FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

An Integrated Measurement and Modeling Study of UFP due to Aircraft Operations at Boston Logan

Sarav Arunachalam
Institute for the Environment
The University of North Carolina at Chapel Hill

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Project Team

- Chowdhury Moniruzzaman, **Sarav Arunachalam**
  - UNC Institute for the Environment
- Chloe Kim, **Jonathan I. Levy**, Claire Schollaert, Bethany Haley, Matthew Simon, **Kevin J. Lane**
  - Boston University School of Public Health

Motivation

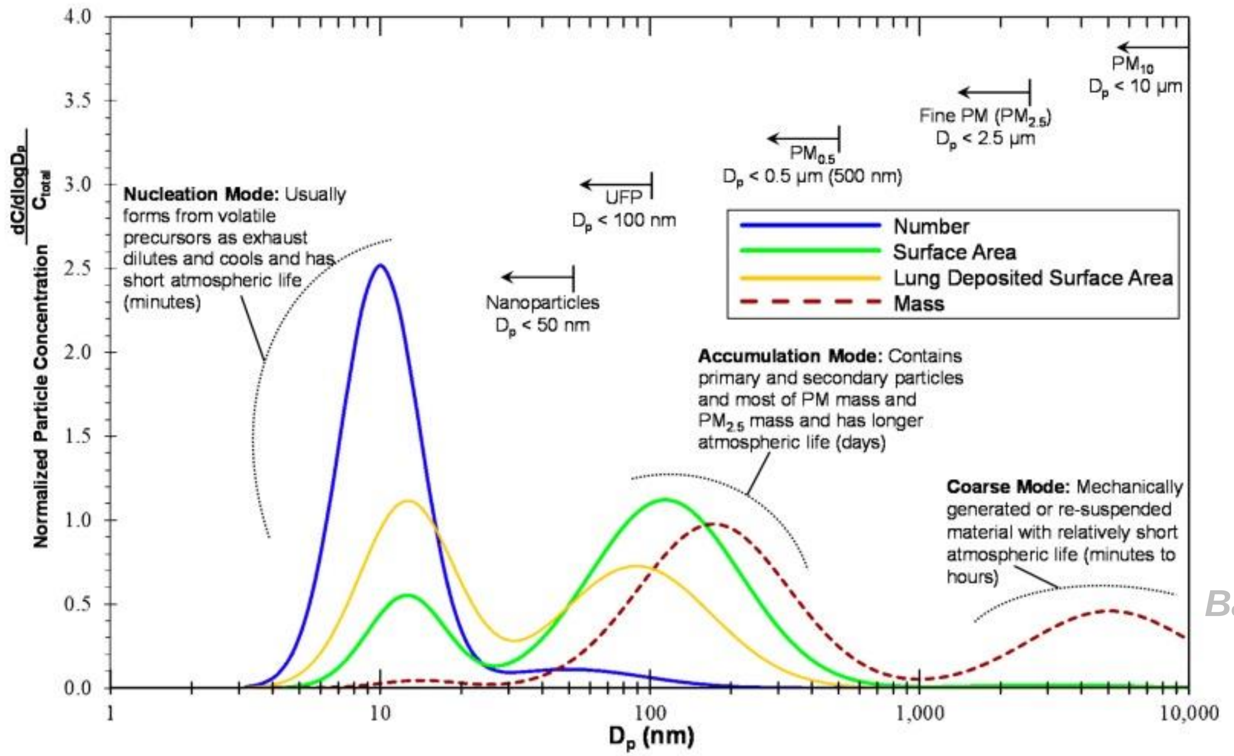
- Recent measurement campaigns at several airports have shown significant levels of Ultrafine Particulate Matter (UFP) due to aircraft LTO operations at Los Angeles, Boston, Amsterdam, Rome, Tianjin, etc.
    - 4- to 5-fold increase to 8-10 km downwind in LAX
    - 1.33- to 2-fold increase to 4-7.3 km downwind in BOS

  Hudda et al 2014, 2016a,b; Keuken et al 2015; Riley et al 2016; Staffogia et al 2016; Ren et al 2016

- Emerging studies show adverse health impacts due to exposure to submicron particles

- Dispersion modeling with multi-component chemistry and aerosol microphysics, combined with measurements will provide integrated assessment of UFP due to aircraft operations at an airport

Particulate Matter (PM)



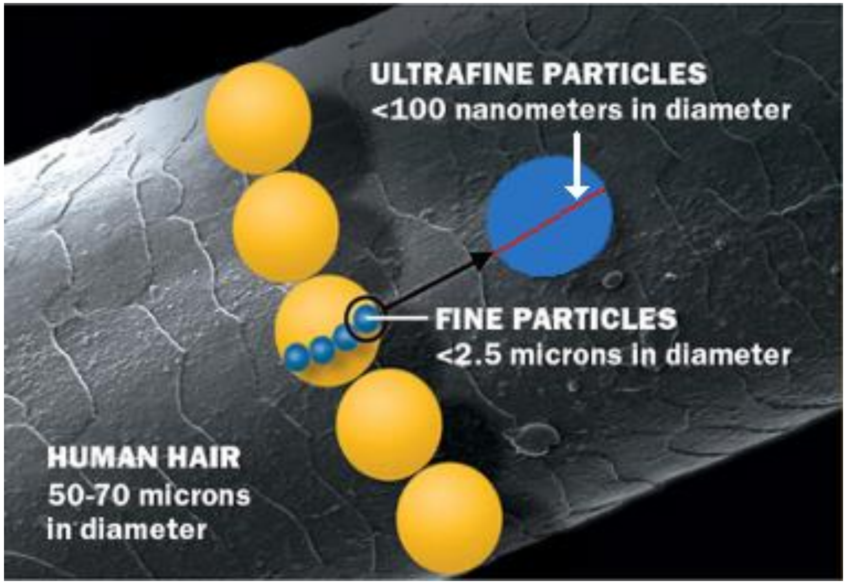
Baldauf et al, 2016

- PM is a mixture of solid particles and liquid droplets found in air
  - Primary particles: directly emitted by various sources
  - Secondary particles: formed by atmospheric chemical reactions
- PM has 3 main physical characteristics
  - Number, Mass and Chemical Composition
- All particles of size < 10 microns have adverse effects on human health, and visibility
  - PM_{10} / $PM_{2.5}$ / $PM_{0.1}$
- Health-based standards exist for PM_{10} and $PM_{2.5}$ on a mass basis
  - The literature on $PM_{0.1}$ based health impacts is evolving

