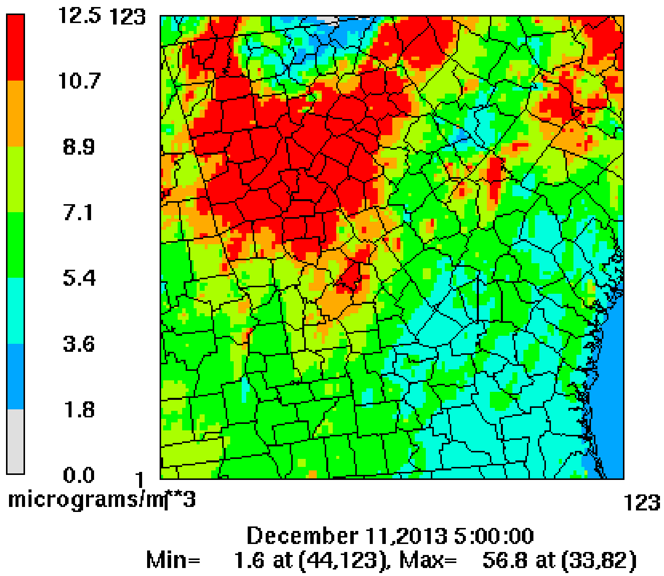
Amount of Change in Source Strengths

L-BFGS algorithm is used for the optimization (R package nloptr)

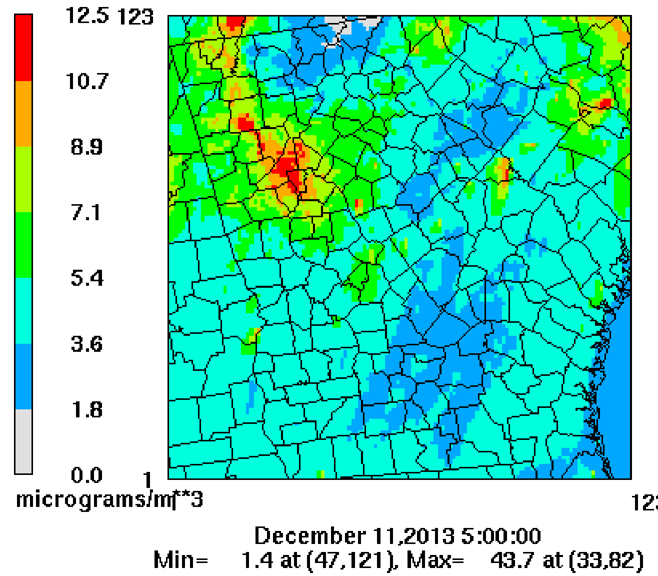
Offline tests of emissions adjustment showed improvement in forecast accuracy.

Dec. 1-7,2013	Area	On-road	Non-road	Point
Adjustment	0.17	0.83	0.85	0.97

Original



Emission Adjusted

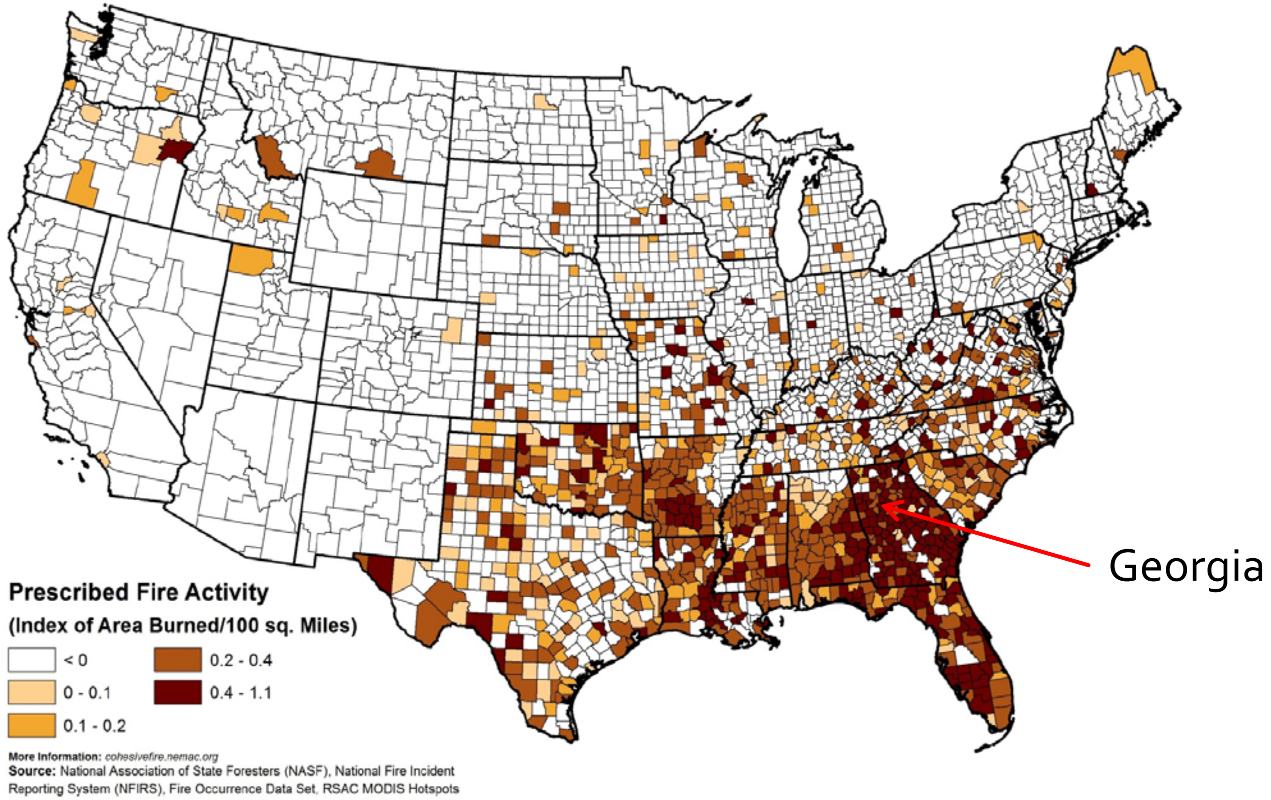


Dec. 8-14, 2013	Obs. (μg/m³)	Sim. (μg/m³)	NFE	NFB
Original	4.64	10.04	86%	85%
Emis adjusted		5.62	54%	39%

Bottom-up methods for prescribed burn (PB) emissions

Prescribed burning (PB) is a major source of $PM_{2.5}$ in Southeastern USA.

PB is practiced to improve native vegetation and wildlife habitat, control insects and disease, and reduce wildfire risk.

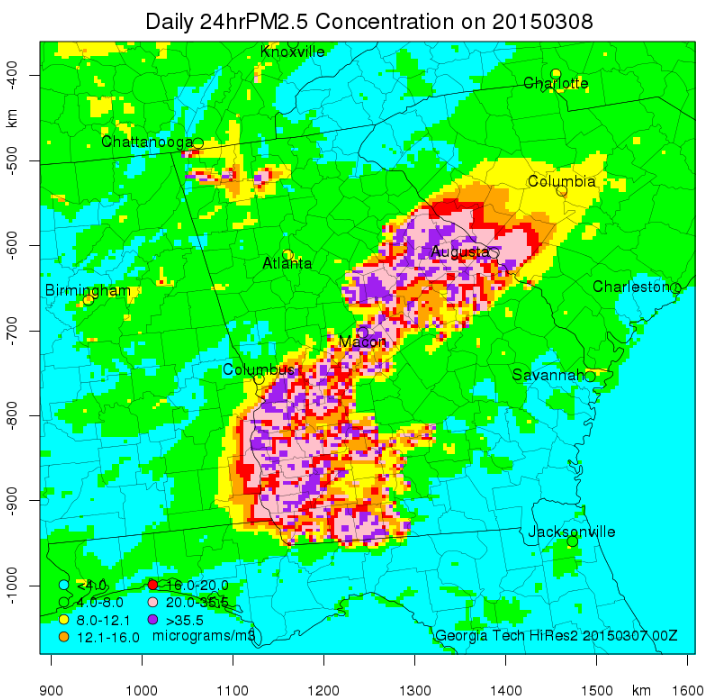


According to US EPA 2011 National Emission Inventory 15% of $PM_{2.5}$ emissions in the USA (840 Gg) are attributable to prescribed burning.

