DOCKETED	
Docket Stamp Updated:	2/8/2022 2:12:56 PM
Docket Number:	19-SPPE-04
Project Title:	SJ2
TN #:	241478
Document Title:	Ada E Márquez Comments on CEQA Comment Letter Appendix A Ref (5 of 8)
Description:	Due to docket staff error, the document was docketed on February 7, 2022, not February 8, 2022.
Filer:	System
Organization:	Ada E. Márquez
Submitter Role:	Public
Submission Date:	2/8/2022 11:59:25 AM
Docketed Date:	2/7/2021

DOCKETED

Docket Number:	19-SPPE-04
Project Title:	SJ2
TN #:	241478
Document Title:	Ada E Márquez Comments on CEQA Comment Letter Appendix A Ref (5 of 8)
Description:	N/A
Filer:	System
Organization:	Ada E. Márquez
Submitter Role:	Public
Submission Date:	2/8/2022 11:05:56 AM
Docketed Date:	2/8/2022

Comment Received From: Ada E. MÃ¡rquez
Submitted On: 2/8/2022
Docket Number: 19-SPPE-04

Ada E MÃ¡rquez Comments - CEQA Comment Letter Appendix A Ref (5 of 8)

Additional submitted attachment is included below.

Current and Potential Actions (cont.)

Permitted Stationary Sources

Regulatory Authority: Air District

- **Existing Programs:**
  - Multiple current regulations to reduce PM from refineries, metal foundries, coke calcining, materials handling
  - New requirements under development to limit condensable PM from refineries and the cement kiln
  - Permitting rules cap PM and precursors region-wide
- **Potential New Programs:**
  - New rule to limit site-wide health risk from PM
  - Modify permitting regulations to address localized health risks

Current and Potential Actions (cont.)

Magnet Sources

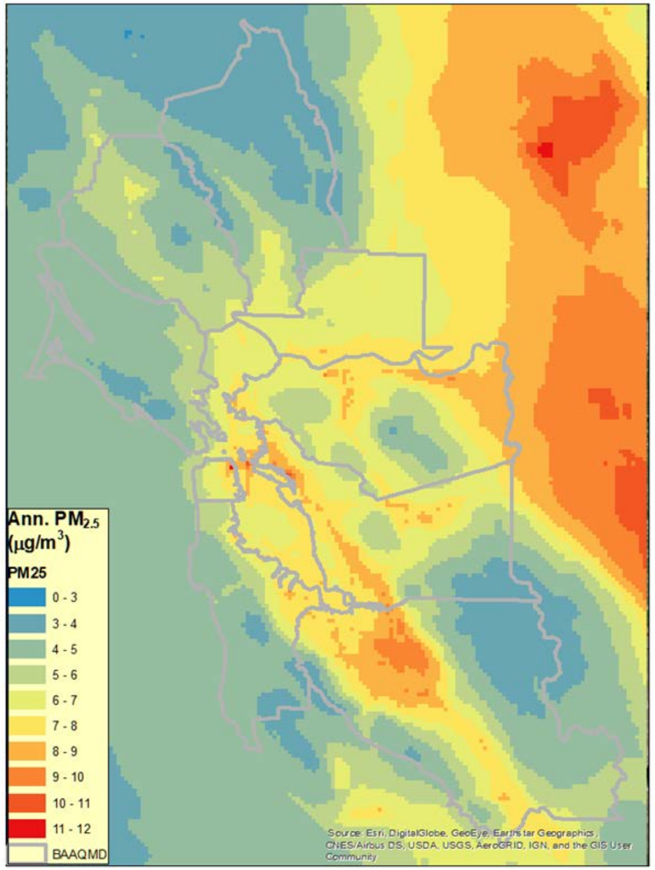
Regulatory Authority:
?

- **Magnet Source Rule(s)**

  Businesses that attract mobile sources: Examples: US Post Office facilities, port warehouses, and distribution centers

  Rule Development status: seeking changes to Air District authority at the state level

Gaps in Authority to Regulate PM



- Fine PM as Toxic Pollutant
- Establish Air Quality Standards for PM
- Magnet Sources of all forms of PM

Reducing Health Impacts of Fine PM

Air District Next Steps

- **Considerations of health impacts**
  - Community-level health exposure assessments
  - Health-benefit analyses
- **Establish “Goals” for PM reductions**
- **Additional Rule Development Efforts**

Questions?

AGENDA: 4A

PRESENTATION TO BAAQMD ADVISORY COMMITTEE

Proposed Guiding Principles for Consideration in Forwarding Recommendations to the BAAQMD on PM2.5 Regulation

Frances Keeler, CCEEB
July 31, 2020

California Council for Environmental and Economic Balance

The California Council for Environmental and Economic Balance (CCEEB) is a nonpartisan, nonprofit coalition of labor, business, and public leaders that advances strategies for a healthy environment and sound economy. CCEEB represents many facilities that operate in the Bay Area Air Quality Management District.

C437

Guiding Principles

Recommendations from the AC to the BAAQMD should:

- Be based on best peer-reviewed science
- Consider input/lessons learned from other agencies
- Consider $PM_{2.5}$ speciation and source apportionment
- Address regional vs local impacts and control strategies
- Include an economic evaluation
- Prioritize strategies by greatest amount of near-term, cost-effective reductions

C438

Scientifically Based Recommendations

Recommendations:

- Must be informed by the best, scientifically-based data possible
  - *Is more data needed and , if so, what is needed?*
- Should be based on peer-reviewed studies
- Should consider guidance developed by other agencies
- Data collection versus modeling
- Should demonstrate causal relationship before recommending controls
- Should be all inclusive

Coordination Between Agencies

- AC should consult other agencies on health standards
  - *CARB – sets SAAQS*
  - *OEHHA*
  - *CA Air Districts*
- AC Should direct Staff to work with other agencies
- AC should consider measures agencies are implementing to reduce PM and how it might advance the goals of the BAAQMD
  - *CARB is adopting many strategies for mobile sources that will reduce $PM_{2.5}$*
  - *BAAQMD has regulations in the plan and in process to further reduce $PM_{2.5}$*
  - *State is developing strategies to address wildfires*

C440

PM Speciation

- Advisory Council must examine speciation
- There are many contributors to PM2.5
  - *Mobile sources*
  - *Commercial sources (restaurants)*
  - *Residential sources (wood burning fireplaces, fire pits, BBQs)*
  - *Material handling*
  - *Industrial combustion sources*
  - *Secondary formation sources*
  - *Naturally occurring sources*
  - *Wildfires*
- Speciation/source apportionment are key to determining the most effective means of reduction
  - *Not about exoneration, but about effectiveness*

C441

Regional vs Local Controls

- $PM_{2.5}$ levels vary at the localized level
  - *Different sources contribute to $PM_{2.5}$ levels in different communities*
- Are regional reductions more effective than localized reductions?
- What is the goal and how do we best achieve it?
- Have the COVID response measures changed impacts on either the regional or local level and is any of the change permanent?

C442

Economic Impacts

- Need to focus limited resources where they will be most effective
- AC should review research that includes economic analysis of potential PM control strategies and identify/recommend proven strategies that can be implemented expeditiously and economically

C443

Prioritize Recommended Measures

- **Identify the goal and recommend:**
  - *Measures with greatest ground-level concentration reductions*
  - *Measure with greatest impact*
  - *Measures available near-term versus future reductions*
  - *Most cost-effective measures*
  - *Measures that reduce the most impactful portion of* $PM_{2.5}$

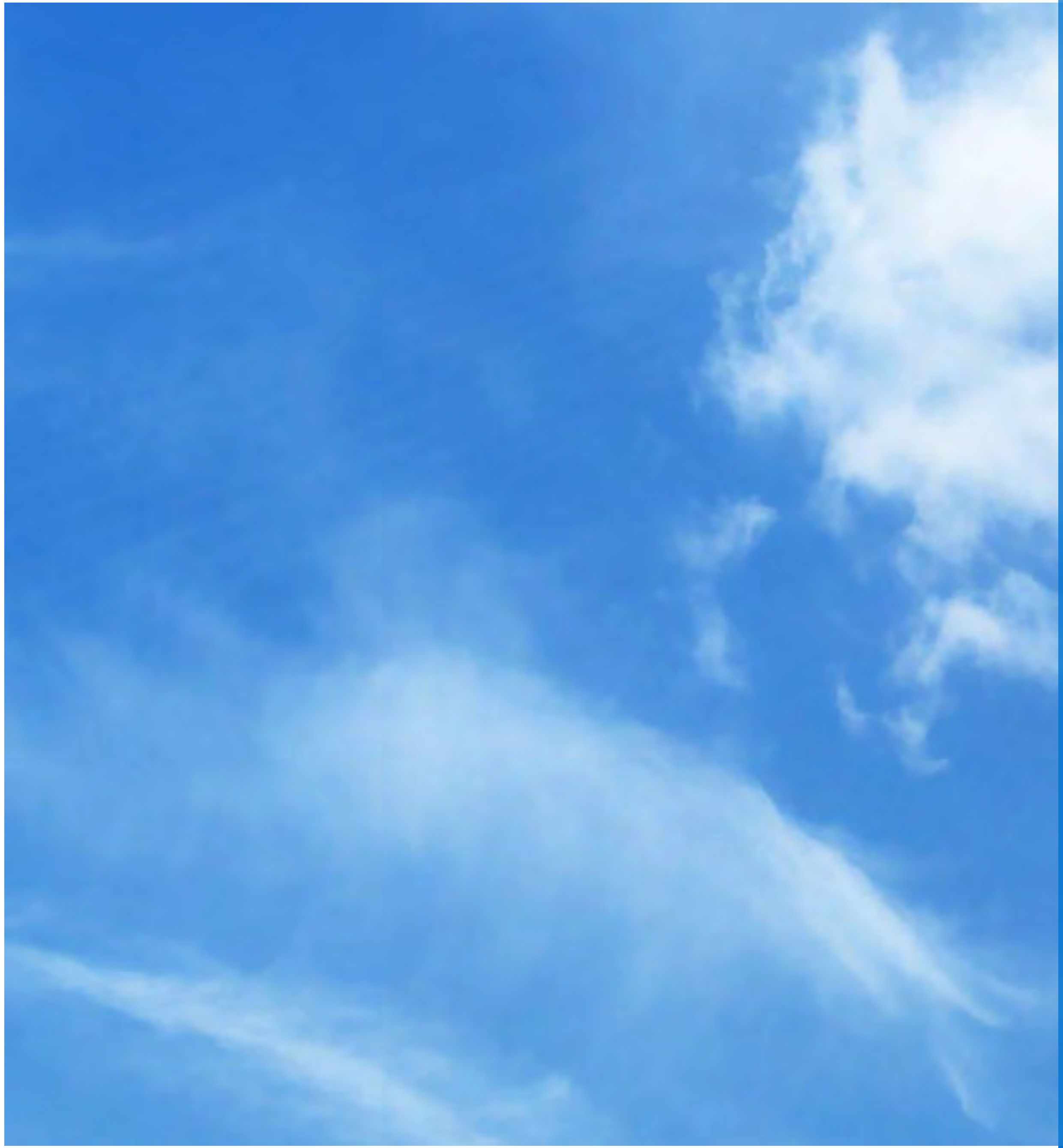
Factors Beyond the Scope of the Advisory Council

- District Authority
  - *State and Federal government establish standards/regulate mobile sources*
- CEQA analysis of control options
- Resources
- Cost-effectiveness threshold

BAAQMD Action on Advisory Council Recommendations

- **Action informed by best, scientifically-based data possible**
  - *Will help determine what to regulate first and where/how to get the most effective reductions*
- **Consider input/peer review/actions from other agencies**
  - *What vetted methods are other agencies doing to reduce $PM_{2.5}$ emissions*
  - *How might those regulations benefit the Bay Area?*
- **Regional vs Local Control**
  - *Where should BAAQMD focus its attention first?*
- **Consider $PM_{2.5}$ speciation/source apportionment**
  - *Important to determining the most effective approach*
- **Include economic evaluation**
  - *How to obtain the greatest cost-effective reductions?*

C446



GRADIENT

Assessing the Health Effects of Particulate Matter

Julie E. Goodman, Ph.D., DABT, FACE, ATS
Gradient

Bay Area Air Quality Management District

Advisory Council Meeting
July 31, 2020

Julie E. Goodman, PhD, DABT, FACE, ATS

- SB, Environmental Engineering, MIT, 1996
- ScM, Epidemiology, Johns Hopkins, 2000
- PhD, Toxicology, Johns Hopkins, 2002

- Cancer Prevention Fellow, National Cancer Institute, 2002-2004
- Principal, Gradient, 2004-Present
- Board of Health, Canton, MA, 2008-Present
- Adjunct Faculty, Harvard School of Public Health, 2009-2017

- Diplomate, American Board of Toxicology
- Fellow, American College of Epidemiology
- Fellow, Academy of Toxicological Sciences

Health Sciences

Epidemiology – The study of the distribution and determinants of health effects

Toxicology – The study of potential adverse health effects of substances on living organisms

C449 GRADIENT

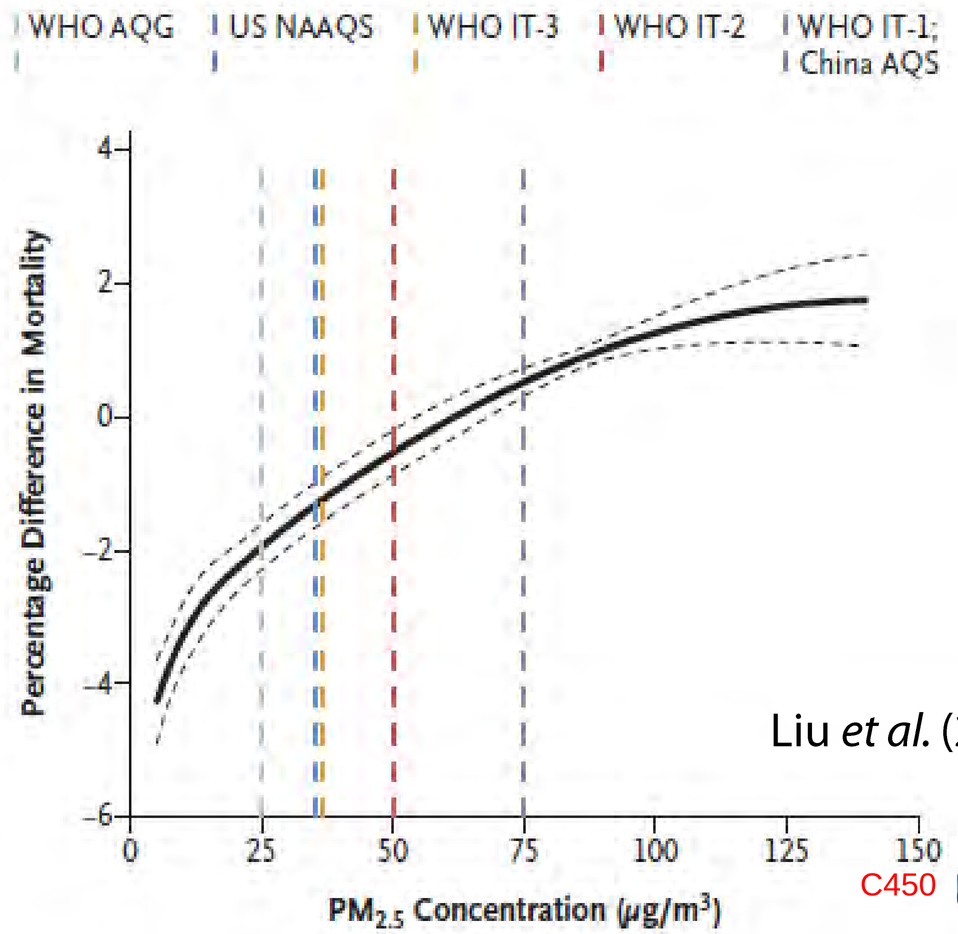
PM Associations vs. Causation

- PM is associated with morbidity and mortality in many traditional epidemiology studies
- Associations, particularly at low concentrations, are small in magnitude
- Association does not always mean causation
- Most likely explanation
  - Bias (*e.g.*, exposure measurement error)
  - Confounding
  - Chance
  - Inappropriate statistical model

The NEW ENGLAND JOURNAL of MEDICINE

ESTABLISHED IN 1812 AUGUST 22, 2019 VOL. 381 NO. 8

Ambient Particulate Air Pollution and Daily Mortality in 652 Cities



Liu *et al.* (2019)

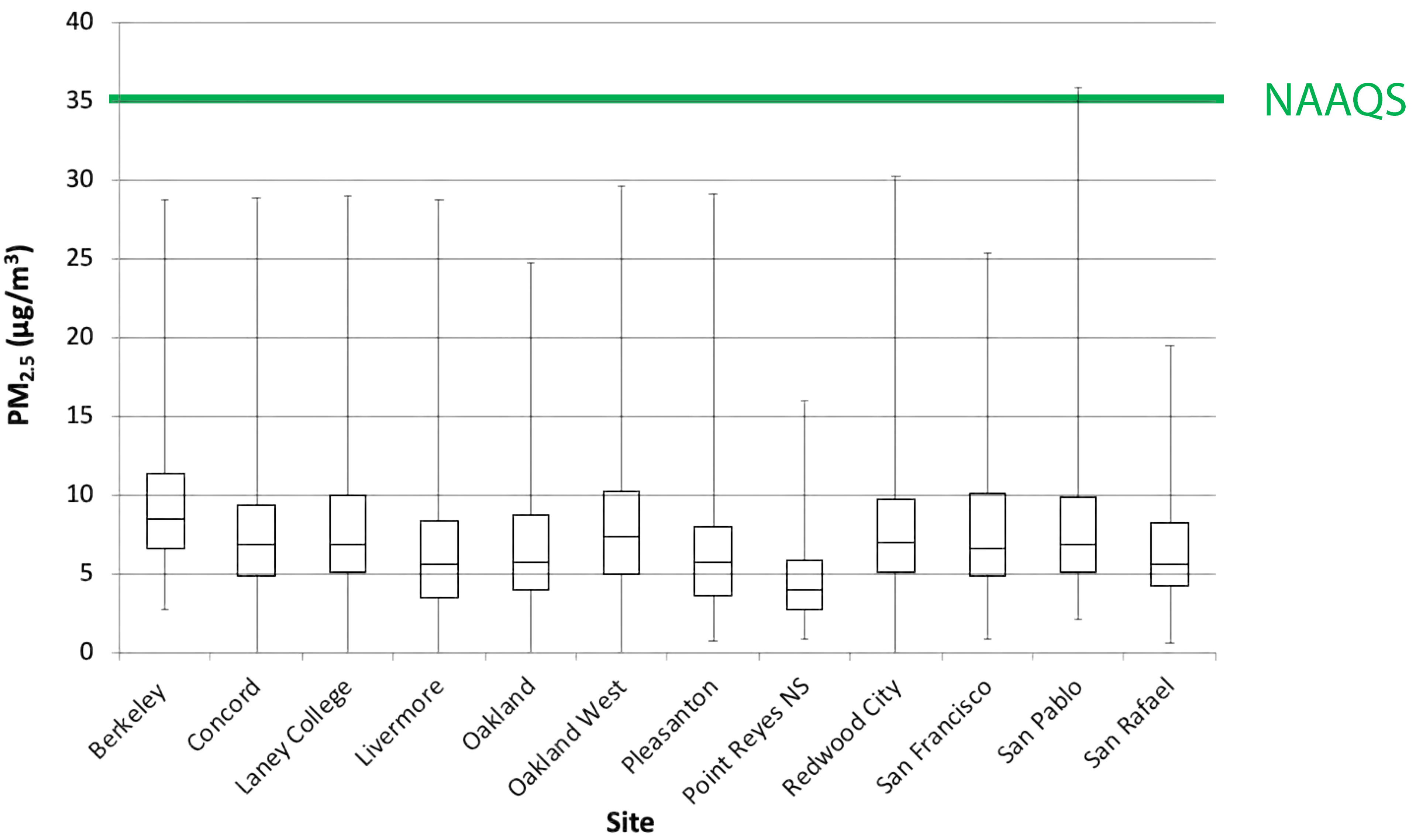
C450 GRADIENT

H. Christopher Frey June Air Quality Presentation, June 2020

- Need to consider population density, multiple pollutants, other factors
- Issues with the validity of using satellite retrieval without ground-based validation
- Larger cities have higher levels of air pollution and an increased opportunity for the spread of disease because there are many more people

There are similar issues with PM epidemiology in general

Daily Average $PM_{2.5}$ Concentrations in the Bay Area, 2019



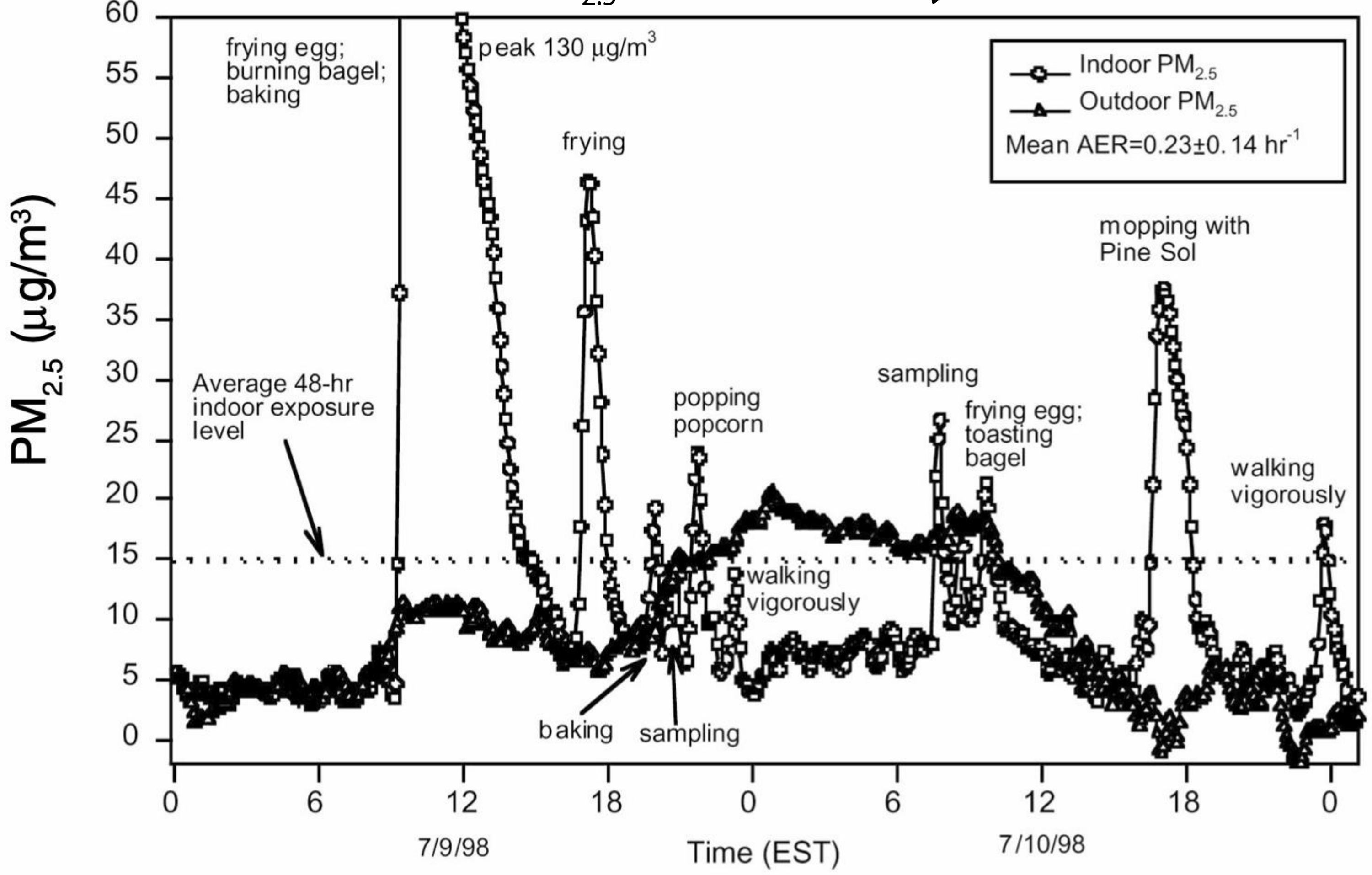
Data from https://www.epa.gov/outdoor-air-quality-data

C452

Exposure Measurement Error – Ambient Air Monitors

- Most studies use ambient air monitors
- People often spend a lot of time away from home
- People spend most time indoors
- Average PM exposures can be higher indoors

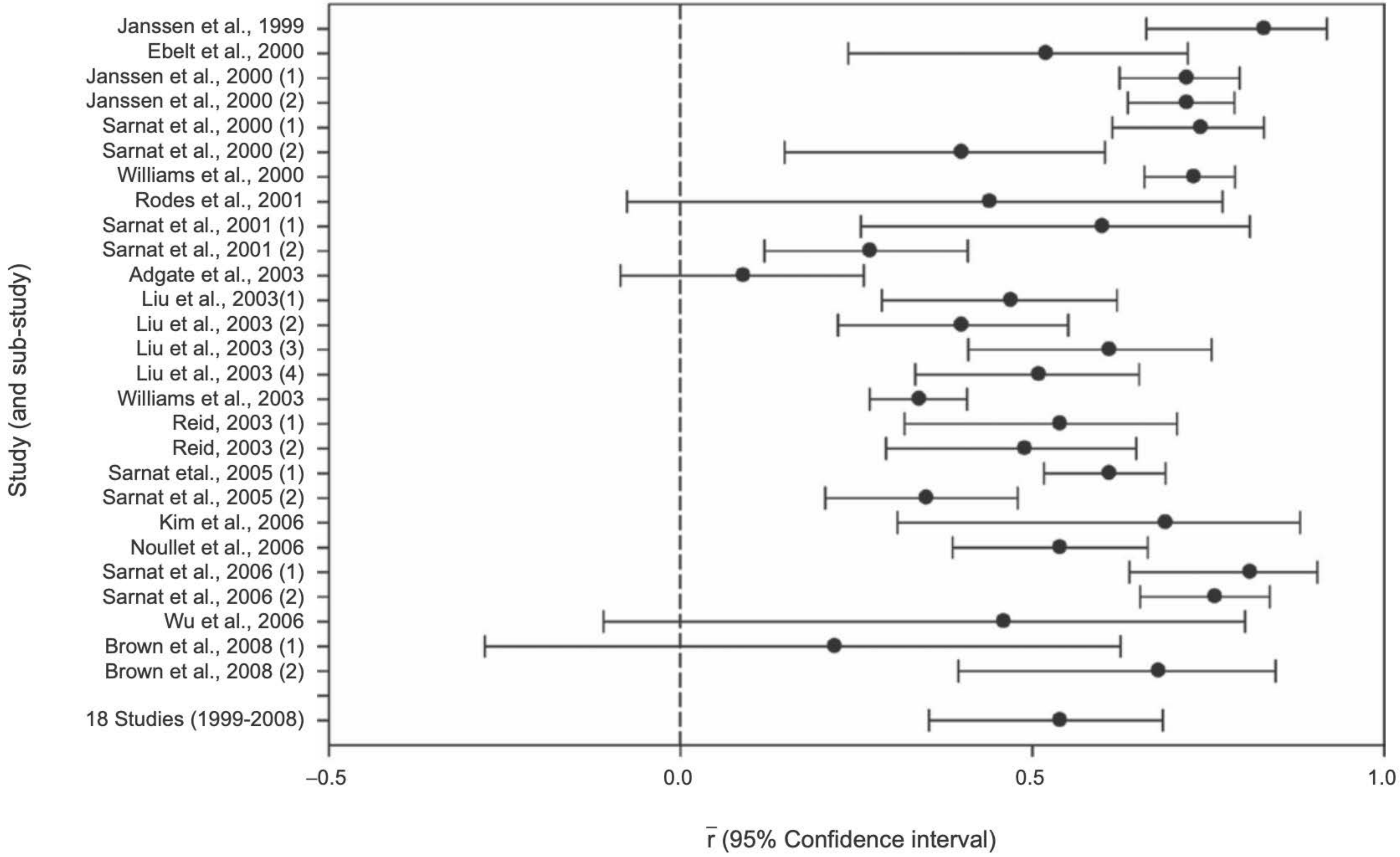
Indoor *vs.* Outdoor $PM_{2.5}$, Boston area, July 9-10, 1988



