Emerging Sensor Technologies to Enhance Understanding of Indoor Air Pollutants

Dr. Andrea Polidori
Advanced Monitoring Technologies Manager

South Coast AQMD
Diamond Bar, CA

South Coast AQMD

AQ-SPEC

Air Quality Sensor Performance Evaluation Center

South Coast AQMD

- ○ **Established in July 2014**
- ○ **Main Goals & Objectives**
  - Provide guidance & clarity
  - Promote successful evolution and use of sensor technology
  - Minimize confusion
- ○ **Sensor Selection Criteria**
  - Commercially available
  - Criteria pollutants & air toxics
  - Real- or near-real time, time resolution ≤ 5-min
  - Sensitivity at ambient levels
  - Continuous operation for two months
  - Retrievable data
  - Low-cost…?

- ***Phase I: Field Testing***
  - ○ Sensor tested in triplicates
  - ○ Two months deployment
  - ○ Comparison with FRM/FEM instruments at a fixed monitoring station
- ***Phase II: Laboratory Testing***
  - ○ State-of-the-art characterization chamber
  - ○ Particle and gas testing
  - ○ T and RH controlled conditions

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

South Coast AQMD

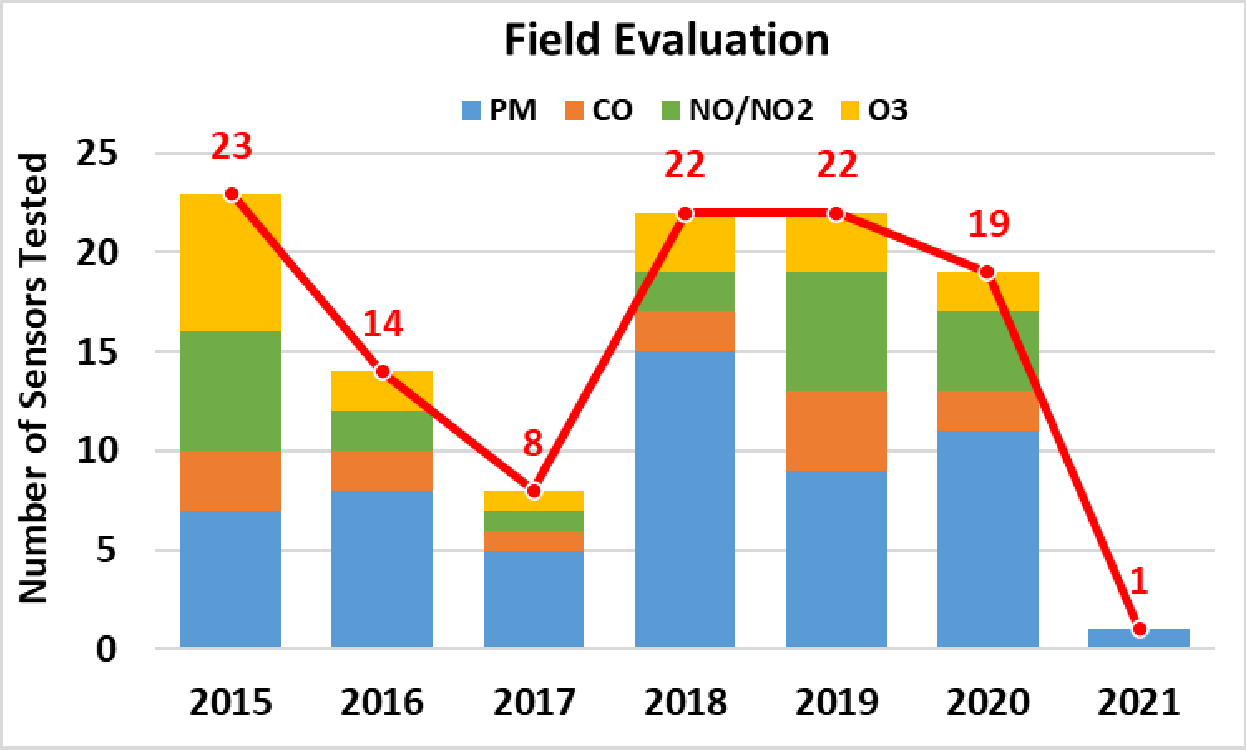
Characteristic	SEnTeC-1	SEnTeC-2
Test Volume	~1.1 m^3	~1.6 m^3
Temperature Range	-32 °C to +177 °C	-70 °C to +180 °C
Humidity Range	10% to 95%	5% to 98%
Maximum Sensor Testing Capability	3-9 sensors	20+ sensors
Specialty Tests (wind, vibration, altitude)	No	Yes
Simultaneous Pollutant Testing	No	Yes
Automatic Pollutant Stabilization	No	Yes
FRM/FEM Instrument Cert.	Criteria Gases and $PM_{2.5}$	Criteria Gases and $PM_{2.5}$ + PM_{10}

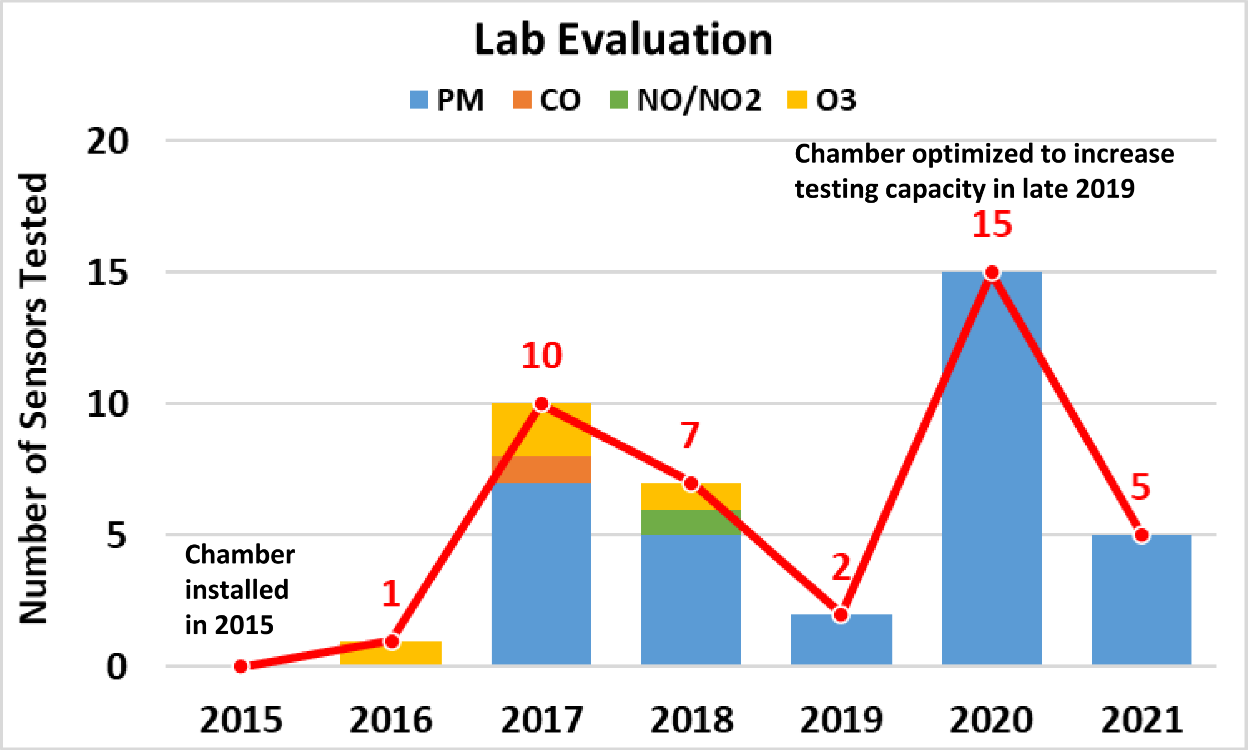
SEnTeC-2 (Sensor Environmental Test Chamber-2)

- Development of sensor performance targets
- Calibration and QA/QC for new Sensor Library program
- Support for mobile testing of sensors and testing under unique conditions

Number of Sensors Tested: PM and Gas Devices

	2015	2016	2017	2018	2019	2020	2021	total
Field	23	14	8	22	22	19	1	109
Lab	0	1	10	7	2	15	5	40
Total	23	15	18	29	24	34	6	**149**