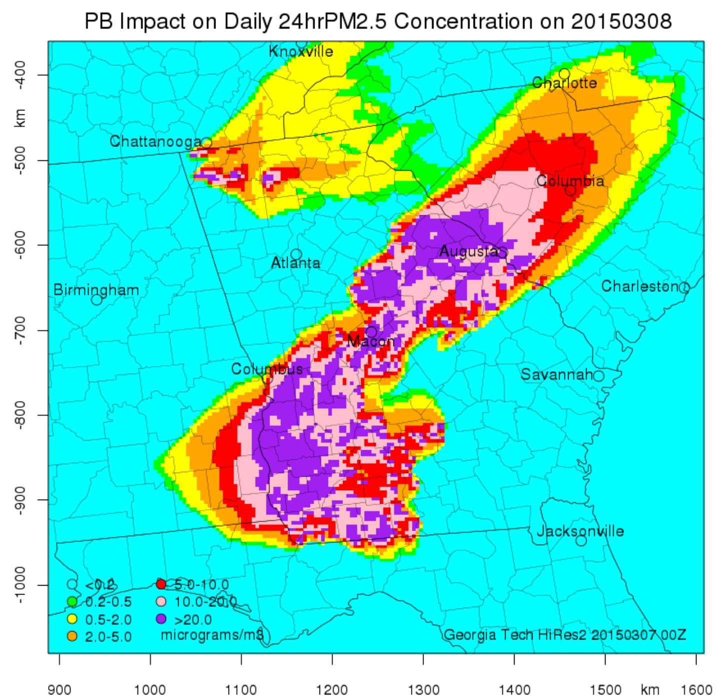
Prescribed burning can yield to dynamic management easier than other sources.

- Burn/no-burn decisions are made daily.
- Decision makers can also consider PB impact forecasts.

PM$_{2.5}$



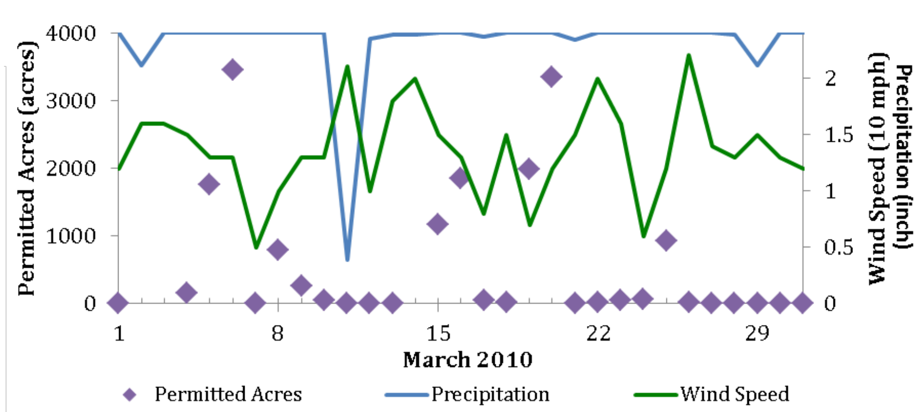
Prescribed Burn Contribution



(The scales for PM$_{2.5}$ and PB contribution are different)

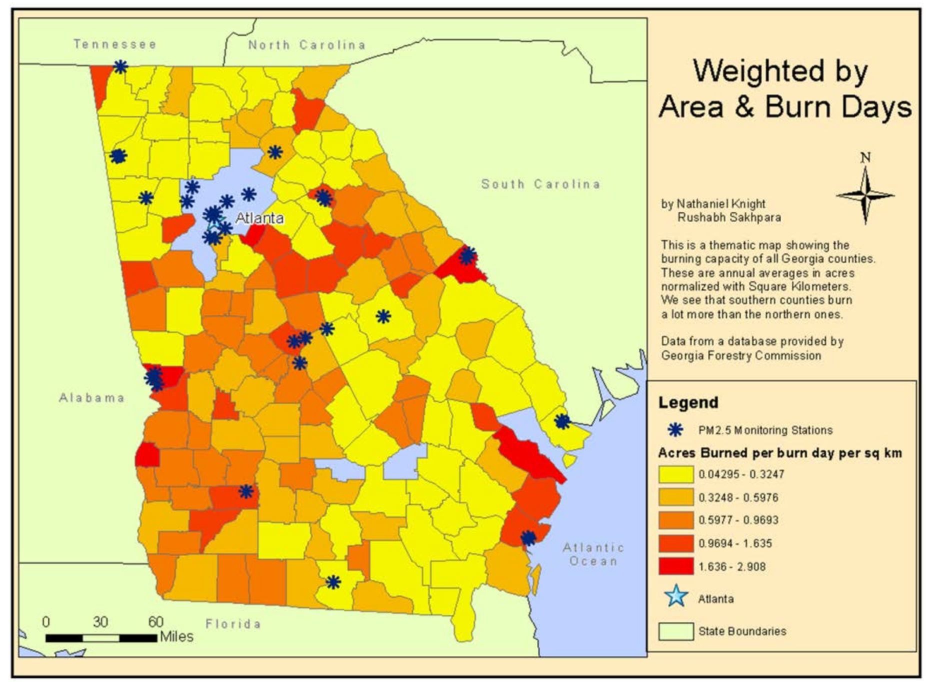
Forecasting PB emissions involves challenging questions: When, where and how much?

- There is a relation between burns and weather.
  - No burns when it rains,
  - Nor when it is windy.



- The locations of the lands treated by PB are known.
  - Georgia Forestry Commission keeps track of burn permits.

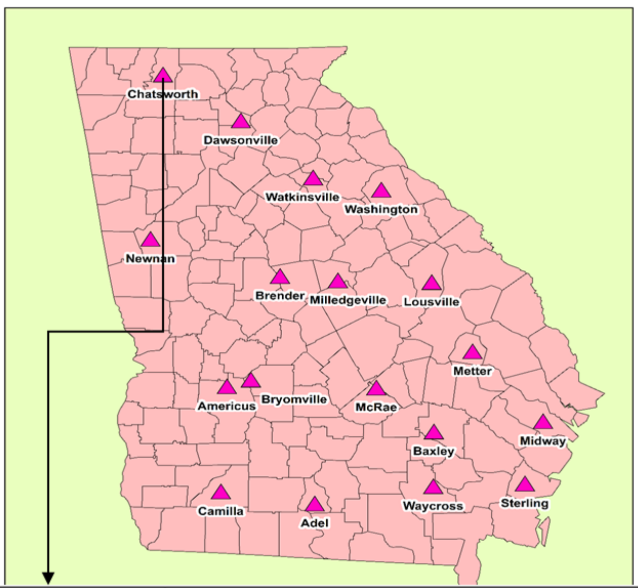
- From the permit data, we derived average daily burn area for each of the 159 counties in Georgia.



We built a burn forecasting model using the fire weather and burn permit data.

- There are 18 fire weather stations in Georgia.