Measurement and Modeling Approach

- Conduct air pollution monitoring of **ultrafine particulate matter (UFP)** underneath flight paths, to assess:
  - Phase 1: the magnitude and spatial distribution of UFP in the vicinity of an **arrival flight path 4R/4L** (2017)
  - Phase 2: the magnitude and spatial distribution of UFP in the vicinity of **all landing and takeoff flight paths** (2018)
- Perform air quality modeling using
  - Phase 1: SCICHEM[1]
  - Phase 2: High resolution CMAQ[2] (12/4/1-km)

PM_{10} vs PM_{25} vs $PM_{0.1}$



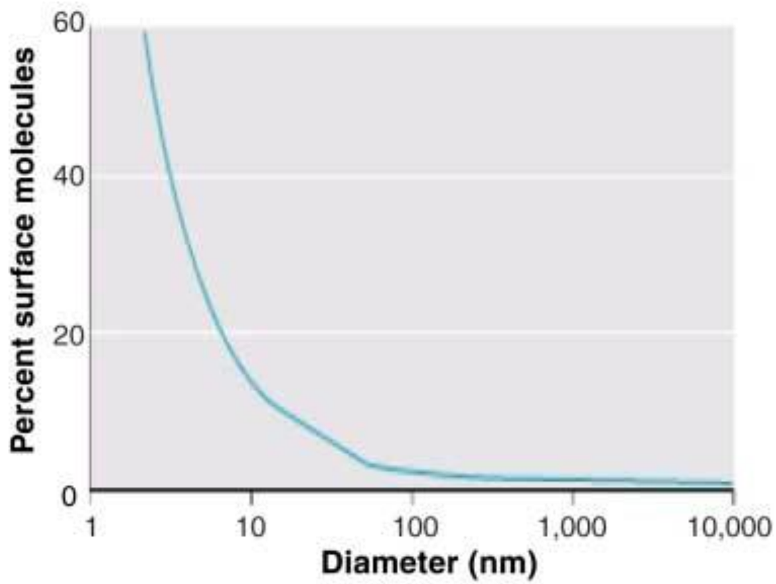
U.S. EPA, 2014

[1]*Second Order Closure Integrated Puff Model with Chemistry, Chowdhury et al, 2015*
[2]*Community Multiscale Air Quality Model, Byun and Schere, 1999*

Particle Number vs. Surface Area

Table 1. Particle number and particle surface area for 10 $\mu g/m^3$ airborne particles (*5*).

Particle diameter (μm)	Particles/ml of air	Particle surface area (μm^2/ml of air)
2	2	30
0.5	153	120
0.02	2,390,000	3000



Nel et al, Science 2006

Source attribution

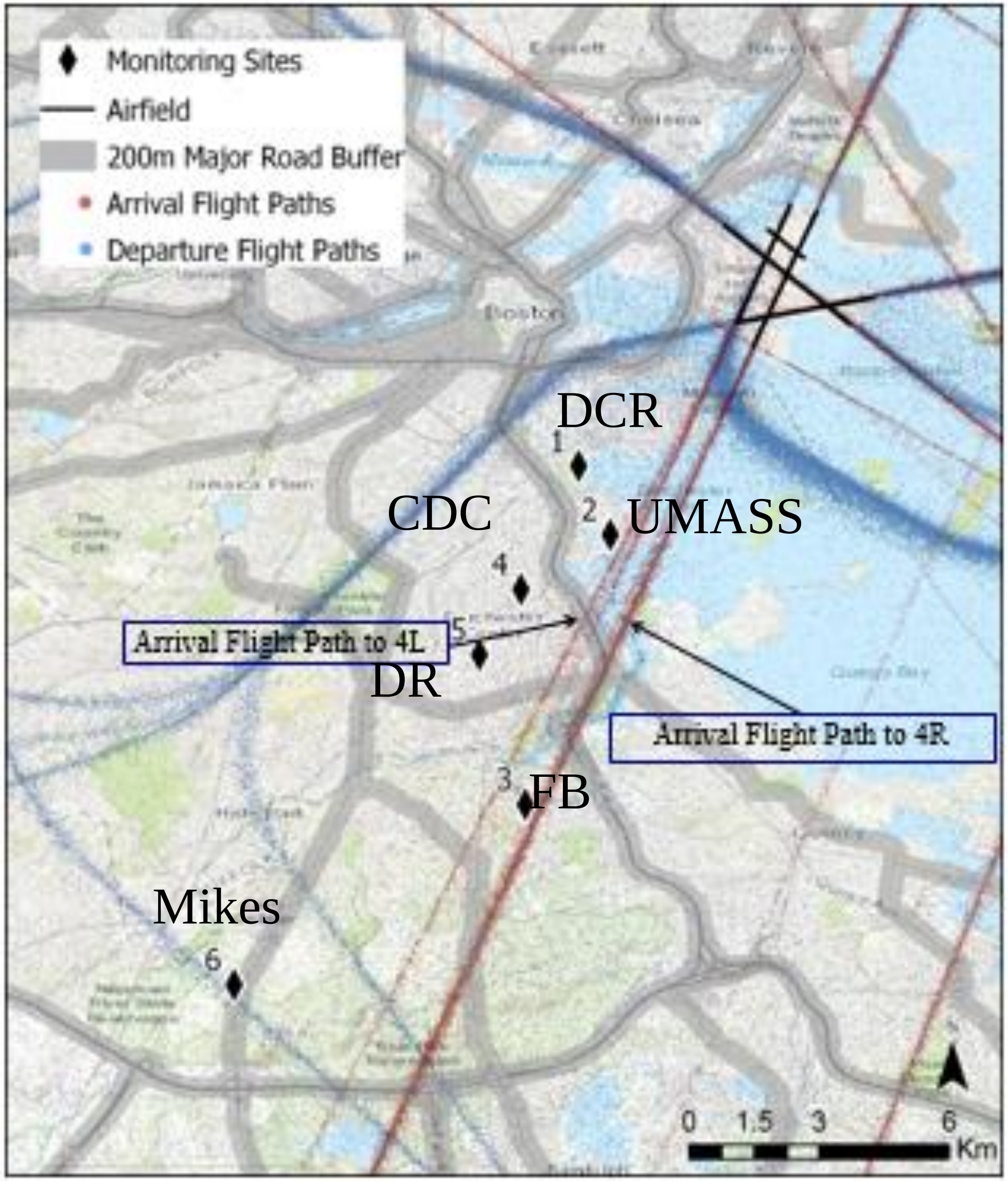
- Definition:
  - Formal quantitative assessment of the amount of ambient air pollution that can be attributed to a given source or source sector
- Two general approaches:
  - Measurement-based
  - Dispersion modeling-based
- Previously used to model particle mass ($PM_{2.5}$)
  - Regional Air Pollutant
  - Existing long-term ambient monitoring infrastructure
  - Dispersion and Regression model applications to source sectors
- Challenges for particle number (UFP)
  - High spatiotemporal variability
  - Complex pollutant dynamics
  - Multiple contributing sources/source sectors
  - Lack of ambient monitoring infrastructure
  - Limitations in emissions inventories (particle number vs. mass)