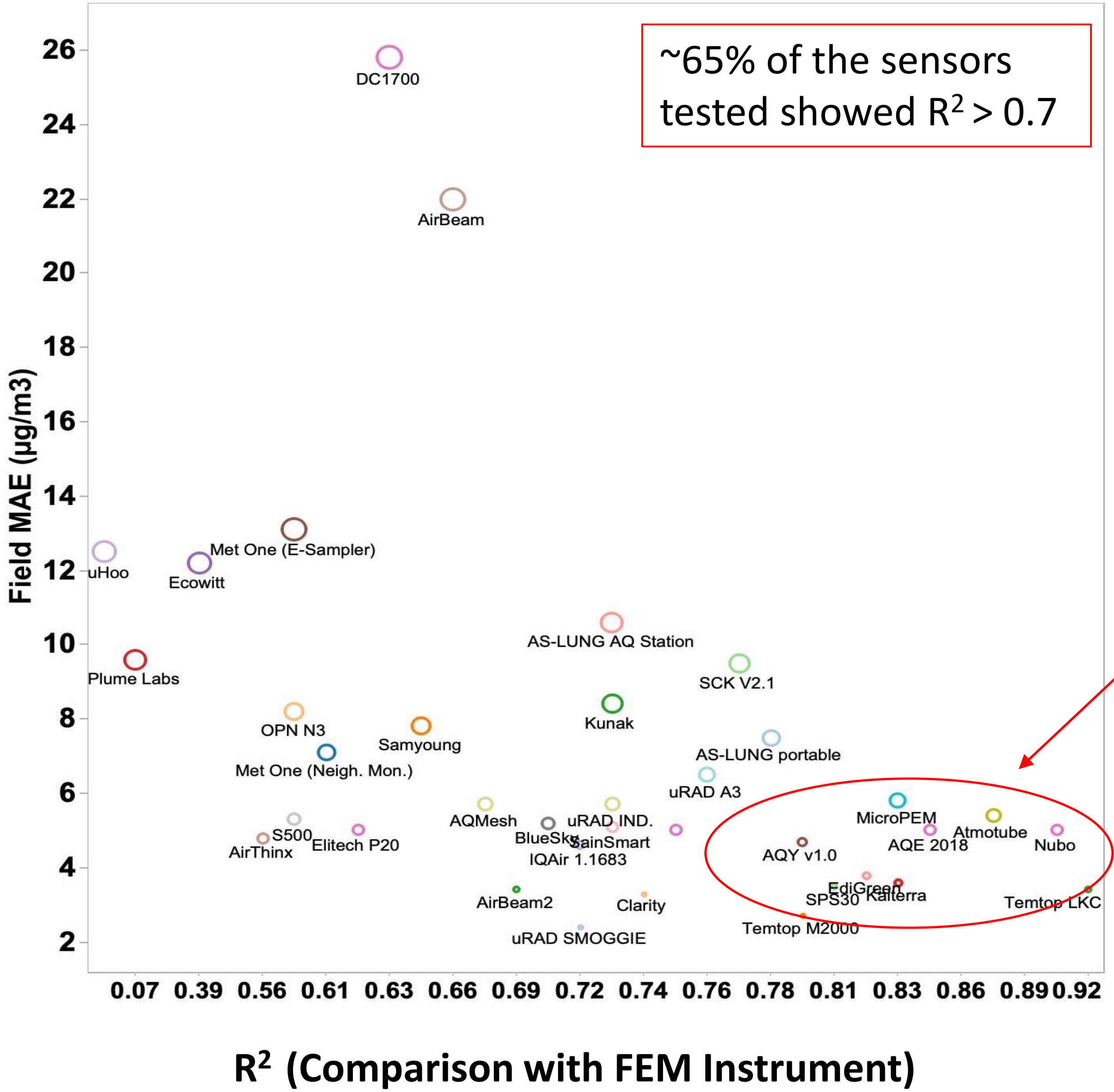




PM Sensor Summary Table: http://www.aqmd.gov/aq-spec/evaluations/summary-pm

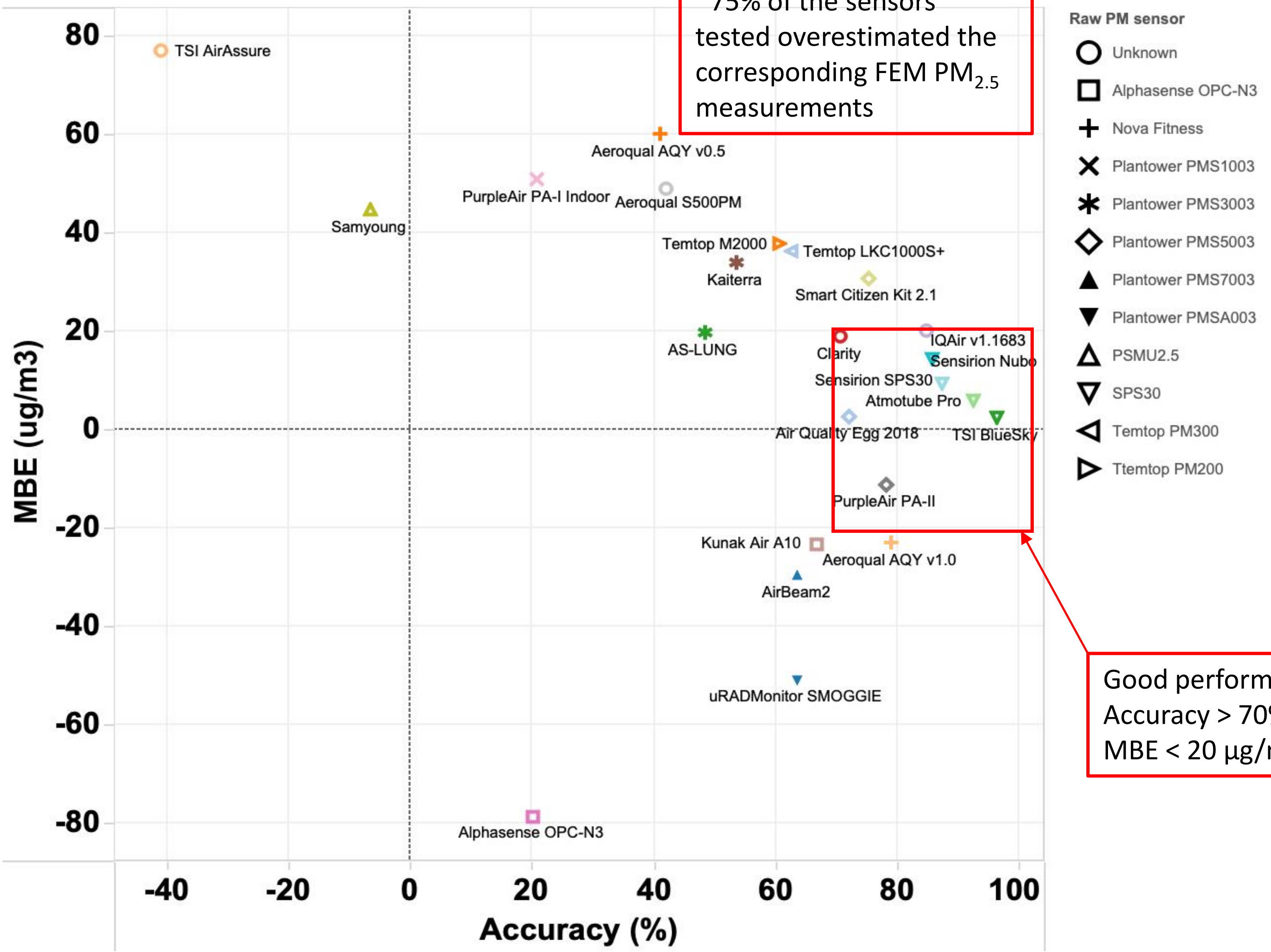
Gas Sensor Summary Table: http://www.aqmd.gov/aq-spec/evaluations/summary-gas

$PM_{2.5}$ Sensors Performance: Field Testing



Good performance:
$R^2 > 0.75$ & MAE < 5 µg/m³

$PM_{2.5}$ Sensors Performance: Lab Testing



~75% of the sensors tested overestimated the corresponding FEM $PM_{2.5}$ measurements

Good performance:
Accuracy > 70% &
MBE < 20 μg/m^3

Overall PM Sensors Performance

PM Sensors

Sensor Image	Make (Model)	Est. Cost (USD)	Pollutant(s)	*Field R^2	*Lab R^2	*Field MAE ($\mu g/m^3$)	*Lab MAE ($\mu g/m^3$)	Summary Report
	Aeroqual (AQY v0.5) Discontinued	$3,000	$PM_{2.5}$	0.84 to 0.87	0.99		28.8 to 36.0	PDF (1,178 KB)
	Aeroqual (AQY v1.0)	$4,000	$PM_{2.5}$	0.76 to 0.81	0.99	4.2 to 5.3	5.4 to 15.1	PDF (674 KB)
			PM_{10}	0.56 to 0.68		35.4 to 38.8		
	Aeroqual (S500-PM)	$1,490	$PM_{2.5}$	0.46 to 0.67	0.99	4.4 to 6.2	11.9 to 32.4	PDF (702 KB)
			PM_{10}	0.15 to 0.24		13.5 to 18.0		
	AethLabs (microAeth)	$6,500	BC (Black Carbon)	0.79 to 0.94				
	Airly	$1,000	$PM_{1.0}$	0.79 to 0.89		4.2 to 5.3		
			$PM_{2.5}$	0.83 to 0.89		4.5 to 5.0		
			PM_{10}	0.34 to 0.37		19.3 to 19.7		
	Air Quality Egg (2018 Model)	$249	$PM_{1.0}$	0.86 to 0.88	0.99	2.1 to 2.3	7.0 to 7.3	PDF (771 KB)
			$PM_{2.5}$	0.84 to 0.85	0.99	4.4 to 5.3	6.1 to 6.6	
			PM_{10}	0.12 to 0.13	-	16.4 to 19.2		
	Air Quality Egg (Version 1)	$200	PM	~ 0.0				
	Air Quality Egg (Version 2)	$240	$PM_{2.5}$	0.79 to 0.85				
			PM_{10}	0.31 to 0.40				
	AirThinx (IAQ)	$1,000	$PM_{1.0}$	0.68 to 0.70		2.4 to 2.5		
			$PM_{2.5}$	0.54 to 0.57		4.8 to 5.0		
			PM_{10}	0.03 to 0.05		19.7 to 19.8		
	Airviz Inc. (Speck)	$150	$PM_{2.5}$	0.32				
	Alphasense (OPC-N2)	$310	$PM_{1.0}$	0.63 to 0.82	0.99			PDF (1,291 KB)
			$PM_{2.5}$	0.65 to 0.80	0.99			
			PM_{10}	0.45 to 0.57	0.99			
	Alphasense (OPC-N3)	$338	$PM_{1.0}$	0.78 to 0.82	0.99	4.4 to 5.0	39.0 to 43.2	PDF (757 KB)
			$PM_{2.5}$	0.52 to 0.67	0.99	7.1 to 9.2	40.3 to 46.9	
			PM_{10}	0.45 to 0.52	0.99	18.0 to 24.1	39.2 to 48.0	
	Applied Particle Technology (MINIMA)	$995	$PM_{1.0}$	0.84 to 0.89		5.0 to 5.6		
			$PM_{2.5}$	0.86 to 0.89		5.8 to 6.5		
			PM_{10}	~0.37		39.4 to 40.3		
	AQMesh (v3.0)	$7,800	$PM_{1.0}$	0.55 to 0.73		2.4 to 3.4		
			$PM_{2.5}$	0.47 to 0.79		2.7 to 7.5		
			PM_{10}	0.24 to 0.58		11.4 to 23.1		
	AS-LUNG (Air Quality Station)	$2,000	$PM_{1.0}$	0.42 to 0.88		3.2 to 7.3		
			$PM_{2.5}$	0.59 to 0.81		8.0 to 12.1		
			PM_{10}	0.15 to 0.23		18.6 to 21.2		
	AS-LUNG (Portable)	$1,000	$PM_{1.0}$	0.86	0.99	3.2 to 4.3	2.6 to 3.4	PDF (875 KB)
			$PM_{2.5}$	0.78	0.99	6.8 to 8.2	12.8 to 13.5	
			PM_{10}	0.11 to 0.14	-	18.9 to 21.6		
	Atmotube (Pro)	$189	$PM_{1.0}$	0.91 to 0.93	0.99	3.6 to 4.6	1.9 to 6.4	PDF (765 KB)
			$PM_{2.5}$	0.88	0.99	4.9 to 5.9	2.9 to 3.8	
			PM_{10}	0.22	-	20.9 to 22.9	-	