Fire Weather Stations

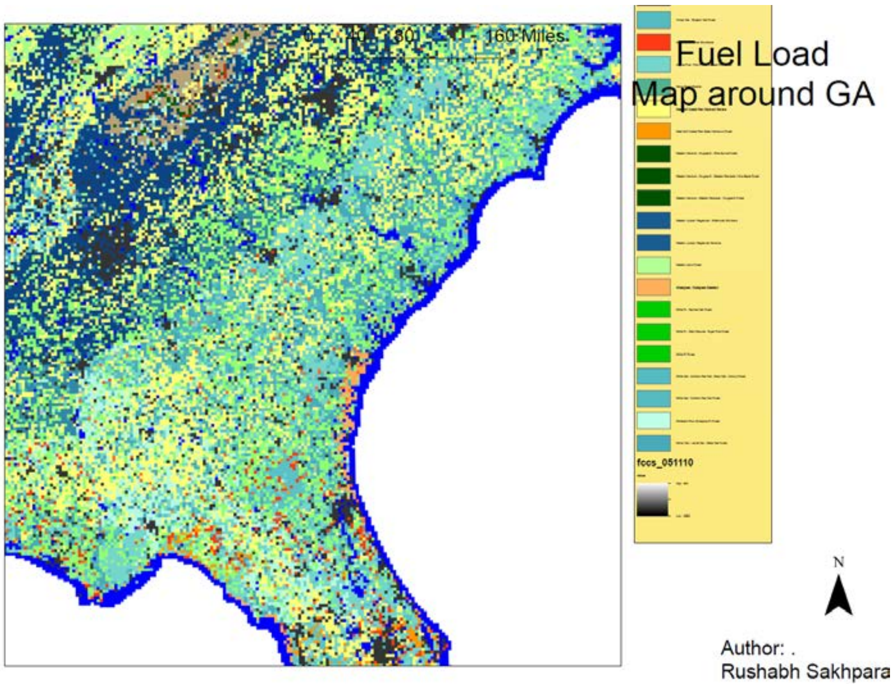


Chatsworth, Ga		Observed NFDRS-88 at 1300 EST Jul 20 2015						
RH (%)	IC	BI	Class Day	KBDI	Wind (mph)	Mx_Wind (mph)	Rn24 (inch)	Dur (Hr)
54	18	22	2 Moderate	359	S 2	S 9	0.29	2
Sow	Temp (°F)	Td (°F)	Tmax (°F)	Tmin (°F)	RHMax (%)	RHMin (%)	HrbGF	WdyGF
0	94	75	92	72	97	58	12	12
1-Hour	10-Hour	100-Hour	1000-Hour	X1000	Herbaceous	Woody	SC	EC
8.0	8.0	16.0	19.9	18.8	84.8	120.7	5	16

- Predictor variables:
  - Temp, RH, WS, Rain duration, Drought Index and some other fire meteorology variables
- Training dataset: 2010-2014 burn permit and observed fire weather data
  - Matched weather data with burn permits in the county of the monitor
  - Single, statewide decision tree model
- The model uses the fire weather forecast to predict whether tomorrow will be a burn day.
  - If burn day in central monitor's county, burn day in the entire fire district.

Forecasted PB emissions are input to CMAQ and their impact is calculated using DDM-3D.

- We are using FCCS fuel load maps.
  - Satellites can provide more up-to-date data.

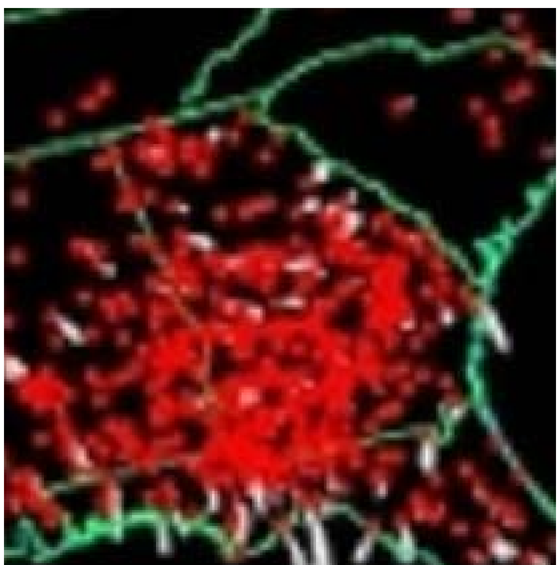


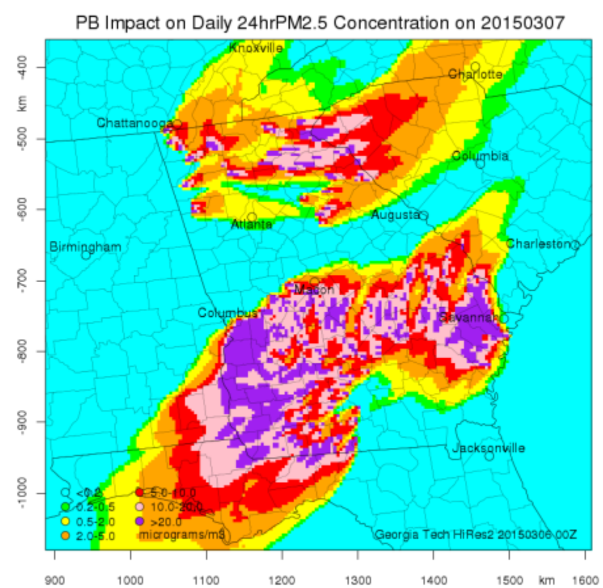
- Estimate emissions for forecasted burns
  - Fuel moisture observations for fuel consumption
  - Emission factors for Southeastern USA fuels
- Calculate plume rise
  - Fraction below/above PBL height using Briggs formulae.
- Forecast impacts of PB emissions on O_3 and $PM_{2.5}$
  - Currently statewide, by fire district and by county in the future.

Satellite fire & smoke analyses can be used for evaluating the PB forecasts.

- We compare our forecast qualitatively to the Hazard Mapping System Fire and Smoke Analysis by NOAA.
- We give each day's forecast a rating based on the agreement in location and density of fires.

February 13, 2015: rated very good

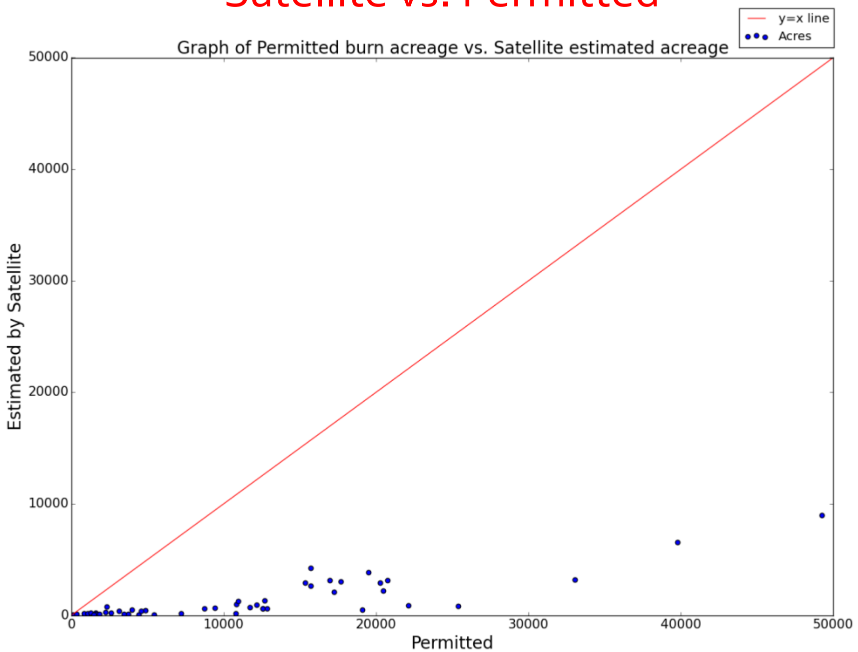




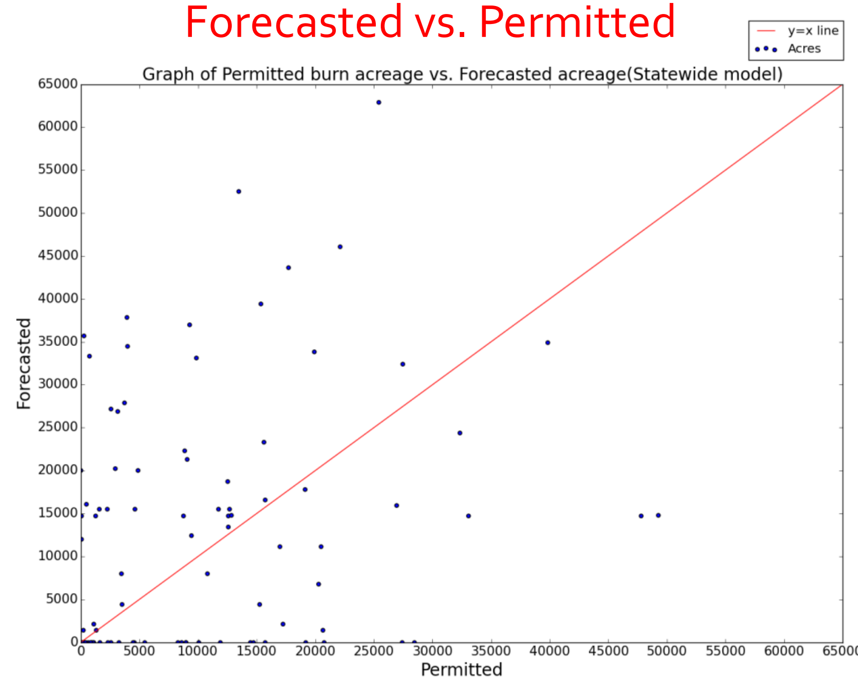
Burn areas from satellites and permitted burn areas can be used for quantitative evaluation.