Long *et al.* (2000)
Harvard School of Public Health

C453

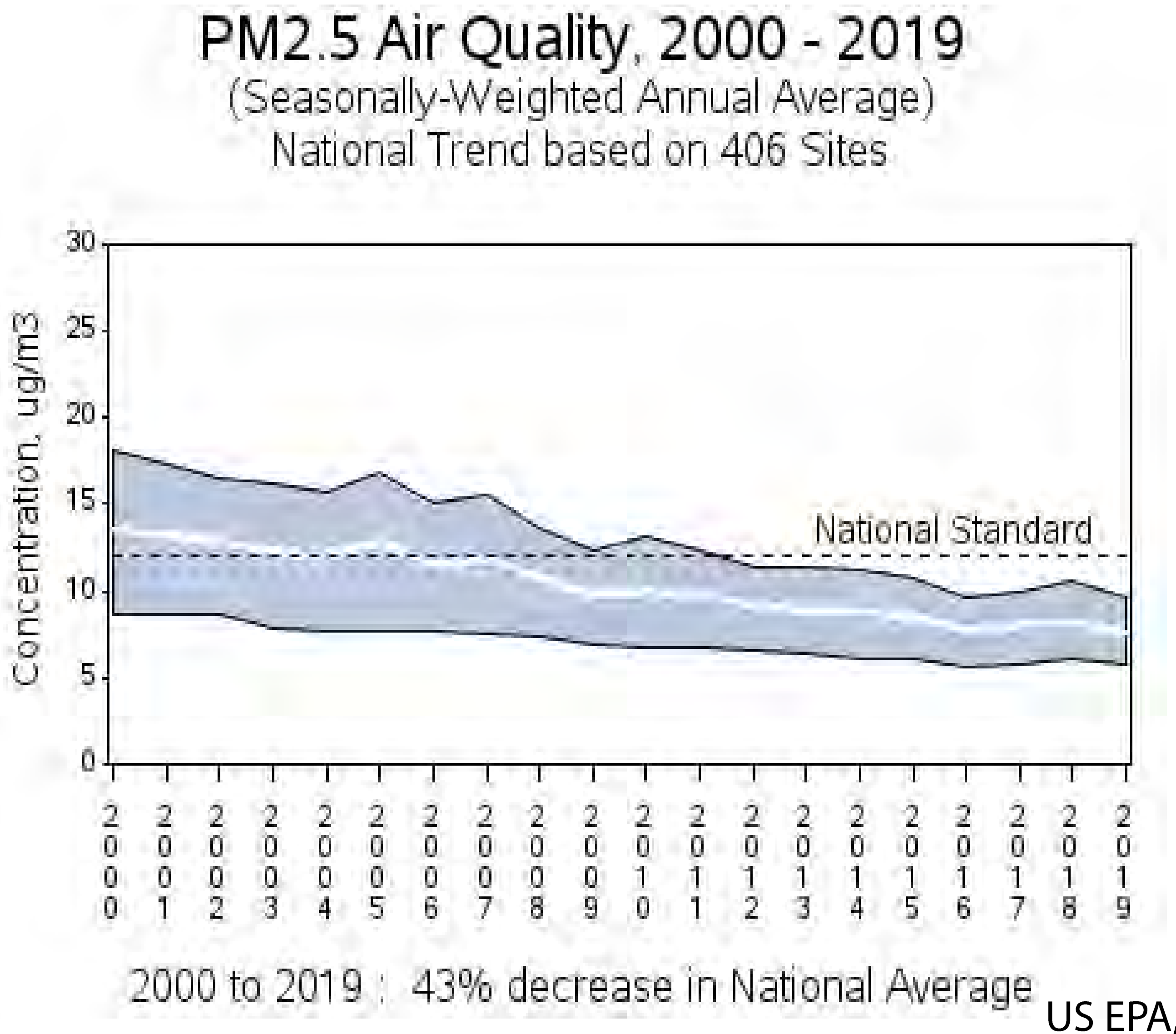
Exposure Measurement Error – Personal vs. Ambient $PM_{2.5}$ Associations Vary



Avery *et al.* (2011)

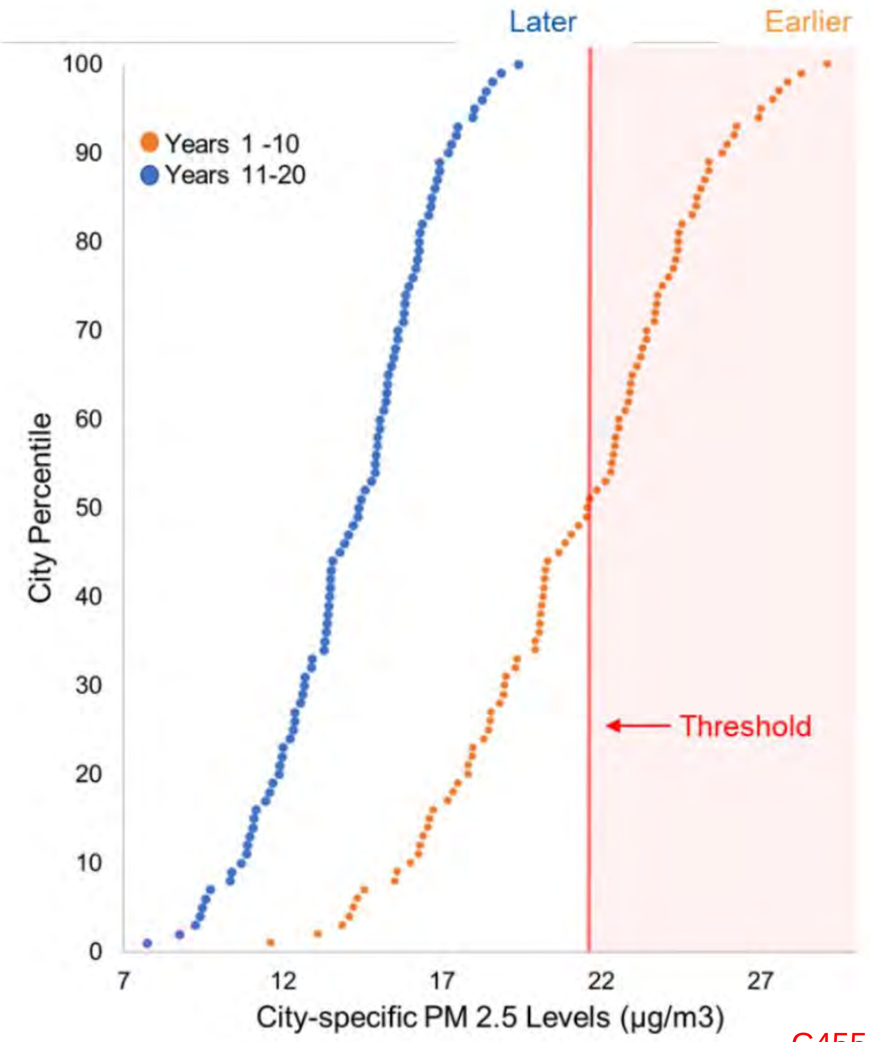
C454 GRADIENT

Exposure Measurement Error – Many Studies Evaluate the Wrong Exposure Window and Overestimate Associations



US EPA, 2020

Figure 1. PM2.5 Distributions in Illustrative Example

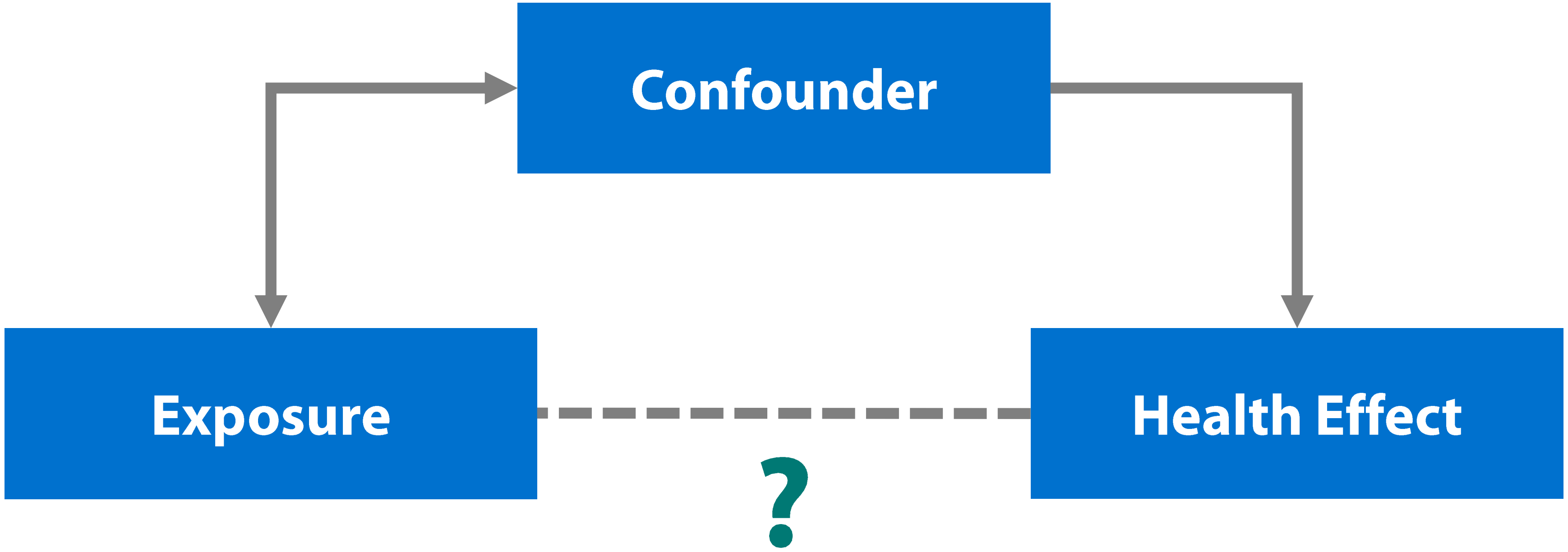


C455

Smith and Chang, 2020

Confounding

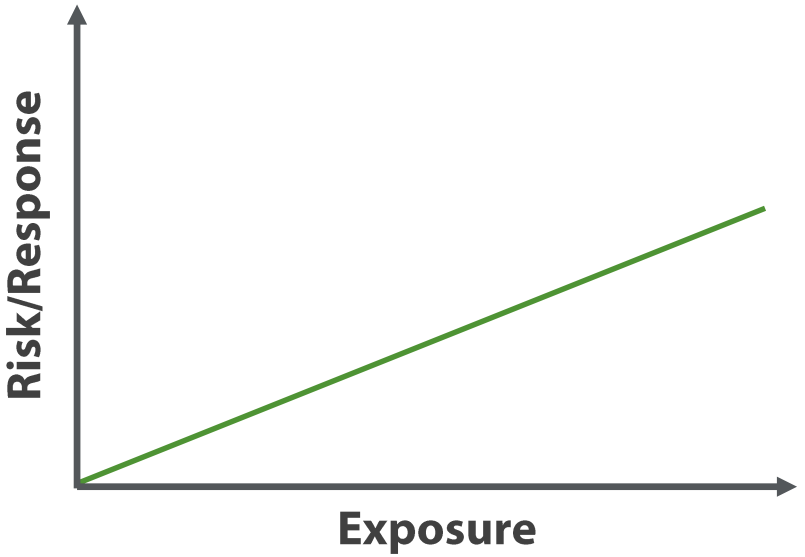
- Other exposure window
- Atmospheric conditions
- Other copollutants, allergens
- Socioeconomic status (SES)
- Lifestyle factors (*e.g.*, smoking)
- Access to health care
- Genetics



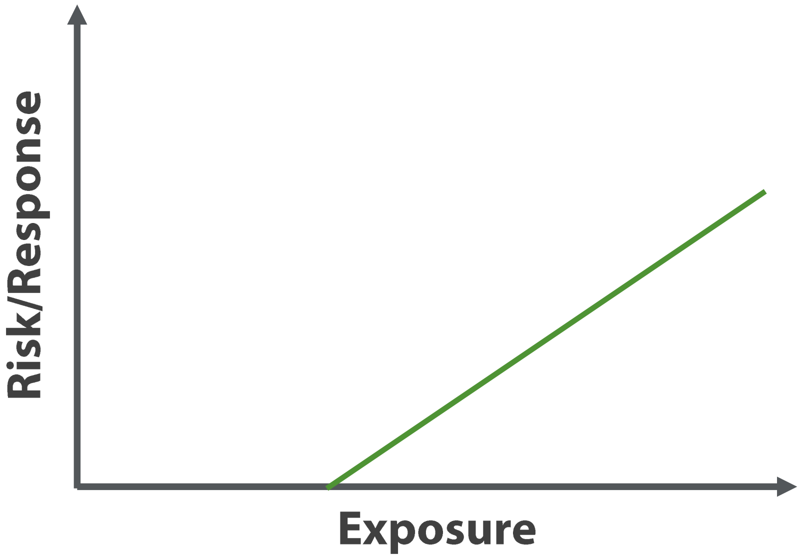
GRADIENT

Model Choice and Measurement Error Linearizes Exposure-response Curve

No Threshold



Threshold



GRADIENT

Measurement Error Linearizes Exposure-response Curve

REVIEW ARTICLE

Measurement error in environmental epidemiology and the shape of exposure-response curves

Lorenz R. Rhomberg, Juhi K. Chandalia, Christopher M. Long, and Julie E. Goodman

Gradient, Cambridge, Massachusetts, USA

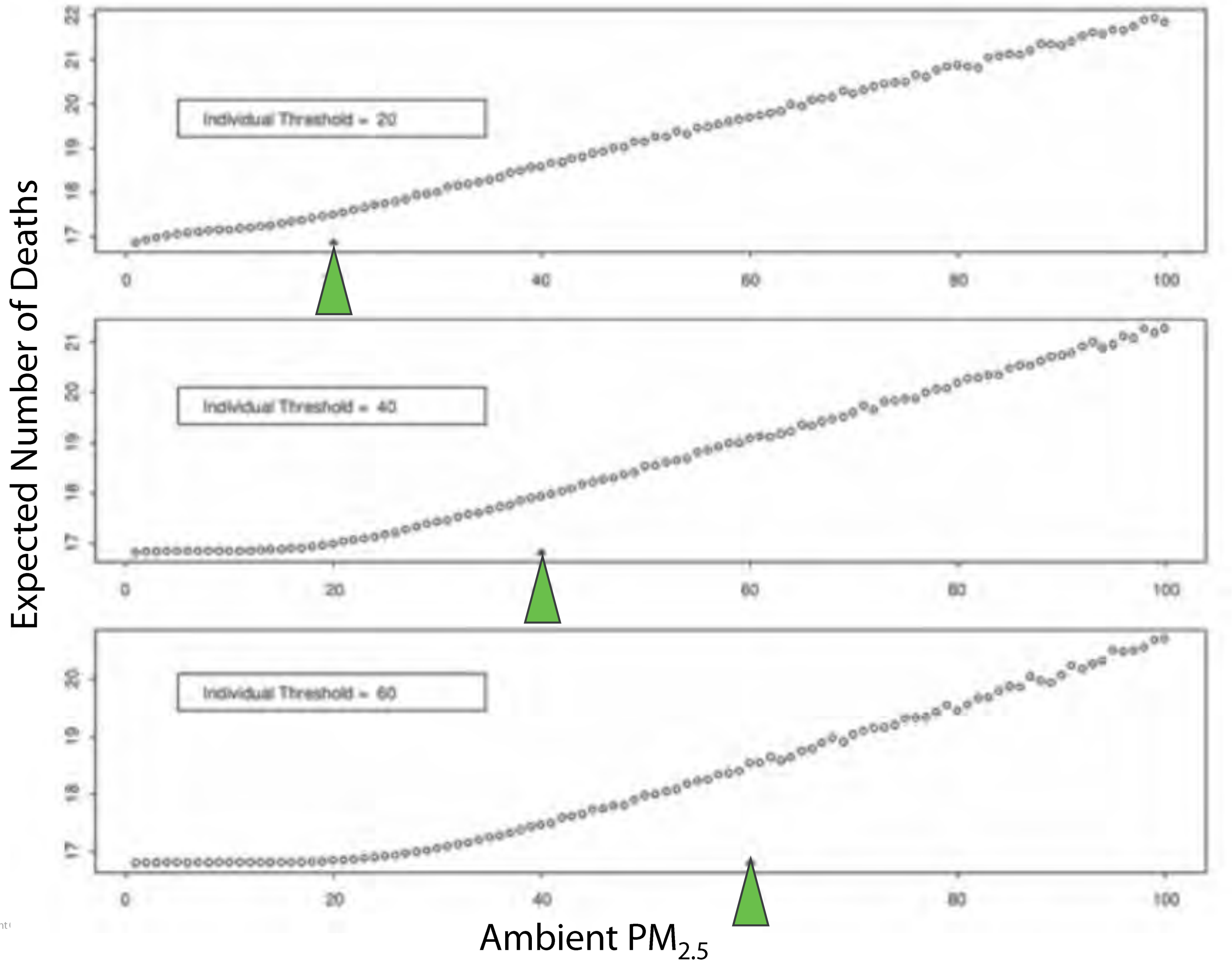
Abstract

Both classical and Berkson exposure measurement errors as encountered in environmental epidemiology data can result in biases in fitted exposure-response relationships that are large enough to affect the interpretation and use of the apparent exposure-response shapes in risk assessment applications. A variety of sources of potential measurement error exist in the process of estimating individual exposures to environmental contaminants, and the authors review the evaluation in the literature of the magnitudes and patterns of exposure measurement errors that prevail in actual practice. It is well known among statisticians that random errors in the values of independent variables (such as exposure in exposure-response curves) may tend to bias regression results. For increasing curves, this effect tends to flatten and apparently linearize what is in truth a steeper and perhaps more curvilinear or even threshold-bearing relationship. The degree of bias is tied to the magnitude of the measurement error in the independent variables. It has been shown that the degree of bias known to apply to actual studies is sufficient to produce a false linear result, and that although nonparametric smoothing and other error-mitigating techniques may assist in identifying a threshold, they do not guarantee detection of a threshold. The consequences of this could be great, as it could lead to a misallocation of resources towards regulations that do not offer any benefit to public health.

Keywords: Epidemiology, exposure, exposure-response, measurement error, risk assessment

C458 GRADIENT

Exposure Misclassification Masks or Biases Thresholds



- True exposure was modeled.
- Corresponding risks calculated for simulated population using error based on observed exposure measurement error.

"True" threshold

Brauer *et al.* (2002)
University of British Columbia

Causal Methods Example – Burns *et al.* (2017)
Health Effects Institute Review of 42 Studies of 38 Interventions

Interventions

- Industrial
- Residential
- Vehicular
- Multiple

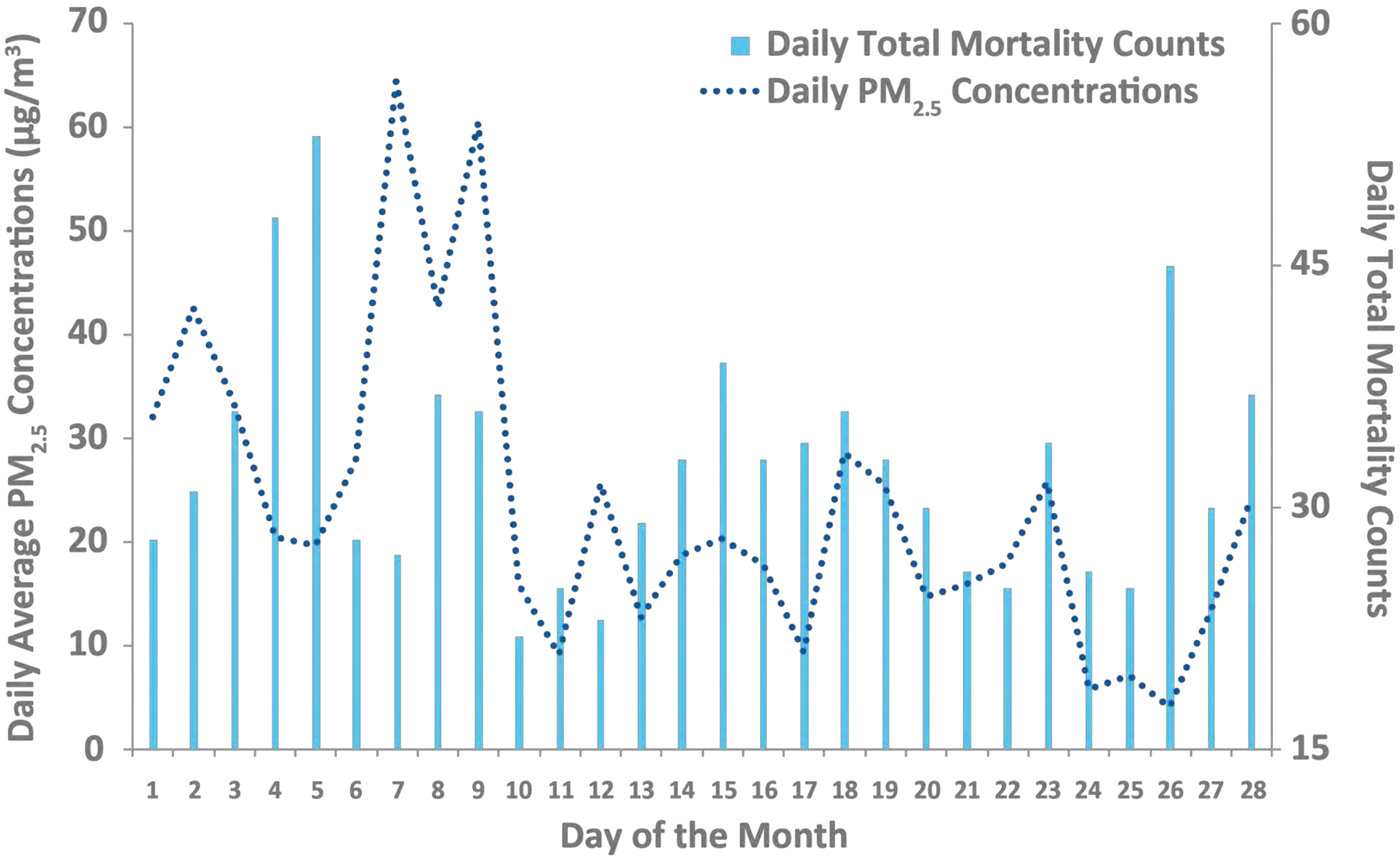
Comparison: *No restrictions*

Primary Outcomes

- All cause mortality
- Cardiovascular Mortality
- Respiratory Mortality
- PM_{10}
- $PM_{2.5}$
- Coarse PM
- Soot
- Black carbon (BC)
- Black smoke (BS)
- Elemental carbon (EC)

Results: "Evidence for effectiveness was mixed. Most included studies observed either no significant association or an association favoring the intervention, with little evidence that the assessed interventions might be harmful."

Example: $PM_{2.5}$ and Mortality in Greater Boston, 2002, after Quebec Forest Fires

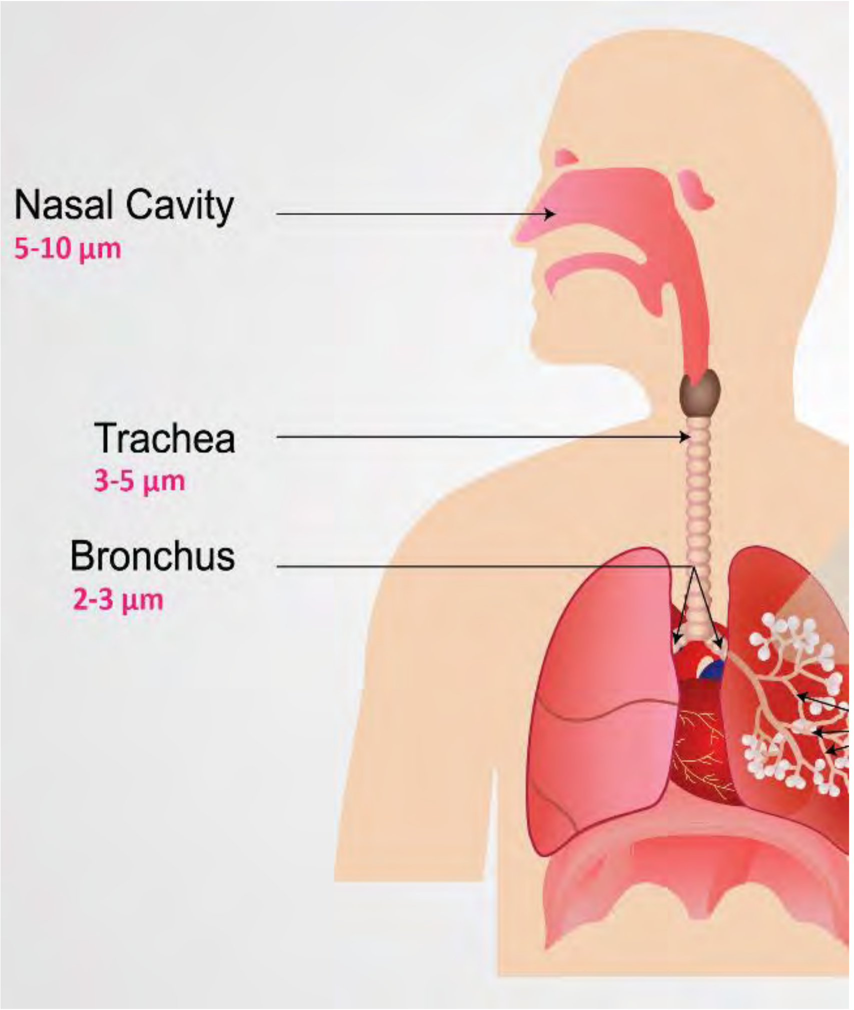


Zu *et al.* (2016)

C461

Toxicity Studies – There is a threshold below which people can be exposed to PM and not experience health impacts

- If exposures are sufficiently low, PM will not cause adverse health effects because it won't overwhelm the body's natural defenses.
- This is supported by experimental studies in humans and animals.
- CARB relies on this principle for all other non-carcinogenic agents.
- There is no justification for assuming one particle will impact health.



The Peer-review Process Is Not Perfect- Long-term PM and Mortality Example

Sources of Bias and Uncertainty		Crouse *et al.* (2012)	Crouse *et al.* (2015)	Villeneuve *et al.* (2015)	Chen *et al.* (2016)	Pinault *et al.* (2016)	Wong *et al.* (2015)	Beelen *et al.* (2014)	Cesaroni *et al.* (2013)	Lepeule *et al.* (2012)	Hart *et al.* (2015)	Shi *et al.* (2016)	Thurston *et al.* (2016)	Di *et al.* (2017a)
$PM_{2.5}$ Exposure Assessment	Central site monitoring (low spatial resolution)									X				
	No validation for $PM_{2.5}$ data						X						X	
	Temporal variation not accounted for	X	X	X	X			X	X					
	Residential mobility not accounted for	X		X		X	X	X		X		X		
	No evaluation on multiple exposure windows	X	X	X	X	X	X	X	X		X	X	X	X
	Personal activities not accounted for (*e.g.,* time spent indoors)	X	X	X	X	X	X	X	X	X	X	X	X	X
	Mismatch of $PM_{2.5}$ exposure window and mortality	X	X	X	X		X	X	X					X
Individual Covariates	No adjustment of individual covariates													
	Information bias (*e.g.,* self-reported covariates)	X	X	X		X	X	X		X	X	X	X	
	Temporal variation not accounted for	X	X	X	X	X	X	X	X	X			X	
	Unmeasured confounding (*e.g.,* pre-existing conditions)	X	X	X	X	X	X	X	X	X	X	X	X	X
Ecological Covariates	No adjustment of ecological covariates													
	Temporal variation not accounted for	X		X	X	X	X	X	X	X	X	X	X	
	Residential mobility not accounted for	X		X		X	X	X				X		
	Unmeasured confounding (*e.g.,* access to health care, violence)	X	X	X	X	X	X	X	X	X	X	X	X	X
Evaluation of Copollutants	No adjustment of copollutants													
	Central site monitoring (low spatial resolution)												X	
	No validation for copollutants data												X	
	Temporal variation not accounted for	X	X	X	X	X	X	X	X	X	X	X	X	
	Residential mobility not accounted for							X					X	
	Personal activities not accounted for (*e.g.,* time spent indoors)		X					X	X				X	X
	Collinearity/nonlinear relationship with $PM_{2.5}$ not addressed/accounted for												X	
	Mismatch of copollutants window and mortality		X					X	X				X	X
Statistical Analyses	Model assumptions not tested/relaxed		X	X		X	X	X	X		X	X	X	X
	C-R curves sensitive to *df* (natural splines)	X	X	X	X	NR	X	X	X				X	
	Nonlinearity not assessed statistically			X		X					X	X	X	X
	Threshold not assessed	X	X		X		X		X	X	X	X	X	X

GRADIENT

Conclusions – PM Threshold Is Likely Higher than Ambient Concentrations

- High concentrations of PM, and every other substance, can impact morbidity.
- There are clearly statistical associations between PM and morbidity and mortality in many epidemiology studies, even at lower, ambient concentrations.
- Evidence does not indicate associations are causal at ambient concentrations.
- There is a threshold below which people can be exposed to PM and not experience health impacts.