Measurement-based

- What does it take to do it well?
  – Measurements with high fidelity at high temporal resolution
  – Sufficient spatial coverage
  – Source activity and meteorological data with equivalent temporal resolution and spatial coverage
  – Study design that can minimize possibility of confounding
  – Regression-based statistical approaches that can leverage source terms to determine source contributions that vary in time and space

- In the case of aviation, this means:
  – << 1-min average measurements (of UFP and other pollutants)
  – Real-time flight activity data
  – Simultaneous measurements at multiple locations at distances from major roadways and other combustion sources

Field Campaign 2017 at Boston Logan

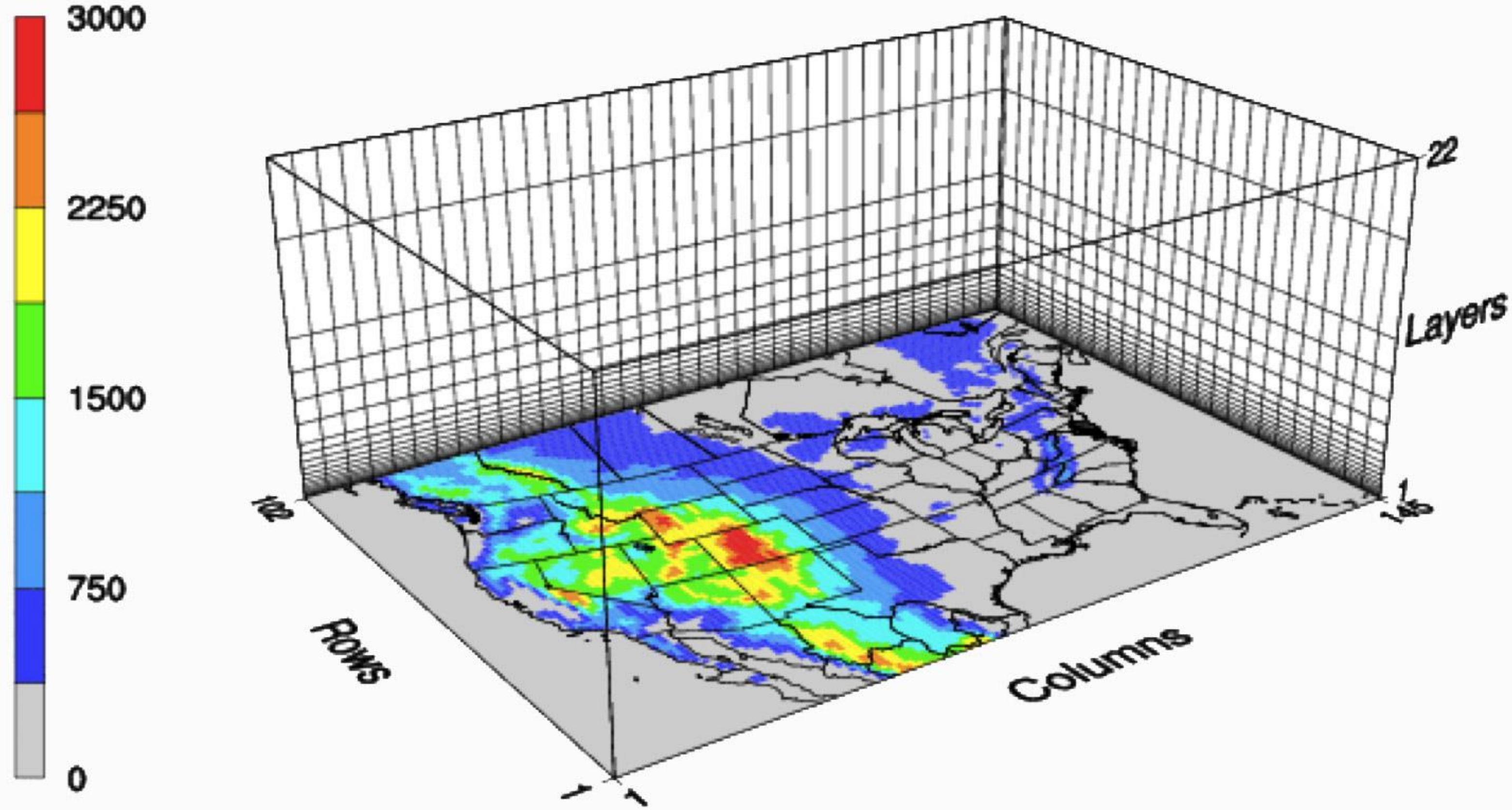


- **Site Selection**
- Focus on arrivals to Boston Logan International Airport on Runway 4R
- 51,858 arrivals in 2016 (most used runway)
- Flight path largely over populated areas
- Sites chosen to be > 200 m from major roadways, at varying distances from airport and from flight path based in part on projected wind direction and runway usage

Model-based

- What does it take to do it well?
  - Include appropriate processes for specific emissions sector
    - Physical and chemical
  - Have good knowledge of source strength
  - Be able to quantify incremental contribution of emission sector, compared to other sources
  - Be computationally efficient
- In the case of aviation (UFP), this means:
  - Being able to model unique 4-D varying profile of aircraft emissions
  - Have emissions inventories of UFP from aircraft
    - Often not the case
  - Include complex PM treatment
    - Coagulation, nucleation and microphysics
    - E.g. CMAQ, CALPUFF *(see Arunachalam et al, ACRP Report 179)*
  - Use source apportionment approaches
    - Brute force techniques or other advanced sensitivity tools
      - DDM, Adjoint, etc.