Most PM sensors showed:

- Minimal down time
- Moderate intra-model variability
- Strong correlation (R^2) with EPA approved instruments (e.g., FEM)

However…

- Sensor "calibration" is needed in most cases
- Very small particles (e.g. < 0.5 µm) are not detected
- Bias in algorithms used to convert particle counts to particle mass

Overall Gas Sensors Performance

Gas-Phase Sensors

Sensor Image	Make (Model)	Est. Cost(USD)	Type	Meas.	*Field R^2	*Lab R^2	*Field MAE (ppb)	*Lab MAE (ppb)	Summary Report
	2B Technologies (POM)	$4,500	UV absorption (FEM Method)	O_3	1.00	0.99			PDF (1,295 KB)
	Aeroqual (AQY v0.5) Discontinued	$3,000	Electrochem	NO_2	0.77	0.98			PDF (1,158 KB)
			Metal Oxide	O_3	0.95	0.98			PDF (1,163 KB)
	Aeroqual (AQY v1.0)	$4,000	Electrochem	NO_2	0.60 to 0.77		4.1 to 5.3		
			Metal Oxide	O_3	0.96 to 0.97		2.4 to 7.3		
	Aeroqual (S-500)	$500	Metal Oxide	O_3	0.85	0.99			PDF (1,197 KB)
	Airly	$1,000	Electrochem	NO_2	0.54 to 0.80		42.4 to 48.1		
				O_3	0.90 to 0.94		19.3 to 22.9		
	Air Quality Egg Ver. 1	$200	Metal Oxide	CO	0.0				
				NO_2	0.40				
				O_3	0.85				
	Air Quality Egg Ver. 2	$240	Electrochem	CO	0.0				
				NO_2	0.0				
	Air Quality Egg Ver. 2	$240	Electrochem	O_3	0.0 to 0.20				
				SO_2	n/a				
	APIS	$4,995	Electrochem	CO	0.87 to 0.90		70.0 to 99.8		
				NO	0.87 to 0.97		1.3 to 2.6		
				NO_2	0.30 to 0.44		6.1 to 9.4		
				O_3	0.73 to 0.83		14.2 to 19.1		
	AQMesh V4.0 Discontinued	$10,000	Electrochem	CO	0.42 to 0.80				
				NO	0.0 to 0.44				
				NO_2	0.0 to 0.46				
				O_3	0.46 to 0.83				
	AQMesh V5.1	$7,800	Electrochem	CO	0.74 to 0.79		40.2 to 55.0		
				NO	0.007 to 0.01		21.7 to 27.3		
				NO_2	0.21 to 0.35		6.9 to 7.4		
				NO_x	0.01 to 0.02		27.4 to 31.4		
				O_3	0.88 to 0.90		13.5 to 38.3		
				SO_2	n/a		n/a		
	CairPol Cairsens (CO)	$1,243	Electrochem	CO	0.93 to 0.94		93.6 to 134.9		
	CairPol Cairsens (NO_2)	$1,198		NO_2	0.0 to 0.12		6.0 to 14.6		
	Igienair (Zaack AQI)	$3,000	Electrochem	CO	0.84 to 0.87		276.0 to 329.6		
				NO_2	0.53 to 0.58		7.2 to 8.0		
				O_3	0.0		20.7 to 23.9		
	Kunak (Air A10)	~$5,000	Electrochem	CO	0.55 to 0.60		38.9 to 42.0		
				NO	0.78 to 0.93		1.1 to 1.7		
				NO_2	0.24 to 0.32		6.6 to 7.4		
				O_3	0.86 to 0.88		4.8 to 5.9		
	Magnasci SRL (uRADMonitor	~$1,300	Electrochem	CO	0.00 to 0.07		224.9 to 290.7		

<u>Most gaseous sensors showed</u>:

- Acceptable data recovery
- Wide intra-model variability range
- CO; NO; O3 (when measured alone): good correlation with FEMs/FRMs
- O3 + NO2: potential interference
- SO2; H2S; VOC: difficult to measure with available sensors

AQ-SPEC: Continuing & New Projects

2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

- Field Evaluations
- Lab Chamber 1
- Lab Evaluations
- EPA STAR Grant
- Sensor Network Deployments
- ASTM Test Standard
- AirSensor Guidebook
- Mobile Platform
- AirSensor & DataViewer
- Cloud Computing
- Google Project
- Mobile Performance Evaluation Protocol
- Lab Chamber 2
- Sensor Library
- Sensor Network Calibration

Testing Protocols and Applications

- Stationary ambient/outdoor – single device
- Stationary ambient/outdoor – network of devices
- Stationary indoor – single device
- Mobile ambient – single device

Data Management Tools

- Open-source – R-package
- Closed-source – Cloud computing

Educational/Community Outreach

- Research grants
- Library

ASTM D22.05: Indoor $PM_{2.5}$ Sensors Test Standards

Increasing relevance and urgency for indoor air monitoring due to COVID-19; $PM_{2.5}$ may be proxy for indoor area crowding and transmission risk

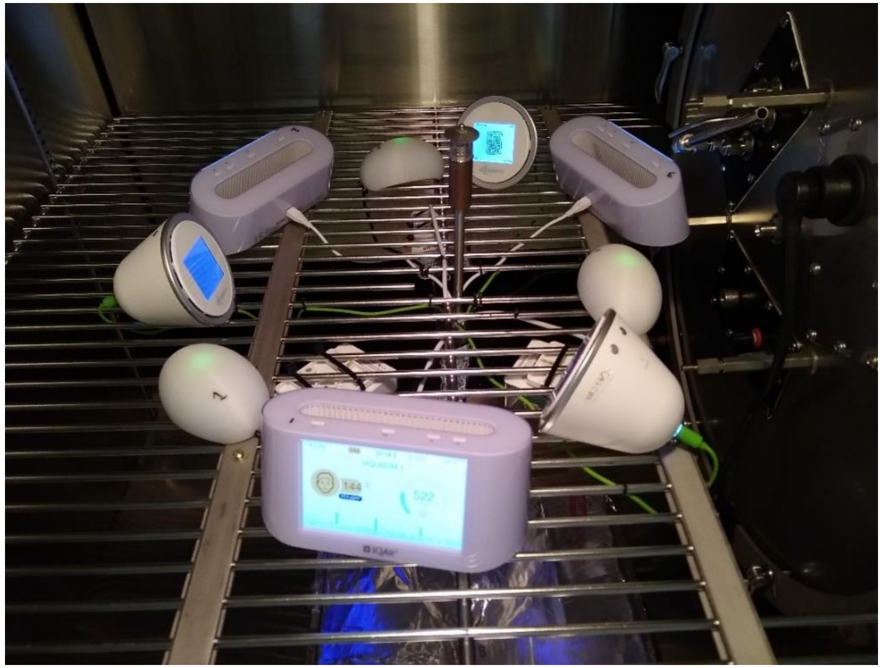
Phase 1
Initial $PM_{2.5}$ Concentration Ramp

Phase 2
T/RH Susceptibility

Phase 3
Coarse PM Interference

Phase 4
Temperature Cycling

Phase 5
Final $PM_{2.5}$ Concentration Ramp (Drift Measure)



- Status:
  - Testing of 4 sensor model completed
  - 8 subcommittee meetings
  - First ballot: Received ~150 comments; all resolved except ONE, awaiting resolution!!!
- Method Revisions:
  - Greater specificity on permissible reference monitors
  - Two particle sources used as proxies for indoor inorganic and organic particles (NaCl and PSL)
  - Gravimetric $PM_{2.5}$ verification method proposed