AGENDA: 5

Bay Area Particulate Matter (PM) Modeling-Based Assessments and Next Steps

Advisory Council Meeting
July 31, 2020

Phil Martien, PhD
Director of Assessment, Inventory, & Modeling Division

Overview

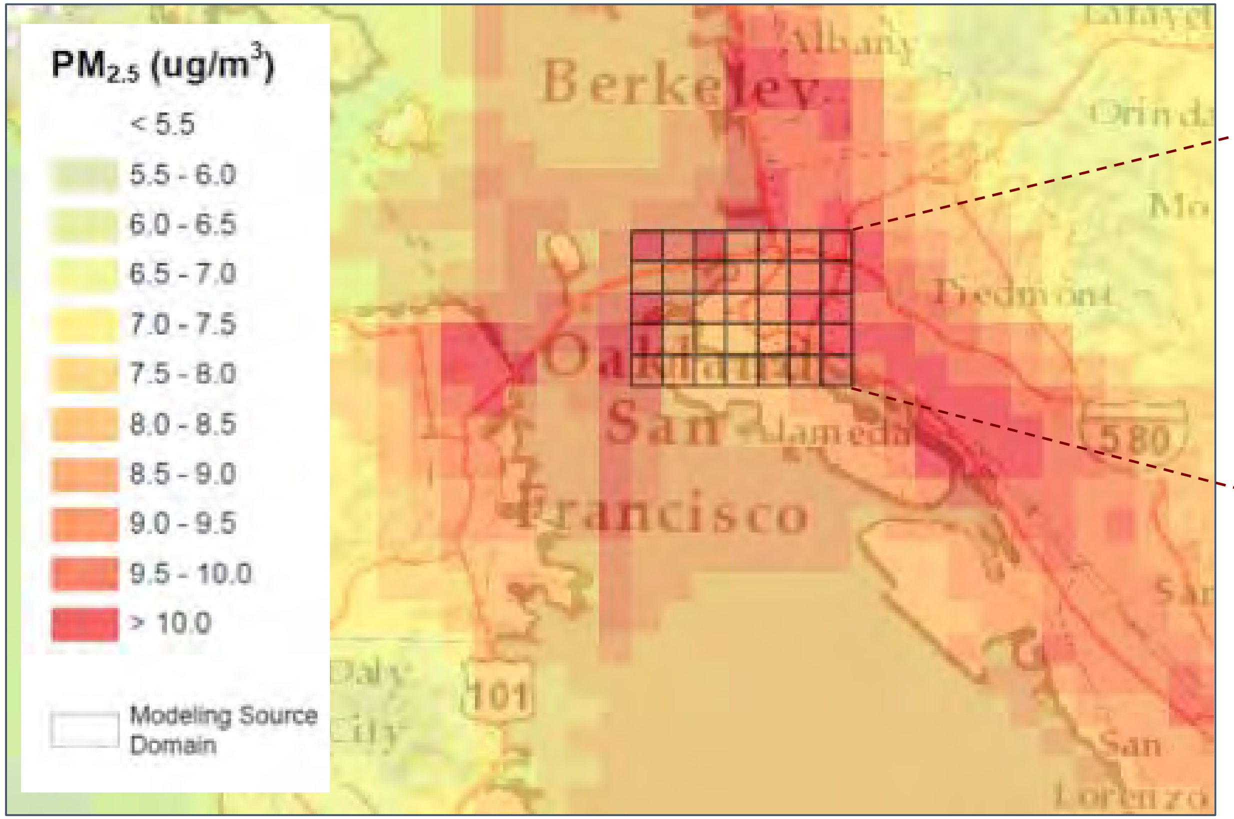
- PM modeling for the West Oakland Community Action Plan
  - Review community-scale assessment
- PM modeling of large industrial sources
  - Chevron Richmond Refinery
- Next Steps

Recent PM Assessments

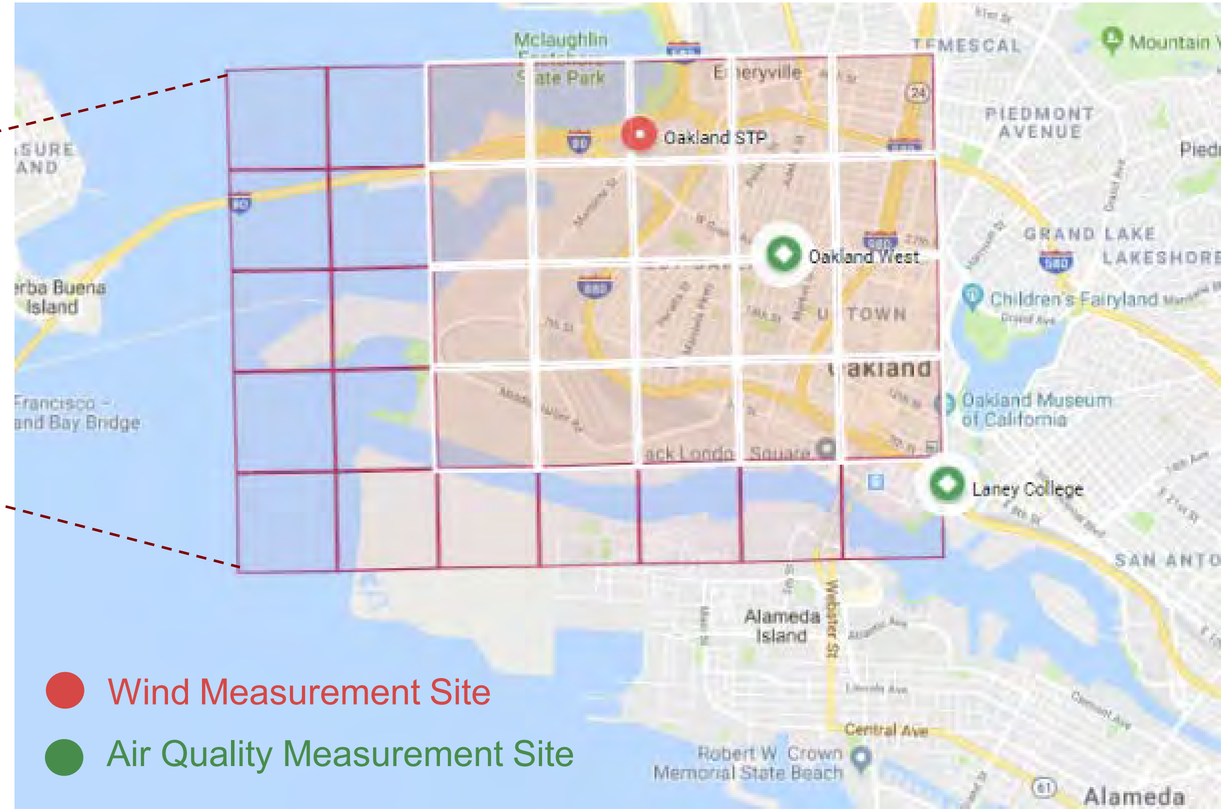
- Identify source-contributions to impacts
  - What is responsible?
- Assess equity of impacts to inform decision-making
  - Support agency goal of reducing air pollution inequities
- Work toward highlighting health risks from fine PM ($PM_{2.5}$) exposures below federal standard
  - Develop a risk framework consistent with “no identified safe level of $PM_{2.5}$”

West Oakland Community Action Plan

Regional-Scale and Community-Scale Modeling (2017)



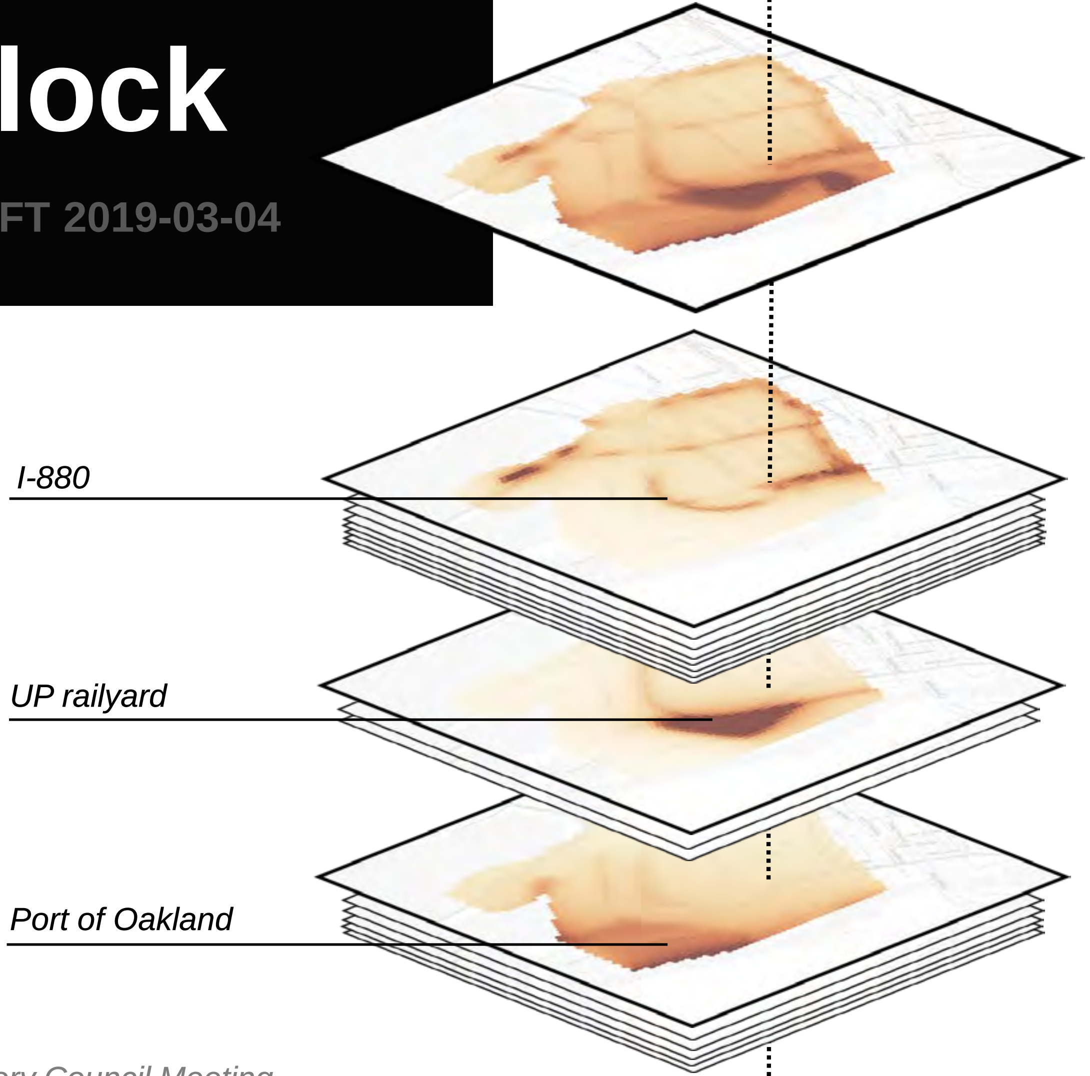
Regional-scale modeling: covers the Bay Area



Local-scale modeling: covers West Oakland, including impacts in receptor area (white) from sources in source area (red)

Block
by
Block

DRAFT 2019-03-04

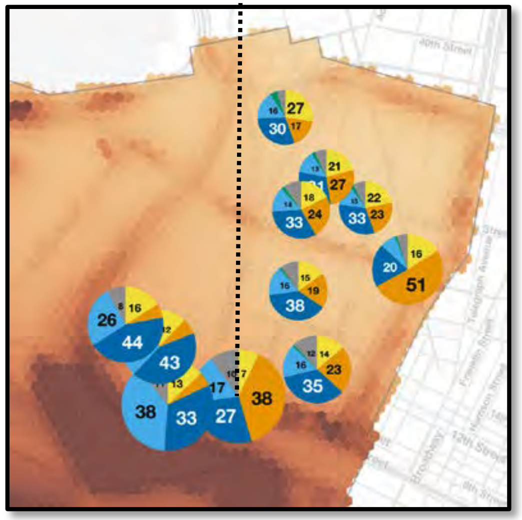


Grand total of modeled impacts from local sources

Sub-total from trucks, cars, and other vehicles on streets and highways

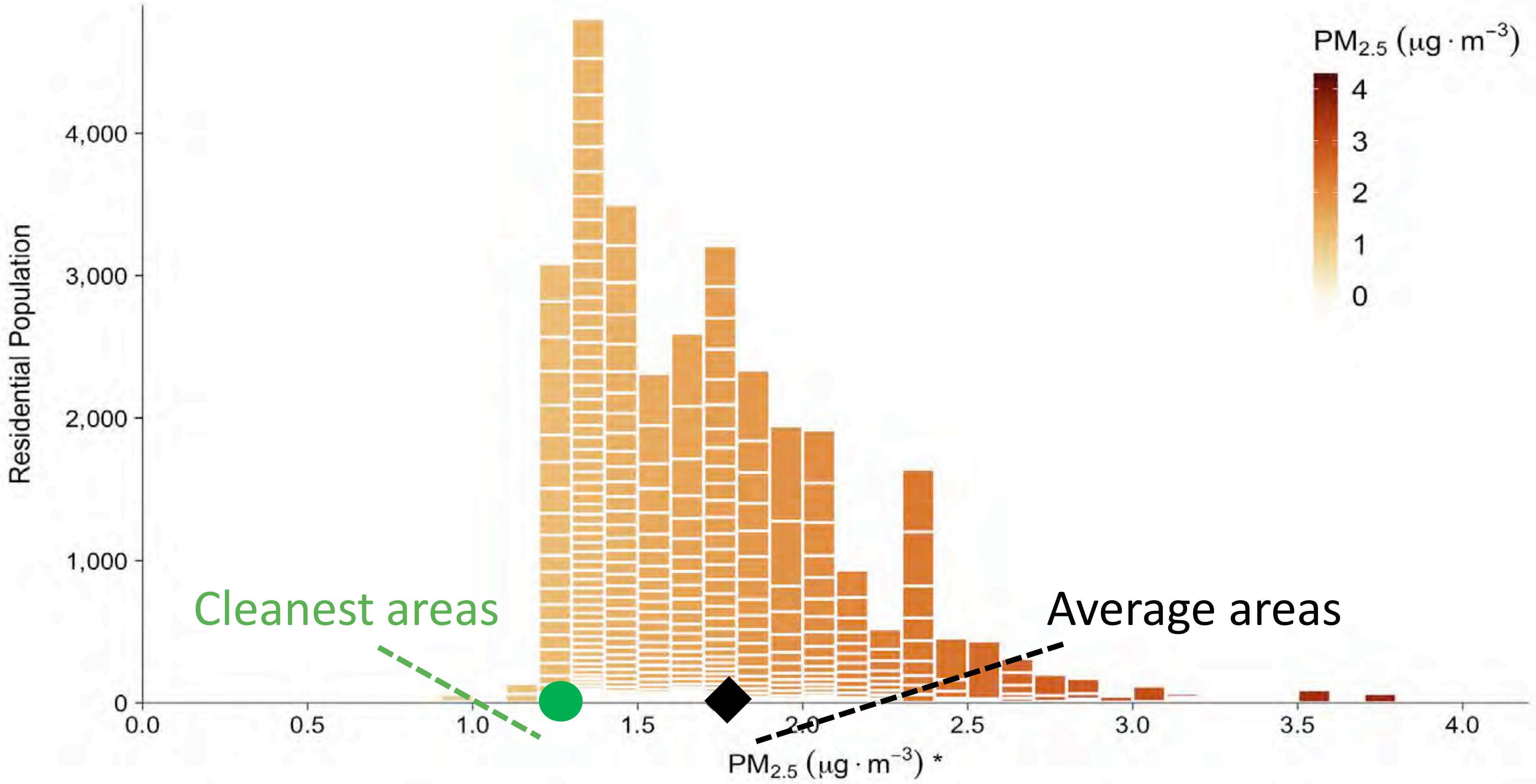
Sub-total from locomotive engines and railyards

Sub-total from harbor craft, ocean-going vessels, drayage, cargo handling, etc.



For any location, we can use the sub-totals to draw pie charts showing the relative impacts of sources A, B, C, etc.

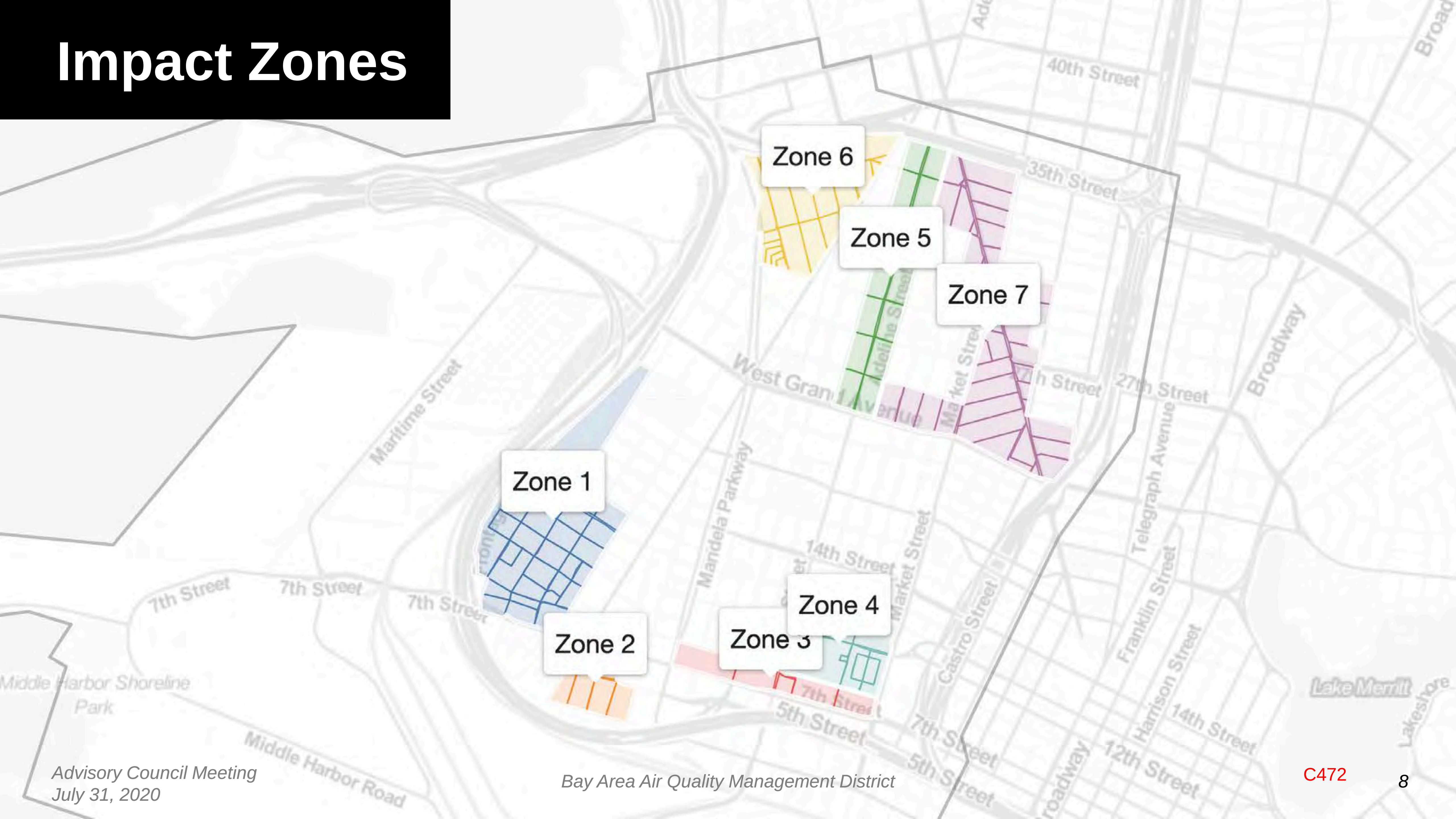
Unequal Impacts: $PM_{2.5}$ Across West Oakland



* Contributed by modeled "present-day" emissions from existing local sources. Impacts from sources outside West Oakland not included.

DRAFT 2019-08-16

Impact Zones

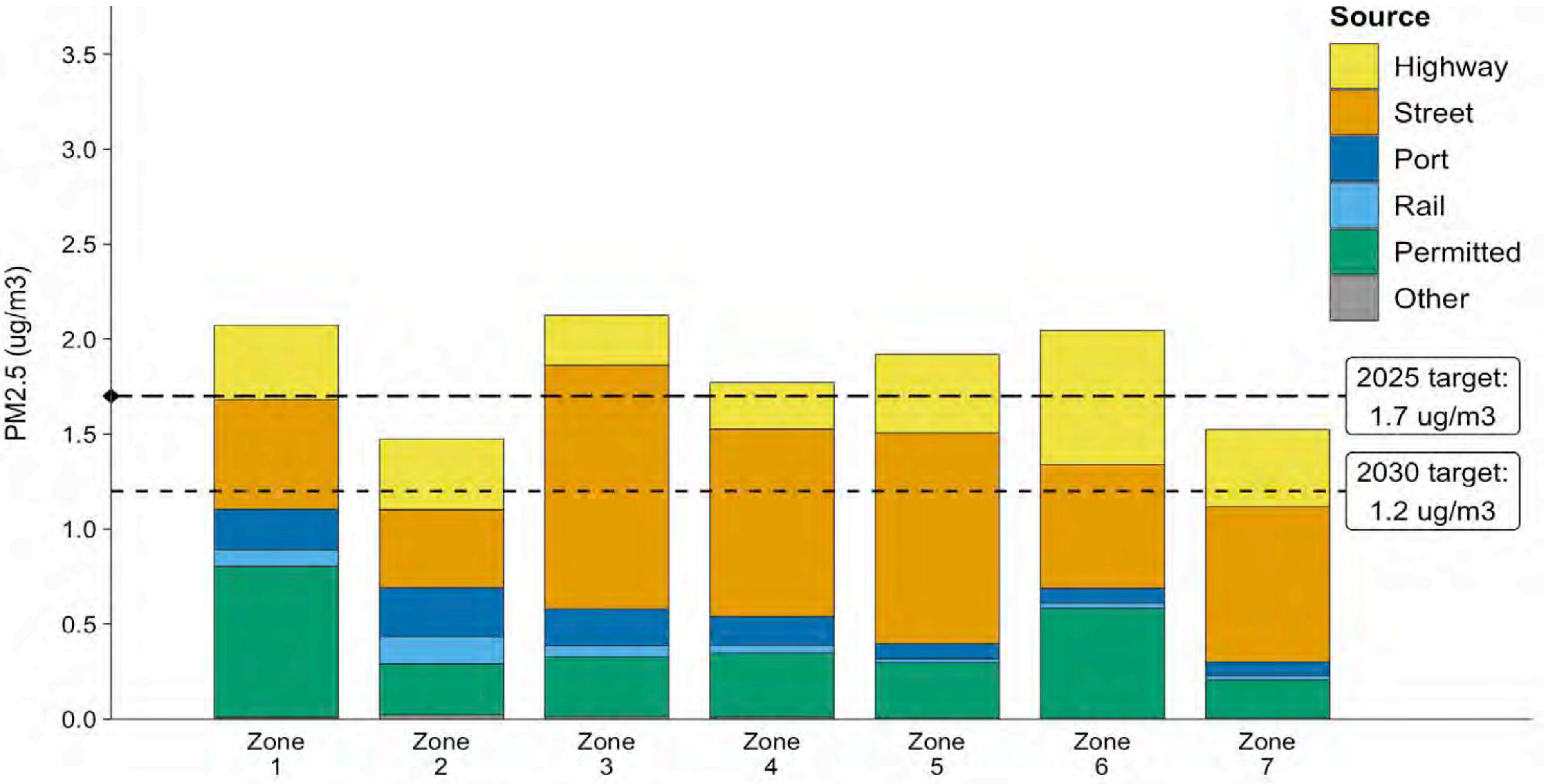


Targets and Source Contributions for $PM_{2.5}$

Targets:

2025 – Today's ***average*** residential neighborhood

2030 – Today's ***cleanest*** residential neighborhood

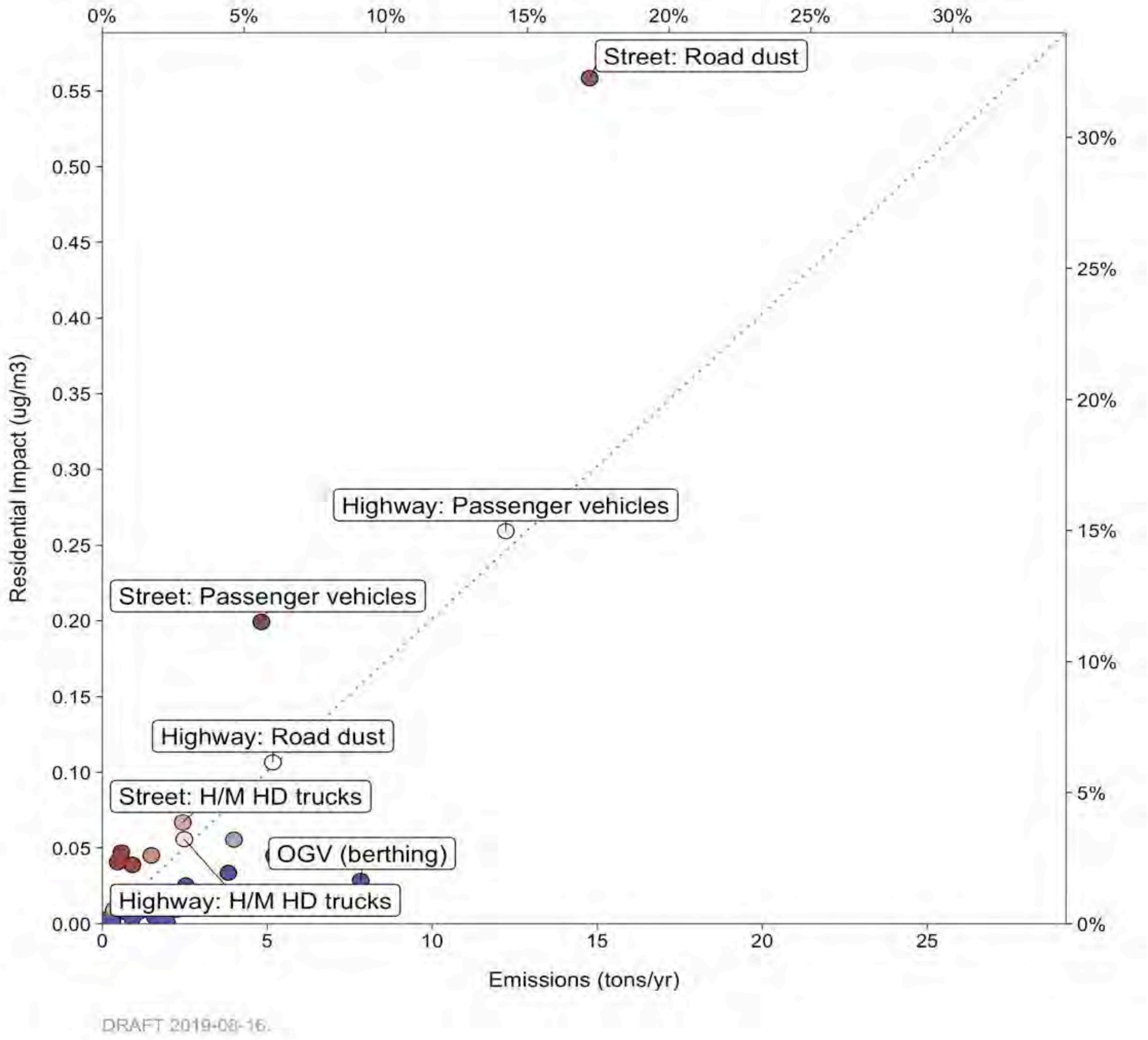


* Contributed by emissions from modeled local sources. Impacts from sources outside West Oakland not included.