- We compare our forecasts to:
  - Burn area and emissions provided by the Biomass Burning Emission Product of NOAA
  - Burn areas permitted by the Georgia Forestry Commission

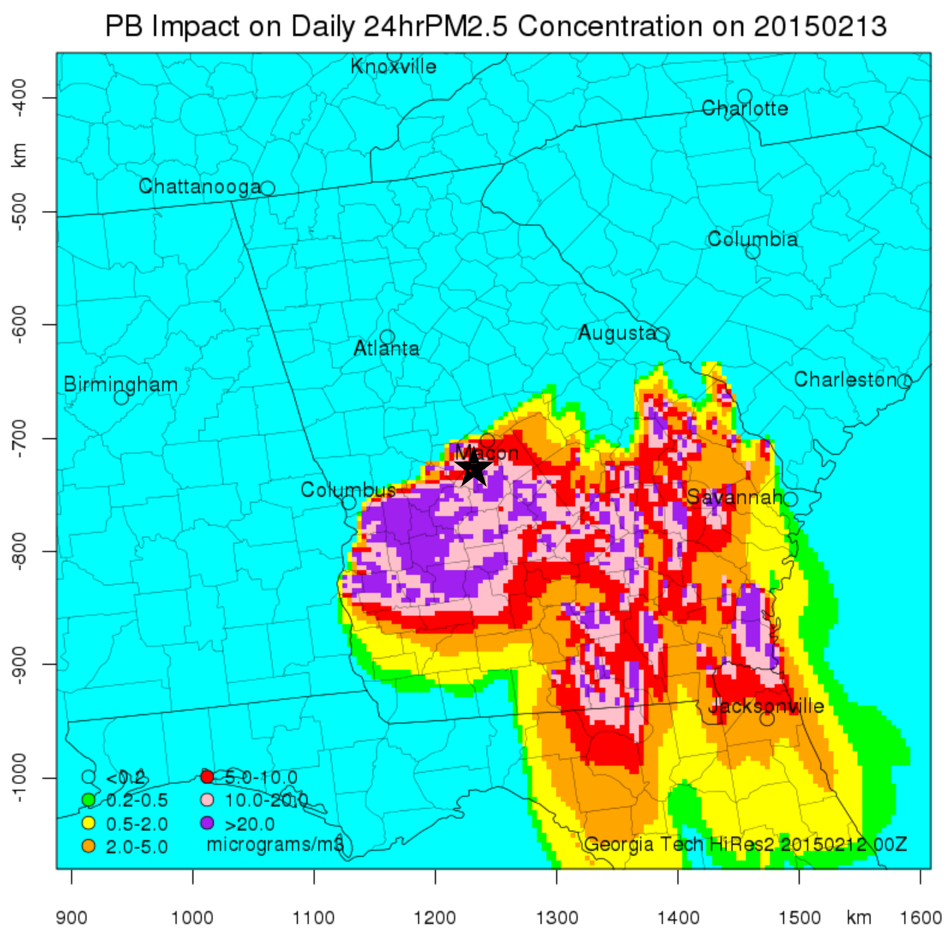
Satellite vs. Permitted



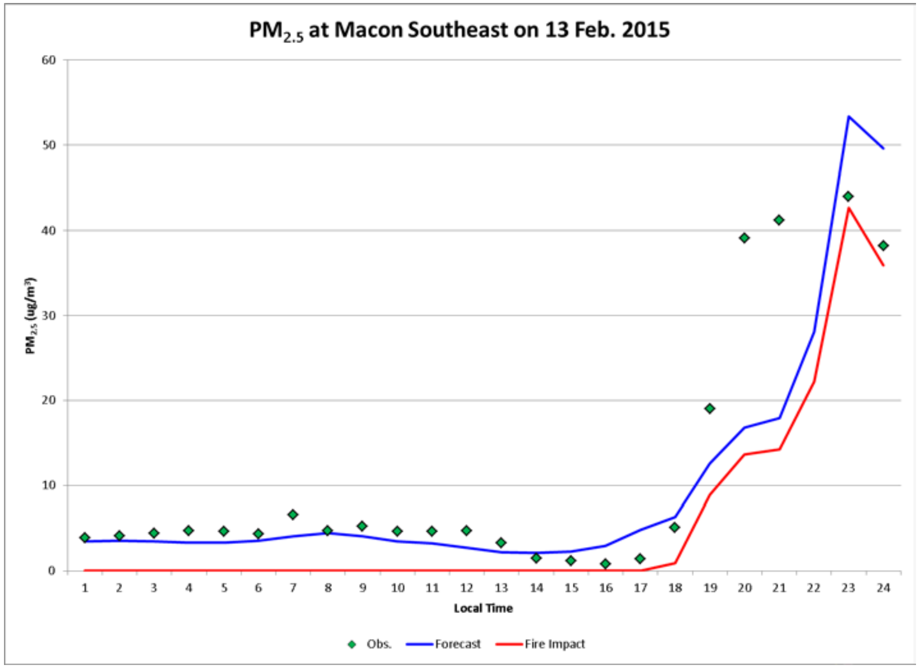
Forecasted vs. Permitted



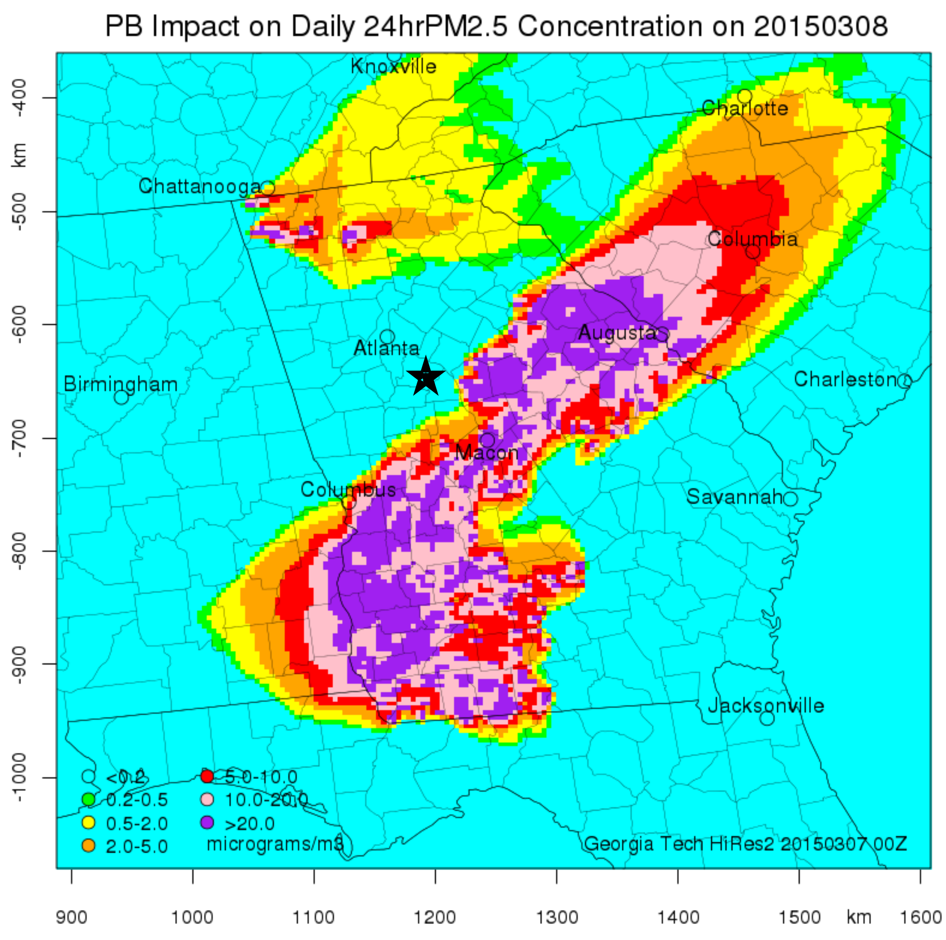
Ground-level $PM_{2.5}$ observations can be used for evaluating the impact forecast.