ASTM D22.05: Indoor CO_2 Sensors Test Standards

Phase 1
Initial CO_2 Concentration Ramp

Phase 2
T/RH Susceptibility

Phase 3
RH Interference

Phase 4
Temperature Cycling

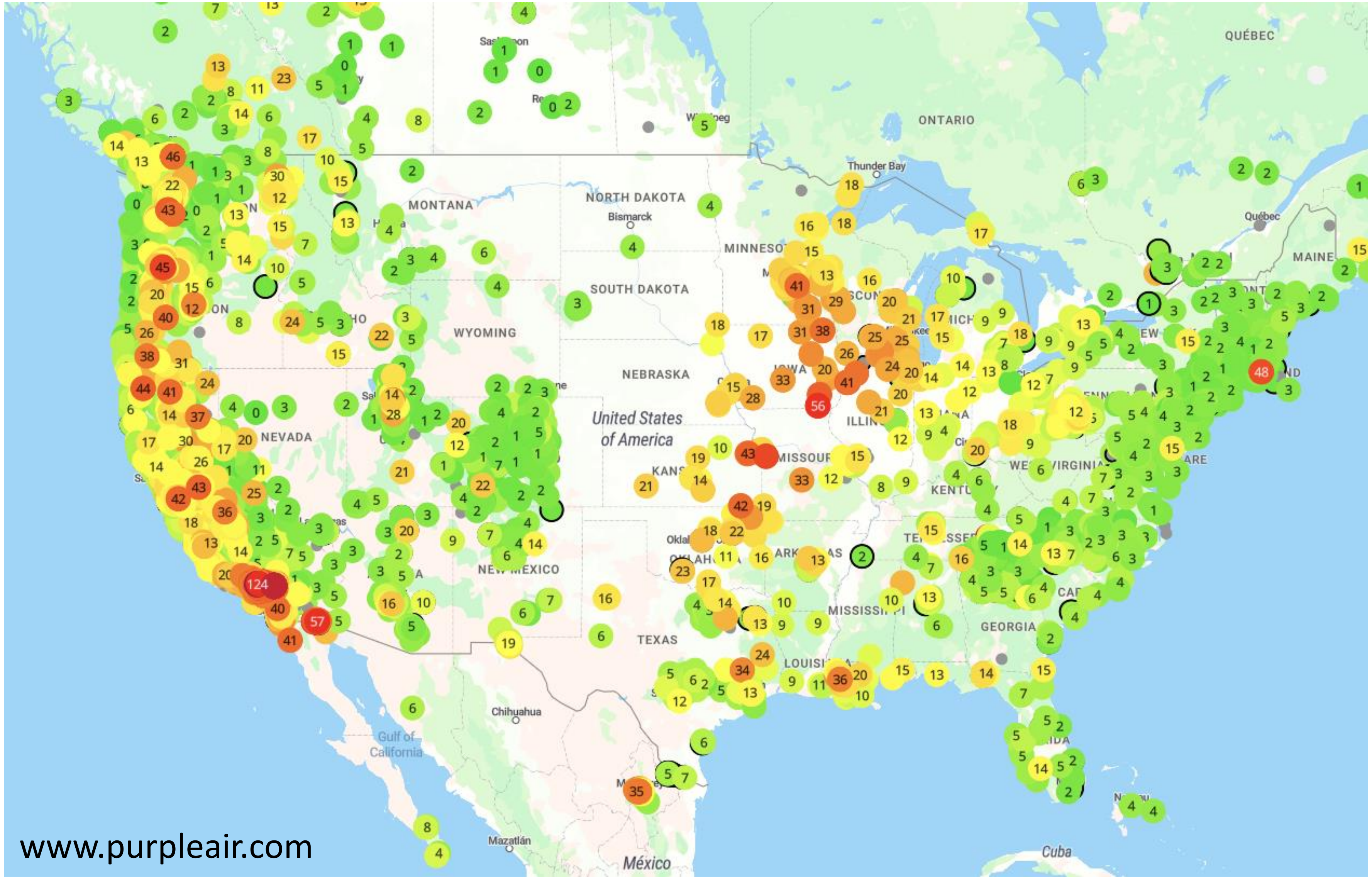
Phase 5
Final CO_2 Concentration Ramp
(Drift Measure)

Increasing relevance and urgency for indoor air monitoring due to COVID-19; CO_2 may be proxy for indoor area crowding and transmission risk

- Status:
  - Testing of 4 sensor models completed
  - 2 subcommittee meetings
  - Test method submitted to ASTM in preparation for ballot
- Method Revisions:
  - Greater specificity on permissible reference monitors
  - Added more specified pressure conditions
  - Added more requirements for reference monitor calibration

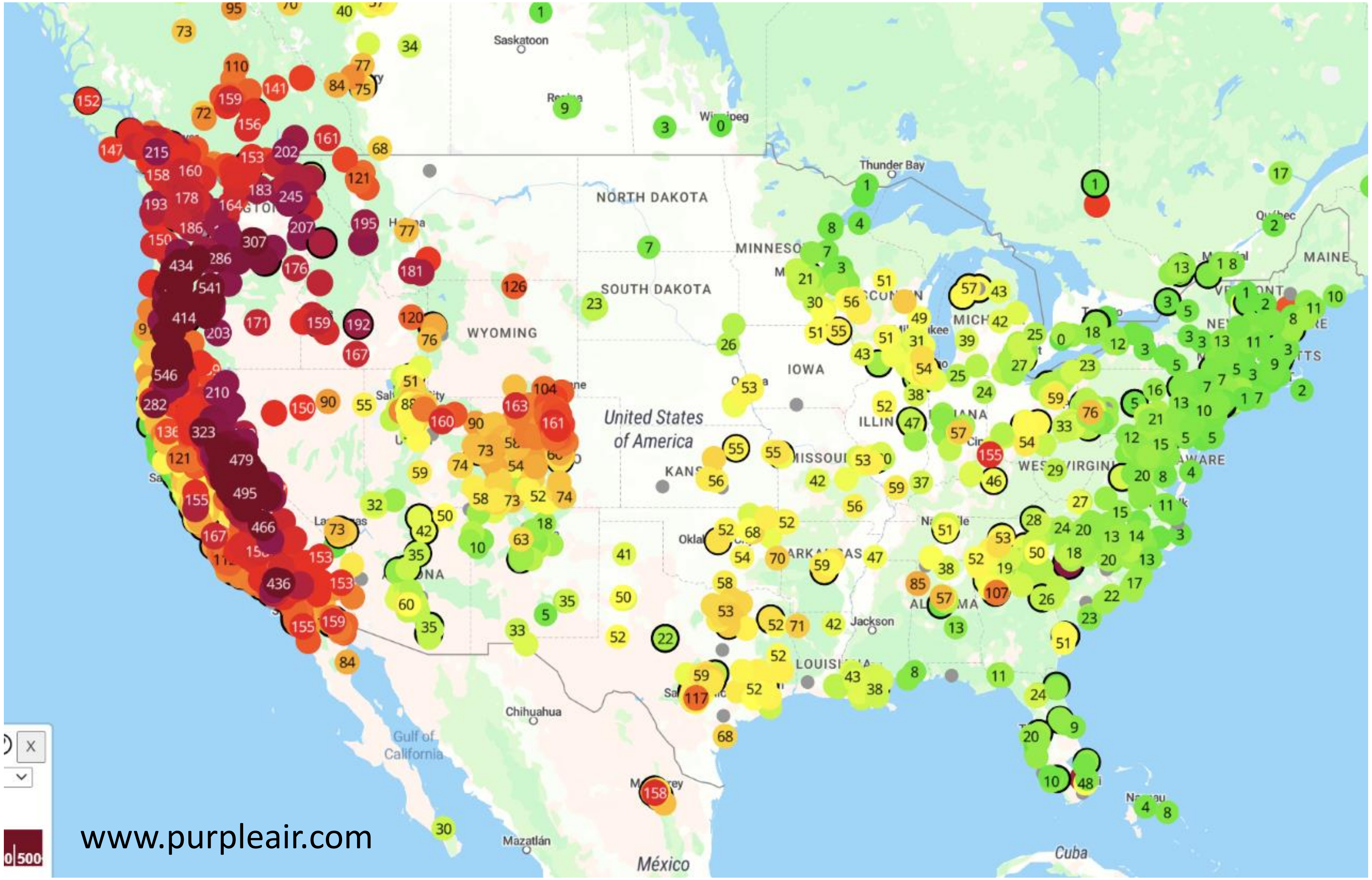
PM2.5 Sensor Application: Example 1 (04/03/21)

PM2.5 in ug/m3

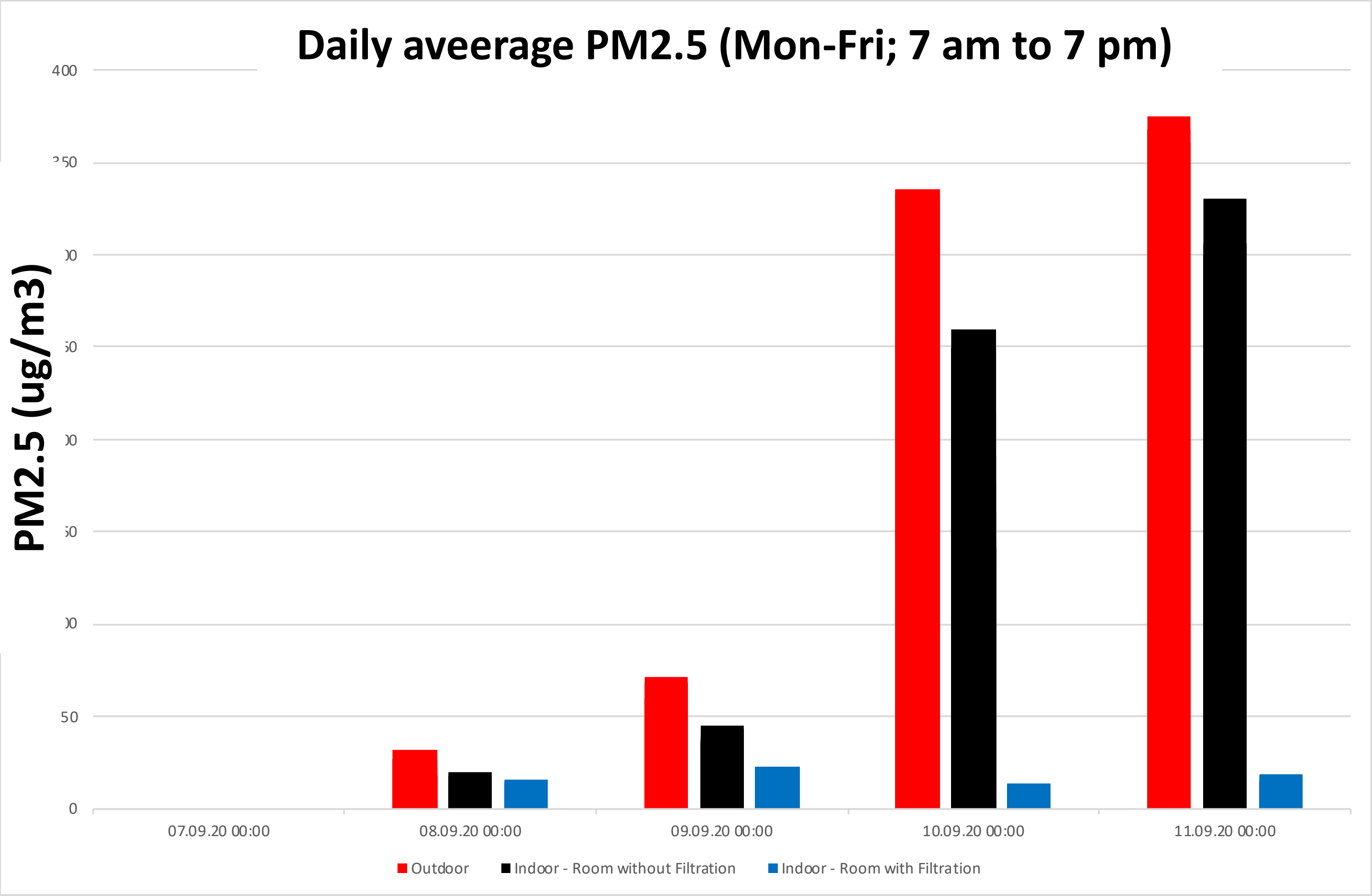


PM2.5 Sensor Application: Example 2 (09/16/20)