DRAFT 2019-08-16

Impact Per Ton: $PM_{2.5}$ in West Oakland

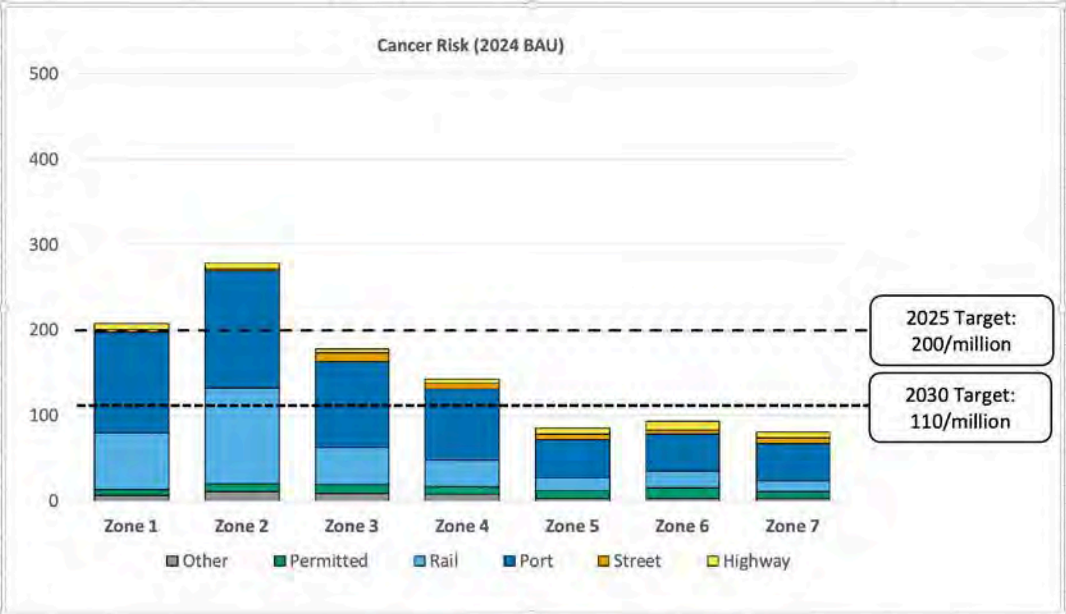
- Circles are modeled local sources
- Red is more impact, blue is less impact
- Percentages are shares of modeled impact
- Some sources have larger **exposure factors** (steeper slopes)



Finding Solutions: “Scenario Tool”

CANCRISK (2024 BAU)

	EMISSIONS 2017	EMISSIONS 2024	CHANGE Relative	CHANGE Additive	ADJUSTED IMPACTS Wt. Avg.	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Highway	**1791.3**	**331.6**	-81%		**7.29**	**7.05**	**6.98**	**4.58**	**4.34**	**6.77**	**10.51**	**6.85**
Passenger vehicles	330.7	158.8	-52%		3.38	2.71	2.45	1.87	1.77	3.63	6.61	3.33
Heavy/Medium HD trucks	1391.8	120.3	-91%		2.72	3.15	3.27	1.90	1.79	2.05	2.41	2.43
Light HD trucks	68.8	52.5	-24%		1.19	1.18	1.26	0.81	0.78	1.09	1.50	1.09
Road dust	0.0	0.0	+0%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Street	**1692.2**	**204.3**	-88%		**6.70**	**2.89**	**2.92**	**10.33**	**6.50**	**6.04**	**4.02**	**7.17**
Passenger vehicles	182.6	86.6	-53%		3.58	1.49	1.66	3.82	3.43	3.14	2.05	4.25
Heavy/Medium HD trucks	1434.1	60.4	-96%		1.65	0.62	0.56	4.56	1.72	1.38	0.90	1.45
Light HD trucks	75.5	57.4	-24%		1.47	0.78	0.71	1.94	1.35	1.52	1.07	1.47
Road dust	0.0	0.0	+0%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Port	**11817.2**	**12768.5**	+8%		**64.80**	**118.05**	**136.29**	**100.21**	**83.15**	**45.53**	**44.53**	**43.37**
OGV (maneuvering)	2858.7	4145.1	+45%		15.35	23.38	28.93	22.57	19.60	11.82	11.56	11.32
OGV (berthing)	3212.1	3901.0	+21%		14.12	22.06	27.99	20.79	17.78	10.80	10.77	10.23
Harbor craft	2931.7	2354.8	-20%		20.72	35.16	43.23	33.69	28.25	14.19	13.75	13.61
Dredging	863.9	591.6	-32%		4.24	7.95	9.65	6.86	5.66	2.67	2.67	2.56
Bunkering	209.5	190.4	-9%		1.53	2.62	3.64	2.57	2.10	1.02	0.98	0.97
Drayage trucks	371.8	88.2	-76%		1.04	2.04	1.94	2.95	1.42	0.61	0.54	0.57
Road dust	0.0	0.0	+0%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cargo handling	1176.6	1293.1	+10%		3.77	7.80	11.86	6.16	4.58	2.31	2.19	2.25
Railyard (BNSF)	57.3	61.5	+7%		1.71	4.10	5.56	2.59	1.95	0.99	0.96	0.93
Railyard (OGRE)	135.5	142.6	+5%		2.33	12.95	3.49	2.04	1.81	1.12	1.10	0.92
Rail	**1636.6**	**1462.5**	-11%		**27.12**	**66.14**	**112.12**	**43.75**	**30.97**	**14.86**	**19.22**	**12.95**
Rail lines	810.2	553.8	-32%		9.80	20.93	25.04	14.37	11.14	7.24	11.92	5.83
Railyard (UP)	826.5	908.6	+10%		17.32	45.21	87.09	29.38	19.83	7.62	7.29	7.13
Permitted	**1101.1**	**1184.8**	+8%		**8.42**	**7.46**	**9.69**	**10.83**	**10.09**	**8.68**	**12.61**	**7.79**
Schnitzer (stationary)	822.8	900.4	+9%		4.52	4.92	7.64	8.23	7.26	3.01	2.58	3.29
EBMUD	110.2	117.0	+6%		1.68	1.16	0.83	0.99	1.06	2.94	5.71	1.90
Dynegy	0.6	0.0	-100%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pinnacle Ag	0.0	0.0	+0%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sierra Pacific	0.0	0.0	+0%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CASS	0.0	0.0	-3%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
California Cereal	0.0	0.0	-3%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA Waste (10th St)	0.0	0.0	+0%		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other facilities	167.5	167.5	-0%		2.21	1.38	1.23	1.60	1.77	2.73	4.32	2.60
Other	**1015.7**	**987.2**	-3%		**4.71**	**6.06**	**10.94**	**8.50**	**7.16**	**3.10**	**2.74**	**3.12**
Ferries	695.2	688.1	-1%		2.95	3.73	5.92	5.51	4.62	1.75	1.55	1.88
Schnitzer (ships)	225.2	277.2	+23%		1.56	1.97	3.13	2.76	2.38	1.09	0.97	1.12
Schnitzer (trucks)	8.3	0.3	-97%		0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00
Truck-related businesses	87.0	21.5	-75%		0.20	0.34	1.88	0.22	0.15	0.26	0.22	0.13
	19054.2	**16938.9**	-11%	-2115.3	**119.04**	**207.64**	**278.94**	**178.20**	**142.21**	**84.98**	**93.63**	**81.26**



Large Industrial Sources:

Chevron Richmond Refinery

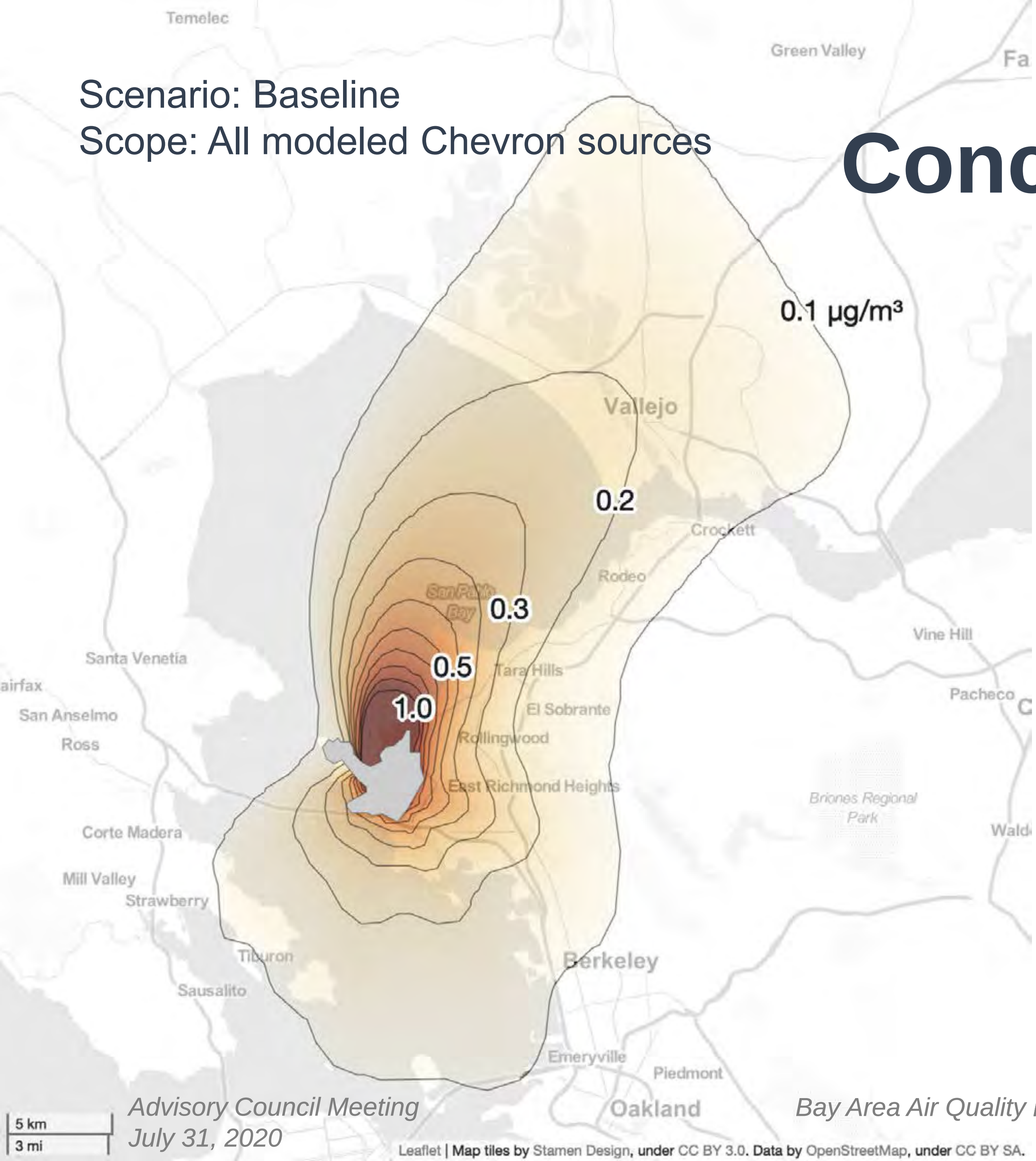
Modeling Study

- **Scope:** Tracking directly emitted (primary) $PM_{2.5}$
  - From all permitted sources at Chevron, including the Fluidized Catalytic Cracking Unit (FCCU)

- **Scenarios:**
  1. Baseline = existing emissions
  2. Additional FCCU emission reductions

- **Approach:** Track plumes with the CALPUFF air quality model to map concentrations (2016-2018)

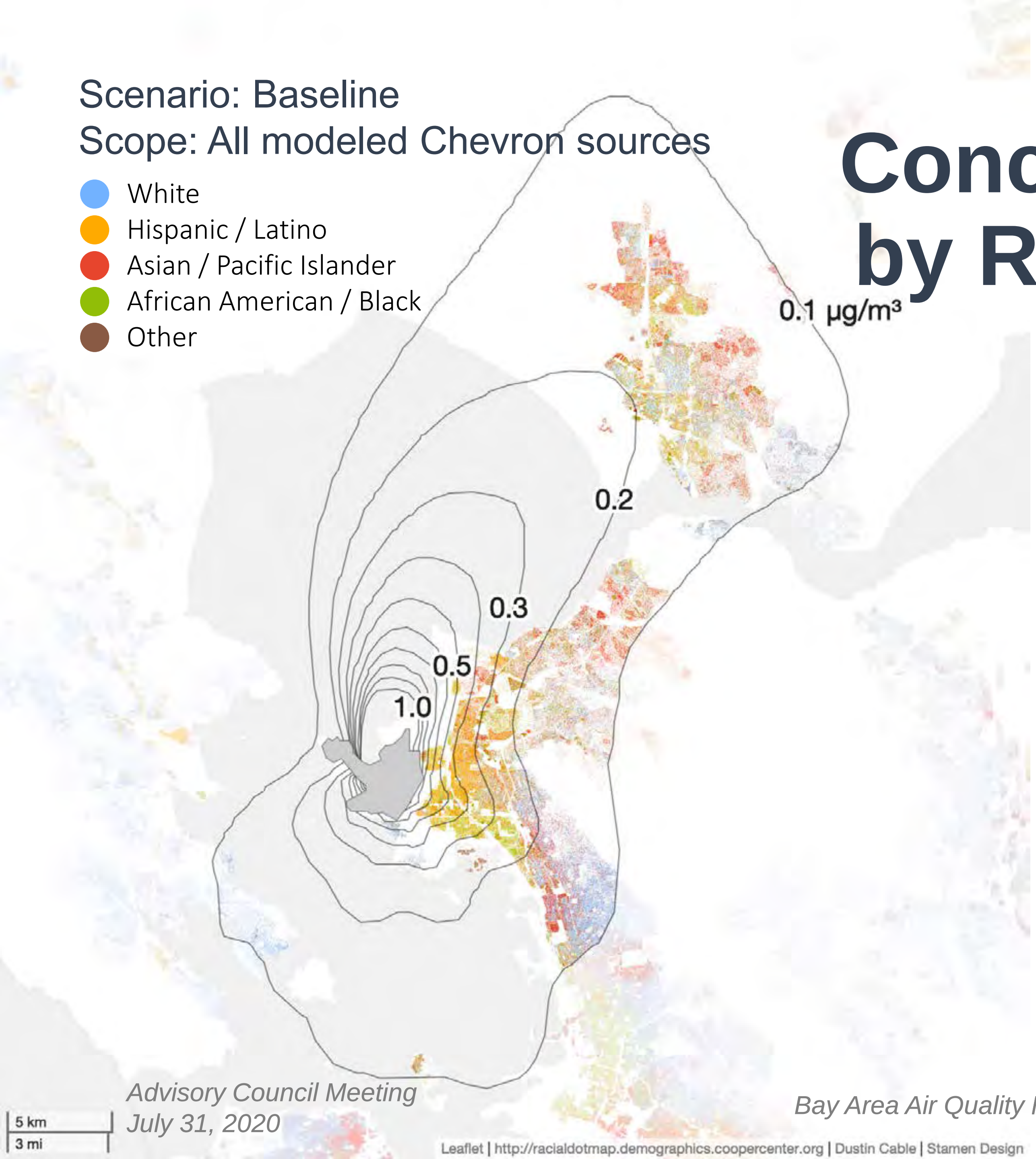
Chevron $PM_{2.5}$ Concentration Impacts by Area



- Modeled annual-average, primary $PM_{2.5}$ concentrations from all sources at Chevron
- Baseline scenario
- Measured annual-average $PM_{2.5}$ at nearby San Pablo site: about 8-10 $\mu g/m^3$*

* Excluding 2017-2018 wildfire days; about 8-13 mg/m³ including wildfire days

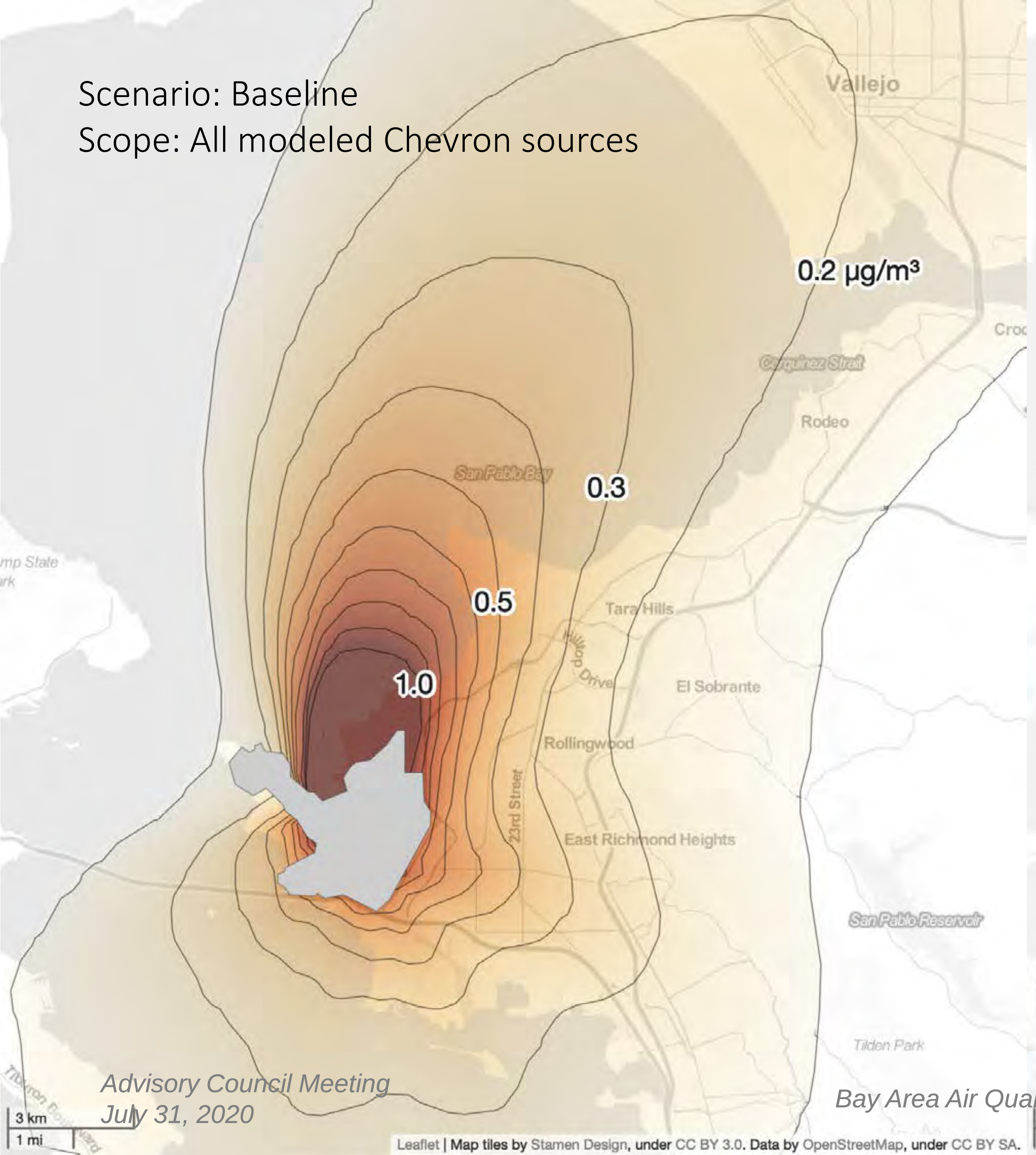
Chevron $PM_{2.5}$ Concentration Impacts by Residents Exposed

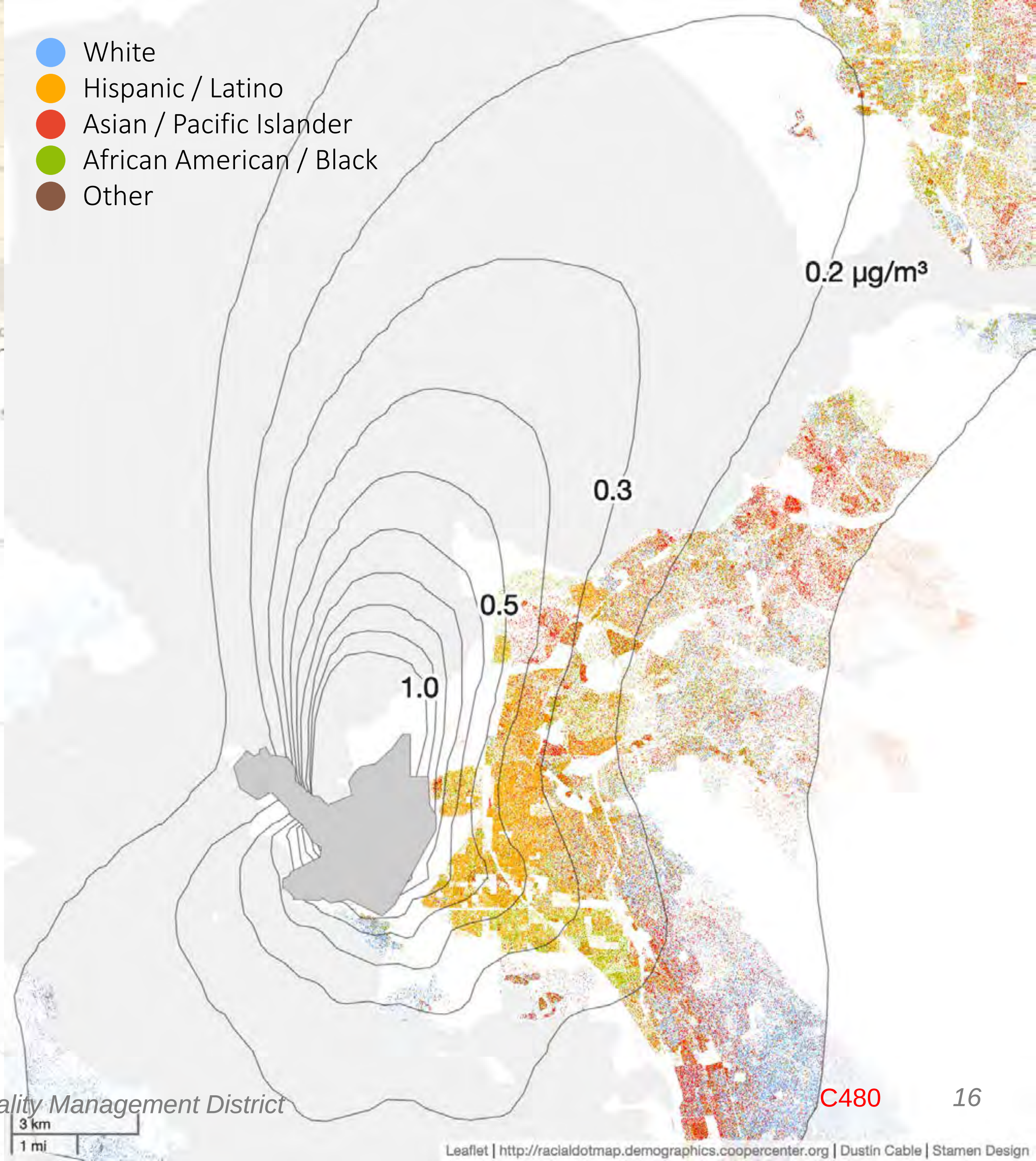


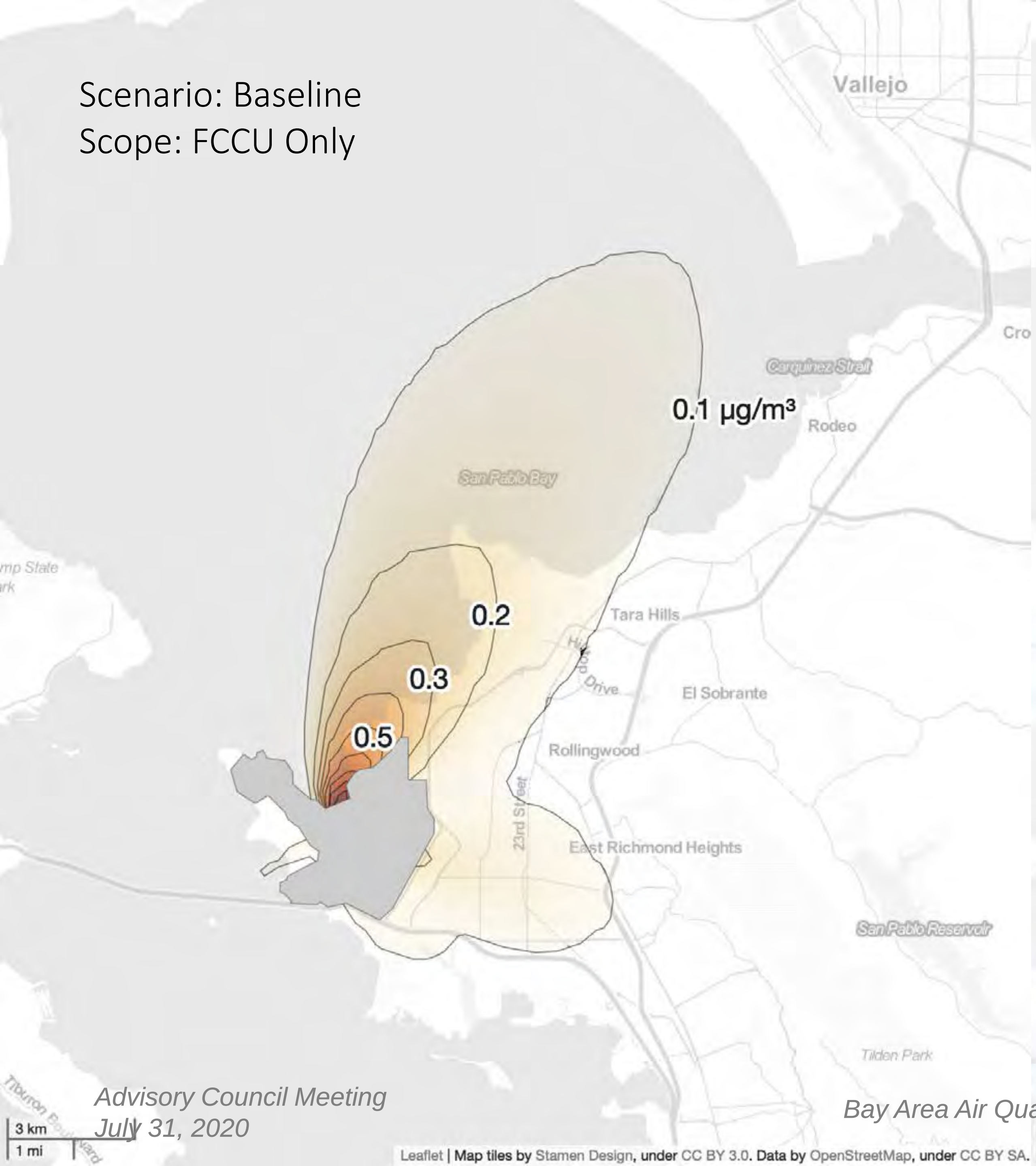
- Each color dot represents one person
- Colors are muted outside the 0.1 $\mu g/m^3$ contour, “the plume”
- Almost half a million people (~449,000) in the plume

Scenario: Baseline

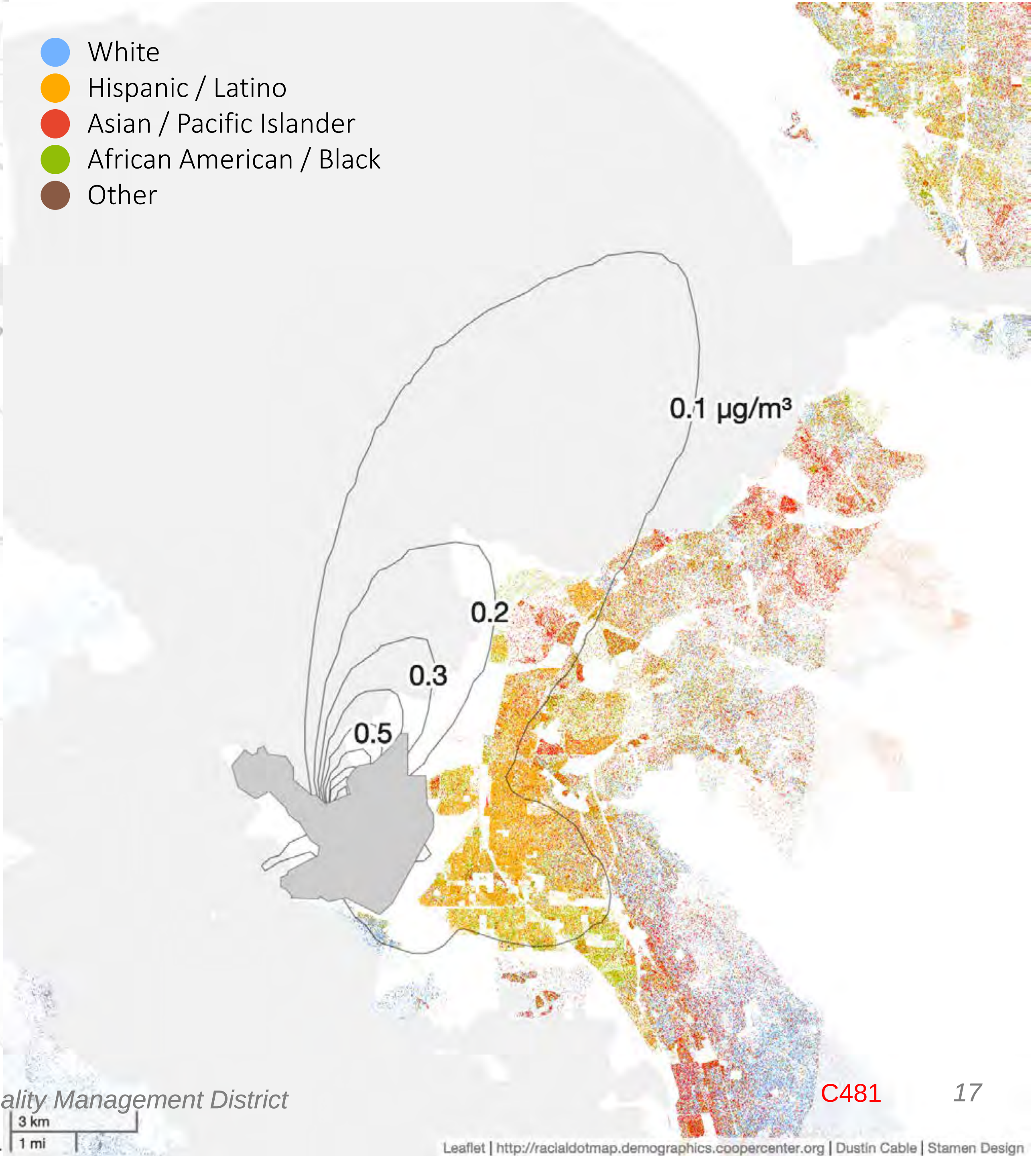
Scope: All modeled Chevron sources







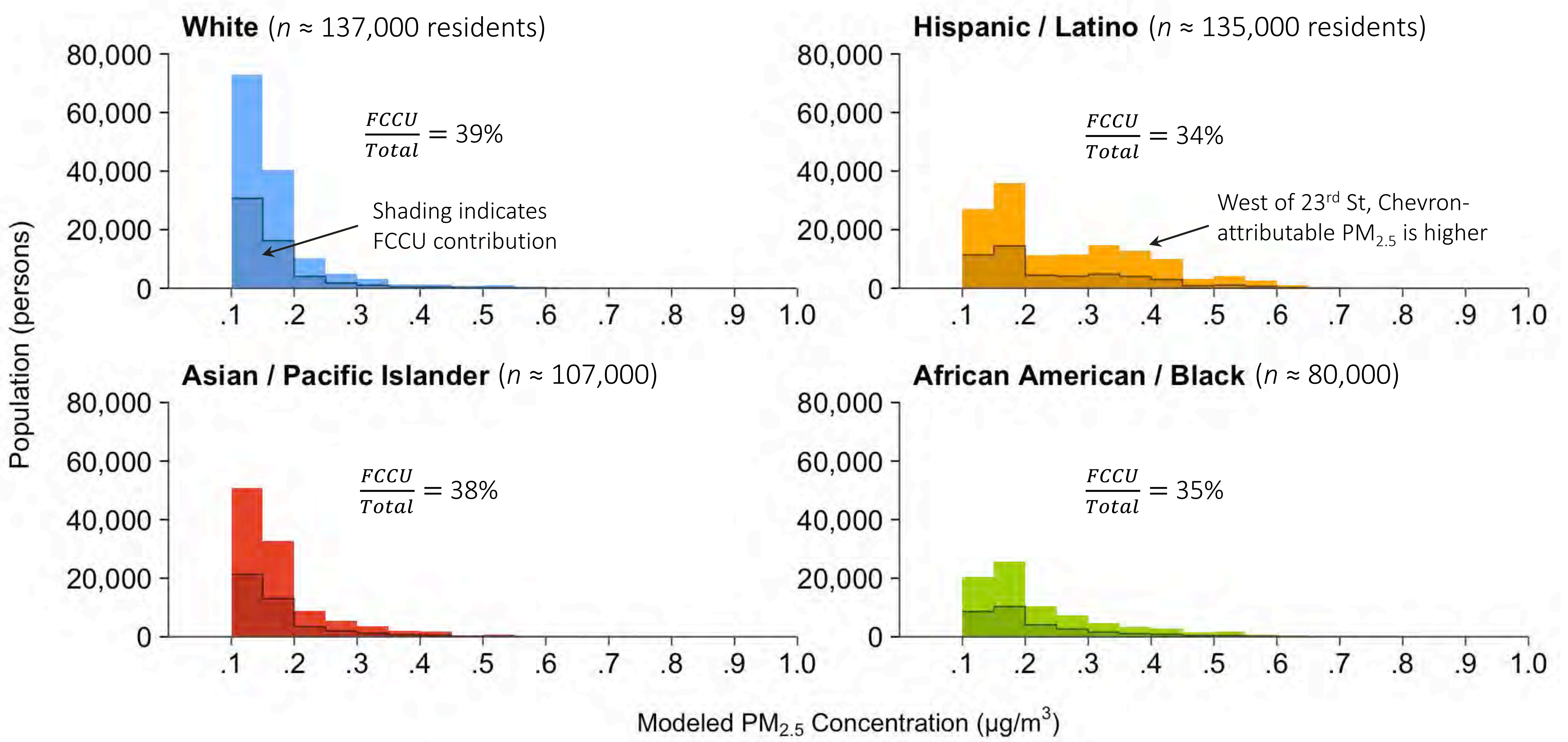
Scenario: Baseline
Scope: FCCU Only
Vallejo
Carquinez Strait
Cro
0.1 µg/m³
Rodeo
San Pablo Bay
0.2
Tara Hills
0.3
El Sobrante
0.5
Rollingwood
23rd Street
East Richmond Heights
San Pablo Reservoir
Tilden Park
3 km
1 mi
Leaflet | Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under CC BY SA.