Hybrid Modeling with CMAQ and SCIPUFF



The CMAQ-APT model is based on CMAQ, which calculates pollutant concentrations in a 3-D grid over the area of interest.

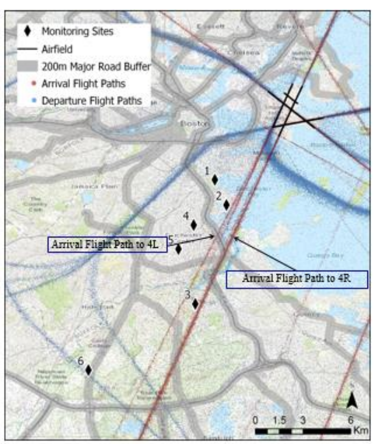
Statistical Methods – Regression Approach

- Descriptive stats based on the meteorology and time of day have informed regression model development
- Spatial-temporal regression models (used in traffic-based UFP modelling)
  - Generalized linear regression
  - Hierarchical modeling
- Machine learning regression (used in $PM_{2.5}$ prediction modeling)
  - Forest Tree
  - Bayesian Kernel Machine Regression
- Once we have a good understanding of covariates of PNC defined as high R^2 and low root mean square error we can move towards prediction
  - Localized but can sometimes lack transferability to other areas

Preliminary Results – UFP Distributions

Table 1. UFP Measurements (Particles/cm^3) at Six Study Sites Near Logan Airport

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Sample Size (days)	98	94	84	86	92	92
Sample Size (seconds)	7,345,615	7,413,902	6,365,917	6,573,947	6,813,861	6,922,535
0.1st percentile	400	500	800	1,200	900	900
1st percentile	900	1,300	1,200	2,100	1,300	1,200
5th percentile	2,000	2,400	2,000	3,500	2,500	2,000
50th percentile	7,400	7,500	5,700	9,200	7,900	5,800
95th percentile	29,300	27,700	13,300	29,100	21,600	15,400
99th percentile	58,800	57,600	22,100	48,300	33,600	23,700
99.9th percentile	93,800	112,000	37,800	73,600	49,000	45,400

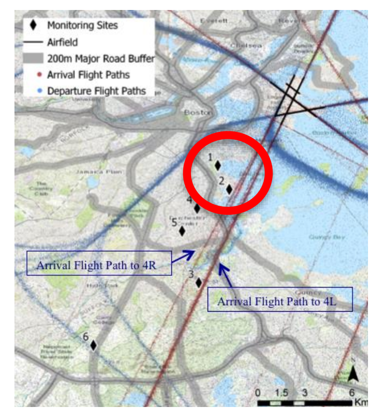


Near-Source Sites

Background Sites

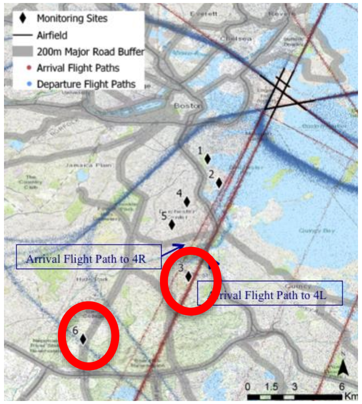
Regression Results - Near-source Sites

Variables		Site 1: Yes Flight Activity (R^2=0.23) Coefficient	P-value	R^2	Site 1: No Flight Activity (R^2=0.14) Coefficient	P-value	R^2	Site 2: Yes Flight Activity (R^2=0.18) Coefficient	P-value	R^2	Site 2: No Flight Activity (R^2=0.13) Coefficient	P-value	R^2
Intercept		43,477.55	***		17,309.31	***		25,848.30	***		14,544.96	***	
	EN	0.78	0.10		0.64	***		0.26	***		0.68	**	
	E	0.53	***		0.49	***		0.27	***		0.68	**	
	ES	0.41	***		0.66	***		0.24	***		0.99	0.96	
	SE	0.40	***		0.52	***		0.22	***		0.70	**	
	S	0.56	0.36		0.56	***		0.33	0.06		0.67	***	
Wind Direction (ref=NE)	SW	0.89	0.80	0.21	0.55	***	0.07	0.26	**	0.20	0.78	*	0.07
	WS	0.49	0.11		0.56	***		0.29	**		0.75	**	
	W	0.31	0.07		0.59	***		-	-		0.83	0.07	
	WN	0.43	0.06		0.78	*		-	-		0.99	0.91	
	NW	0.29	***		0.79	*		0.20	***		1.19	0.13	
	N	0.47	***		0.52	**		-	-		0.73	0.13	
Temperature	1°C	0.97	***	0.08	0.99	***	0.01	0.99	0.56	0.00	0.98	***	0.03
Rush Hour (ref=Non-Rush Hour)	Rush Hour	1.04	0.67	0.00	1.33	***	0.03	0.79	0.05	0.02	1.35	***	0.04
Wind Speed	1 (meter/sec)	0.98	0.45	0.00	0.94	***	0.02	0.99	0.73	0.00	0.96	***	0.01
Mixing Height	1000 meter	0.96	0.52	0.00	0.98	0.33	0.00	0.94	0.49	0.00	1.05	0.05	0.00
Freq	1 arrival aircraft	1.00	0.70	0.00	-	-	-	1.01	0.25	0.01	-	-	-