PM2.5 in ug/m3



2020 Bay Area Wildfire Air Pollution Impact



- 2020 wildfires demonstrated effectiveness of high efficiency air filtration systems under extreme conditions
- Even with outdoor levels exceeding 300+ µg/m3, indoor PM2.5 remained below 25 µg/m3
- Data is from unoccupied classrooms

IQAir®

Smart HVAC Air Filter Monitoring
(South Coast AQMD Air Filtration Program)

- Most schools replace medium efficiency filters on a fixed schedule, typically 3-4 time a year
- Wireless differential pressure sensors help characterize filter loading in HVAC systems
- Data from wireless sensors allows to switch from a fixed filter replacement schedule to a demand-based schedule
- Average filter life can be increased with smart filter monitoring

Wireless differential pressure sensor

Wireless differential pressure sensor installed on roof air handler

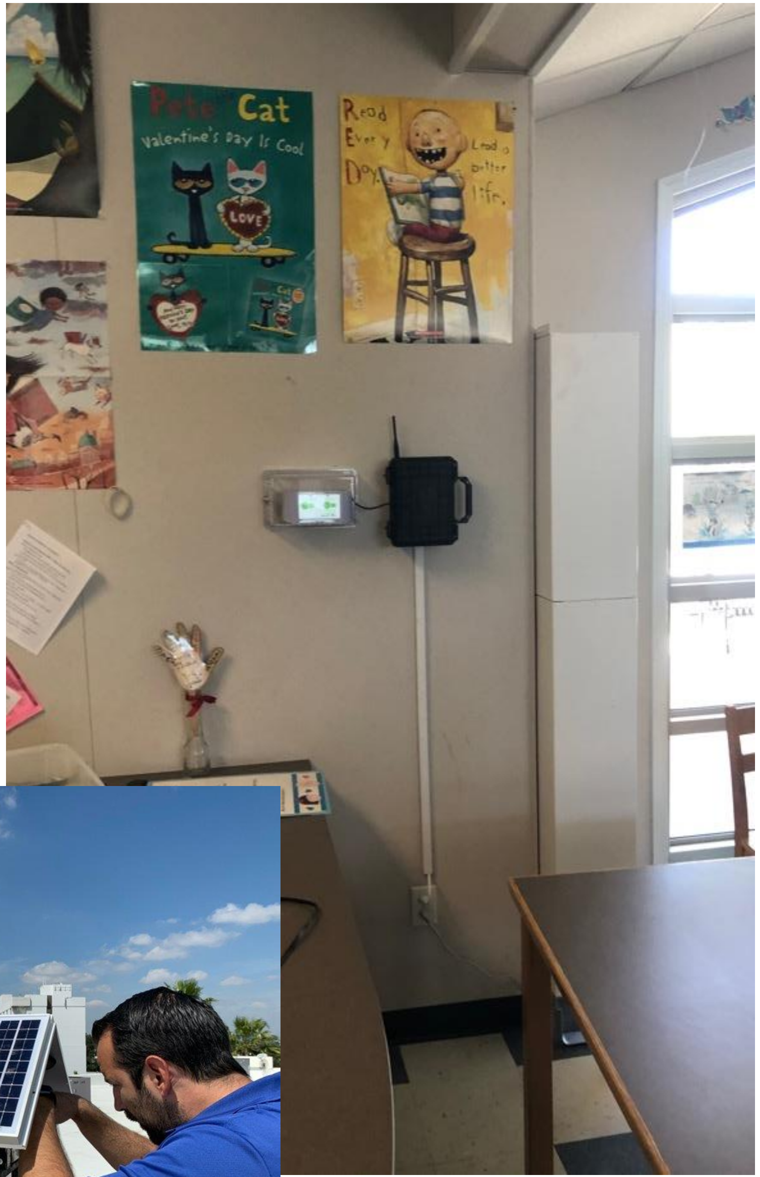
IQAir®

Smart Occupancy-Based Thermostats
(South Coast AQMD Air Filtration Program)

- Many US classrooms still have manually controlled thermostats (often not used)
- Occupancy-based thermostats can help ensure that HVAC systems run when they are needed the most
- Typical installation: smart wall-mounted thermostat + wireless ceiling motion sensor

Manually controlled thermostat

Occupancy activated thermostat



Indoor / Outdoor Monitoring

- PM 2.5, CO_2, temperature and humidity
- Teachers can see when ventilation is necessary or to be avoided