White
Hispanic / Latino
Asian / Pacific Islander
African American / Black
Other
0.1 µg/m³
0.2
0.3
0.5
3 km
1 mi
Leaflet | http://racialdotmap.demographics.coopercenter.org | Dustin Cable | Stamen Design

$PM_{2.5}$ Exposures by Race/Ethnicity

Scenario: Baseline
Scope: Census blocks with 0.1 μg/m³ $PM_{2.5}$ or more from Chevron



Next Steps

- Richmond/San Pablo Community Action Plan
- Additional refineries/large industrial facilities
- Methodology for estimating increased adult mortality risk from local sources of $PM_{2.5}$
  - Highlight risks below the federal standard
  - Based on a recent California epidemiological study
  - Development in partnership with US Environmental Protection Agency (EPA) and the Office of Environmental Health Hazards Assessment (OEHHA)

Summary

- Identify source-contributions to impacts
  - What is responsible?
- Assess equity of impacts to inform decision-making
  - Support agency goal of reducing air pollution inequities
- Work toward highlighting health risks from $PM_{2.5}$ exposures below federal standard
  - Develop a risk framework consistent with “no identified safe level of $PM_{2.5}$”

Particulate Matter:
Spotlight on Health Protection

Appendix D: Advisory Council Information

APPENDIX D: AIR DISTRICT WEBPAGES

Information about the Air District, including air quality forecasts, can be found by visiting https://www.baaqmd.gov. In addition, information about the Air District's Spare the Air program can be found by visiting https://www.sparetheair.org.

PARTICULATE MATTER CONFERENCE WEBPAGE

Webcast, audio, presentation materials, reports and meeting minutes for the Advisory Council Particulate Matter Symposium series can be found by visiting https://www.baaqmd.gov/pmconference.

AIR DISTRICT ADVISORY COUNCIL AGENDAS, MINUTES AND MEDIA

Additional information about the Air District's Advisory Council, including Advisory Council member biographies, reports, and meeting information can be found by visiting https://www.baaqmd.gov/about-the-air-district/advisory-council. Meeting dates in the Particulate Matter Symposium series:

- October 28, 2019
- December 9, 2019
- May 12, 2020
- July 31, 2020
- October 9, 2020
- November 9, 2020
- December 3, 2020
- December 16, 2020

APPENDIX D: ADVISORY COUNCIL MEMBER BIOGRAPHIES

The following are the biographies of each of the seven Air District Advisory Council members who participated on the Advisory Council over the course of the particulate matter conference series.

CHAIRPERSON STAN HAYES

Principal Emeritus, ENVIRON (now Ramboll)

Stan Hayes has more than 40 years of experience in environmental science and engineering, with particular emphasis on air impact and health risk analysis for both national ambient air quality standards (NAAQS) and hazardous air pollutant (HAP) purposes, including air quality modeling, strategic and regulatory policy analysis, climate assessment, compliance evaluation, exposure and health risk assessment, and air monitoring and meteorological data analysis.

He is a Fellow of the Air & Waste Management Association, for which he has chaired or co-chaired national and international specialty conferences on climate change, greenhouse gas reporting, and homeland security. Previously, he was a member of the U.S. EPA Science Advisory Board Risk and Technology Review (RTR) Methods Panel.

Chairperson Hayes is the primary author of more than 70 scientific papers and presentations, as well as several hundred technical reports on air-related subjects. He has provided expert testimony before federal, state, and local regulatory agencies and in court. Upon invitation, he has given scientific briefings to members of the California legislature and political leaders elsewhere.

For 25 years, until 2015, he was a Principal with global environmental consulting firm ENVIRON (now Ramboll). He is now emeritus.

Chairperson Hayes earned an M.S. in aeronautics and astronautics and a B.S. in mechanical engineering, both from Stanford University.

VICE CHAIR MICHAEL KLEINMAN

Professor, Environmental Toxicology, Co-Director of the Air Pollution Health Effects Laboratory, Adjunct Professor in College of Medicine, University of California, Irvine

Michael T. Kleinman is UC Irvine Professor of Environmental Toxicology and Co-Director of the Air Pollution Health Effects Laboratory in the Department of Community and Environmental Medicine, and Adjunct Professor in the College of Medicine.

Dr. Kleinman brings to the Advisory Council expertise in the health effects of air pollution on animals and humans, as well as expertise in the development of analytical techniques for assessing biological and physiological responses to exposure to environmental contaminants and for determining concentrations of important chemical species in air.

The research in Dr. Kleinman's laboratory uses immunological and molecular methods to examine the mechanisms by which toxic agents affect the lung and heart. Current studies include the effects of ambient particles on blood pressure and heart rate in sensitive animal models. Other studies examine the link between asthma and environmental exposures to ambient particles near real-world pollutant sources, such as freeways in Los Angeles. Research focuses on mechanisms of cardiopulmonary injury following inhalation of toxic compounds. State-of-the-art methods are used to evaluate the roles of free radicals and oxidative stress in sensitive human volunteers and laboratory animals. In vitro methods are used to evaluate specific mechanisms.

Dr. Kleinman's current studies involve inhalation exposures to manufactured and combustion-generated nanomaterials as fine and coarse particles using state-of-the-art field exposure systems and real-time physiological monitoring methods. Dr. Kleinman's team is also pursuing how these mechanisms affect pathological and physiological changes in the heart and lungs.

Other interests include analytical and atmospheric chemistry, environmental sampling and analysis, and the application of mathematical and statistical methods to environmental and occupational assessments of exposure and risk.

Dr. Kleinman received a Ph.D. in Environmental Health Sciences from New York University.

TIM LIPMAN

Co-Director, UC Berkeley Transportation Sustainability Research Center

Timothy E. Lipman is an energy and environmental technology, economics, and policy researcher and lecturer with the University of California, Berkeley. He is serving as Co-Director for the campus' Transportation Sustainability Research Center (TSRC), based at the Institute of Transportation Studies, and has also served as Director of the U.S. Department of Energy Pacific Region Clean Energy Application Center (PCEAC).

Dr. Lipman's research focuses on electric-drive vehicles, fuel cell technology, combined heat and power systems, biofuels, renewable energy, and electricity and hydrogen energy systems infrastructure. Most of his research projects are related to the transformation of energy systems to support motor vehicles and buildings, examining how both incremental and "leap frog" technologies can be applied to reduce greenhouse gas emissions and other negative environmental and social impacts of energy use. A central concept for his research is that the electrification of the transportation sector can realize synergy with a concentrated effort to reduce the carbon intensity of the electrical grid, yielding benefits for the electricity sector as well as the expanded use of electricity, hydrogen, and biofuels.

Dr. Lipman received his Ph.D. in Environmental Policy Analysis with the Graduate Group in Ecology at UC Davis (1999). He also has received an M.S. degree in the technology track of the Graduate Group in Transportation Technology and Policy, also at UC Davis (1998), and a B.A. from Stanford University (1990).

JANE C.S. LONG

Associate Director for Energy and Environment, retired, Lawrence Livermore National Lab

Jane Long retired from Lawrence Livermore National Laboratory, where she was the Principal Associate Director at Large, Fellow in the LLNL Center for Global Strategic Research, and the Associate Director for Energy and Environment. She is currently a chairperson of the California Council on Science and Technology's committees on California's Energy Future and assessment of hydraulic fracturing. Her current work involves strategies for dealing with climate change, including reinvention of the energy system, geoengineering, and adaptation.

Dr. Long was the Dean of the Mackay School of Mines, University of Nevada, Reno, and Department Chair for the Energy Resources Technology and the Environmental Research Departments at Lawrence Berkeley National Lab.

Dr. Long is a fellow of the American Association for the Advancement of Science, an Associate of the National Academies of Science (NAS), and a Senior Fellow and council member of the California Council on Science and Technology (CCST) and the Breakthrough Institute.

She holds a bachelor's degree in engineering from Brown University and a master's and Ph.D. from UC Berkeley.

DR. LINDA RUDOLPH

Director, Center for Climate Change and Health

Linda Rudolph is a public health physician with more than four decades of experience in local and state government and non-profit organizations. Currently, Dr. Rudolph is the Director of the Center for Climate Change and Health at the Public Health Institute, where her work has focused on building capacity in local health departments to integrate climate change into public health practice and on supporting health professionals as climate and health champions. She previously served as Deputy Director for Chronic Disease Prevention and Health Promotion in the California Department of Public Health. At CDPH, Dr. Rudolph was the founding chair of the California Health in All Policies Task Force under the auspices of the Strategic Growth Council.

Dr. Rudolph has also served as the Health Officer and Public Health Director for the City of Berkeley, Chief Medical Officer for Medi-Cal Managed Care, and Medical Director for the California Workers' Compensation Division. She is board-certified in Occupational Medicine and worked for many years in occupational health, initially with the Oil, Chemical, and Atomic Workers' International Union.

She received her M.D. from the University of California, San Francisco, and her M.P.H. and B.A. from UC Berkeley.

GINA M. SOLOMON, M.D., M.P.H.

Clinical Professor, Division of Occupational and Environmental Medicine, UCSF;
Principal Investigator, Public Health Institute

Gina Solomon is a Clinical Professor in the Division of Occupational and Environmental Medicine at the University of California San Francisco (UCSF) and a Principal Investigator at the Public Health Institute in Oakland, CA. She served as the Deputy Secretary for Science and Health at the California Environmental Protection Agency (CalEPA) from 2012 to 2017, and as a senior scientist at the Natural Resources Defense Council from 1996 to 2012. She was also the director of the occupational and environmental medicine residency program at UCSF, and the co-director of the UCSF Pediatric Environmental Health Specialty Unit.

Dr. Solomon's work has spanned a wide array of areas, including children's environmental health, the health effects of diesel exhaust, reproductive toxicity of environmental chemicals, cumulative impacts and environmental justice, and the use of novel data streams to screen chemicals for toxicity.

She has also done work in exposure science for air pollutants, pesticides, mold, and heavy metals. She conducted environmental exposure studies in Louisiana in the aftermath of Hurricane Katrina and during the Gulf oil spill, published the first study documenting children's exposure to diesel exhaust inside school buses, and served on the Scientific Guidance Panel for Biomonitoring California, a statewide program to measure contaminants in people. Dr. Solomon has also done work on the health effects of climate change. She published a study documenting the large spike in emergency department visits in California during the 2006 heat wave, and has published work documenting the health costs of climate-related events. She works to educate health care professionals and students about the health effects of climate change.

During her tenure at CalEPA, Dr. Solomon advised the Secretary on a wide range of issues related to chemicals in consumer products, toxic air contaminants, drinking water contaminants, and pesticides. She was also involved in recommending policy changes in the aftermath of the Chevron Richmond refinery fire. She chaired the California Interagency Refinery Task Force and successfully spearheaded regulations to improve refinery safety in California. Dr. Solomon has served on multiple boards and committees of the National Academies of Science, the U.S. EPA Science Advisory Board, and the National Toxicology Program's Board of Scientific Counselors. She also serves on the U.S. EPA Board of Scientific Counselors Chemical Safety for Sustainability subcommittee.

Dr. Solomon received her bachelor's degree from Brown University, her M.D. from Yale University, and completed her M.P.H. and her residency and fellowship training in internal medicine and occupational and environmental medicine at Harvard University.

SEVERIN BORENSTEIN

E.T. Grether Professor of Business Administration and Public Policy, Haas School of Business; Faculty Director of the Energy Institute at Haas.

Severin Borenstein is E.T. Grether Professor of Business Administration and Public Policy at the Haas School of Business and Faculty Director of the Energy Institute at Haas. He is an affiliated professor in the Agricultural and Resource Economics department and the Energy and Resources Group at UC Berkeley. He is also Director emeritus of the University of California Energy Institute. Borenstein has been a research associate of the National Bureau of Economic Research (NBER) since 1992 and served as co-Director of NBER's research project on e-commerce in 1999-2000. Prior to coming to Haas in 1996, he taught at the University of Michigan and University of California at Davis. He has won awards for undergraduate and graduate teaching, and in 2005 received U.C. Berkeley's Distinguished Faculty Mentor Award for graduate student mentoring.

Borenstein's research focuses broadly on business competition, strategy, and regulation. He has published extensively on airline, oil and gasoline, and electricity markets, as well as on insurance, e-commerce, mining, natural gas, and other industries. Borenstein's recent research has focused on competition and profitability in the airline industry, the impact of oil prices on gasoline markets, alternative models of retail electricity pricing, and the economics of renewable energy and climate change. He is a past editor of the *Journal of Industrial Economics*, past associate editor of *The Review of Economics and Statistics* and past member of the editorial boards of *American Economic Journal: Economic Policy, Journal of Economic Literature*, and *Journal of the Association of Environmental and Resource Economists*.

During 1997-2003, Borenstein was a member of the Governing Board of the California Power Exchange. He served on the California Attorney General's gasoline price taskforce in 1999-2000. In 2010-11, Borenstein was a member of U.S. Secretary of Transportation Ray LaHood's Future of Aviation Advisory Committee. In 2012-13, he served on the Emissions Market Assessment Committee, which advised the California Air Resources Board on the operation of California's Cap and Trade market for greenhouse gases. In 2014, he was appointed to the California Energy Commission's Petroleum Market Advisory Committee, which he chaired from 2015 until the Committee was dissolved in 2017. From 2015 to May 2020, he served on the Advisory Council of the Bay Area Air Quality Management District. In January 2019, he was appointed to the Governing Board of the California Independent System Operator.

Borenstein has received the 2005 Distinguished Service Award from the Public Utility Research Center at the University of Florida, the Power Association of Northern California's 2014 Achievement Award, the Industrial Organization Society's 2015 Distinguished Fellow Award and the International Association for Energy Economics' 2015 Award for Outstanding Contributions to the Profession.

Borenstein grew up in Oakland and Berkeley, California, where he attended public schools and graduated from Berkeley High School. He received his undergraduate degree from U.C. Berkeley and Ph.D. in economics from MIT.

Assessing the environmental impact of data centres part 1: Background, energy use and metrics

Article *in* Building and Environment · December 2014

DOI: 10.1016/j.buildenv.2014.08.021

4 authors, including:

Beth Whitehead
Operational Intelligence

Deborah Andrews
London South Bank University

Graeme Maidment
London South Bank University

Building and Environment 82 (2014) 151–159

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Assessing the environmental impact of data centres part 1: Background, energy use and metrics

Beth Whitehead [a, *, 1], Deborah Andrews [a], Amip Shah [b], Graeme Maidment [a]

[a] Faculty of Engineering Science and The Built Environment, London South Bank University, 103 Borough Road, London, SE1 0AA, UK
[b] HP Labs, 1501 Page Mill Rd, Palo Alto, CA, 94304, USA

ARTICLE INFO

Article history:
Received 15 May 2014
Received in revised form
13 August 2014
Accepted 14 August 2014
Available online 23 August 2014

Keywords:
Data centres
Environmental impact
Carbon footprint
Life cycle assessment
Data centre metrics
Energy consumption

ABSTRACT

Data centres consume high levels of energy to power the IT equipment contained within them, and extract the heat they produce. Because of the industry's heavy reliance on power, data centre metrics have historically used operational efficiency as a proxy for sustainability. More recently the industry has begun to recognise that its focus needs to go beyond energy consumption, with the creation of metrics for issues such as carbon, water and compute efficiency. However, single-issue metrics often consider only the operational phase, omitting impacts from other issues, during other stages in a facility's lifetime. Further approaches exist to assess more holistically the impact of data centres, such as building environmental assessment methods, but none have the capacity to capture fully the interlinked nature of a system, where improvements in one area and to one impact, can adversely affect a totally different area and totally different impacts.

The following review of literature summarises the approach of the data centre industry to environmental impact, and provides direction for future research. Part 1 describes the energy consumption of the ICT industry and in particular data centres; current knowledge on the environmental impact of the industry; and how single-issue metrics have risen to prominence.

1. Introduction

Data centres contain IT equipment used for the processing and storage of data, and communications networking [1]. They are the backbone of IT networks across the globe [2,3] and include extensive supporting infrastructures required to power and cool the IT equipment. A data centre can be as simple as a single rack in a server closet or as complex as a large warehouse, typically having built-in redundancy for the avoidance of downtime.

Data centres are high energy consumers. In 2007 the ICT industry was estimated to account for 10% of total UK electricity consumption [4], and 2% of global anthropogenic CO_2 [5], approximately equal to the direct emissions of the aviation industry operation. The operation of data centres already accounts for around a quarter of these emissions [4], and is believed to have the fastest growing carbon footprint from across the whole ICT sector [5].

This energy consumption has drawn the attention of data centre owners and operators. Firstly because of the cost of energy bills, and more recently because of it's impact on the environment. However, exclusive consideration of energy consumption has meant that other impacts and stages in a data centres life cycle are not well understood.

This two-part literature review seeks to present the current energy consumption and environmental impact of the data centre industry, and how it is monitored, assessed and benchmarked, and concludes the need for a more holistic approach to the management of environmental impact in the future. It does not seek to establish ways in which to reduce the impact. The review aims to focus the industry on why it has approached environmental issues in the current manner, highlight the need for a change in approach, and suggest further research and work required to enable this. Part 1 describes the energy consumption of the ICT industry and in particular data centres; current knowledge on the environmental impact of the industry; how the industry benefits the environment; and how single-issue metrics

* Corresponding author. Tel.: +44 (0) 7739 019960.
E-mail addresses: bethfwhitehead@gmail.com, BethWhitehead@dc-oi.com (B. Whitehead).
[1] Permanent address: Operational Intelligence, 74 Kelvedon Close, Kingston upon Thames, Surrey, KT2 5LF, UK.

http://dx.doi.org/10.1016/j.buildenv.2014.08.021
0360-1323/

have risen to prominence. Part 2 builds on this foundation to describe the use of building environmental assessment methods and tools; and based on both parts of the review, concludes the need to apply life cycle thinking to assess the environmental impact of data centres.

2. Data centres

Data centres house servers, and networking and storage equipment, and are considered the central nervous system of the 21st century. They contain comprehensive mechanical and electrical infrastructures to support the energy intensive computing required to perform one or more of the following functions [6,7]:

- The physical housing of IT equipment such as computers, servers, switches, routers, data storage devices, racks, and related equipment.
- The storage, management, processing and exchange of digital data.
- The provision of application services or management for data processing, such as web hosting, internet, intranet and telecommunication.

Data centres vary in size from a single rack in a server closet to huge server farms with floor areas reaching 150,000 m^2. Some occupy floors within offices and others are steel sheds on dedicated sites like that shown in Fig. 1. Large facilities contain data halls as shown in Fig. 2, which contain racks of IT equipment; the remaining floor space houses power and cooling equipment. Typically, the extensive floor space required for the supporting infrastructures can be as much as two [9] to four (when there are no external services) [10] times greater than the data halls themselves. Tight controls on air quality mean that the data halls do not include windows, and in the UK are often built using a steel frame and concrete floor construction resulting in large, windowless boxes. They are high energy consumers, both for power and the extraction of the heat dissipated from the IT equipment, and although some have huge floor plates, they are incredibly low occupancy facilities.

Data centres are used by businesses, corporations, educational establishments and governments, to provide web hosting and the internet, the storage of company information, and the processing of business transactions. They can be public (accessible to all, such as those for Google searches) or private (for the storage of company information on network drives) and, based on the importance of continued access to the data, display varying levels of [12]:

Fig. 1. Facebook data centre [8].

Fig. 2. Inside a data hall [11].

- Reliability – probability that a component/system/data centre operates without failure over a set time period. Facilities can have the same availability, but a facility that has one outage per year is more reliable than a facility that has many failures lasting the same amount of time.
- Availability – the average time per time period (for example a year) that a component/system/data centre operates as designed, without downtime. For example 0.99999 availability is a facility that has a total yearly downtime of 315 s.
- Redundancy – the topology of supporting infrastructures that ensure a component/system/data centre remains available in the event of a failure.

Facilities are described using Tier classifications [13] – Tier I to Tier IV – which refer to the topology of the facility's supporting infrastructures (power and cooling), and reflect how the building performs under planned and unplanned outages. The ability of a data centre to continue to perform its function in the event of a problem is determined by the amount of redundancy (spare plant) built into the design. For example, two mains power feeds to a site would ensure continued operation if one feed is lost, because operations can be switched to the other. The amount of redundancy incorporated into a data centre is dependent on whether or not the business linked to the facility can continue relatively unharmed in the event of a fault.

The Tiers were established by the Uptime Institute (an industry research body), to provide a common language across which the availability and reliability (redundancy) of different facilities can be compared, and are described in Table 1.

3. ICT and the internet

Worldwide, the number of data centres is growing, in part, due to the increase in access to PCs (personal computers) and the internet. The global PC installed base (including laptops) is well documented, and has grown rapidly from 242 million in 1995 [15,16] to 592 million in 2002 [5] and 1 billion in 2009 [17]. Furthermore, projections up to 2004 [15,16] 2014 [17] and 2020 [5], and shown in Fig. 3, fit with a pattern of exponential growth suggested by these early figures; most of which will require access to the internet and networks supported by data centres [17].

Furthermore, at the end of 2012, 34.3% of the global population were internet users [18], a penetration that grew from less than 1% in 1995 [19], as shown in Fig. 4, and equated to a rise from 0.04% to 6% in less developed countries [15]. Between 2000 and 2012,

Table 1
Summary of Tier classifications [14].

Tier		Site level infrastructure topology
Tier I	Basic capacity	Site-wide shutdowns are required for maintenance or repair work. Capacity or distribution failures will impact the site.
Tier II	Redundant capacity components	Site-wide shutdowns for maintenance are still required. Capacity failures may impact the site. Distribution failures will impact the site.
Tier III	Concurrently maintainable	*Each and every* capacity component and distribution path in a site can be removed on a planned basis for maintenance or replacement without impacting operation. The site is still exposed to an equipment failure or operator error.
Tier IV	Fault tolerant	An individual equipment failure or distribution path interruption will not impact operations. A fault tolerant site is also concurrently maintainable.

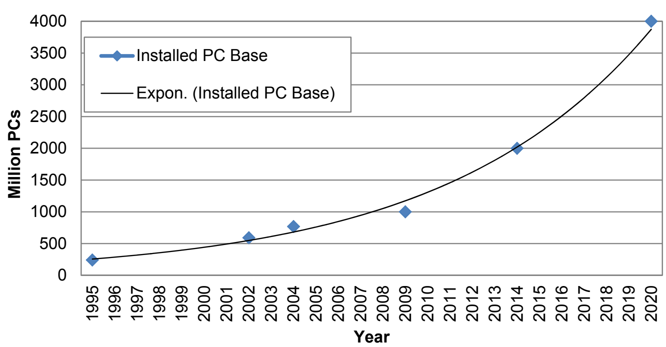


Fig. 3. Global PC installed base.

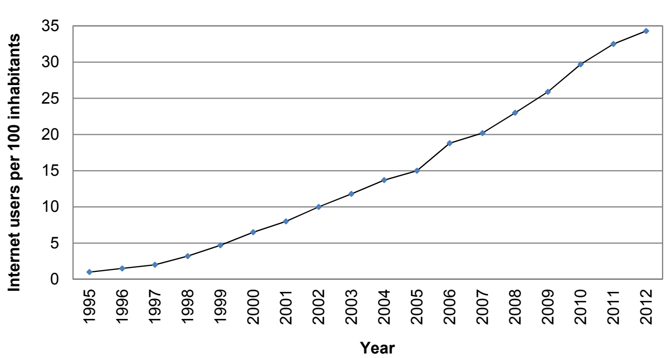


Fig. 4. Worldwide internet users [18,19].

because of rapid growth in parts of the developing world such as Africa, the Middle East and Latin America, access to the internet increased by 566% [18] (Fig. 5).

As global access to the internet increases and more businesses move their operations online, more ICT equipment is used and as a result more data centres are required [9]. In addition, as the internet has expanded, it is used in a more demanding manner. More powerful applications and faster speeds, and the online hosting of media and social networking sites [20] have therefore led to increases in the overall demand of data centres on power.

4. Operational energy use of ICT and data centres

Power demands in the UK have meant that the infrastructure is near breaking point, with demand set to outstrip supply by 2017 if a 'do nothing' approach is adopted for its generation [4]. Furthermore, in 2004 the UK 'became a net importer of energy' [4], making it politically vulnerable [3], and by 2016 the safety margin in the National Grid is expected to reach 4%, equivalent to a blackout risk of 1 in every 12 years [21]. The efficient use of energy by ICT, and in particular data centres, is therefore a key concern of the ICT industry.

4.1. Office and network equipment

The earliest research into the energy consumed by the ICT industry focused on IT components such as computers and peripherals (printers). Concern in the US was led by the Lawrence Berkeley National Laboratory (LBNL) as early as the 1980s, where research showed rising trends in energy use by personal computers and office equipment [22–24]. In 1983 LBNL estimated total average energy use by office equipment of 0.1 kWh/m^2/year, and projected levels would reach 0.4 kWh/m^2/year by 2011 [23].

In 1999, updated US research found office and network equipment consumed 74 TWh/year – 2% of total electricity or 3% when telecommunications equipment and electronics manufacturing were included [25]. By the start of the millennium, further research with improved data readings estimated higher levels of overall electricity usage of 97 TWh/year – 3% of total electricity [26] – showing an overall upward trend since research started.

4.2. The internet

Since the start of the internet, users have continued to increase as discussed in section 2.3. Alongside this growth in internet use there has been much speculation around the amount of electricity required to run it. At the end of the 1990s, Forbes published an article summarising a non-peer-reviewed report which assumed

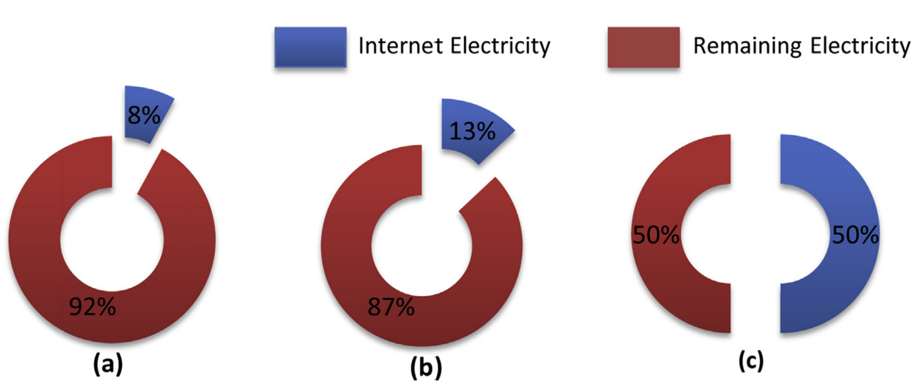


Fig. 5. Proportion of US electricity used for the internet (a), including embodied and operational impacts (b), and projected over next one to two decades (c).

the largest power draws of each equipment type (peak power without consideration of actual utilisation) and applied them universally [26]. The report claimed that 8% of all US electricity was used to power the internet, a figure which grew to 13% if embodied and operational energy for chips and computers was included, and 50% when projected over the ensuing one to two decades [27] as shown in Fig. 5.