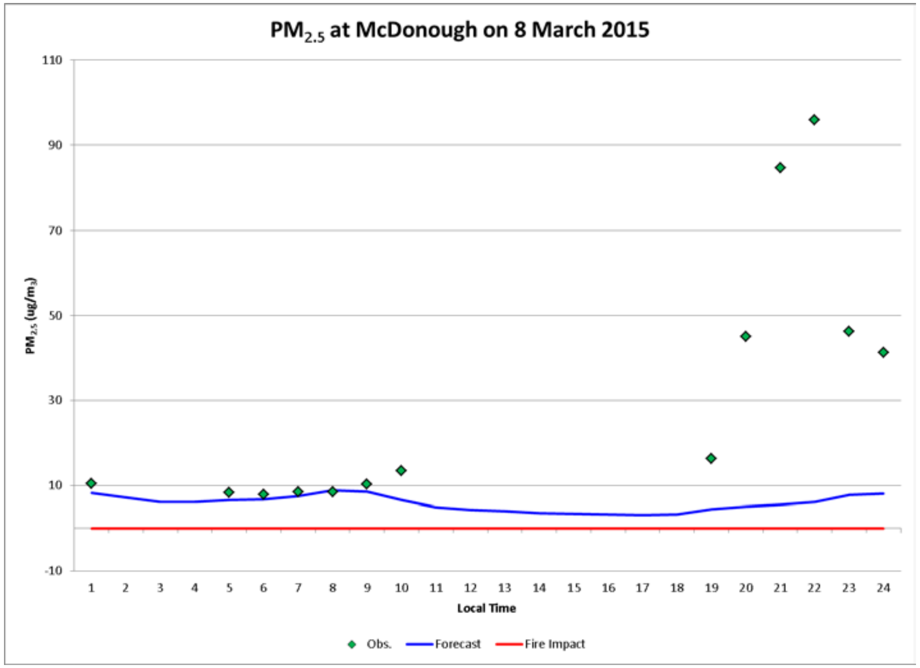
A hit (true positive)



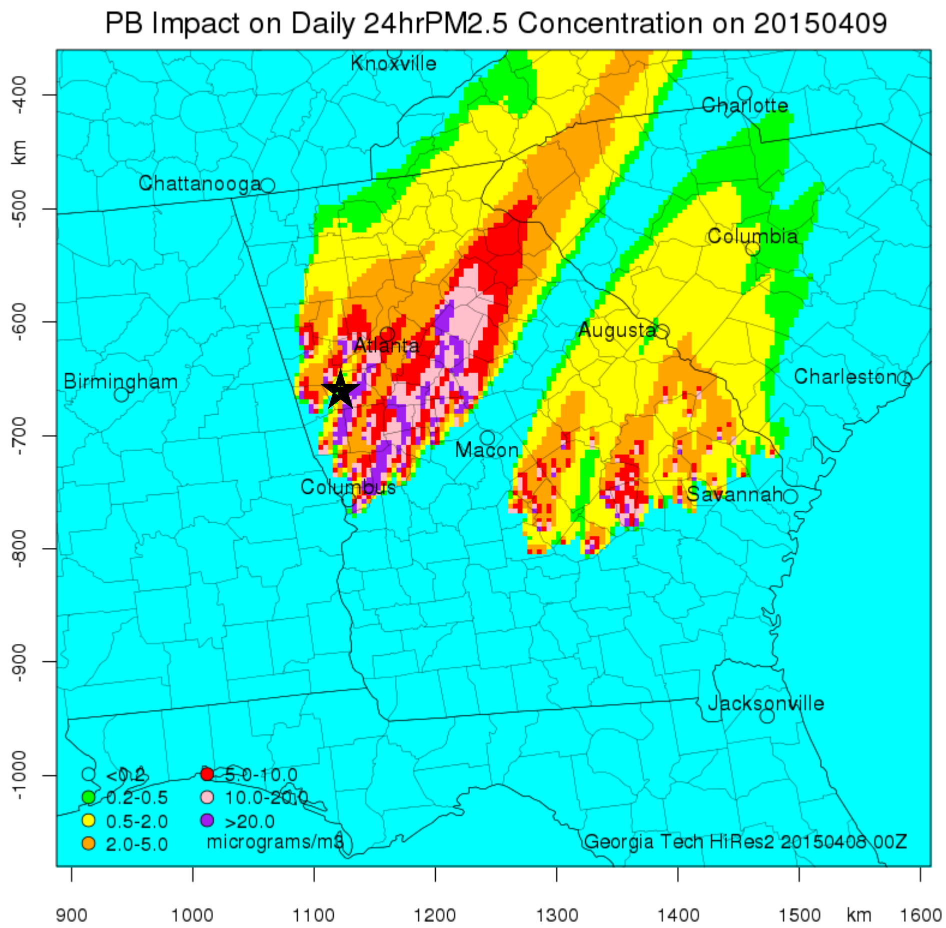
There are cases where the burn forecast can be improved.



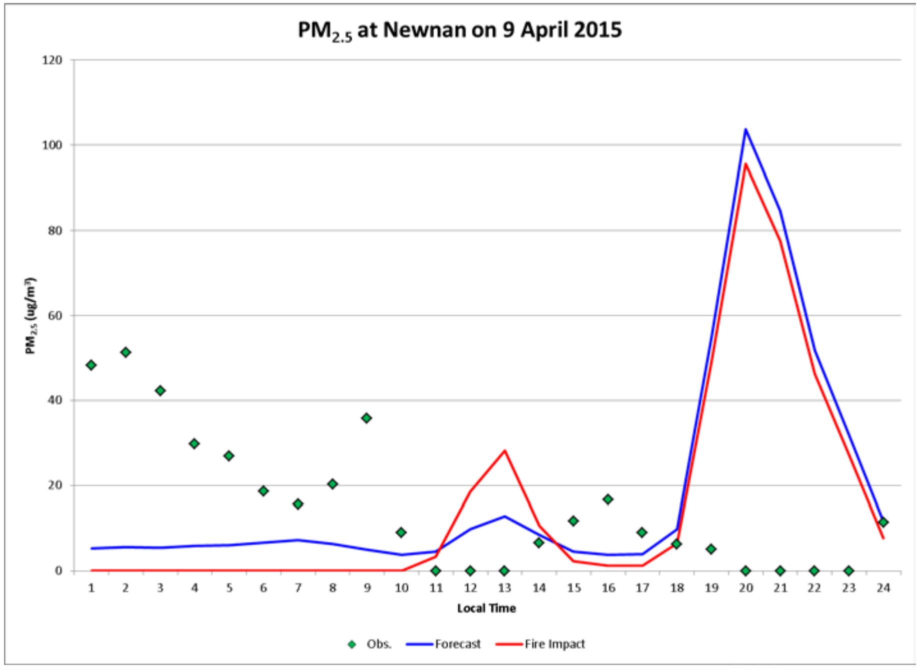
A miss (false negative)



Each burn impact case must be analyzed carefully.