IQAir®

Indoor / Outdoor PM2.5 Measurements

30 Sensors

12 Outdoor Sensors

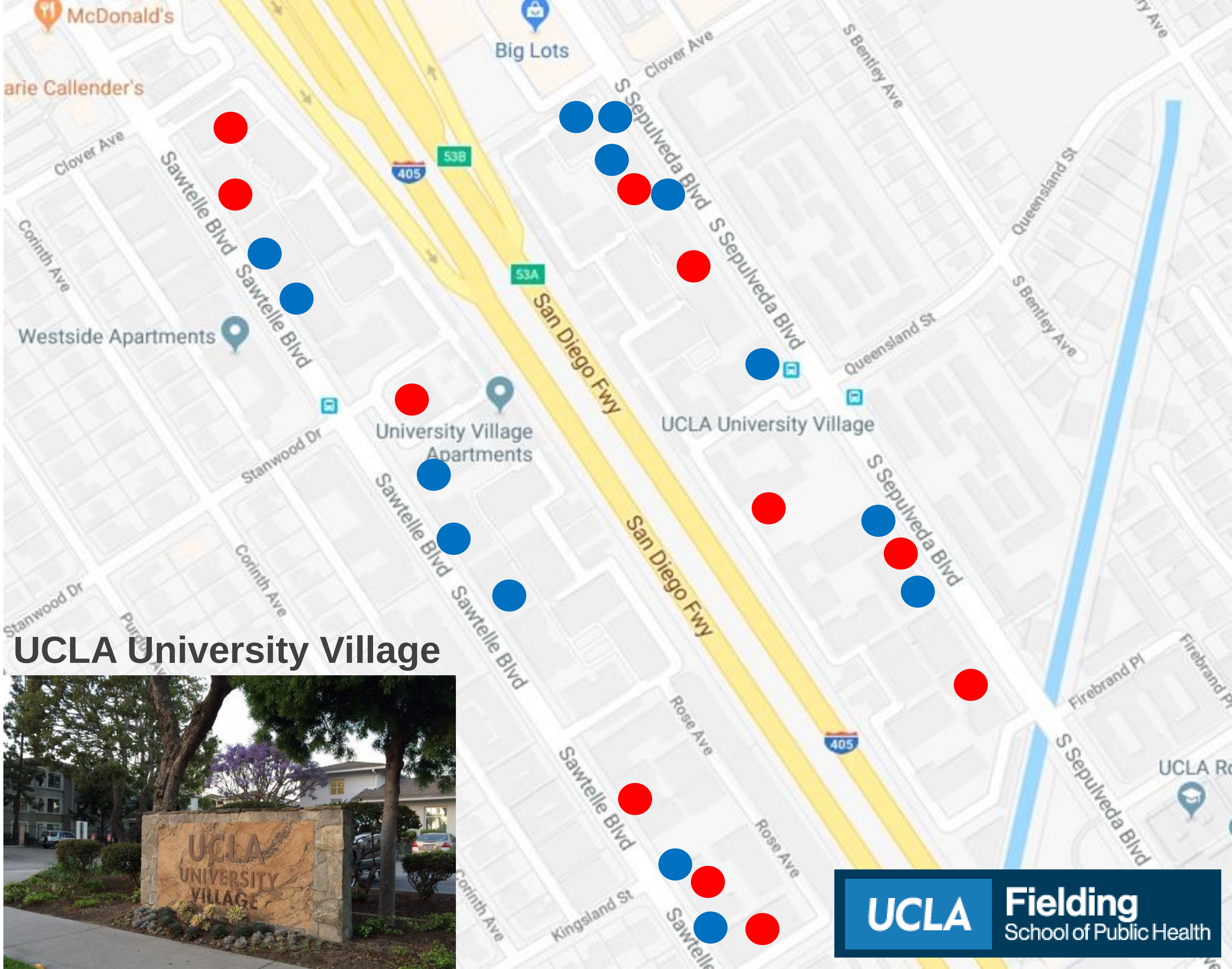
6 in Sawtelle

6 in Sepulveda

18 Indoor Sensors

8 in Sawtelle

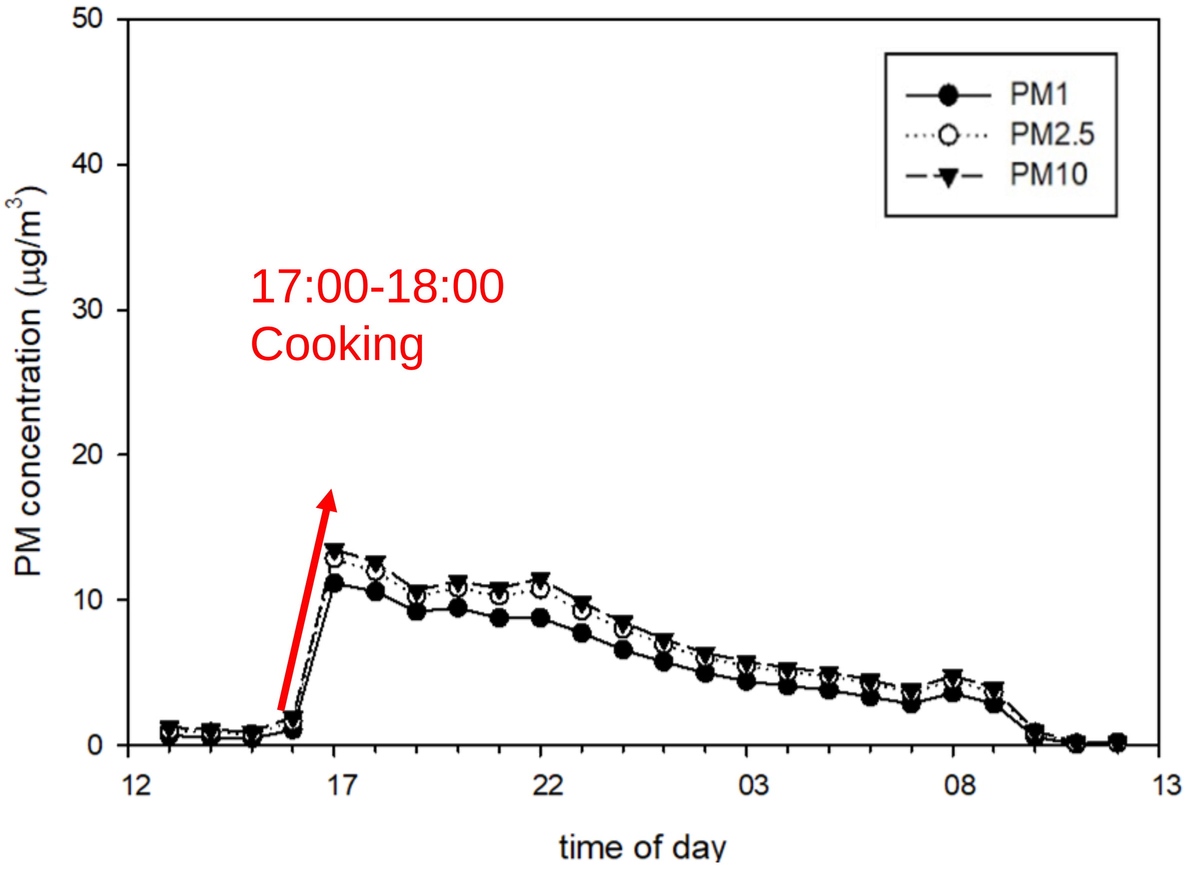
10 in Sepulveda

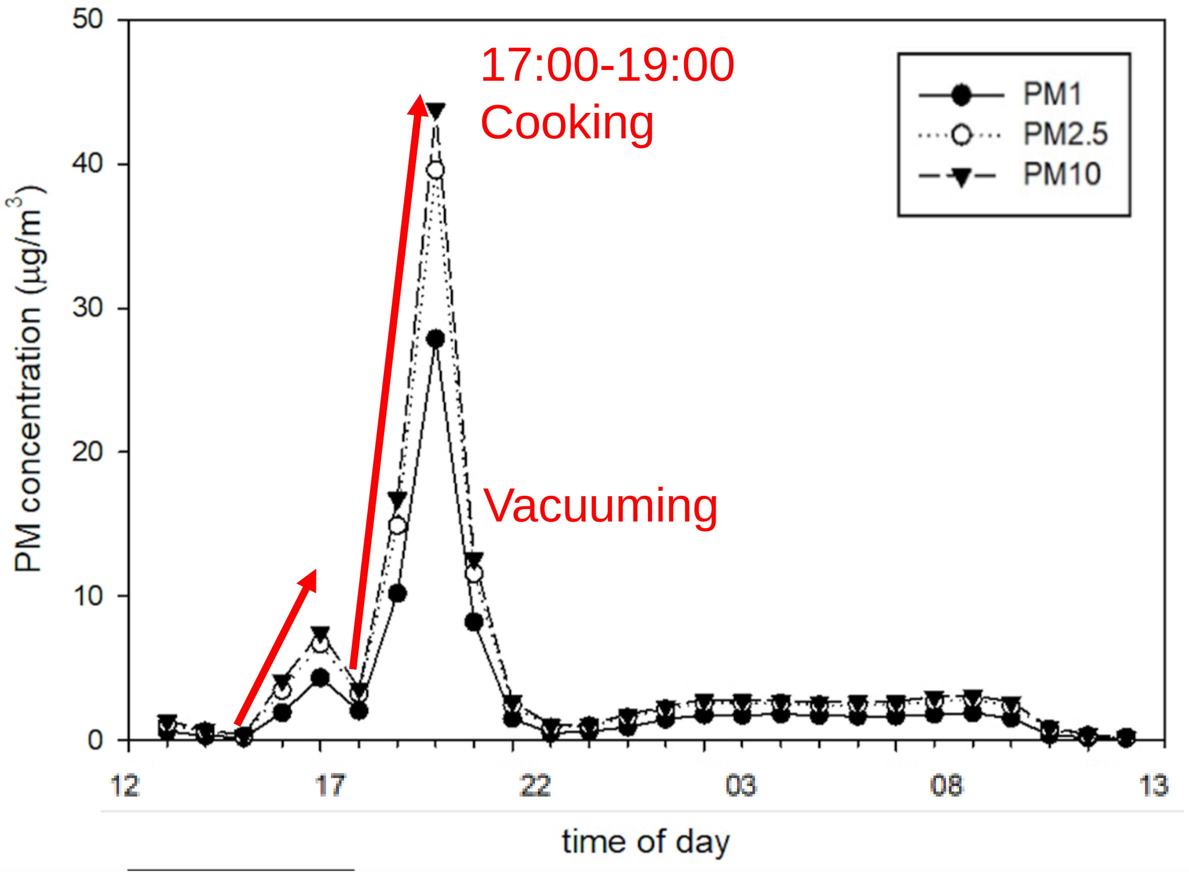


UCLA University Village

UCLA Fielding School of Public Health

Indoor Sources: Cooking and Vacuuming