These figures, however, have been widely rebuffed by research showing the article assumptions were overestimated almost eightfold [28–30]. This was later independently confirmed by the work of RAND [31] for the US DoE, in which four scenarios were built for the electricity requirements of a digital society from 2001–2021, and in which even the largest projected growth in digital devices was found to result in only a modest effect on electricity demands of 5.5% [31].

Nonetheless, the statistic persists and continues to be quoted today by journalists, and although it has been a catalyst for improved research, it shows the need to handle energy data with care.

4.3. Data centres

As access to IT and the internet has grown, so too has the number of data centres, and their consumption of electricity. There is little early evidence of peer-reviewed estimates on energy use of data centres [32,33], especially those that include infrastructure energy [34], but after incorrect estimates [28] made by Huber [27] were widely spread and then refuted, industry-wide research began to grow. Importantly in 2001, studies based on actual usage data, as opposed to assumptions, began to emerge [35,36] as shown in Fig. 6.

Early industry figures, based on overestimated facility assumptions and incorrect footprint areas, suggested data centre power demand (including infrastructure draw) could be as high as 2150–2690 W/m^2 [6] and frequently well over 1000 W/m^2 [35]. However, total computer room power densities based on actual usage data were approximated in 2001 at a much lower 355 W/m^2 [35], and emphasised the errors in assumptions made in previous studies. The data centre studied by Mitchell–Jackson et al. [35] was later investigated in more detail. From 2001 to 2002, the study of one internet data centre (IDC) found an increase in computer room floor area of 33%, yet due to energy efficiency measures, the same power density of 355 W/m^2 was displayed [36]. This shows that as early as 2000, efforts were being made to improve operational efficiency.

Later, the benchmarking of six data centres resulted in average densities in 2004 in the order of 538 W/m^2 [6], with the benchmarking of a further 22 data centres in 2006 yielding densities ranging from 54 to 1000 W/m^2 [37,38]. The figures, while sufficiently different, reflect the widely varying levels of efficiency that are displayed in facilities, and the upward trend in densities and the changes to technology over time.

Research into energy consumption of data centres was initially focused on power densities as described above. However, more recently this focus has shifted to total electricity consumption in areas across the globe, and is dominated by the work of Jonathon Koomey. In the period from 2000 to 2005, aggregate worldwide electricity use by servers doubled, largely due to increased numbers of cheap volume servers, and in part due to a small increase in power use per unit [33]. In 2000, annual data centre electricity consumption in western Europe (shown in Fig. 7) was 18.3 TWh, a figure that rose to 41.3 TWh in 2005, and assuming a 12% year-on-year growth was projected to reach 72.5 TWh by 2010 [34].

In 2007 the US EPA Energy Star programme compiled a Report to Congress which concluded that in 2006 US data centres and servers consumed 61 TWh of electricity – 1.5% of the country's overall demand and double that in 2000 [1] and equivalent to 33,672 kgCO_2e (calculated using conversion factors from the IEA 2013 edition of fuel combustion emissions [[39], page 110]).

Later, in 2011, Koomey [40] published a report for The New York Times which revisited the previous global and US projections from his 2008 paper [34]. The study found a slow-down in the growth of electricity because of efficiency improvements, the recession, and virtualisation, resulting in only a 56% growth in worldwide electricity consumption between 2005 and 2010, rather than a doubling as it did from 2000 to 2005 [40], as was projected by the Report to Congress [1]. As a result, global annual consumption grew from 70.8 TWh (37,382 kgCO_2e) in 2000 to 152.5 TWh (82,650 kgCO_2e) in 2005 and 238 TWh (125,900 kgCO_2e) in 2010 [39,40] as shown in Fig. 8.

Furthermore, if the 2010 consumption from the 2011 Koomey study [40] is extrapolated to 2015 (assuming the same 56% growth seen between 2005 and 2010, and split evenly between the five year period) a global consumption of 291 TWh is found in 2012 [34,40] and 371.1 TWh (197,500 kgCO_2e) by 2015 as shown in Fig. 8.

In addition to the research by Koomey [34,40], DatacenterDynamics (DCD) initiated a yearly census of the industry. In 2012, the DCD [41] Industry Census found a total global data centre power use of 322 TWh, 1.8% of global electricity use, and comparable to that suggested for 2011 by Koomey [40] of between 1.7 and 2.2%. Using a world average kgCO_2e per kWh of electricity generation this is equivalent to 171,630 kgCO_2e [39].

Moreover, the census found that the UK currently has the third highest global actual power demand of 2.70 GW in 2011 and 2.85 GW in 2012 [42] and 3.10 GW in 2013 [43], and which is forecast to reach 3.68 GW by 2016 [43] and shown in Fig. 9.

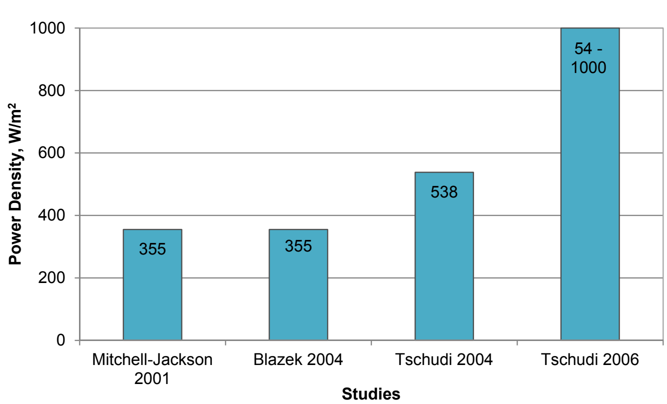


Fig. 6. Studies of data centre power densities.

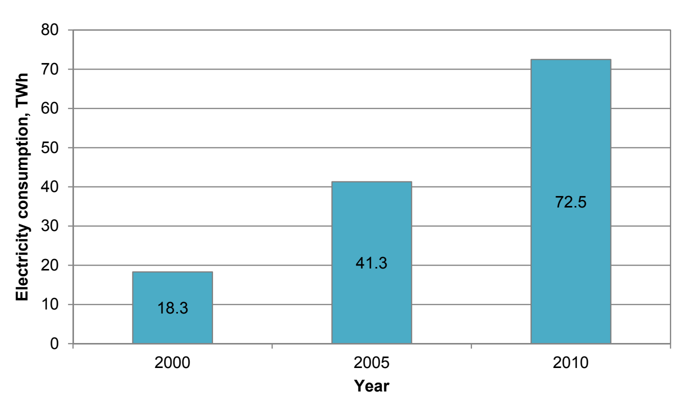


Fig. 7. Data centre electricity consumption in western Europe.

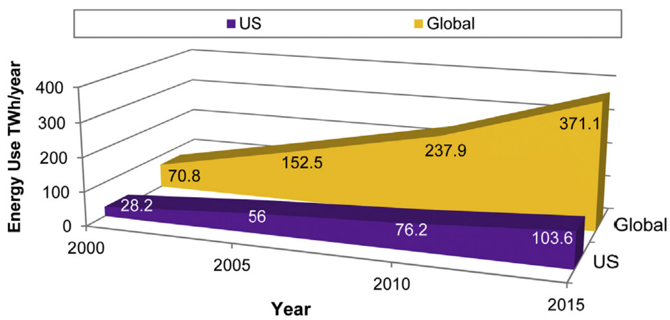


Fig. 8. Data centre energy use extrapolated to 2015 [40].

Assuming that the data centres are running 24 × 7, using the Carbon Trust conversion factors [44] for the UK electricity grid in 2013, this would have produced 10,536 kgCO_2e in 2011, 11,122 kgCO_2e in 2012, 12,097 kgCO_2e in 2013 and will create 14,361 kgCO_2e in 2016.

Furthermore, in 2011 the UK was estimated to have 7.59 million m^2 of dedicated data centre space – equivalent to 14 Pentagons – and a total maximum power consumption of 6.4 GW [45] or 24,975 kgCO_2e.

Throughout the energy literature reviewed in this section, early values for consumption across the industry were consistently varied as shown in Fig. 6. The differences reflect the difficulty in obtaining accurate data on energy use because of the lack of monitoring, the constant change in technologies, increasing densities, and changing approaches to calculating the consumption, and the reluctance of owners to share energy data [35,36].

Later results from Koomey [40] and DatacenterDynamics [43] are in the same order of magnitude and seem comparable. However, although there is a good correlation between the studies, the Koomey work recognises that further research is needed, based on actual energy use, and that while the DCD Census [41] is based on a sample of the industry, it is extrapolated to build the overall picture. It is clear therefore that both sets of results are exposed to uncertainties that need attention to improve their accuracy.

5. The impact of ICT and data centres on climate change

The growing power demand of data centres has led to a heightened awareness of their increasing impact on climate change from greenhouse gas (GHG) emissions. Comprehensive research into the impact of the whole ICT industry on climate change has been dominated by GeSI [5,46], but has been strengthened by recent research by Malmodin et al. [47].

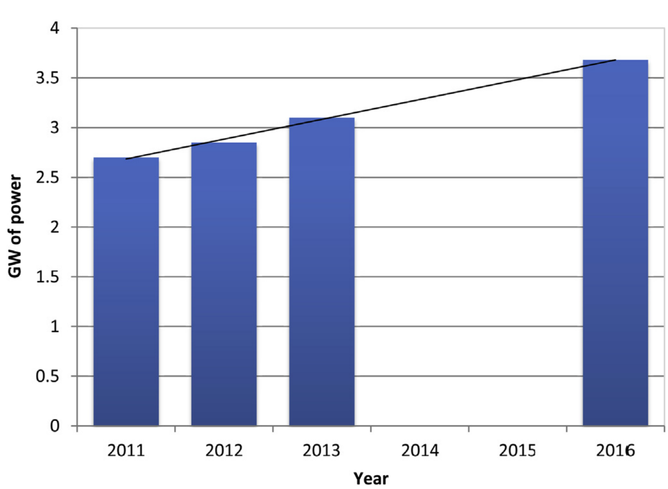


Fig. 9. UK actual power demand by data centres from 2011 to 2016.

In 2012 the growth in GHG emissions (embodied and operational) from the ICT industry was projected to rise at a faster rate than the total global footprint [46]. Note *footprint* and *emissions* are used interchangeably in this section, and refer to the GHG emissions including CO_2 and all GHGs converted to CO_2-equivalent (CO_2e). Of the three main sectors of the ICT industry, data centres are projected to have the fastest rate of growth at 7% per annum (p.a.) from 2011 to 0.29 GtCO_2e in 2020 [46]. This growth echoes those found in an earlier study by GeSI [5] that suggested a rise in footprint of 7% p.a. from 2002 to 2020, but concluded a higher overall impact in 2020 due to an actual measured increase (rather than projected) of 9% p.a. from 2002 to 2011, and shown in Fig. 10.

In the 2008 study, GeSI estimated that ICT accounted for 2% of the global GHG footprint – a figure supported by research from Gartner [48] – and would grow to 2.8% by 2020. By 2011, however, research based on more accurate data and altered behaviours in the industry, meant only a 1.9% share of the total footprint was found [46].

A similar study by Malmodin et al. [47] compared its results to the first (Smart 2020) report [5], and found different percentage shares of the total global footprint, created by the use of old data in the 2008 GeSI [5] report, and therefore an elevated ICT carbon footprint. In the SMARTer 2020 report [46] these figures were updated, but the percentage share of the footprint by 2020 remained higher (2.3%) than in the Malmodin et al. [47] study (1.9%), suggesting these modelling differences remain.

Of the ICT impact, servers and cooling were found by Gartner [48] to account for 23% of carbon dioxide emissions. However, the GeSI report [5], which was more detailed and based on more accurate information, found a figure (including power systems and embodied impacts) closer to 14% shown in Fig. 11 below. Of this 14%, out-dated volume servers accounted for over a third of the impact, a figure reflected in the Koomey [34,40] studies. Although the difference in figures is big, it is clear that this is due to the omission of embodied impacts from PCs and monitors in the Gartner data [48].

6. ICT as a key enabler

Whilst the operation of ICT impacts negatively on climate change, ICT also has the potential to impact beneficially by enabling the reduction of emissions in other sectors. The potential of the internet (which cannot exist without data centres) to improve efficiency and reduce carbon emissions across sectors other than ICT was recognised as early as the 1990s when Romm et al. [49] noted the potential for the internet to turn retail buildings into websites and trucks into fibre optics.

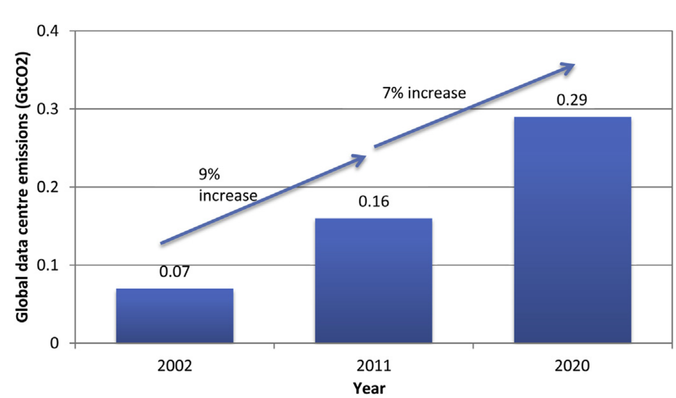


Fig. 10. Growth in data centre GHG emissions – 2002 to 2020.

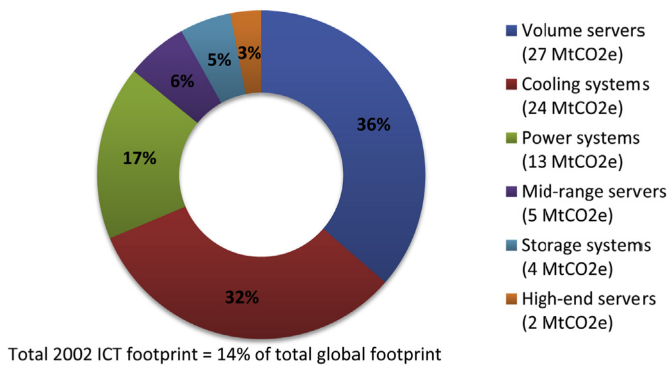


Fig. 11. Composition of global data centre footprint in 2002 [5].

Between 1997 and 1998, total US energy consumption increased by only 1%, yet the economy grew 4% year-on-year, and in 1998 GHG emissions rose by only 0.2%, the lowest since the recession year of 1991 [49]. These trends were largely attributed to increased low-energy production of computers and software (one third) and the knock-on gains in efficiency (two thirds) from their use [49].

This research by Romm et al. [49] is further backed by US EIA data [[50], Fig. 1.7], which illustrates the continued decrease in primary energy consumption per real dollar of GDP (gross domestic product) between 1973 and 2012. Alongside the growth in use of ICT discussed previously, the trend suggests that a growth in ICT occurs with a lowered increase in GHG emissions, which if continued could lead to an overall reduction in emissions.

6.1. Sources of savings from the use of ICT in other industries

The potential savings achieved by using ICT come from a number of areas: dematerialisation (the swapping of high carbon products for low carbon alternatives), energy, transport, buildings and industry [49,51], and can be achieved through smart grids, smart logistics, smart buildings and smart motor systems [5].

The reduced rate in increase of emissions discussed previously is largely influenced by the indirect effects of ICT, rather than dematerialisation. In 2008 GeSI [5] estimated that ICT could save up to 7.8 $GtCO_2e$ by 2020, a figure that is 5.5 times the projected impact of the ICT industry itself (1.4 $GtCO_2e$). However, in 2012 GeSI [46] increased this abatement potential to 9.1 $GtCO_2e$ by 2020, 7.2 times the projected industry impact of 1.3 $GtCO_2e$, which was reduced to take into account new technologies, improved data, and increased baseline emissions.

Building on the work of Romm et al. [49] and Turner et al. [51], GeSI [46] presented four main ways ('change levers') by which ICT can reduce emissions within other sectors: digitalisation and dematerialisation, improved data collection and communication, system integration, and optimisation of processes. Through the adoption of these methods, an abatement potential of 9.1 $GtCO_2e$ by 2020 is projected to come from improved efficiency within six sectors [46]:

- transport – ICT can improve logistics and create new technologies;
- agriculture and land-use – ICT can be used to control irrigation systems remotely;
- buildings – software can be used to more accurately design buildings in a way that reduces air conditioning and heating;
- manufacturing – software can be used to automate and optimise processes;
- power – software can be used to respond to dynamic changes in demand; and
- service and consumer – for example the move to online retail.

Although there are barriers to the realisation of the reduction potentials discussed in this section – such as poor economics and finance, lack of awareness and resistance to behavioural change – the potential of ICT to indirectly reduce climate change far outweighs the direct impact of data centres and the ICT industry. It is therefore clear that data centres will continue to grow in number, and reduction of their environmental impact will become increasingly important.

7. Data centre metrics

With the growing energy consumption discussed in section 4, efforts to improve the operational efficiency of data centres and the components they contain have been widespread. As a result, a number of common metrics and methods of assessment have been adopted to monitor and benchmark their performance.

Most metrics focus on the efficient use of individual resources during the operation of a data centre, and by this virtue can also help to reduce operational expenditure. Table 2 gives a summary of

Table 2
Commonly adopted metrics.

Metric		Equation
PUE	Power usage effectiveness [52–56,62]	$=\frac{\sum \text{Facility power}}{\sum \text{IT equipment power}}=\frac{P_{\text{mechanical}}+P_{\text{electrical}}+P_{\text{miscellaneous}}+P_{\text{IT}}}{P_{\text{IT}}}$
ERF	Energy reuse factor [62,64]	$=\frac{\text{Reuse energy outside of the data centre}}{\text{Total data centre source energy}}$
GEC	Green energy coefficient [62]	$=\frac{\text{Green energy used by the data centre}}{\text{Total data centre source energy}}$
SI-EER	Site infrastructure energy efficiency ratio [32]	Same as PUE
DCiE	Data centre infrastructure efficiency [53,54]	$=\frac{1}{\text{PUE}}$
DCeP	Data centre energy productivity [62,65]	$=\frac{\text{Useful work produced in the data centre}}{\text{Total data centre energy consumed producing this work}}$
ScE	Server compute efficiency	$=\frac{\text{No. of samples where server provides a primary service}}{\text{Total no. of samples over the time period}}\times 100$
A primary service is the main service provided by the server, for example the primary service of a mail server is to provide email [60]		
DCcE	Data centre compute efficiency [60]	$=\frac{\sum \text{ScE from all servers}}{\text{Total number of servers}}$
DPPE	Data centre performance per energy [59]	$=\frac{\text{IT equipment utilisation factor}\times\sum \text{IT equipment capacity}}{\sum \text{Data centre energy consumption}-\text{Green energy}}$
DC-EEP	Data centre energy efficiency and productivity [32]	$=\text{SI}-\text{EER}\times\text{IT productivity per embedded Watt}$
CUE	Carbon usage effectiveness [58,62,66]	$=\frac{CO_2\text{ emitted }(\text{kg}CO_2\text{e})}{\text{Unit of energy (kWh)}}\times\frac{\text{Total data centre energy}}{\text{IT equipment energy}}$
WUE	Water usage effectiveness (site) [66,67]	$=\frac{\text{Annual site water usage}}{\text{IT equipment energy}}$
WUE_{source}	Water usage effectiveness (source) [67]	$=\text{WUE}+\frac{\text{Annual source energy water usage}}{\text{IT equipment energy}}$
EDE	Electronics disposal efficiency [63]	$=\frac{\text{Weight of responsibly disposed of IT EEE}}{\text{Total weight of disposed of IT EEE}}$

some of the most common metrics used by the data centre industry.

Developed by The Green Grid [52–56], PUE (power usage effectiveness) is the most widely adopted metric, with reports from research analysts at Gartner that 80% of all new large data centres will have adopted the metric by 2015 [57]. The metric is used to measure the ratio of total power delivered to site to that used by the IT equipment, and is analogous to the miles per gallon metric for the fuel consumption of a car. It is dimensionless, and has an ideal value of 1.0 [58]; although Shiino [59] (2010) found actual values ranged from 1.25–3.75. Whilst Koomey [40] found values in the range of 1.36–3.6, from the EPA Energy Star programme's study of 61 data centres, and an average value of 1.92. In real terms this mean value of PUE shows that the average data centre consumes almost double the power required for just the IT equipment in power losses, cooling, lighting and other miscellaneous loads.

The PUE metric drives the need to minimise power used by anything other than IT. However, there are concerns that the metric does not consider the actual productivity or efficiency of the equipment [54,59]. As a result, a data centre in which no infrastructure upgrades are made actually achieves an improved PUE as the IT equipment ages and uses more power.

Recognising the need to consider more than just energy use, CUE and WUE consider operational carbon and water usage, following the same format as PUE. ScE and DCcE [60] consider the efficiency of the data centre compute infrastructure, and allow users to focus on operational efficiency, much like PUE. While DCeP is a productivity metric, which attempts to quantify the useful work performed by a data centre through a number of complex proxies [61,62] and is more advanced than the xUE family (PUE, CUE, WUE). EDE seeks to address the need for a metric to quantify the extent to which IT consumers are disposing of IT equipment responsibly at the end of their life [63]. Finally ERF quantifies the amount of energy reused outside of the data centre and GEC looks at the amount of renewable energy used. The remaining metrics are a variation on these themes.

7.1. Metric evaluation

There are a number of concerns with current data centre metrics. Most importantly, they are generally only concerned with the operational phase of data centres, and do not coherently account for other impacts that occur, for example, when the components are being manufactured (embodied impacts).

Although originally no consideration was made to the renewables content of the source electricity, the introduction of GEC (green energy coefficient) [62] allows for comparison of two sites with equivalent PUE values, one of which uses energy generated from renewable sources and the other of which relies on energy from coal-fired power stations. However, The Green Grid [62] currently only recognises three authorities across the world that issue green energy certificates that satisfy their requirements as proof of renewables content, in the EU, Japan and USA. It is also unclear whether purchase of these certificates is prohibitively expensive to facilities in countries where a high renewables content is almost a given. Nonetheless, the metric remedies the inability for global comparisons.

When The Green Grid metric WUE_{source} was released it introduced an important area of expansion that is omitted from most of the other industry metrics. Firstly, it considers water – not energy – and secondly, it considers the water used not only during the operation of the data centre (for example for humidification), but also during the production of the power that is used on site. Much like GEC now does for power usage. The metric, alongside CUE, recognises that impacts due to the existence of a data centre occur not only when it is in operation, but also in the production process, and acknowledges that environmental burden comes from more than just energy use.

This inclusion of impacts from the production phase is in line with life cycle thinking, in which the impact that a product or service has on the planet is assessed from the moment raw materials are extracted until eventual disposal of the product, while crucially considering more environmental impacts than simply energy and water use.

Without holistically considering the life cycle of a data centre for various environmental impacts and stages of the life cycle, it is hard to know how energy efficiency measures in the operational phase impact on other parts of the life cycle. For example, it is difficult to know whether the current drive to raise server inlet temperatures, and reduce or eliminate the need for mechanical cooling, could adversely affect the embodied impacts (impacts experienced pre- and post-operation) of servers due to a potential decrease in the time between technology refresh. In other words 'pollution shift' is difficult to gauge without relevant research.

Furthermore, the industry does not have a way to manage and assess when equipment should be replaced, based on an evaluation of the reduced efficiency and additional environmental impact from the replacement component against the energy savings that will be made as a result of the replacement [63]. The introduction of the EDE metric, which is concerned with the disposal of IT equipment, is incredibly important in this argument. Not only does the metric follow life cycle thinking, alongside the release of The Green Grid's guidelines to the application of life cycle assessment (LCA) to data centres [68], the introduction of EDE and similar metrics indicates that the industry is beginning to see the need to consider more than single-issue metrics with a life cycle approach, and recognises the need for benchmarking and tools to facilitate the change.

8. Conclusions

The review of literature in part 1 presents a clear picture of the rising access to ICT and it's increased energy consumption. However, there is still uncertainty in the true values of this consumption, and how it will continue to grow into the future. Historic information on installed equipment has changed, as more accurate information becomes available, meaning projections are dynamic and need revisiting on a yearly basis. Work is required to ensure this information is more accurate in the first instance. In addition, data centre asset management needs a better handle of the amount of servers that are installed, and consuming energy to idle, but are unused for compute. It is noted by Koomey [40] that the omission idle servers from the estimates could mean the industry is actually consuming more than currently known. Irrespective of model uncertainties, energy consumption by data centres continues to grow, and although ICT is an enabler for energy reduction in other industry, its consumption needs to be monitored.

In response to rising energy consumption, and with growing concerns about energy security and availability [3], environmental impact has become increasingly important for the data centre industry. One method adopted to monitor and benchmark this impact is data centre metrics.

Metrics, such as power usage effectiveness (PUE), focus on operational efficiency, using it as a proxy for sustainability. These metrics have gained in popularity because of the documented rise in operational energy consumption, but miss impacts that are embodied in the facility due to energy consumed and emissions created during the manufacturing and disposal of data centres and their components [69]. By only considering one issue – for instance energy, water or carbon – in one stage of the facility's lifetime, it is not possible to detect the effect that improving the efficiency of one issue has on another at any other point of the building's lifetime [69].

Although the industry's primary concern is the financial implications of this rising energy consumption, the industry is becoming increasingly aware of its environmental impact and its vulnerability from the uncertain future of its fuel supply. In response to the resulting rise in energy bills, and power infrastructures pushed to their limits, the industry has focused almost exclusively on energy efficiency as a proxy for sustainability. The metrics have instigated a change in behaviour for the industry to one with more concern for sustainability, however, 'pollution shift' cannot be accurately evaluated by them and tends to be considered by intuition.

There is currently little evidence of detailed research that considers the impact using a life cycle perspective. In order to ensure impacts are not going unnoticed because of the operational focus, it is imperative that more research is conducted into the interrelated nature of environmental impact. This research should look to provide greater information on the most environmentally impacting parts of the facility beyond operational consumption; and seek to determine whether a life cycle perspective is required. The work of GeSI [46] and Malmodin et al. [47] already points to the contribution ICT has to the global footprint of GHG emissions, and should be strengthened by more detailed research.

As single metrics are so widely adopted by the industry, future work from life cycle benchmarking should look to establish similar simple metrics for a wide range of impacts, to enable the broadest section of the industry to use and report against them. These could take a similar form to impact factors for electricity from different energy mixes, and global warming potential of different refrigerants, to allow designers and owners to understand their impact more holistically.

Finally it should be reiterated that this paper seeks to provide a picture of the current impact of the industry and methods used to monitor it. It does not include consideration of how the impact can be reduced.

Other options for assessing the impact of data centres are discussed in part 2 of this paper. This concluding part describes and critiques the use of building environmental assessment methods and tools; and based on both parts of the review, concludes the need to apply life cycle thinking to more holistically assess the environmental impact of data centres.

Acknowledgements

This paper has been developed with the financial support of the Engineering and Physical Sciences Research Council (EPSRC), EP/H50169X/1 and HP; who have also gone to great lengths to share their knowledge and expertise in the fields of data centres and sustainable IT. Additional support and review of work was provided by supervisors: Dr Robert Tozer, Dr Alan Dunn and Sophia Flucker.