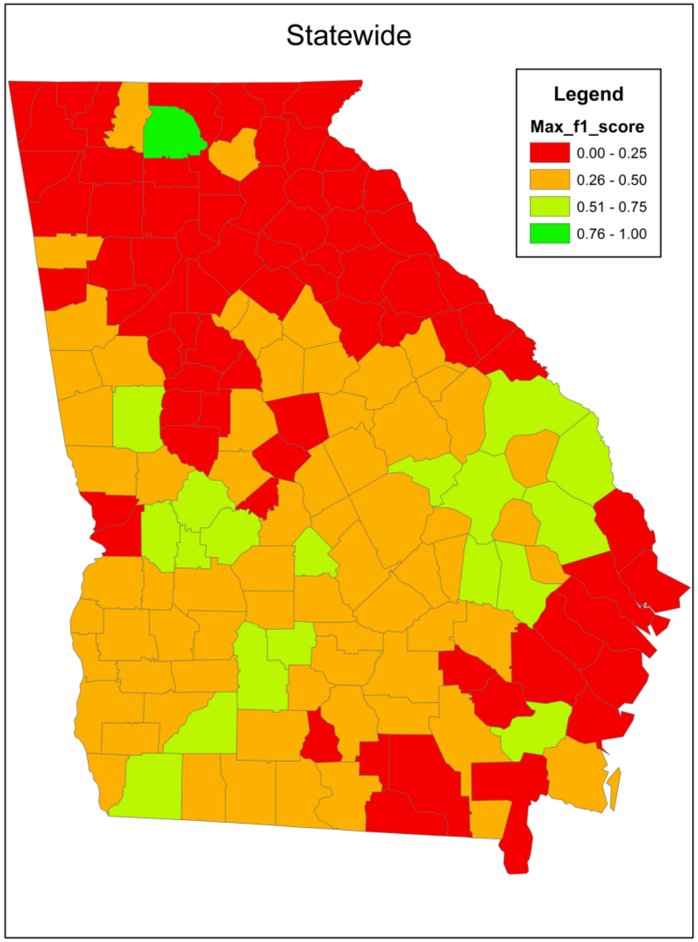


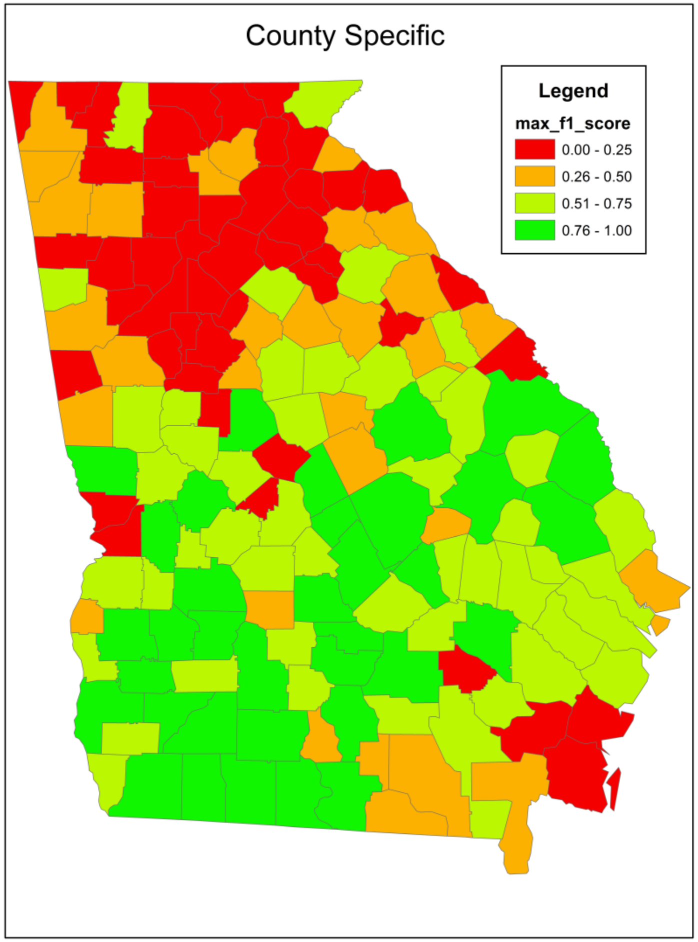
A false alarm (false positive)



County-specific models perform much better than the statewide burn forecast model.

- Based on the F1 Score (harmonic mean of precision and recall)





Summary & Conclusions

- We have started source impact forecasting and dynamic emissions adjustments with the Hi-Res2 air quality forecasting system (https://forecast.ce.gatech.edu).
- Forecasting prescribed burn impacts may be very beneficial for dynamic air quality management.
- We are forecasting prescribed burn emissions for accurate forecasting of the burn impacts.
  - County-specific regression models will yield much more accurate burn forecasts than the statewide model we used so far.
- Evaluation of the forecasted PB impacts is a difficult task.
  - Satellites do not seem to detect the low intensity prescribed burns.
  - There are only a handful of PB impacts at the ground monitoring sites.

Acknowledgements

- NASA (Air Quality Applied Sciences Team)