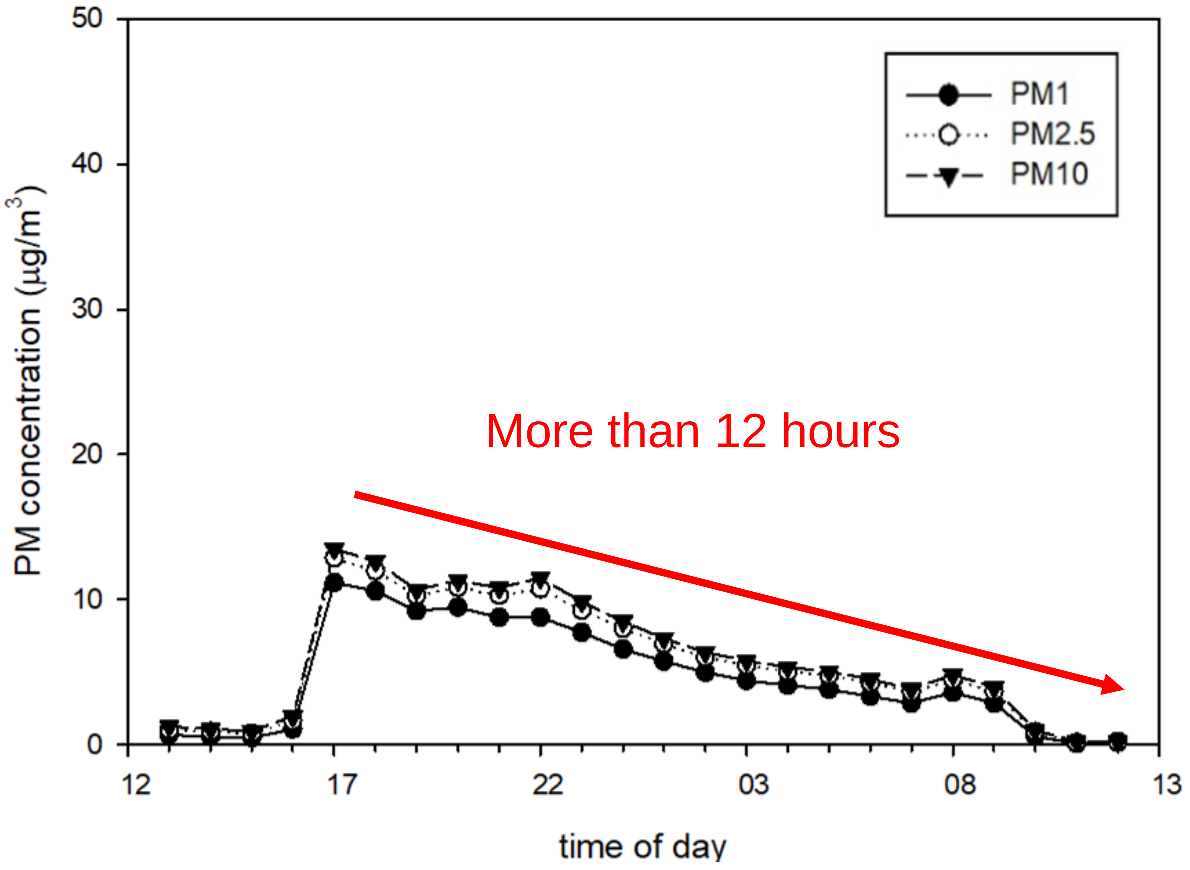




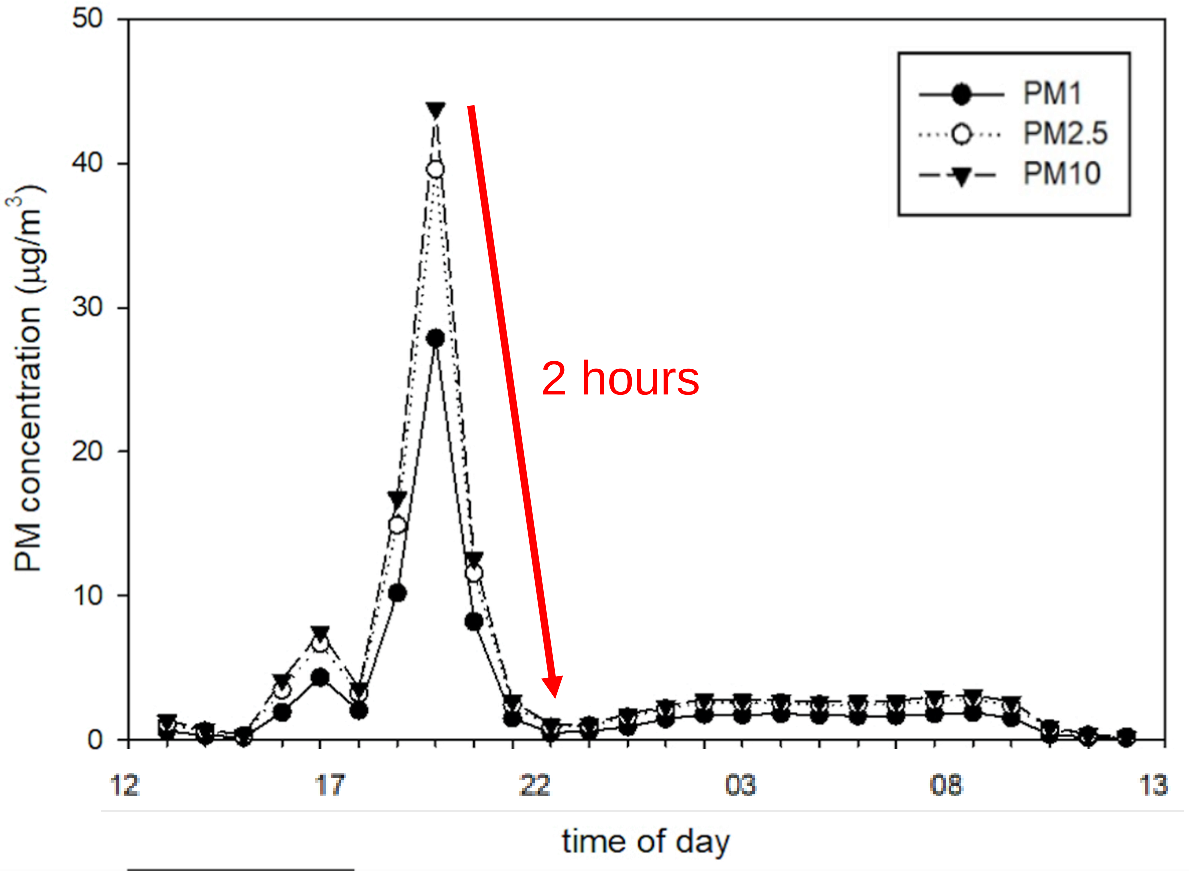
Hourly PM Concentration in one apartment during two separate days

Indoor Sources: Cooking and Vacuuming

Fan over stove off



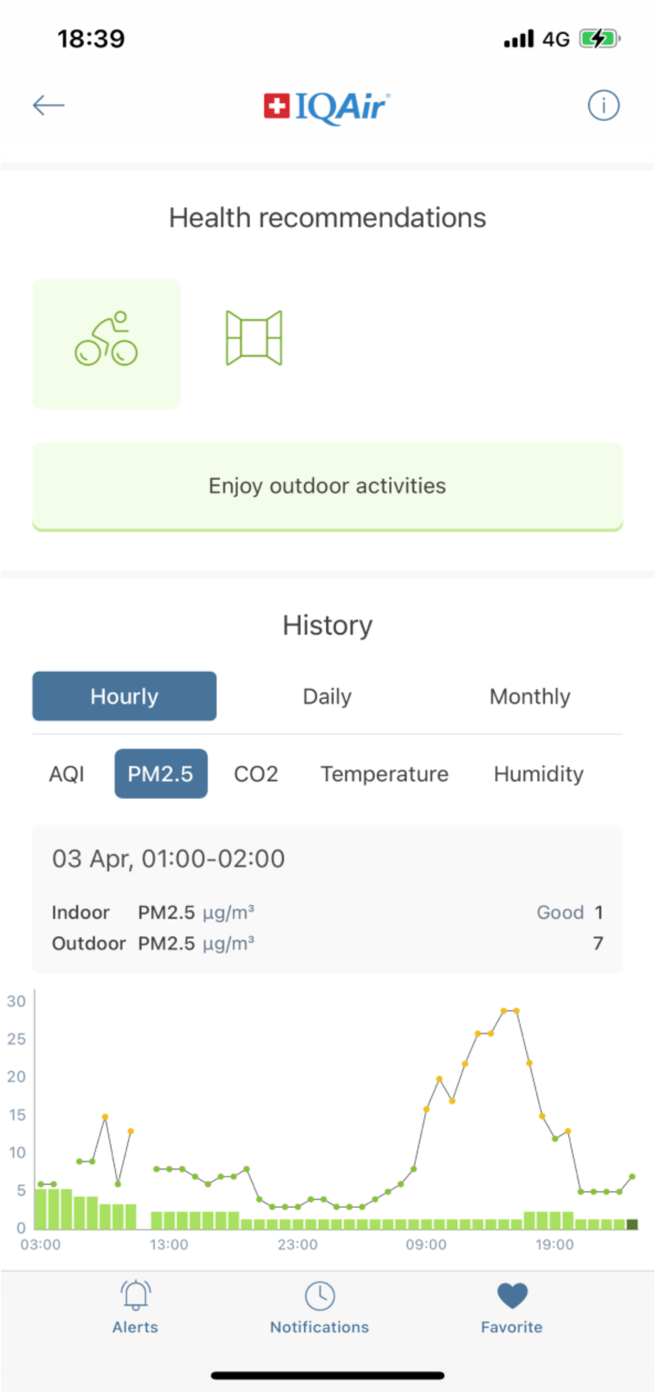
Fan over stove on

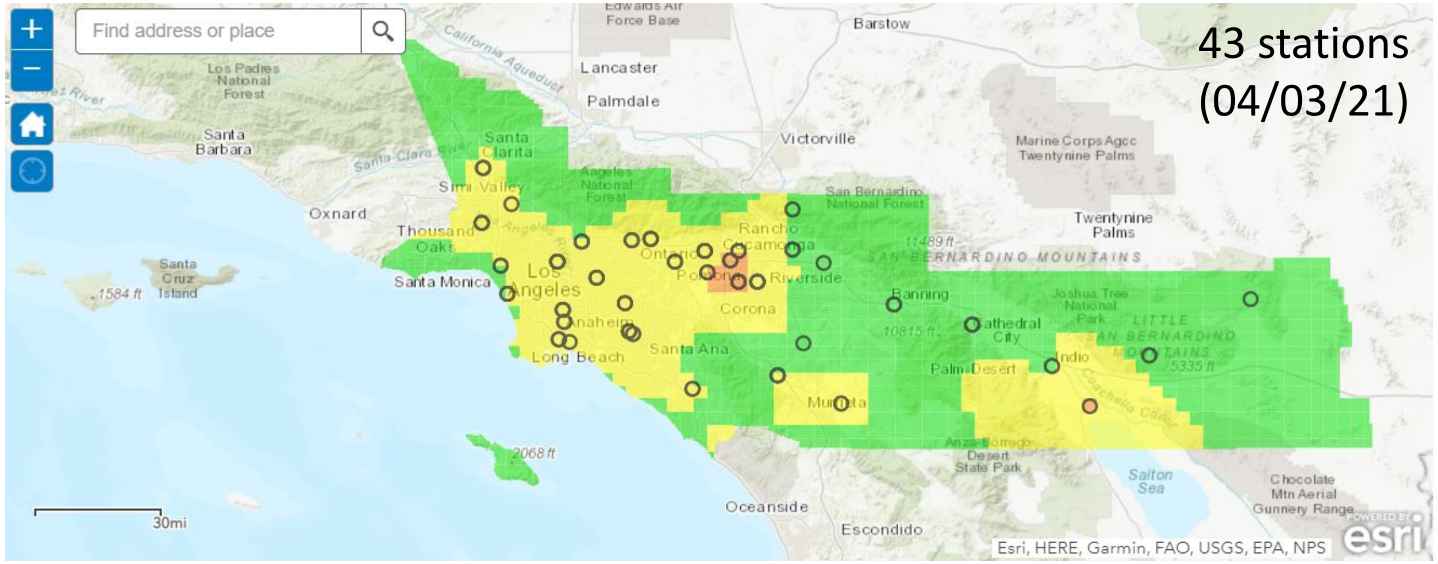


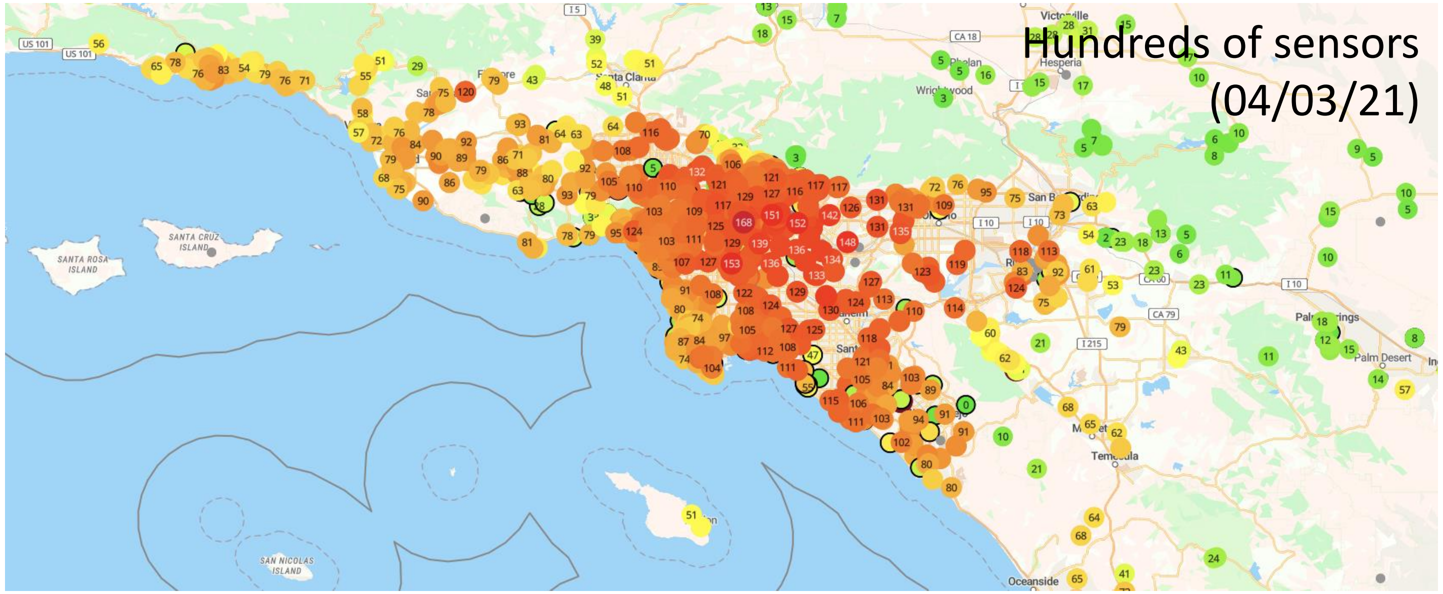
Hourly PM Concentration in one apartment during two separate days