References

[1] US EPA. Report to congress on server and data center energy efficiency. Public law 109–431; 2007. Available from: http://hightech.lbl.gov/documents/DATA_CENTERS/epa-datacenters.pdf [accessed 04.10.10].
[2] Covas MT, Silva CA, Dias LC. Multicriteria decision analysis for sustainable data centers location. Int Trans Oper Res 2012;20(3):269–99.
[3] Uddin M, Rahman AA. Energy efficiency and low carbon enabler green IT framework for data centers considering green metrics. Renew Sustain Energy Rev 2012;16:4078–94.
[4] Global Action Plan. An inefficient truth; 2007. Available from: http://greenict.org.uk/sites/default/files/An%20Inefficient%20Truth%20-%20Executive%20Summary.pdf [accessed 03.08.10].
[5] GeSI. SMART 2020: enabling the low carbon economy in the information age; 2008. Available from: http://www.smart2020.org/_assets/files/02_Smart2020Report.pdf [accessed 01.07.10].
[6] Tschudi W, Xu T, Sartor D, Nordman B, Koomey J, Sezgen O. Energy efficient data centers. Final report to California Energy Commission; 2004. Available from:, http://escholarship.org/uc/item/1s93b4rd [accessed 16.01.11].
[7] LBNL. Definition of data center; 2010. Available from: http://hightech.lbl.gov/DCTraining/definitions.html [accessed 17.09.10].
[8] Intel Free Press. Outside facebook data center. Available from:; 2012. Creative commons license: https://www.flickr.com/photos/intelfreepress/6722296855. https://creativecommons.org/licenses/by/2.0/legalcode [accessed 09.07.14].
[9] Shah A, Krishnan N. Optimization of global data center thermal management workload for minimal environmental and economic burden. IEEE Trans Comp Packag Technol 2008;31(1):39–45.
[10] ISG. Data center case study. HP Enterprises; 2014. Available from: http://www.isgplc.com/datacenters/casestudy/default.asp#thebuilding [accessed 11.07.14].
[11] Dennis van Zuijlekom. End-of-life. Available from:; 2013. Creative Commons License: https://www.flickr.com/photos/dvanzuijlekom/8522770418. https://creativecommons.org/licenses/by/2.0/legalcode [accessed 09.07.14].
[12] Arno R, Friedl A, Gross P, Schuerger R. Reliability of example data center designs selected by tier classification. In: Tallahassee, FL, USA: proceedings of industrial and commercial power systems technical conference (I&CPS); 2010.
[13] Uptime Institute. Data center site infrastructure. Tier standard: topology; 2012. Available from: http://uptimeinstitute.com/publications [accessed 24.07.13].
[14] Uptime Institute. Data center site infrastructure. Tier standard: operational sustainability; 2013. Available from: http://uptimeinstitute.com/publications [accessed 24.07.13].
[15] Chinn MD, Fairlie RW. ICT use in the developing world: an analysis of differences in computer and internet penetration 2010. Rev Int Econ 2010;18(1):153–67.
[16] PRB. How many people have ever lived on the earth?; 2011. Available from: http://www.prb.org/Articles/2002/HowManyPeopleHaveEverLivedonEarth.aspx [accessed 09.06.13].
[17] Stamford C. Gartner says more than 1 billion PCs in use worldwide and headed to 2 billion units by 2014; 2008. Available from: http://www.gartner.com/newsroom/id/703807 [accessed 23.06.08].
[18] IWS – Internet World Stats. Internet world stats usage and population statistics; 2013. Available from: http://www.internetworldstats.com/stats.htm [accessed 09.06.13].
[19] ITU. Measuring the information society; 2012. Available from: http://www.itu.int/ITU-D/ict/publications/idi/ [accessed 19.10.10].
[20] Leiner BM, Cerf VG, Clark DD, Kahn RE, Kleinrock L, Lynch DC, et al. A brief history of the internet. ACM SIGCOMM Comput Commun Rev 2009;39(5):22–31.
[21] Buchanan A. Will GB's lights stay on and will the gas keep flowing: a look at the next decade?; 2013. Available from: https://www.ofgem.gov.uk/ofgem-publications/64123/lecture-19th-february-2013.pdf [accessed 08.08.13].
[22] Harris J, Roturier J, Norford LK, Rabl A. Technical assessment: electronic office equipment. LBL-25558-Rev; 1988. Available from:, http://www.ntis.gov/search/index.aspx?frm_qry_Search=DE89013375 [accessed 06.10.10].
[23] Piette MA, Eto JH, Harris JP. Office equipment energy use and trends. LBL-31308. UC-350; 1991. Available from:, http://dx.doi.org/10.2172/7001015 [accessed 06.10.10].
[24] Koomey JG, Cramer M, Piette MA, Eto JH. Efficiency improvements in US office equipment: expected policy impacts and uncertainties. LBL-37383 UC-1600; 1995. Available from:, http://enduse.lbl.gov/info/LBNL-37383.pdf [accessed 06.10.10].
[25] Kawamoto K, Koomey JG, Nordman B, Brown RE, Piette MA, Ting M, et al. Electricity used by office equipment and network equipment in the U.S.: detailed report and appendices; 2001. Available from: http://enduse.lbl.gov/projects/infotech.html [accessed 07.10.10].
[26] Roth KW, Goldstein F, Kleinman J. Energy consumption by office and telecommunications equipment in commercial buildings. Volume I: energy consumption baseline. In: Asilomar, Pacific Grove, CA, USA: proceedings of 2002 ACEEE summer study on energy efficiency in buildings; 2002.
[27] Huber P.W. Dig more coal – the PCs are coming (updated: 31.05.99). Available from: http://www.forbes.com/forbes/1999/0531/6311070a_2.html [accessed 04.10.10].
[28] Koomey JG, Kawamoto K, Nordman B, Piette MA, Brown RE. Memorandum LBNL – 44698; 1999. Available from: http://enduse.lbl.gov/SharedData/IT/Forbescritique991209.pdf [accessed 04.10.10].
[29] Koomey JG, Chong H, Loh W, Nordman B, Blazek M. Network electricity use associated with wireless personal digital assistants; 2004. Available from: http://hightech.lbl.gov/documents/DATA_CENTERS/koomeyfinalPDAarticle.pdf [Accessed 04.10.10].
[30] Koomey JG. Sorry, wrong number – how to separate fact from fiction in the information age. IEEE Spectr 2003;40(6):11–2.
[31] Baer WS, Hassell S, Vollaard BA. Electricity requirements for a digital society; 2002. Available from: http://www.rand.org/pubs/monograph_reports/MR1617/index.html [accessed 04.10.10].
[32] Brill KG. Data center energy efficiency and productivity. Site infrastructure institute white paper; 2007. Available from: http://www.uptimeinstitute.org/symp_pdf/(TUI3004Chttp://www.uptimeinstitute.org/symp_pdf/(TUI3004C)DataCenterEnergyEfficiency.pdf [accessed 05.11.10].
[33] Koomey JG. Estimating total power consumption by servers in the US and the world; 2007. Available from: http://sites.amd.com/us/Documents/svrpwrusecompletefinal.pdf [accessed 08.10.10].

[34] Koomey JG. Worldwide electricity used in data centers. Environ Res Lett 2008;3:8.

[35] Mitchell-Jackson J, Koomey JG, Nordman B, Blazek M. Data center power requirements: measurements from silicon valley. Energy 2003;28(8):837–50.

[36] Blazek M, Chong H, Loh W, Koomey JG. Data centers revisited: assessment of the energy impact of retrofits and technology trends in high-density computing facility; 2004. Available from: http://hightech.lbl.gov/documents/DATA_CENTERS/blazekfinalpdf.pdf [accessed 07.10.10].

[37] Greenberg S, Mills E, Tschudi W, Rumsey P. Best practices for data centers; lessons learned from benchmarking 22 data centers. In: Asilomar, Pacific Grove, CA, USA: proceedings of 2006 ACEEE summer study on energy efficiency in buildings; 2006.

[38] Tschudi W, Mills E, Greenberg S, Rumsey P. Measuring and managing data-center energy use. Findings – and resulting best practices – from a study use in 22 data centers. HPAC Engineering; March 2006. p. 45–51.

[39] IEA. CO_2 emissions from fuel combustion highlights. 2013 ed. 2013 Available from: http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2013.pdf [accessed 14.07.14].

[40] Koomey JG. Growth in data center electricity use 2005 to 2010; 2011. Available from: http://www.analyticspress.com/datacenters.html [accessed 01.02.12].

[41] DCD. DCD Industry census 2012: energy. DatacenterDynamics Focus 2012;3(26):38–41.

[42] DCD. DCD Industry census 2012: UK energy. DatacenterDynamics Focus 2012;3(26):46–50.

[43] DCD. DCD Industry census 2013: UK figures. DatacenterDynamics Focus 2013;3(32):82–3.

[44] Carbon Trust. Conversion factors. Energy and carbon conversions 2013 update; 2013. Available from: http://www.carbontrust.com/media/18223/ctl153_conversion_factors.pdf [accessed 14.07.14].

[45] DCD. Special market report: data centers in the United Kingdom; 2011. Available from: http://www.datacenterdynamics.com/research/uk-market-report [Accessed 19.03.12].

[46] GeSI. SMARTer 2020: the role of ICT in driving a sustainable future; 2012. Available from: http://www.gesi.org/SMARTer2020 [accessed 22.03.13].

[47] Malmodin J, Bergmark P, Lunden D. The future carbon footprint of the ICT and E&M sectors. In: Zurich, Switzerland: proceedings of the first international conference on information and communication technologies for sustainability; 2013.

[48] Gartner. Green IT: a new industry shockwave. In: Orlando, Florida, USA: gartner presentation in: gartner symposium/ITxpo; 2007.

[49] Romm J, Rosenfeld A, Herrmann S. The internet economy and global warming. A scenario of the impact of e-commerce on energy and the environment. Version 1; 1999. Available from: http://www.p2pays.org/ref%5C04%5C03784/0378401.pdf [accessed 04.10.10].

[50] US EIA. Monthly energy review – February 2014. 1. Energy overview. Fig 1.7; 2014. Available from:, http://www.eia.gov/totalenergy/data/monthly/index.cfm#summary [accessed 22.03.14].

[51] Turner V, Bigliani R, Ingle C. Reducing greenhouse gases through intense use of information and communication technology: part 1. IDC White Paper; 2009. Available from:, http://download.intel.com/pressroom/archive/reference/IDCWP31R.pdf [accessed 13.10.10].

[52] The Green Grid. Green grid metrics: describing datacenter power efficiency. White Paper; 2007. Available from:, http://www.thegreengrid.org/~/media/WhitePapers/Green_Grid_Metrics_WP.ashx?lang=en [accessed 24.05.10].

[53] The Green Grid. Green grid data center power efficiency metrics: PUE and DCIE. White Paper #6; 2008. Available from:, http://www.thegreengrid.org/~/media/WhitePapers/White_Paper_6_-_PUE_and_DCiE_Eff_Metrics_30_December_2008.pdf?lang=en [accessed 01.02.12].

[54] The Green Grid. Usage and public reporting guidelines for the green grid's infrastructure metrics PUE/DCiE. White Paper #22; 2009. Available from:, http://www.thegreengrid.org/library-and-tools.aspx [accessed 12.12.10].

[55] The Green Grid. Recommendations for measuring and reporting overall data center efficiency. Version 1 – measuring PUE at dedicated data centers. Task force report; 2010. Available from:, http://www.thegreengrid.org/en/Global/Content/Reports/RecommendationsForMeasuringandReportingOverallDataCenterEfficiency [accessed 17.01.11].

[56] The Green Grid Global Task Force. Recommendations for measuring and reporting overall data center efficiency. Version 2 – measuring PUE for data centers; 2011. Available from: http://www.thegreengrid.org/en/Global/Content/Reports/RecommendationsForMeasuringandReportingOverallDataCenterEfficiencyVersion2 [accessed 19.05.11].

[57] Stamford C. Gartner says energy-related costs account for approximately 12 percent of overall data center expenditures; 2010. Available from: http://www.gartner.com/newsroom/id/1442113 [accessed 04.09.13].

[58] The Green Grid. Carbon usage effectiveness (CUE): a green grid data center sustainability metric. White Paper #32; 2010. Available from:, http://www.thegreengrid.org/library-and-tools.aspx [accessed 12.12.10].

[59] Shiino T. Japan's approach to reducing greenhouse gas emissions from data centers; 2010. Available from: http://www.nri.co.jp/english/opinion/papers/2010/pdf/np2010157.pdf [accessed 17.01.11].

[60] The Green Grid. The green grid data center compute efficiency metric: DCcE. White Paper #34; 2010. Available from:, http://www.thegreengrid.org/library-and-tools [accessed 02.02.11].

[61] The Green Grid. Proxy proposals for measuring data center productivity. White Paper #17; 2009. Available from:, http://www.thegreengrid.org/library-and-tools.aspx [accessed 12.12.10].

[62] The Green Grid. Harmonizing global metrics for data center energy efficiency. Global taskforce reaches agreement regarding data center productivity. March 13, 2014; 2014. Available from: http://www.thegreengrid.org/library-and-tools.aspx [accessed 22.03.14].

[63] The Green Grid. Electronics disposal efficiency (EDE): an IT recycling metric for enterprises and data centers. White Paper #53; 2013. Available from:, http://www.thegreengrid.org/library-and-tools.aspx [accessed 07.03.13].

[64] The Green Grid. ERE: a metric for measuring the benefit of reuse energy from a data center. White Paper #29; 2010. Available from:, http://www.thegreengrid.org/library-and-tools.aspx [accessed 12.12.10].

[65] The Green Grid. A framework for data center energy productivity. White Paper #13; 2008. Available from:, http://www.thegreengrid.org/library-and-tools.aspx [accessed 12.12.10].

[66] The Green Grid. The green grid introduces data center sustainability metrics. Porter Novelli Press Release; 2010. Available from: http://eon.businesswire.com/news/eon/20101202005473/en/data-center%3B-energy-efficiency%3B-carbon%3B-power-usage [accessed 02.12.10].

[67] The Green Grid. Water usage effectiveness (WUE): a green grid data center sustainability metric. White Paper #35; 2011. Available from:, http://www.thegreengrid.org/library-and-tools [accessed 31.01.12].

[68] The Green Grid. Data centre life cycle assessment guidelines. White Paper #45, v2; 2012. Available from:, http://www.thegreengrid.org/library-and-tools.aspx [accessed 20.11.12].

[69] Shah A, Bash C, Sharma R, Christian T, Watson BJ, Patel C. The environmental footprint of data centers. In: San Francisco, California, USA: proceedings of IPACK2009(2009); 2009.

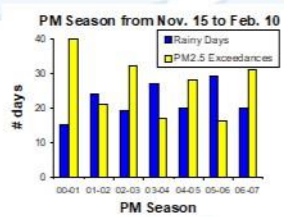
BAY AREA AIR QUALITY MANAGEMENT DISTRICT

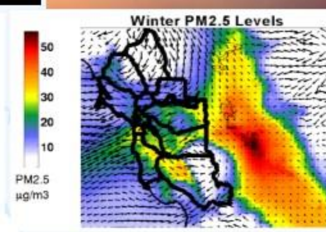
375 Beale Street, San Francisco, CA 94105

Air Quality Modeling and Analysis Section Publication No. 201901-017-PM

Fine Particulate Matter Data Analysis and Regional Modeling In the San Francisco Bay Area to Support AB617

January, 2019





Prepared by the Air Quality Modeling and Analysis Section:

Saffet Tanrikulu, Manager
Stephen Reid, Senior Atmospheric Modeler
Bonyoung Koo, Senior Atmospheric Modeler
Yiqin Jia, Atmospheric Modeler
James Cordova, Air Quality Meteorologist
Jeff Matsuoka, Research Analyst
Yuanyuan Fang, Statistician

Executive Summary

E1. Background

The adoption of Assembly Bill 617 (AB617) established collaborative programs to reduce community exposure to air pollutants in neighborhoods most impacted by air pollution. Air District staff have been working closely with the California Air Resources Board (ARB), other local air districts, community groups, community members, environmental organizations, regulated industries, and other key stakeholders to reduce harmful air pollutants in Bay Area communities.

The purpose of this data analysis and regional modeling effort is to support the District's AB617 activities by assessing pollutant formation, quantifying the relative contribution of emission sources to ambient pollution levels, and assessing population exposures and the benefits of emission controls in impacted communities around the Bay Area. Our initial assessments focus on fine particulate matter ($PM_{2.5}$) concentrations in West Oakland, and follow-up analyses will include air toxics evaluations in West Oakland and expansion of our technical assessments to other communities.

For the $PM_{2.5}$ analyses, we evaluated ambient meteorological and air quality data, and applied the U.S. EPA's Community Multi-Scale Air Quality (CMAQ) model to simulate pollutant concentrations at a 1-km horizontal resolution over the entire Bay Area for 2016. Then we repeated the simulation with West Oakland's anthropogenic emissions removed from the modeling inventory, leaving all other model input parameters unchanged. We calculated annual average $PM_{2.5}$ concentrations using the output of each simulation. The first simulation provided the annual average $PM_{2.5}$ concentrations for 2016 over the entire Bay Area, which will be used for $PM_{2.5}$ exposure analyses and health impacts assessments. The second simulation provided an estimate of background $PM_{2.5}$ levels in West Oakland (i.e., the $PM_{2.5}$ concentrations that would exist in the absence of local West Oakland sources). Background $PM_{2.5}$ concentrations will then be combined with local-scale modeling of West Oakland sources using the AERMOD dispersion model to provide a complete picture of $PM_{2.5}$ levels in the community and the relative contribution of different emission sources to those levels.

E2. Major Findings

E2.1 Regional $PM_{2.5}$ Concentrations

The CMAQ model generally captured the observed $PM_{2.5}$ pattern within the 1-km domain (Figure E1). High concentrations in both simulations and observations are evident in the northern San Joaquin Valley, along the I-580 and I-880 corridors from Richmond to the Oakland Airport, along the I-101 corridor near Redwood City, and in the San Jose metropolitan area. In the Sacramento area, the model shows overestimation biases and $PM_{2.5}$ concentrations do not compare as well to observations as in the Bay Area. For Sacramento and other counties outside the Bay Area, we relied on the ARB's emission inventories, and further evaluation of these data may be warranted. The model also shows high concentrations along the I-880 corridor from Oakland Airport to San Jose and along the Delta from Antioch to Brentwood, although observations are unavailable in these areas.

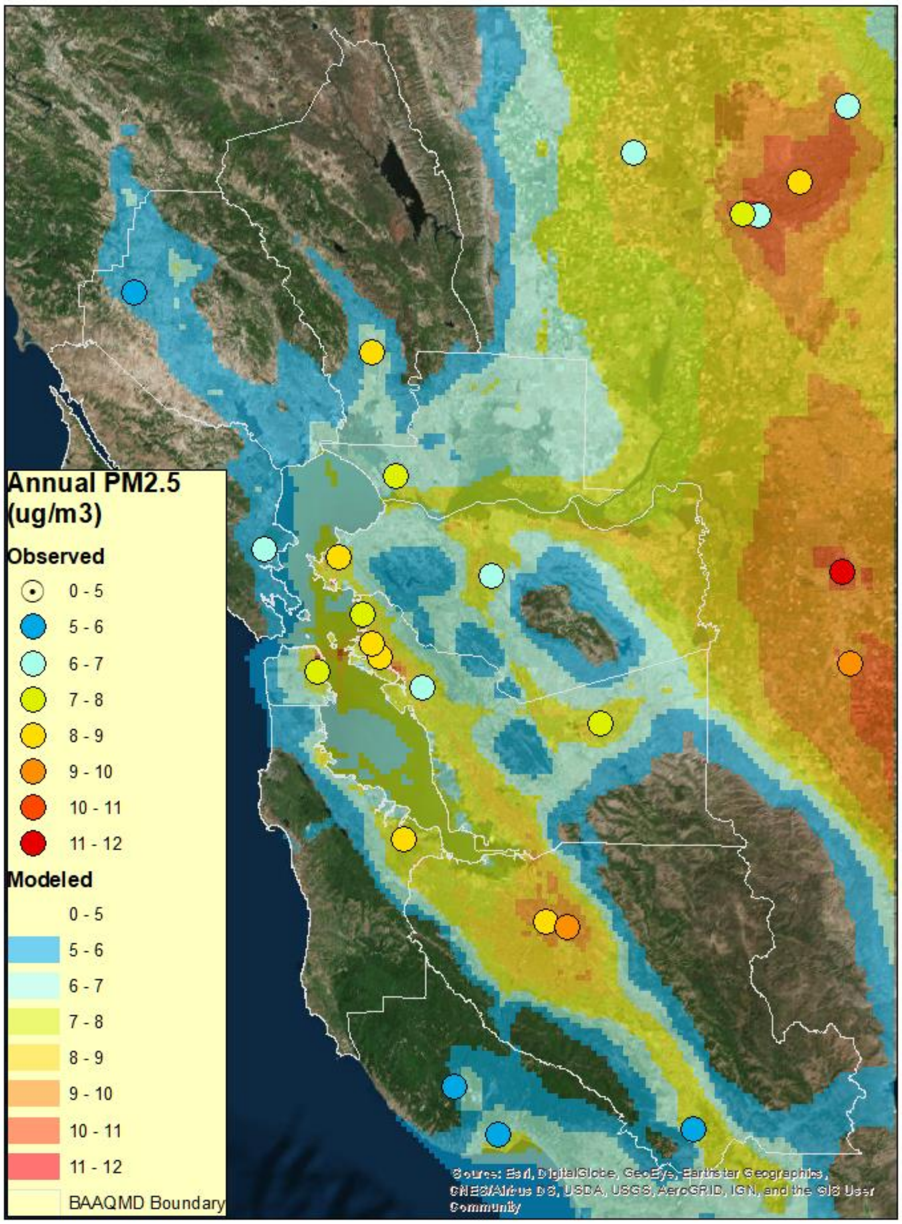


Figure E1: Spatial distribution of simulated and observed annual average $PM_{2.5}$ concentrations within the 1-km modeling domain.

Site by site comparisons between the simulations and observations (Figure E2) show that at most Bay Area sites (including the West Oakland Air Monitoring Station), the simulated annual average $PM_{2.5}$ concentrations are within ±1.0 μg/m^3 of observations. At a few sites (Concord, Oakland and Gilroy), the annual average $PM_{2.5}$ concentrations were overestimated, and at one site (Napa), the annual average PM2.5 concentration was underestimated by as much as 2.1 µg/m^3. Causes of these over and underestimations are under investigation.

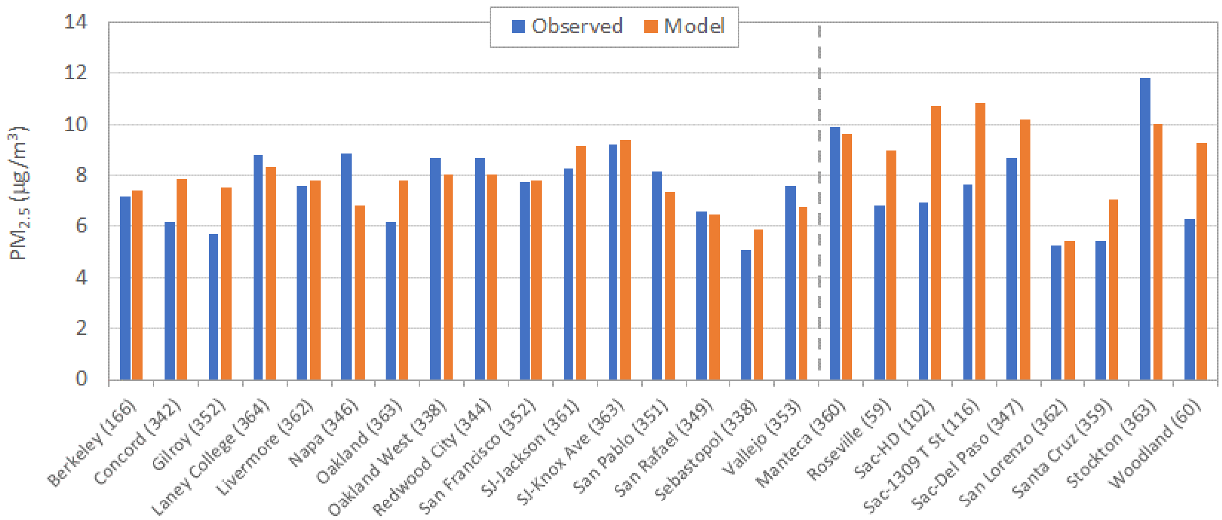


Figure E2: Annual mean observed vs. modeled $PM_{2.5}$ concentrations at monitoring sites within the 1-km modeling domain. The number of valid observations is shown in parentheses for each site.

E2.2 Estimating Background $PM_{2.5}$ in West Oakland

Figure E3 shows the annual average $PM_{2.5}$ concentrations for the base case within the West Oakland local-scale modeling domain that will be used for AERMOD. The highest and lowest annual average $PM_{2.5}$ concentrations are 9.3 µg/m^3 and 7.1 µg/m^3, respectively. A concentration gradient is evident within the domain. Cells with relatively higher concentrations extend along the eastern boundary and northwestern corner of the domain. A concentration gradient is also evident in the West Oakland community, an area within the red border in the figure. The eastern half of the community has slightly higher concentrations than the western half.

The spatial distribution of the annual average $PM_{2.5}$ concentrations is similar to the spatial distribution of West Oakland's emissions (Figure E4). The Chinatown area in the southeastern corner of the West Oakland local-scale domain has the highest emissions and concentrations. The cell along the southern boundary with the area's lowest concentration (7.1 µg/m^3) also has the lowest emissions (1.4 lbs/day).

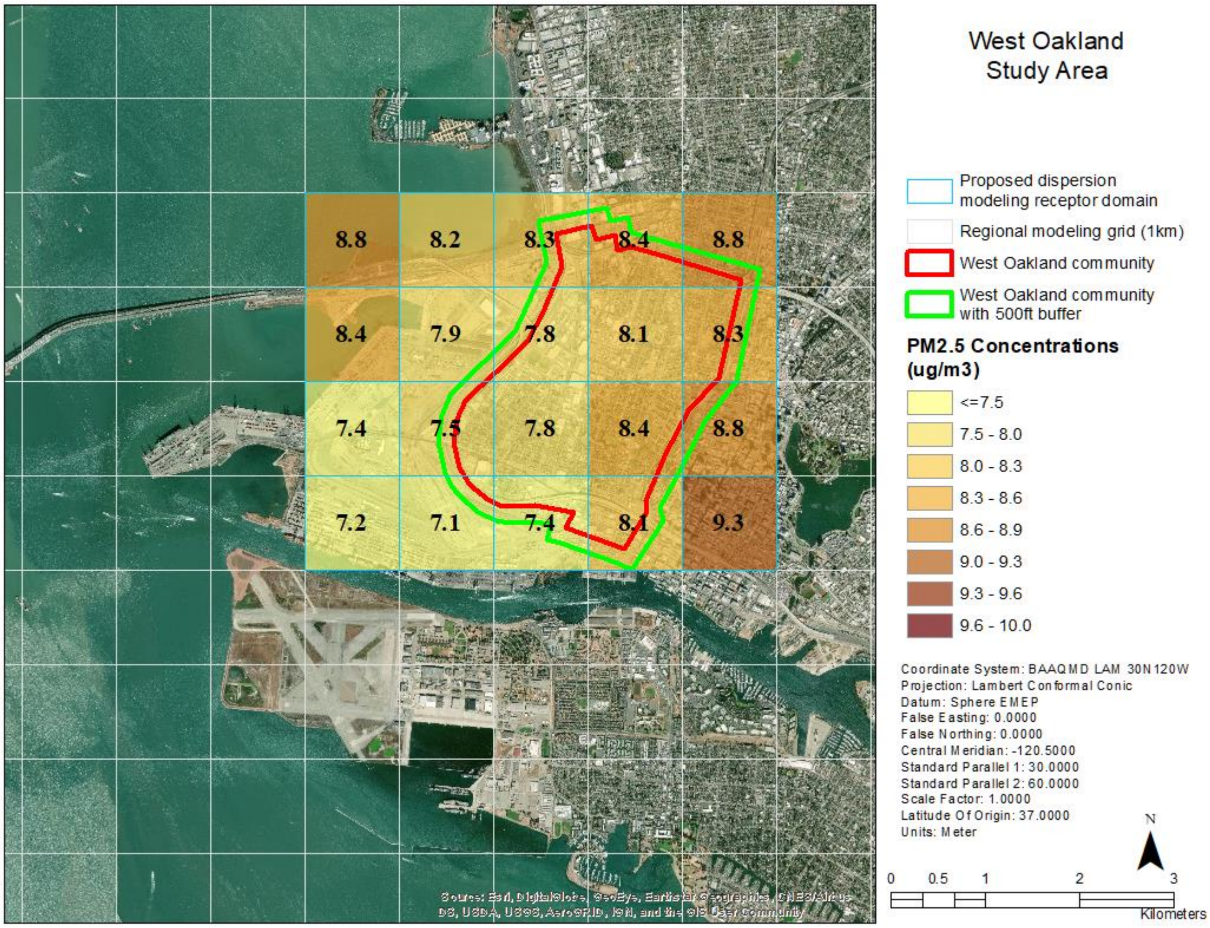


Figure E3: Spatial distribution of the simulated annual average $PM_{2.5}$ concentrations in the West Oakland modeling domain.

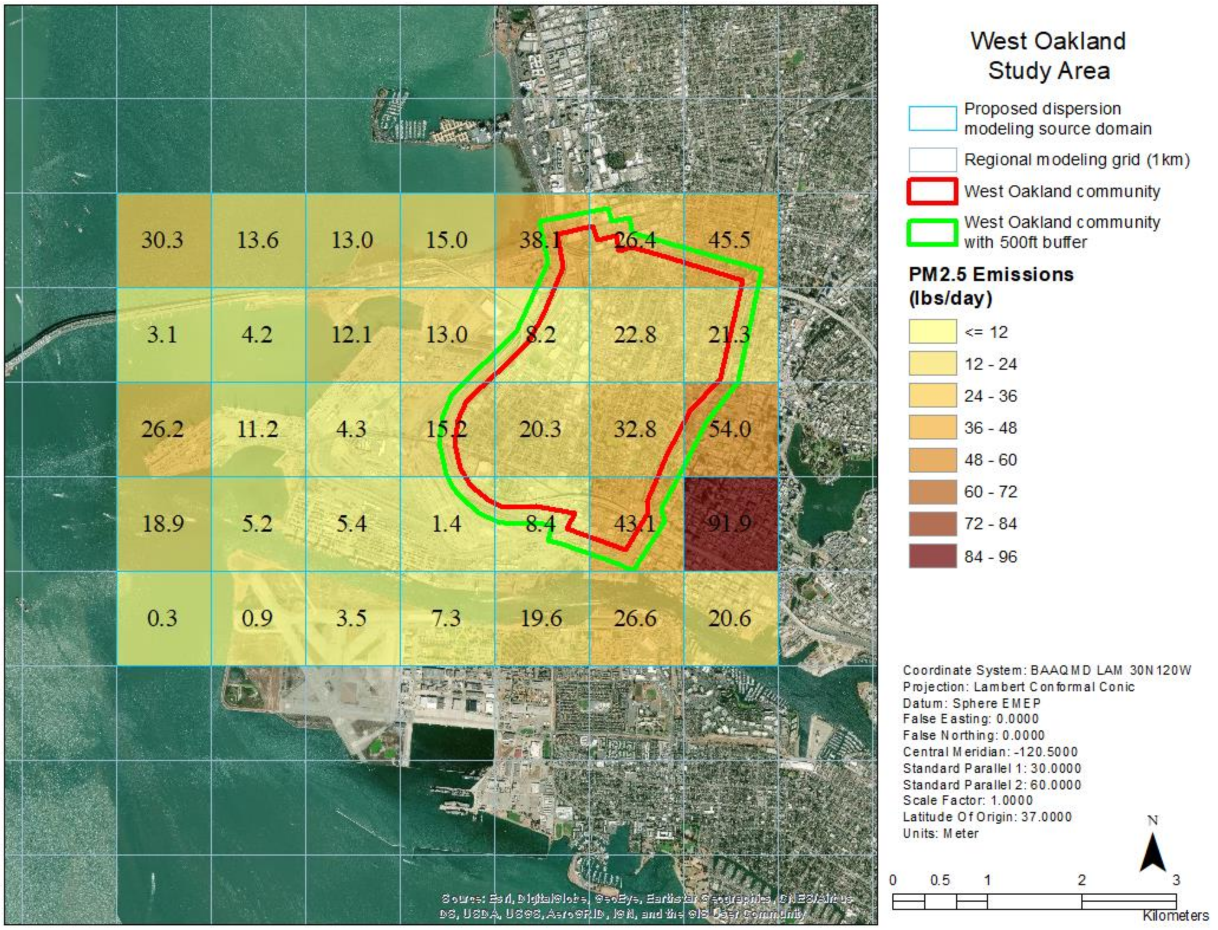


Figure E4: Spatial distribution of annual average $PM_{2.5}$ emissions in West Oakland.