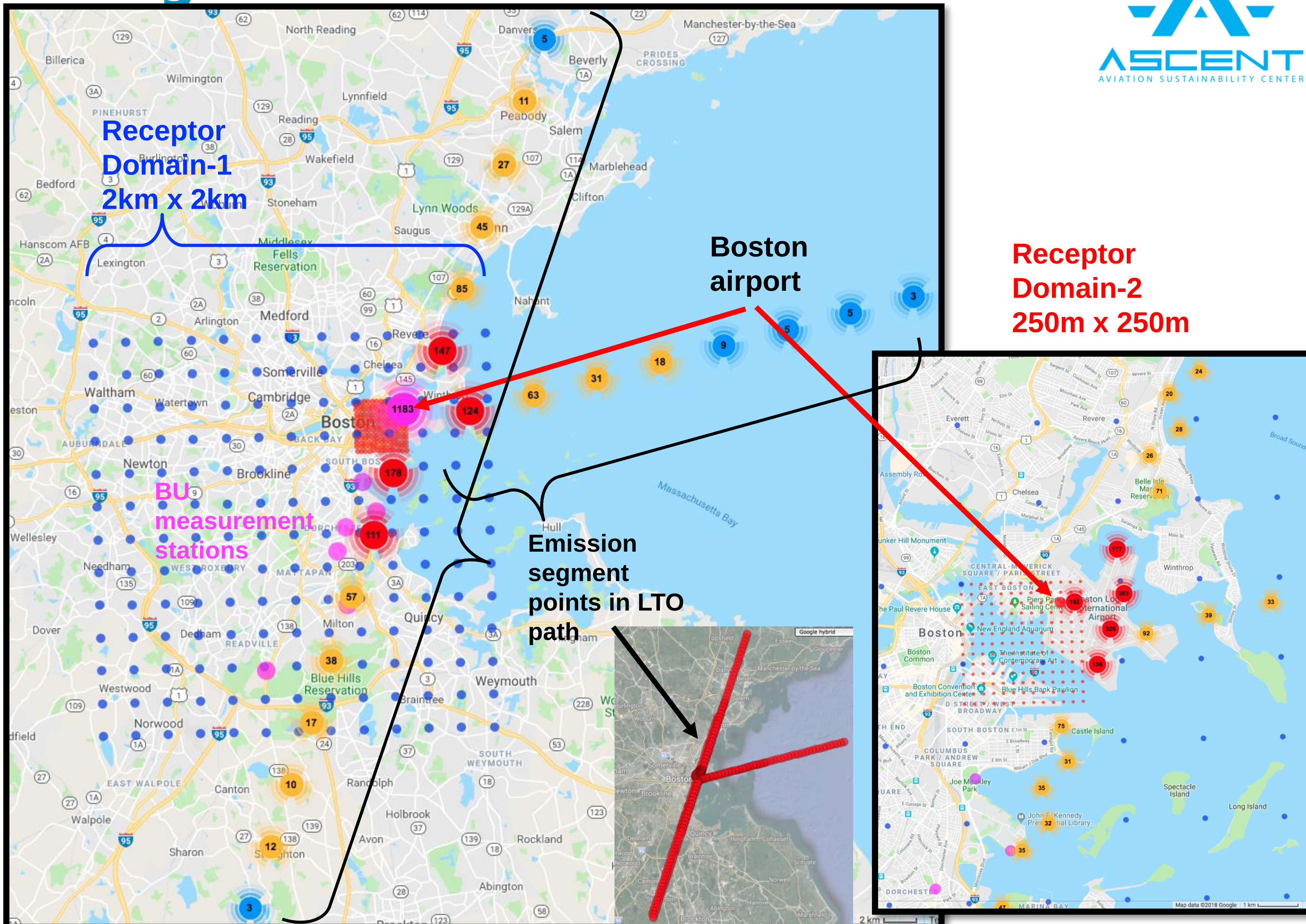


Regression Results - Background Sites

		Site 3						Site 6					
		R^2=0.06			R^2=0.15			R^2=0.03			R^2=0.17		
		Coefficient	P-value	R^2	Coefficient	P-value	R^2	Coefficient	P-value	R^2	Coefficient	P-value	R^2
Intercept		8,006.43	***		5,967.00	***		5,733.03	**		6,406.06	***	
	EN	0.91	0.56		1.05	0.72		0.95	0.69		1.06	0.60	
	E	1.01	0.93		1.91	***		1.11	0.38		1.80	***	
	ES	1.11	0.53		1.71	***		0.97	0.85		1.76	***	
	SE	1.13	0.52		1.55	**		1.05	0.79		1.46	***	
	S	1.11	0.80		1.35	*		0.81	0.51		1.25	*	
Wind Direction (ref=NE)	SW	0.85	0.62	0.05	1.60	***	0.07	1.25	0.57	0.04	1.38	**	0.08
	WS	2.08	0.07		1.77	***		0.68	0.25		1.50	***	
	W	-	-		1.60	***		-	-		1.48	***	
	WN	1.31	0.51		1.58	***		0.85	0.69		1.54	***	
	NW	1.31	0.50		1.84	***		0.61	0.22		1.44	**	
	N	-	-		2.22	**		-	-		2.56	**	
Temperature	1°C	1.01	0.49	0.00	0.99	*	0.01	1.02	**	0.03	1.00	0.10	0.00
Rush Hour (ref=Non-Rush Hour)	Rush Hour	1.08	0.42	0.03	1.23	**	0.38	1.00	0.97	0.03	1.16	***	0.40
Wind Speed	1 (meter/sec)	0.99	0.72	0.00	0.93	***	0.04	1.06	**	0.03	0.93	***	0.05
Mixing Height	1000 meter	0.85	*	0.04	1.00	0.94	0.00	0.89	*	0.02	1.00	0.86	0.00
Freq	1 arrival aircraft	1.00	0.81	0.00	-	-	-	1.00	0.60	0.00	-	-	-