UCLA Fielding School of Public Health

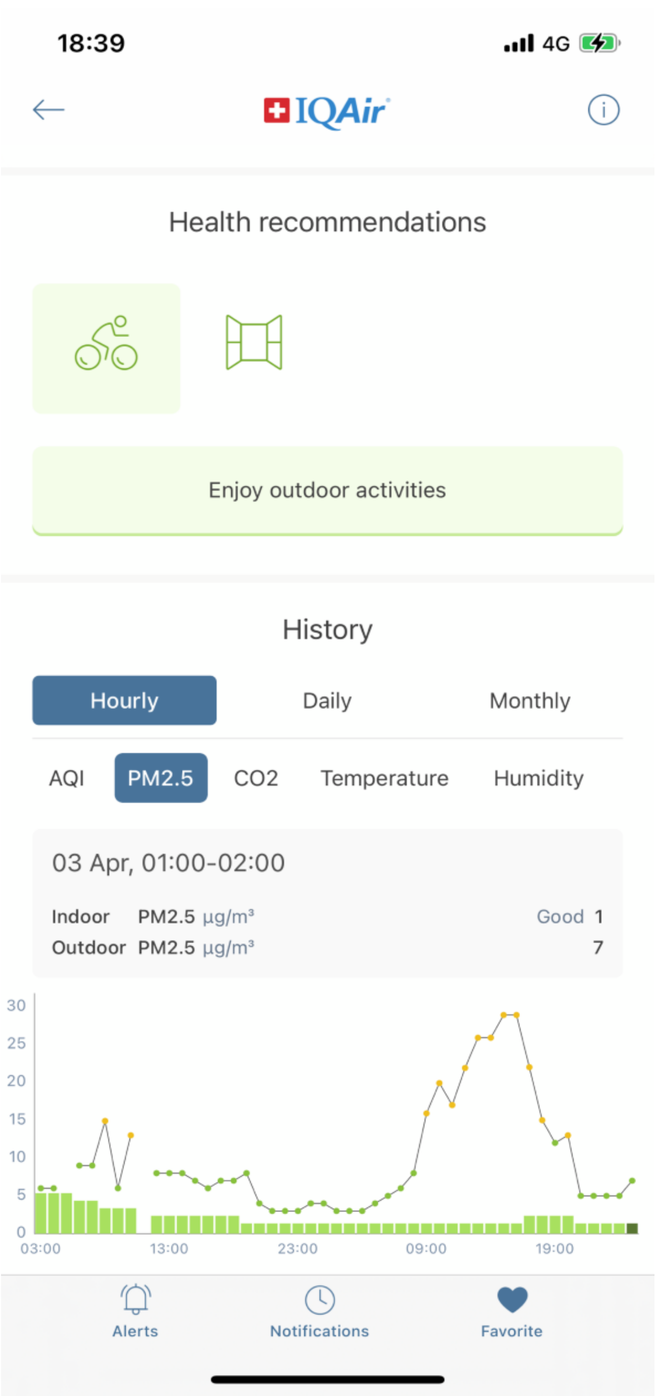
Local, Regional and Global View

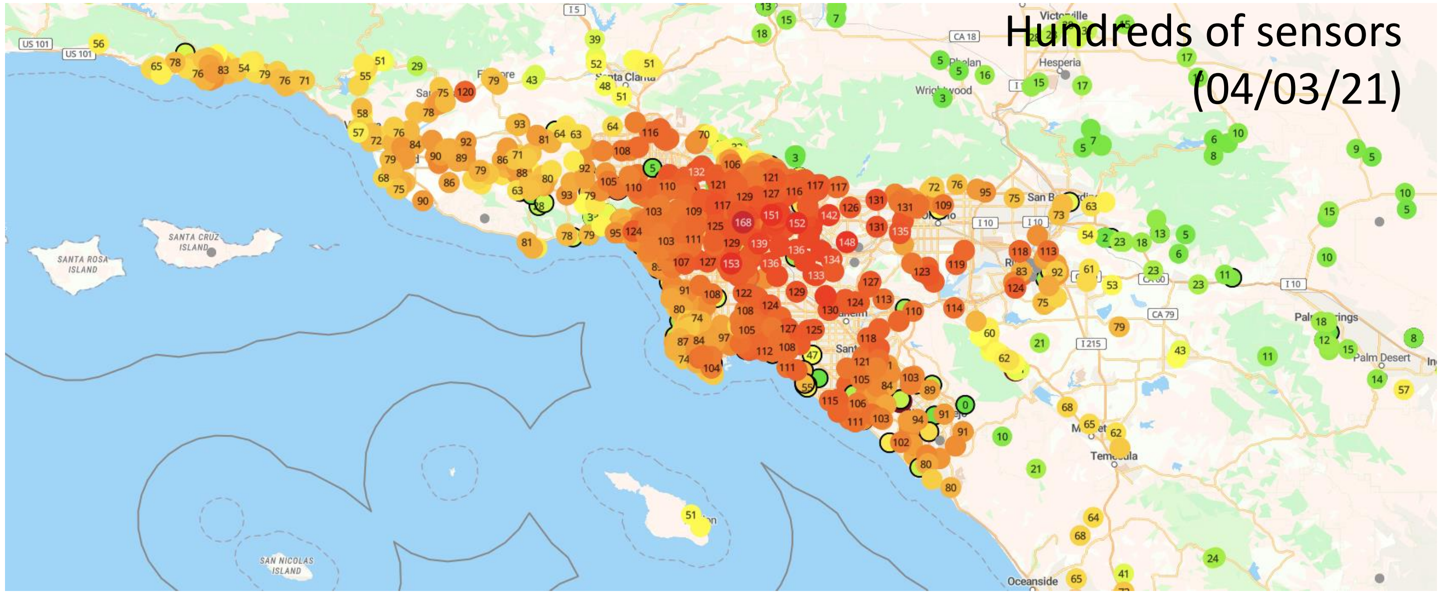


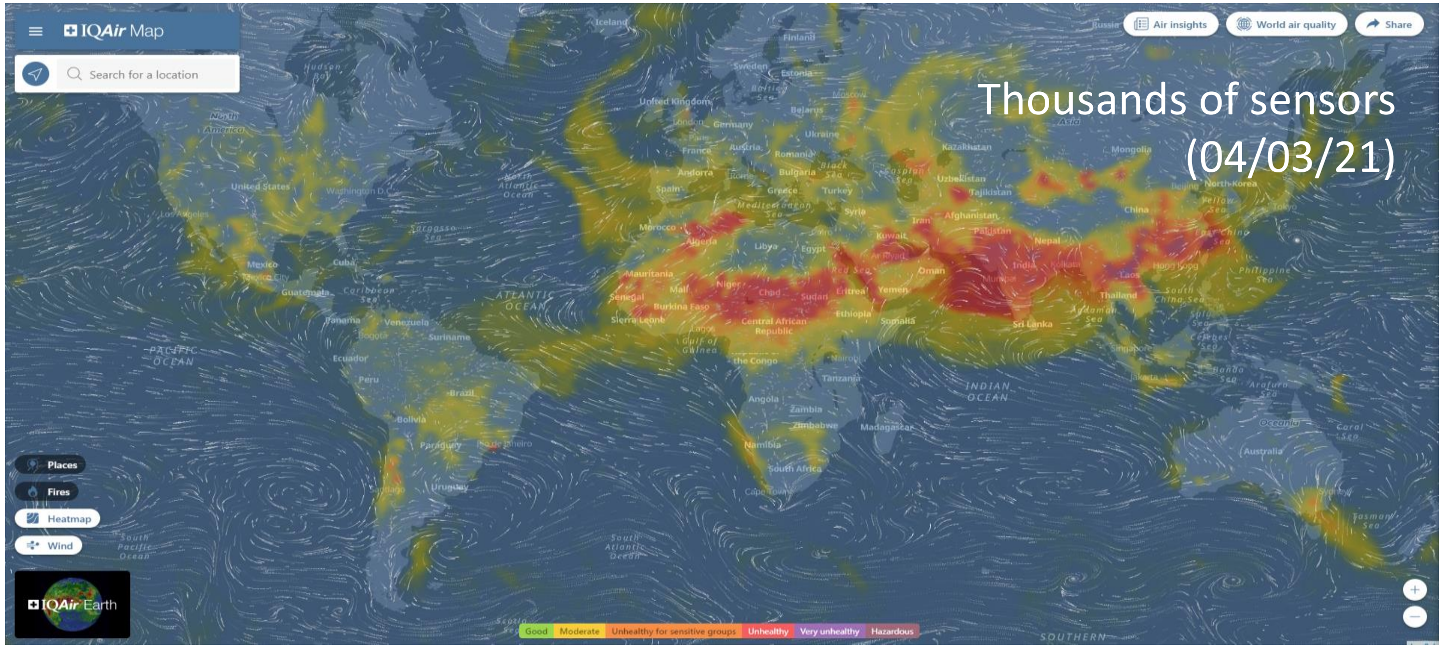




Local, Regional and Global View







Acknowledgements

South Coast AQMD
AQ-SPEC
Air Quality Sensor Performance Evaluation Center

Dr. Vasileios Papapostolou
Dr. Ashley Collier-Oxandale
Berj Der Boghossian
Dr. Brandon Feenstra
Dr. David Herman
Dr. Michelle Kuang
Randy Lam
Dr. Wilton Mui

UCLA Fielding School of Public Health

Dr. Yifang Zhu
(Professor; Department of Environmental Health Sciences)

IQAir®

Frank Hammes
(IQAir CEO)

Thanks!

Dr. Andrea Polidori
(apolidori@aqmd.gov)