AQAST
NASA Air Quality Applied Sciences Team

- US EPA

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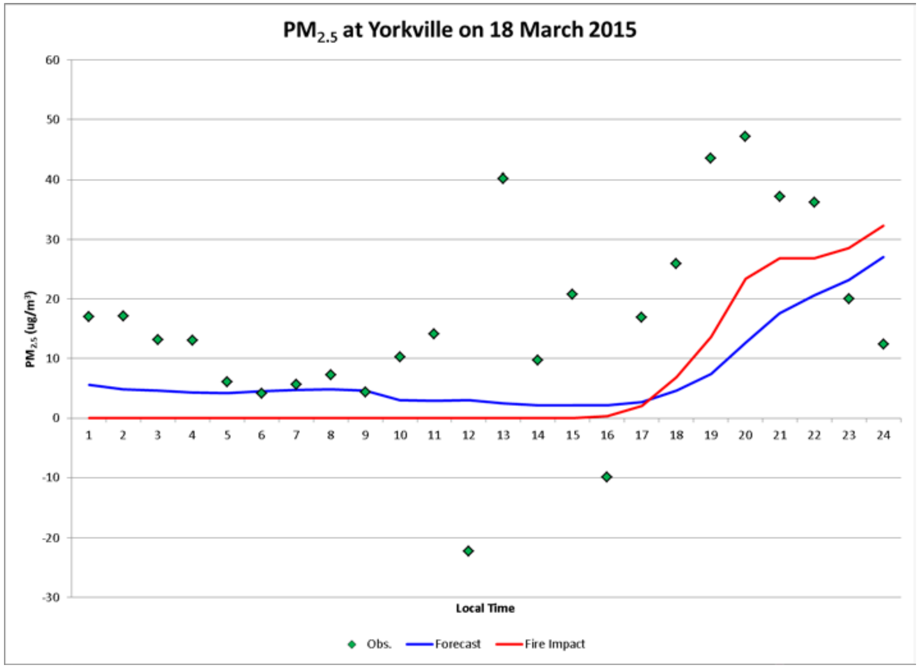
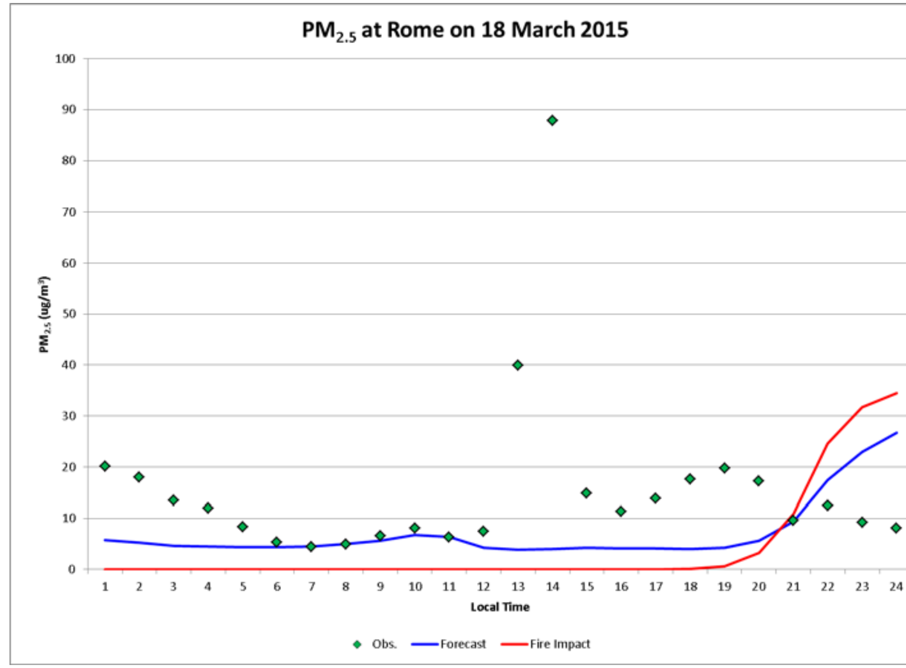
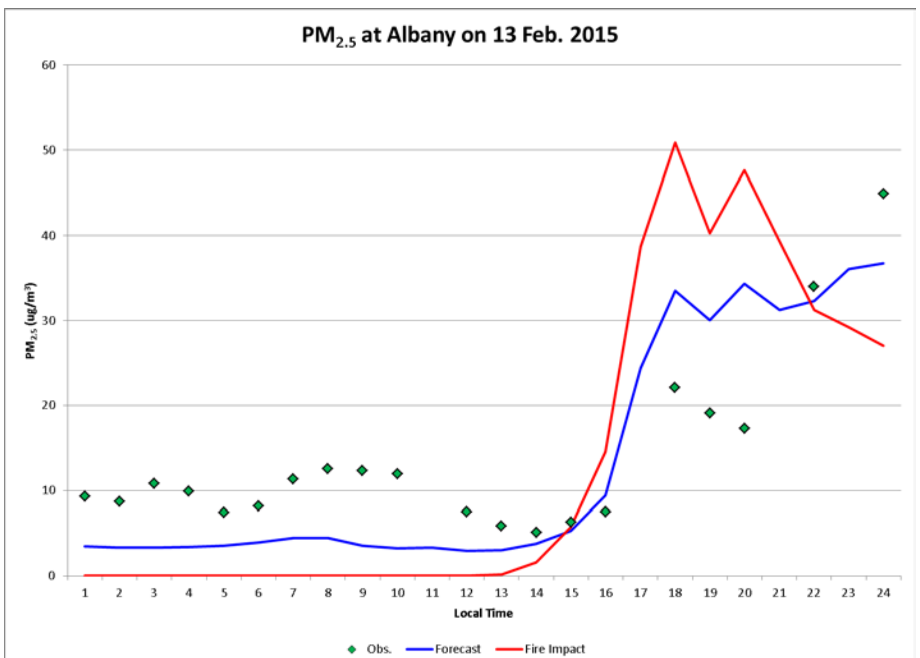
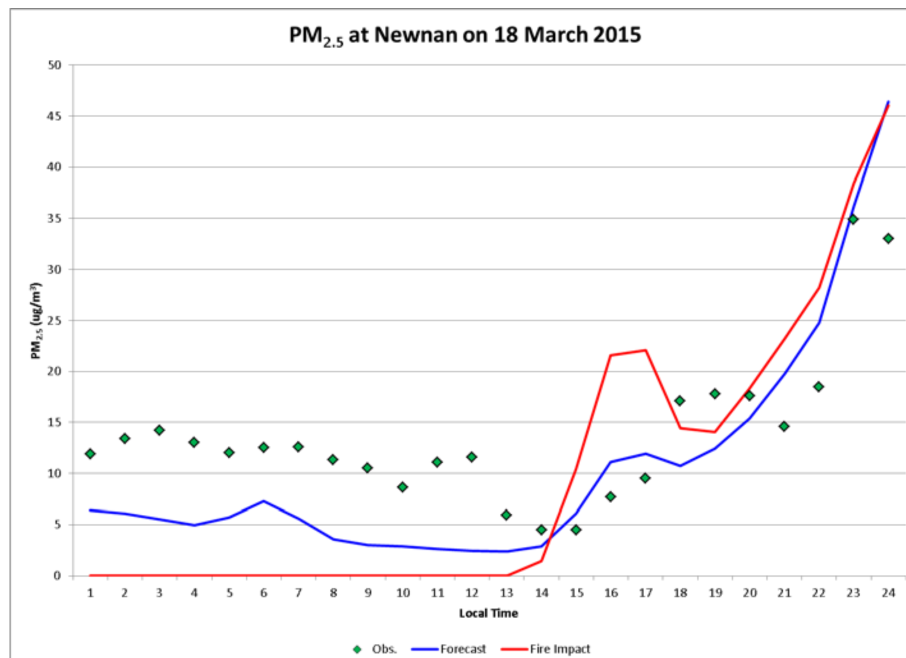
- Georgia Environmental Protection Division
- Georgia Forestry Commission

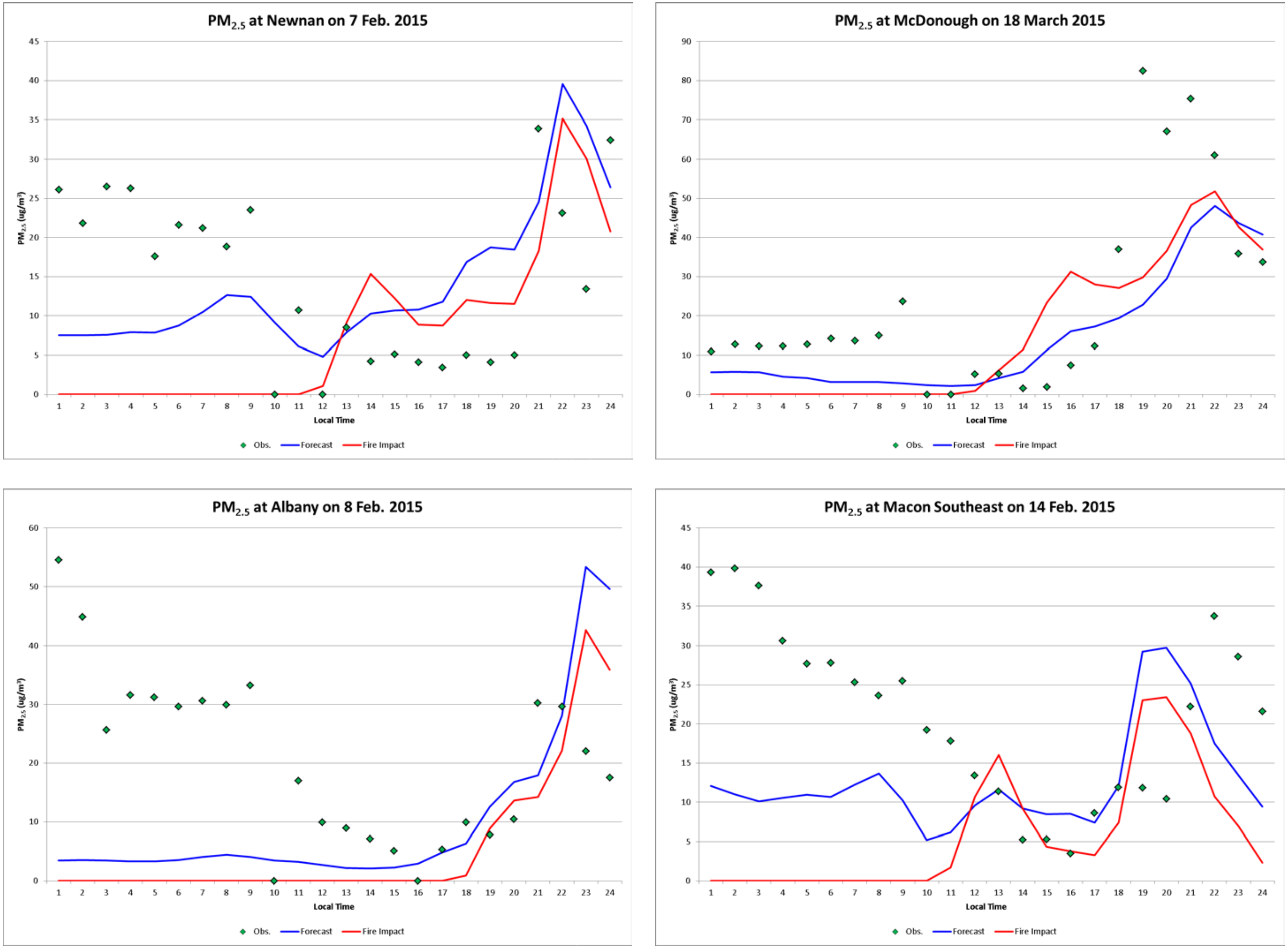
Supplement


PM2.5 at Yorkville on 18 March 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact


PM2.5 at Rome on 18 March 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact


PM2.5 at Albany on 13 Feb. 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact


PM2.5 at Newnan on 18 March 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact



PM2.5 at Newnan on 7 Feb. 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact
PM2.5 at McDonough on 18 March 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact
PM2.5 at Albany on 8 Feb. 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact
PM2.5 at Macon Southeast on 14 Feb. 2015
PM2.5 (ug/m³)
Local Time
Obs.
Forecast
Fire Impact

Lesson learned: the burn forecast needs improvement.

We use the F1 score for evaluating the burn forecast models.

- F1 Score: Harmonic mean of precision and recall

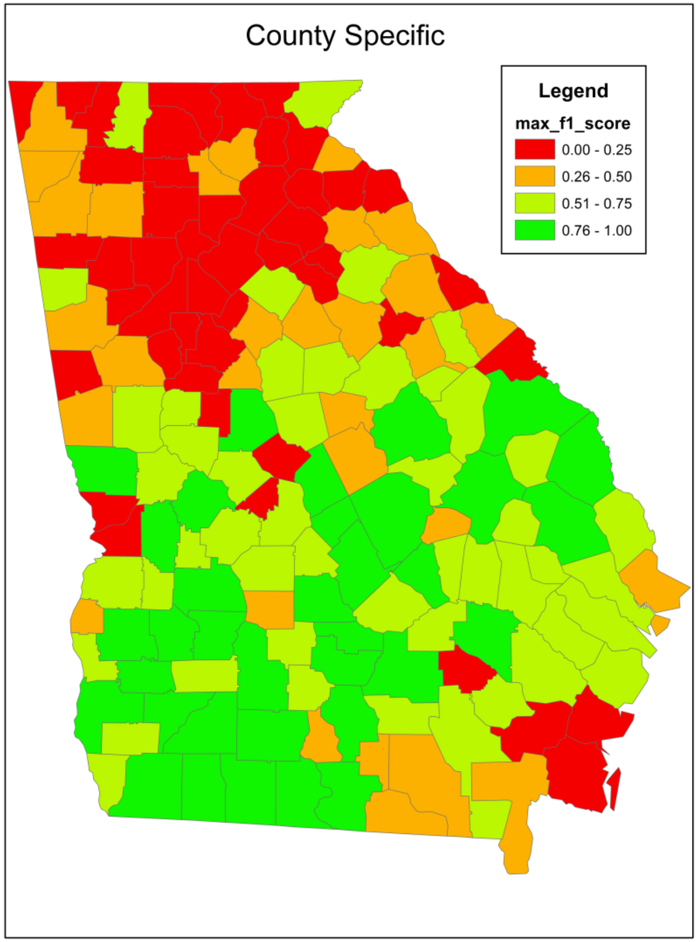
$$\frac{Precision \times Recall}{(Precision + Recall)/2}$$

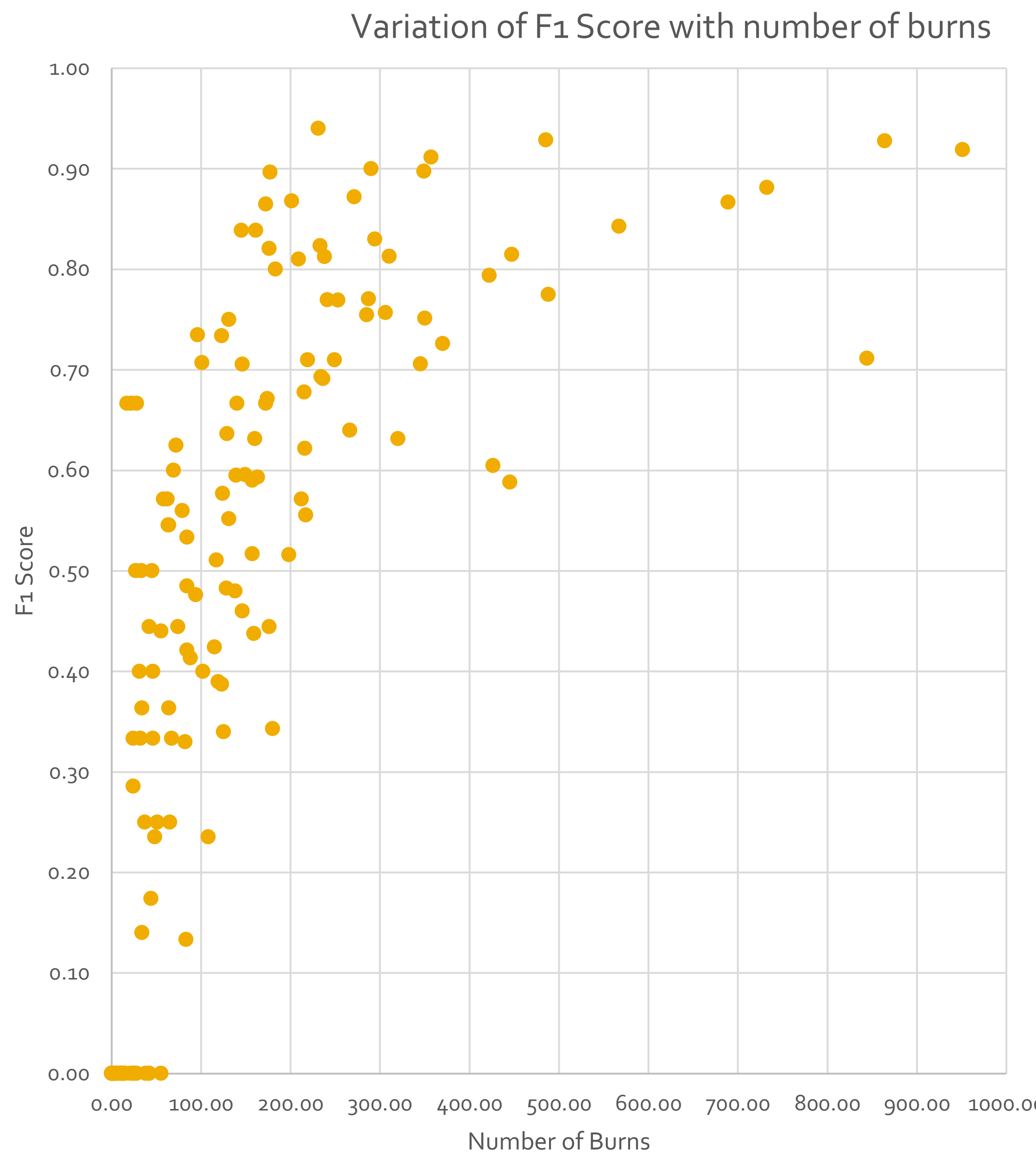
- Precision

$$\frac{True\ Positives}{True\ Positives\ +\ False\ Negatives}$$

- Recall

$$\frac{True\ positives}{True\ Positives\ +\ False\ Positives}$$


County Specific
Legend
max_f1_score
0.00 - 0.25
0.26 - 0.50
0.51 - 0.75
0.76 - 1.00


Variation of F1 Score with number of burns
F1 Score
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700.00
800.00
900.00
1000.00
Number of Burns

Lesson learned: intra-annual variation of burn acreage is very large.

- Monthly average burn day acreage should lead to better burn impact forecast performance compared to annual average.