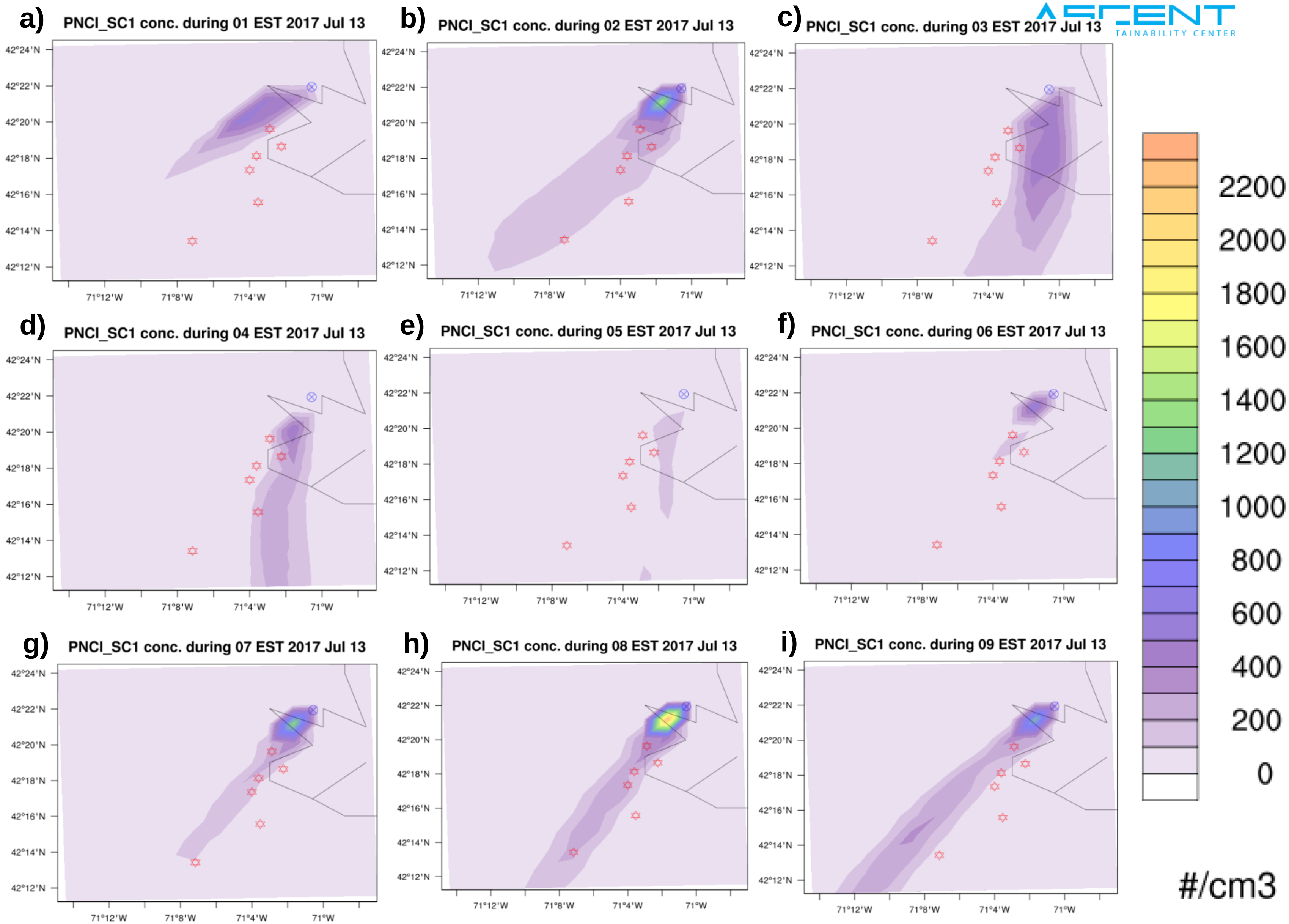
Modeling domain and emission sources



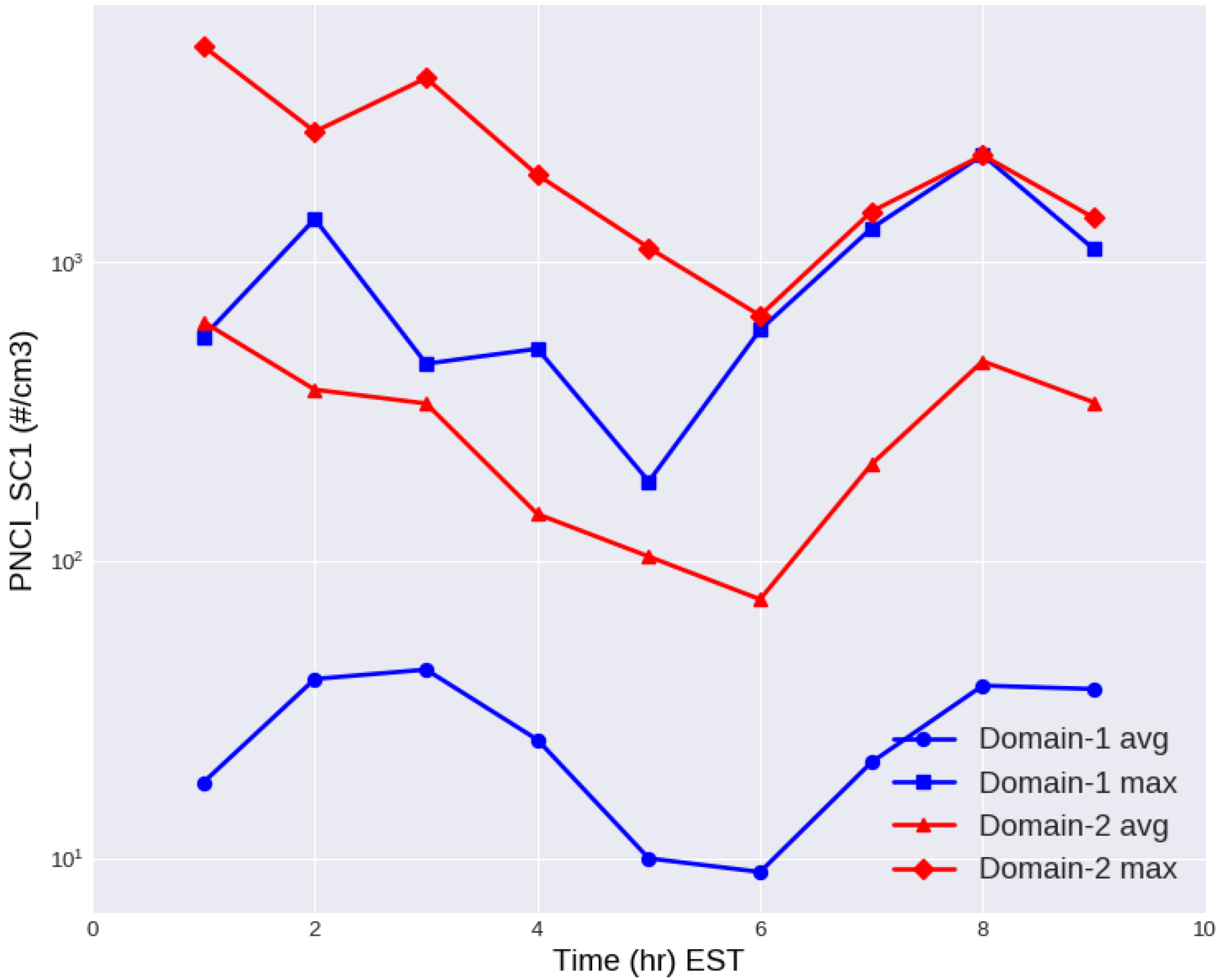
SCICHEM modeling domain and emission sources for Boston Logan

https://mapmakerapp.com

Hourly UFP in Domain 1 on July 13, 2017 (only emissions and dispersion)

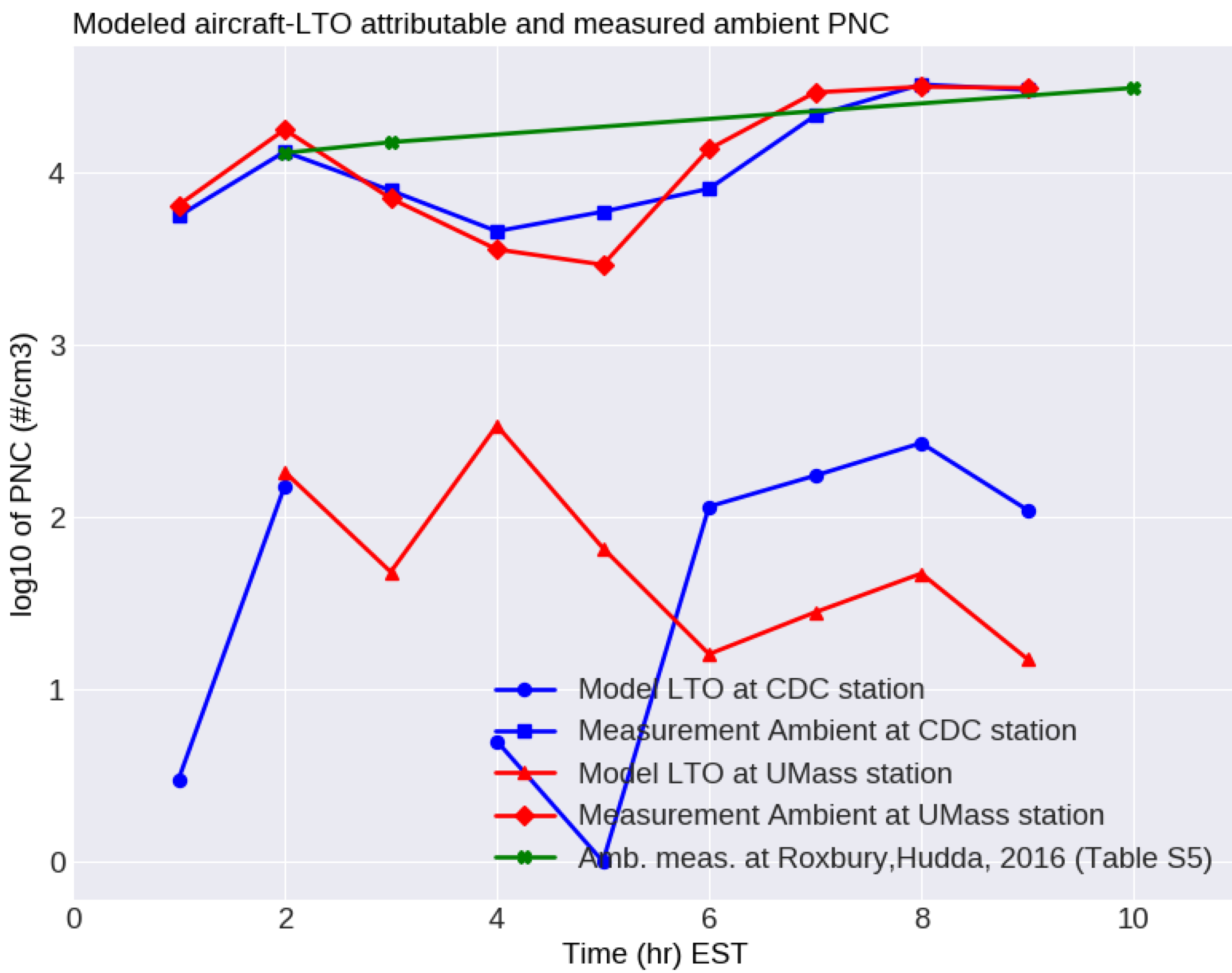


Hourly domain average and domain maximum UFP (only emissions and dispersion in 2 receptor domains)



- Domain 2 (closer to terminal area) has higher concentrations than Domain 1

Modeled and Measured UFP on July 13, 2017



- ❑ **Modeled estimates without aerosol microphysics**
- ❑ **Including nucleation will increase the LTO attributable UFP**

Summary

- Regression model of measured UFP using flight activity and wind direction was able to separate contribution of aircraft sources from Runway 4R from other sources
- Maximum modeled PNC were 2292 #/cc in receptor domain 1 at 9 AM and 5307 #/cc in domain 2 at 2 AM neglecting nucleation and coagulation
  - Corresponding domain average PNC ranged from 9 - 43 #/cc in domain 1 and 74 - 631 #/cc in domain 2
- Model evaluation at 2 measurement stations showed that model prediction follows the diurnal trend at CDC station
- Additional work ongoing to include multi-pollutant treatment, source characterization and aerosol processes in SCICHEM
  - This will improve model comparison against observations
- Next Steps
  - Expand measurement campaign to include both arrival and landing flight paths
  - Start developing high resolution CMAQ based application that includes all aerosol processes

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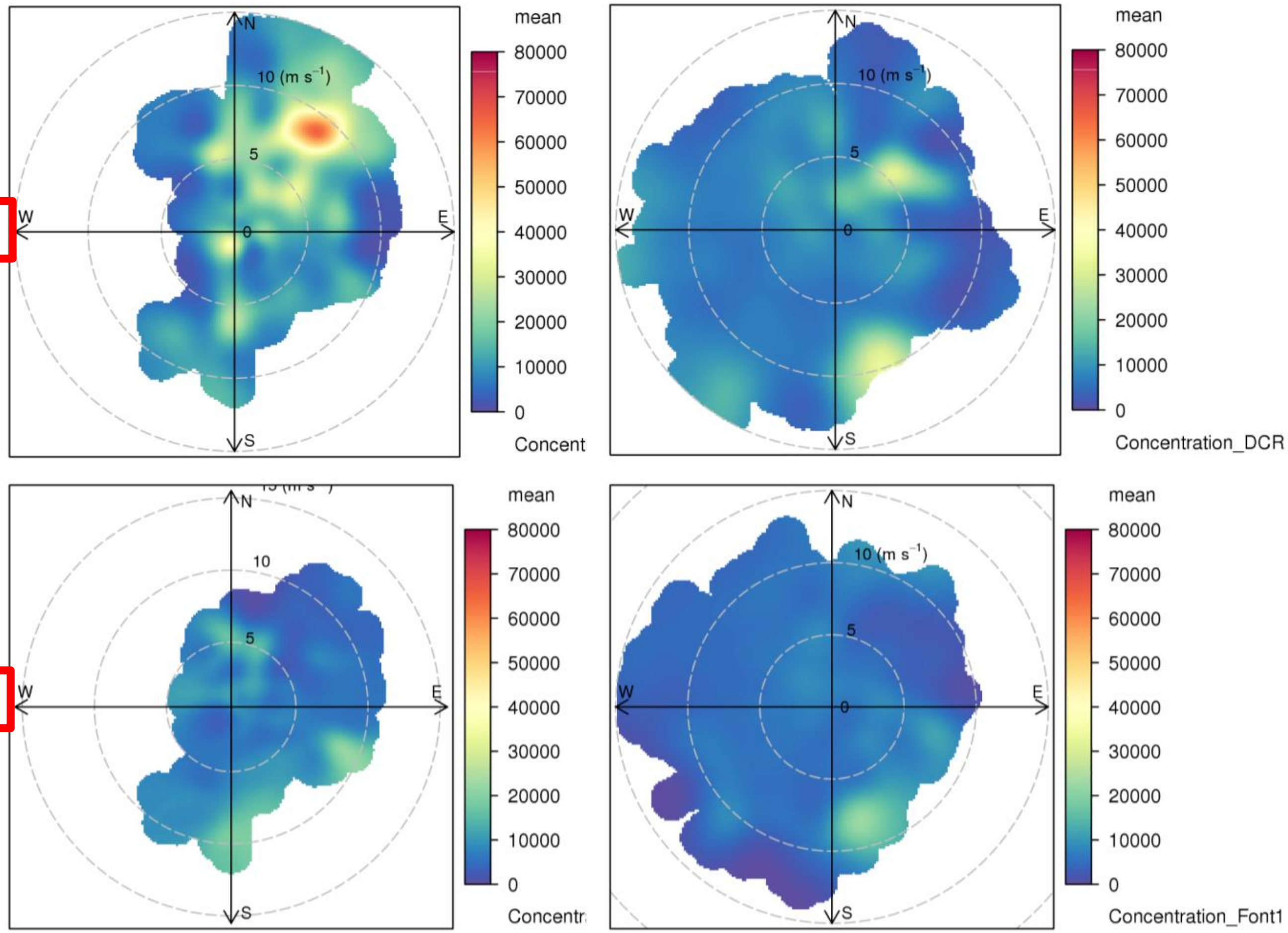
Concentration-WindRose plots

High arrival flight activity

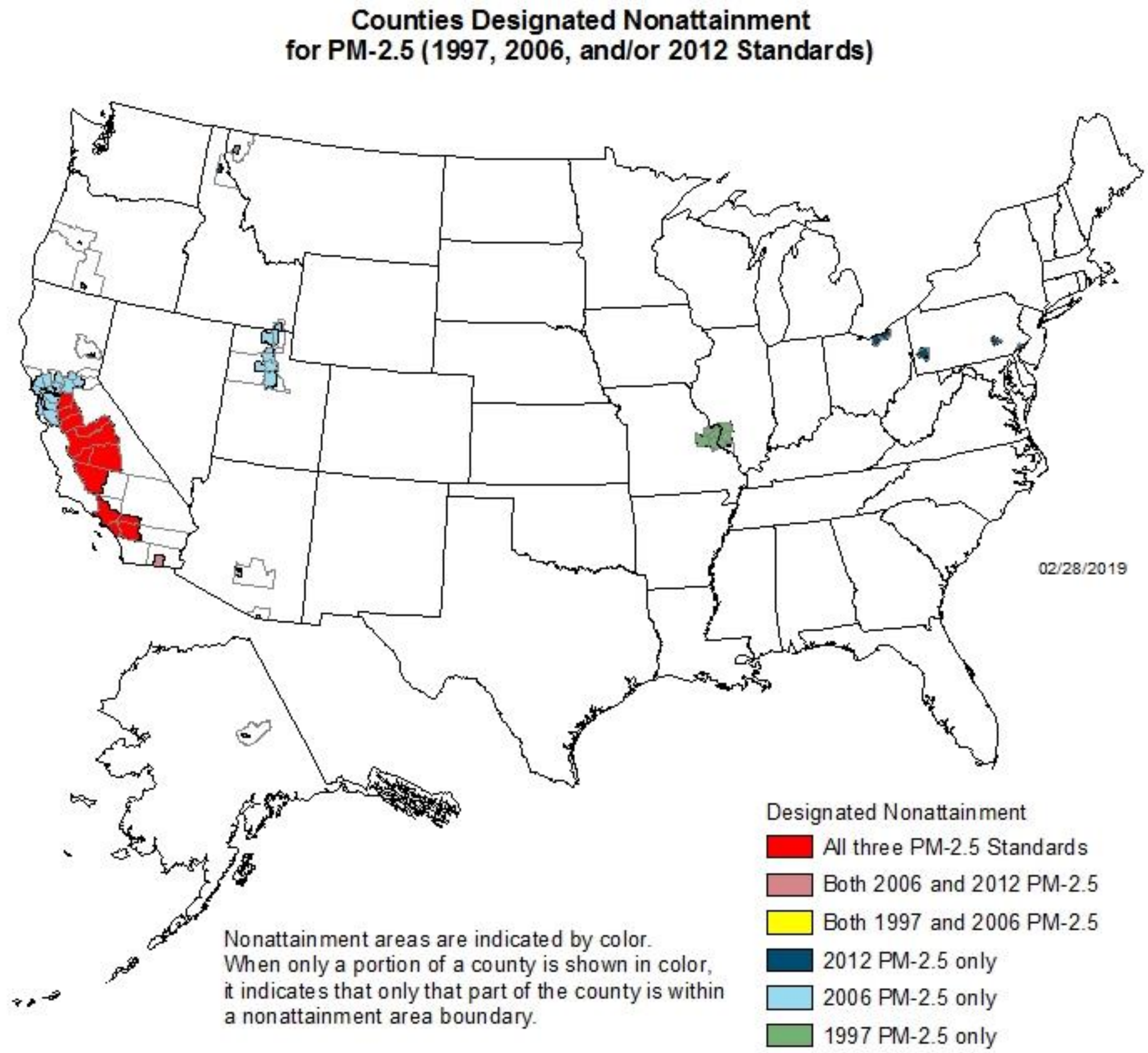
No arrival flight activity

DCR – Site 1

FB – Site 3



Multipollutant nonattainment areas



Source: U.S. EPA Green Book, 2019