Figure E5 shows the annual average $PM_{2.5}$ concentrations for the control case, i.e., a simulation without West Oakland's anthropogenic emissions. Compared to Figure E3, the spatial gradient in the annual average concentrations decreased significantly in the absence of West Oakland emissions across the local-scale domain. The location of the maximum annual average $PM_{2.5}$ concentrations has shifted from Chinatown to near the Bay Bridge, suggesting the influence of transport from the northwest corner of the domain.

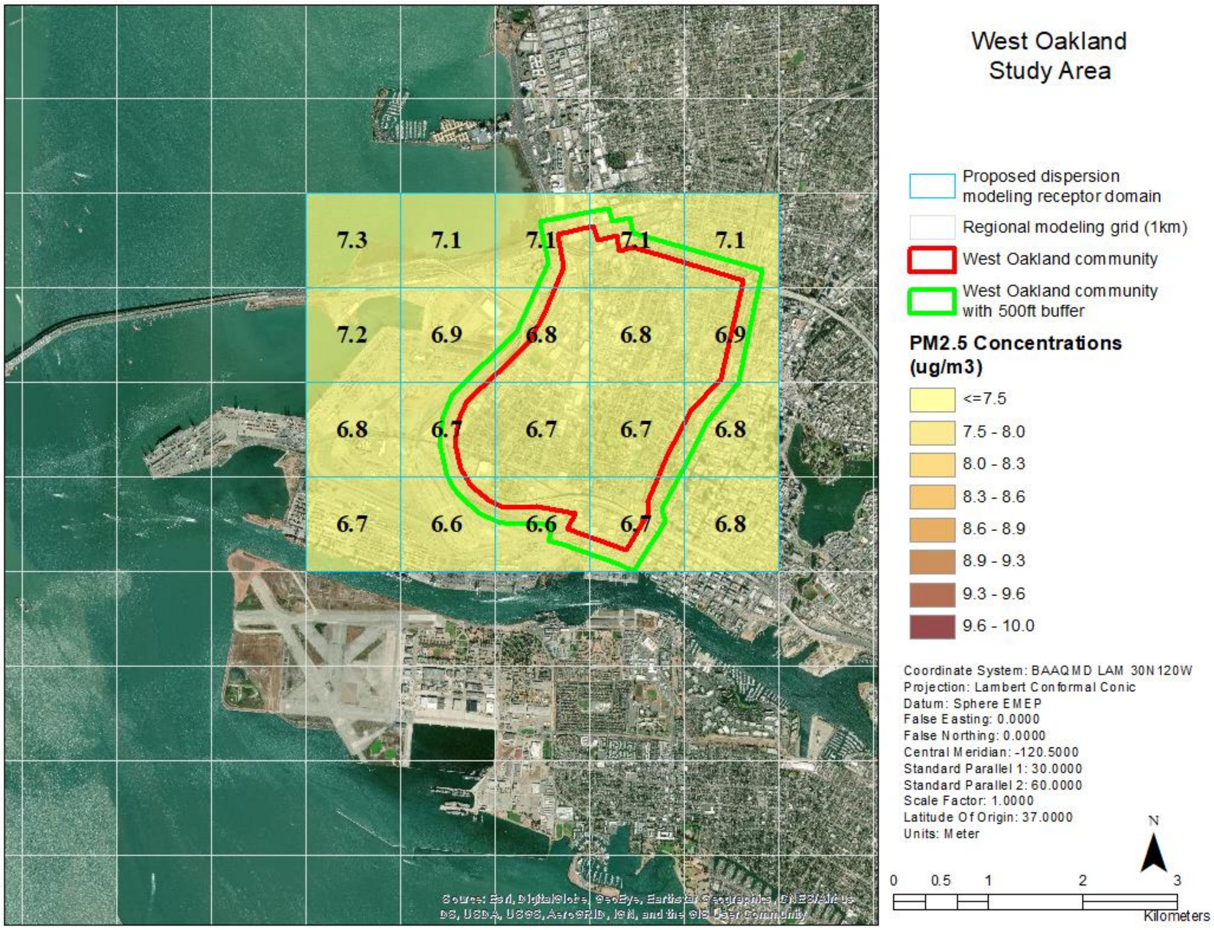


Figure E5: Spatial distribution of the simulated $PM_{2.5}$ concentrations without West Oakland's anthropogenic emissions.

Figure E6 shows the difference between the base and control cases. Based on the figure, the Chinatown area would benefit the most (2.5 µg/m^3) from zeroing out all anthropogenic emissions in the West Oakland local-scale domain. The West Oakland community (within the red border) would benefit by $PM_{2.5}$ reductions ranging from 0.8 µg/m^3 to 1.7 µg/m^3. The southwest corner of the modeling domain would be the least benefitted area, with a reduction of about 0.5 µg/m^3.

Note that these $PM_{2.5}$ concentrations and reductions represent the average value across a 1x1 km grid cell. Higher concentrations and reductions are possible at the sub-grid cell level, and these finer-scale gradients will be investigated with the local-scale AERMOD modeling.

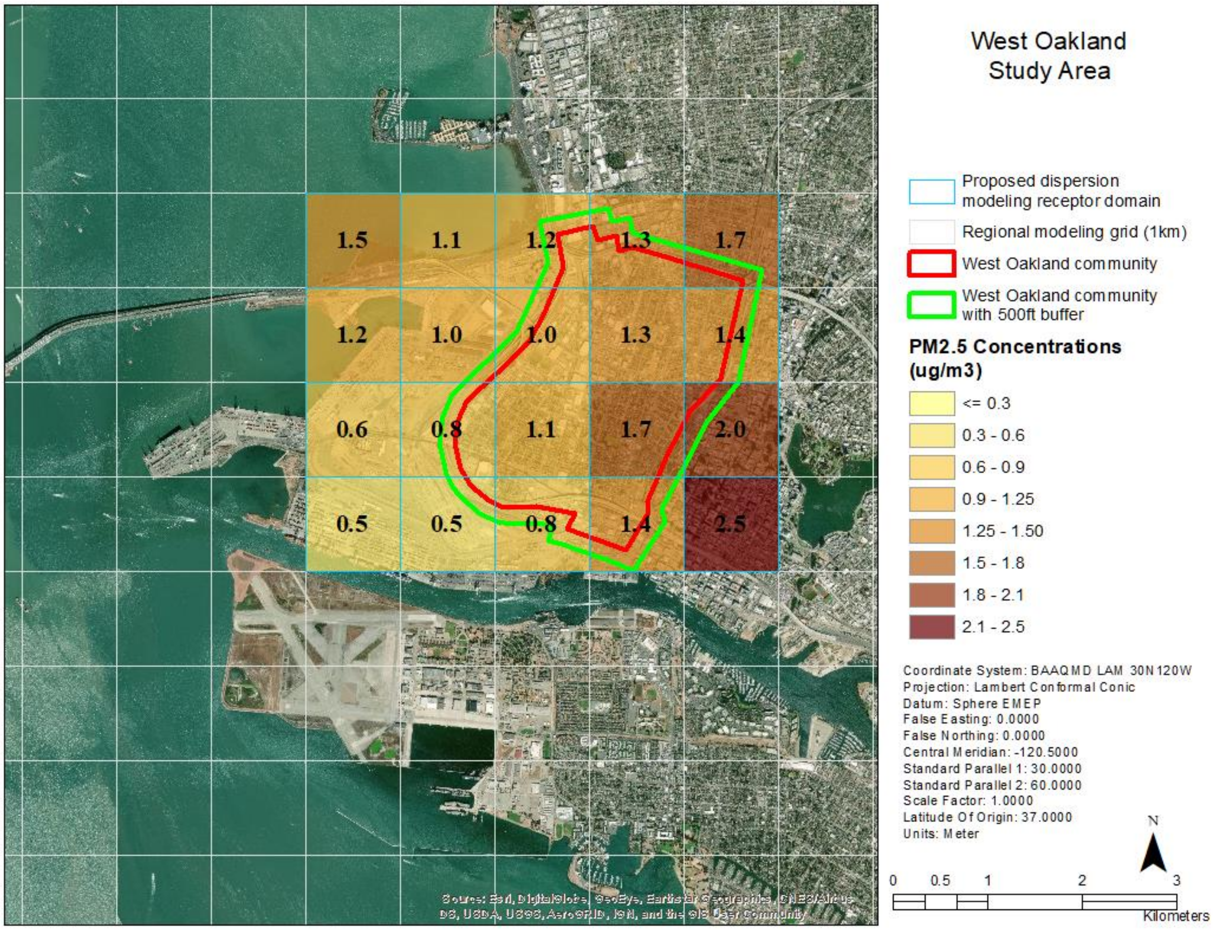
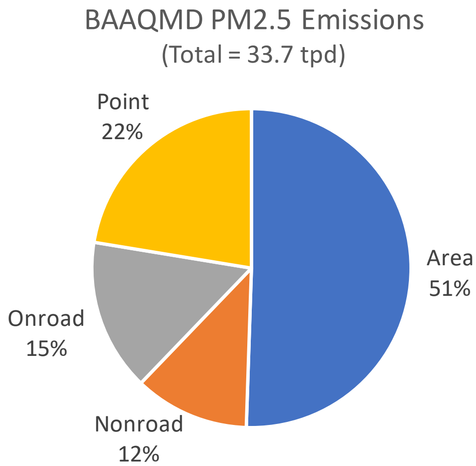


Figure E6: Difference between the simulated annual average base and control case $PM_{2.5}$ concentrations.

E3. Discussion

West Oakland is a unique area in terms of its geographic location, emissions, meteorology and air quality. In the West Oakland local-scale domain, annual average $PM_{2.5}$ emissions are 0.35 tons per day (tpd), about 1% of the Bay Area total. Onroad and nonroad mobile sources account for 66% of total $PM_{2.5}$ emissions. Area sources account for 24% of total $PM_{2.5}$ emissions, a significantly smaller percentage compared to the Bay Area total $PM_{2.5}$ emissions (Figure E7).

West Oakland is also impacted by pollutant transport from outside sources for all seasons. During spring, summer and fall, prevailing winds from the west, northwest and, to a lesser degree, from the southwest transport pollutants from downtown San Francisco, the San Francisco Peninsula, and shipping emissions from the Pacific Ocean and the Bay. During winter, occasional easterly airflow transports polluted air from the Central Valley through the Delta. West Oakland is also open for sea salt intrusion, which mostly occurs during spring, and the transport of wildfire emissions from the Sierras, other northern California locations and state of Oregon during the wildfire season. Transport to West Oakland from southern California, neighboring counties and intercontinental transport are also possible.[1]



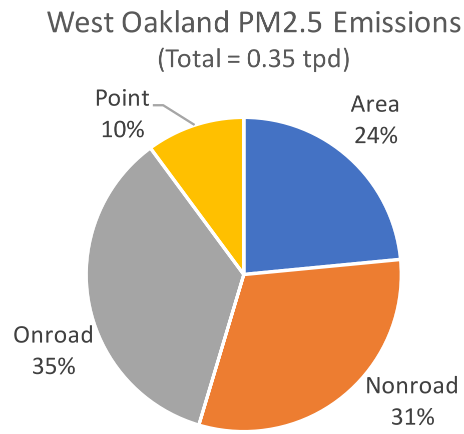


Figure E7: $PM_{2.5}$ emissions by source sector for the District (left) and West Oakland (right).

February, September and December usually exhibit the highest $PM_{2.5}$ concentrations in West Oakland (Figure E8). PM is elevated in February because of the contribution of wood burning emissions, secondary PM formation and near stagnant atmospheric conditions. Elevated PM in September is mainly influenced by wildfire emissions. In December, PM levels are significantly influenced by wood burning and cooking, which generally increases during the holidays, and relatively calm and foggy atmospheric conditions.

The remaining months exhibit PM levels around 8 $\mu g/m^3$, except July, August and October. The strong afternoon seabreeze in July and August lowers concentrations through atmospheric mixing, while October is a month with relatively low wind speeds and highly variable wind directions. The usual transport from nearby sources are not dominant during this month.

The CMAQ model is generally able to replicate the month-to-month variation in observed $PM_{2.5}$ concentrations in West Oakland (Figure E8). The model slightly overestimates PM during winter months and underestimates PM during summer months, a pattern that is typical of the CMAQ modeling system. The somewhat significant underestimation in September is likely due to lack of wildfire emissions in the CMAQ simulations.

[1] Note that this analysis did not seek to quantify the impact of various sources of transported pollution on West Oakland. Rather, to be consistent with AB617 goals, the focus was on the impact of local emissions.

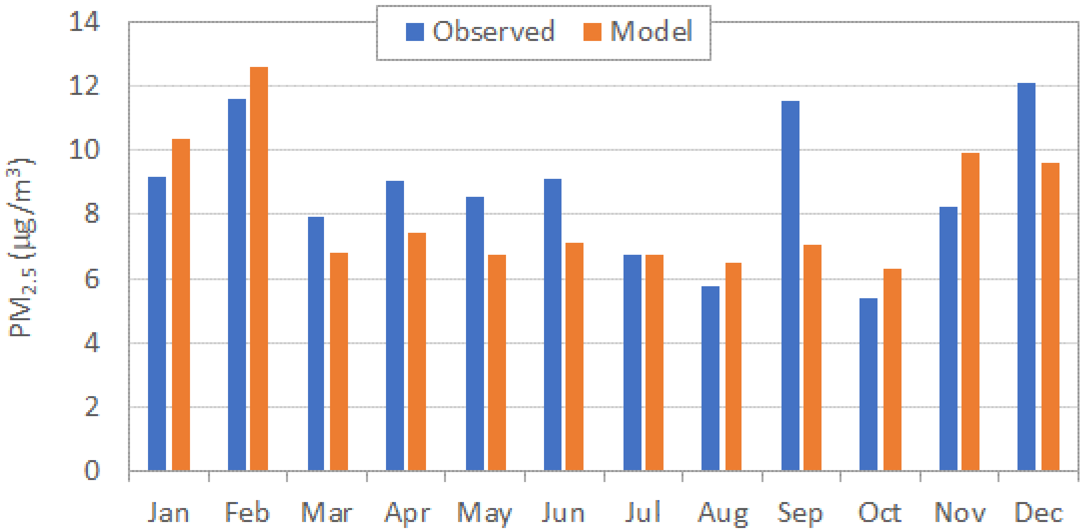


Figure E8: Monthly average simulated and observed $PM_{2.5}$ concentrations in West Oakland.

Fine Particulate Matter Data Analysis and Regional Modeling in the San Francisco Bay Area to Support AB617

1. Introduction

The adoption of Assembly Bill 617 (AB617) established collaborative programs to reduce community exposure to air pollutants in neighborhoods most impacted by air pollution. Air District staff have been working closely with the California Air Resources Board (ARB), other local air districts, community groups, community members, environmental organizations, regulated industries, and other key stakeholders to reduce harmful air pollutants in Bay Area communities.

The purpose of this data analysis and regional modeling effort is to support the District's AB617 activities by assessing pollutant formation, quantifying the relative contribution of emission sources to ambient pollution levels, and assessing population exposures and the benefits of emission controls in impacted communities around the Bay Area. Our initial assessments focus on fine particulate matter ($PM_{2.5}$) concentrations in West Oakland, and follow-up analyses will include air toxics evaluations in West Oakland and expansion of our technical assessments to other communities.

For the $PM_{2.5}$ analyses, we evaluated ambient meteorological and air quality data, and applied the U.S. EPA's Community Multi-Scale Air Quality (CMAQ) model to simulate pollutant concentrations at a 1-km horizontal resolution over the entire Bay Area for 2016 (Figure 1.1). Then we repeated the simulation with West Oakland's anthropogenic emissions removed from the modeling inventory, leaving all other model input parameters unchanged. We calculated annual average $PM_{2.5}$ concentrations using the output of each simulation. The first simulation provided the annual average $PM_{2.5}$ concentrations for 2016 over the entire Bay Area, which will be used for $PM_{2.5}$ exposure analyses and health impacts assessments. The second simulation provided an estimate of background $PM_{2.5}$ levels in West Oakland (i.e., the $PM_{2.5}$ concentrations that would exist in the absence of local West Oakland sources).

Background $PM_{2.5}$ concentrations will be combined with local-scale modeling of West Oakland sources using the AERMOD dispersion model to provide a complete picture of $PM_{2.5}$ levels in the community and the relative contribution of different emission sources to those levels. Figure 1.2 shows the AERMOD modeling domain for West Oakland. The area outlined in blue represents the "source domain," and all significant emissions sources in that area will be modeled in the AERMOD simulations. The red hatched area represents the "receptor domain," or the area for which pollutant concentrations will be calculated by AERMOD.

The application of the CMAQ model involves the preparation of meteorological and emissions inputs, model runs, analysis of simulated pollutant concentrations, and the evaluation of model performance via comparison between simulated and observed pollutant concentrations. A simulation year of 2016 was selected because (1) this is a recent year that is likely to be representative of current conditions in West Oakland and other communities; and (2) special measurement studies that took place in 2016 provide additional ambient data to support evaluations of model performance.

District staff have been applying and evaluating the CMAQ model in the Bay Area over the last several years, along with the Weather Research and Forecasting (WRF) model, which provides meteorological inputs for CMAQ. Findings from previous modeling work are documented in a District report on $PM_{2.5}$ data analysis and modeling (Tanrikulu et al., 2009) and in the District's 2017 Clean Air Plan (BAAQMD, 2017). Both the CMAQ and WRF models were tested and evaluated for many cases in the Bay Area and their performance has been iteratively improved. The 2016 simulations used the best-performing configuration of the model. The 2016 emissions inputs have been updated to reflect ARB's most recent estimates and have been evaluated to the extent possible.

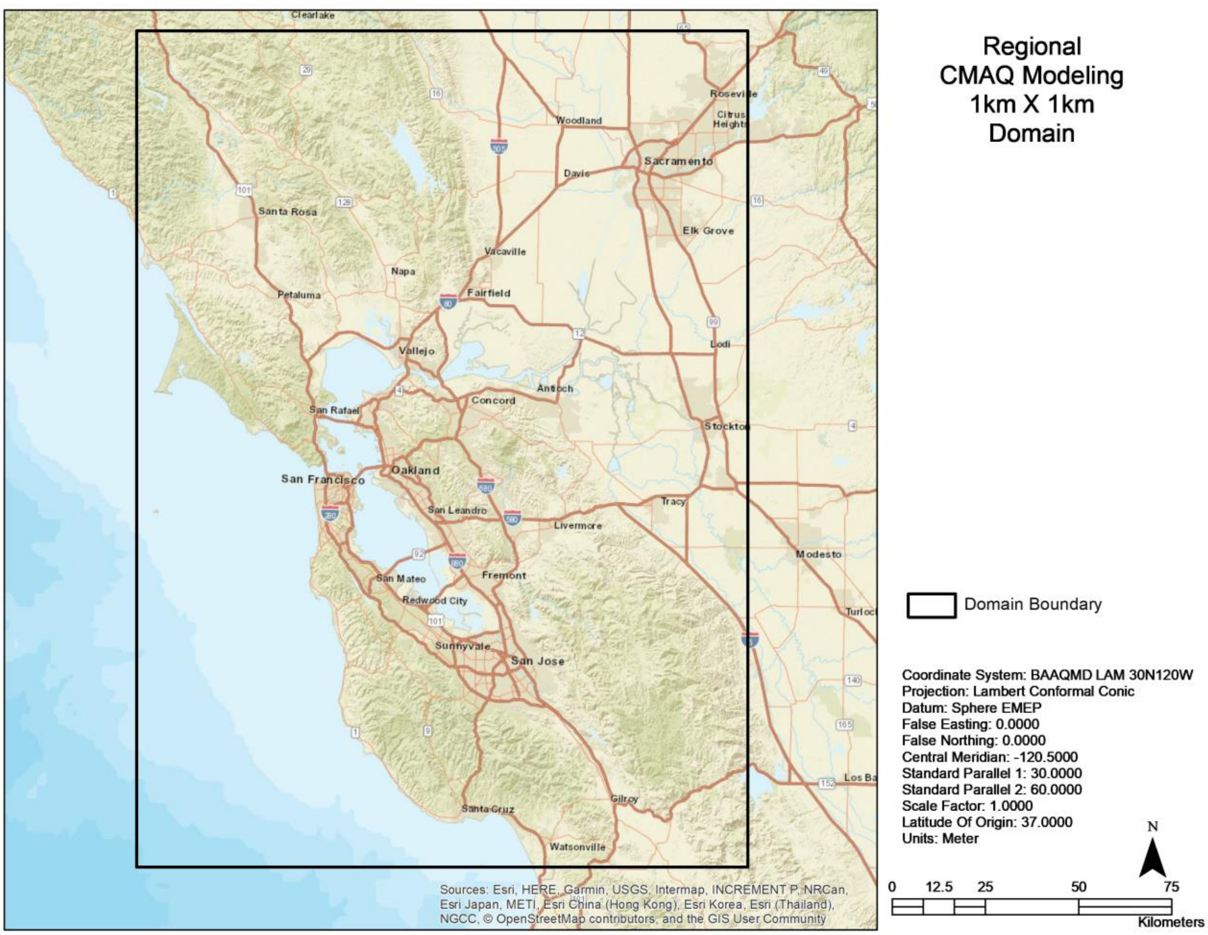


Figure 1.1: The regional 1-km modeling domain used for CMAQ simulations.

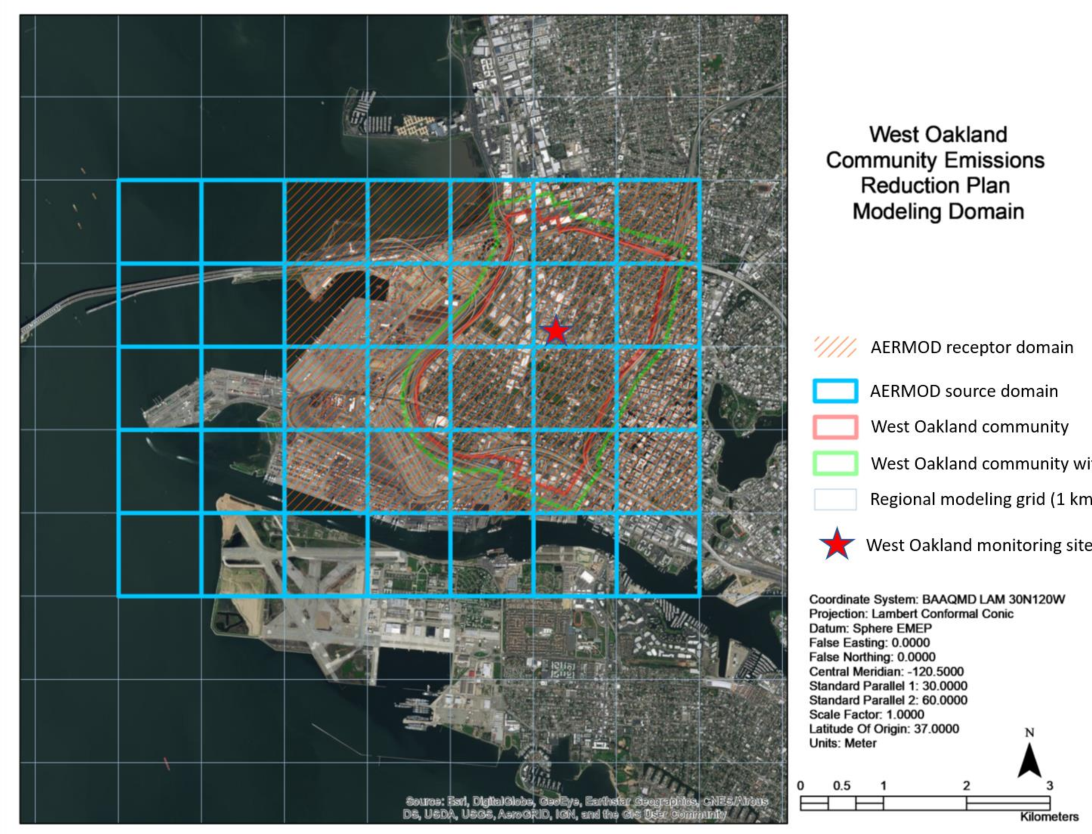


Figure 1.2: The West Oakland AERMOD modeling domain. The area outlined in blue represents the AERMOD source domain, and the red hatched area represents the AERMOD receptor domain.

1.1 $PM_{2.5}$ and Its Health Impacts

$PM_{2.5}$ is a complex mixture of suspended particles and liquid droplets in the atmosphere that have an aerodynamic diameter of 2.5 microns (µm) or less. An individual particle typically begins as a core or nucleus of carbonaceous material, often containing trace metals. These *primary* (directly emitted) particles usually originate from the incomplete combustion of fossil fuels or biomass. Layers of organic and inorganic compounds then deposit onto a particle, causing it to grow in size. These layers are largely comprised of *secondary* material that is not emitted directly. Secondary PM instead forms from chemical reactions of precursor gases released from combustion, agricultural activities, household activities, industrial sources, vegetation, and other sources. As a particle grows larger, gravity eventually causes it to be deposited onto a surface. Naturally emitted dust particles generally have diameters too large to be classified as $PM_{2.5}$.

Major human health outcomes resulting from $PM_{2.5}$ exposure include: aggravation of asthma, bronchitis, and other respiratory problems, leading to increased hospital admissions; cardiovascular symptoms, including chronic hardening of arteries and acute triggering of heart attacks; and decreased life expectancy, potentially on the order of years. Smaller particles have increasingly more severe impacts on human health as compared to larger particles. This occurs in part because smaller particles can penetrate more deeply into the human body. For the Bay Area, public health impacts from $PM_{2.5}$ may well exceed the combined impacts of all other currently regulated air pollutants.

District staff have previously evaluated the health and monetary impacts of $PM_{2.5}$ concentrations in the Bay Area for 2010. Findings of this evaluation are documented in a report by Tanrikulu, et al. (2011).

1.2 Formation of $PM_{2.5}$ in the Bay Area

In the Bay Area, $PM_{2.5}$ concentrations can build up during winter months (December, January and February) under stable atmospheric conditions that trap pollutants near the ground. Winters with frequent stagnant periods tend to have a higher number of days with elevated $PM_{2.5}$ than winters with more periods of windy and stormy conditions. Consecutive stagnant, clear winter days are typically required for $PM_{2.5}$ episodes to develop. $PM_{2.5}$ episodes are regional in nature and impact most Bay Area locations.

The Chemical Mass Balance (CMB) model was previously applied for $PM_{2.5}$ source apportionment using specialized measurements mostly obtained during the years 1999-2014. CMB is a statistical receptor model that uses speciated $PM_{2.5}$ measurements to estimate the contribution of individual source categories to observed $PM_{2.5}$ levels. CMB analyses for the Bay Area showed that primary combustion sources (both fossil fuels and biomass) were the largest $PM_{2.5}$ contributors in all seasons. The biomass combustion contribution to peak $PM_{2.5}$ levels was about 2-4 times higher during winter than for other seasons. Secondary $PM_{2.5}$ levels were mostly elevated during the winter months, with ammonium nitrate being the key component of wintertime secondary $PM_{2.5}$. This semi-volatile $PM_{2.5}$ component is stable in its solid form during the cooler winter months. Secondary ammonium sulfate $PM_{2.5}$ levels were generally low ($< 1\text{-}2\ \mu g/m^3$) but non-negligible. Sea salt, geological dust, and tire and brake wear contributed minimally to $PM_{2.5}$ concentrations (Tanrikulu et al., 2009).

Meteorological cluster analysis, a data mining technique, was implemented to determine how weather patterns impact $PM_{2.5}$ levels. Clustering was applied to measurements from every winter day across more than 10 years. This method provided a robust representation of how prevailing weather conditions affected the development of $PM_{2.5}$ episodes. Such episodes generally developed under: stable atmospheric conditions inhibiting vertical dispersion; clear and sunny skies favoring enhanced secondary $PM_{2.5}$ formation; and pronounced overnight drainage (downslope) flows off the Central Valley rims, causing low-level air in the Central Valley to empty through the Delta and into the Bay Area along its eastern boundary. Atmospheric transitions of aloft weather systems profoundly influenced the surface winds that determine $PM_{2.5}$ levels. Surface conditions stagnated whenever an upper-level high pressure system moved over Central California. Persisting high pressure conditions allowed $PM_{2.5}$ buildup, and Bay Area 24-hour elevated $PM_{2.5}$ generally occurred after 2-4 days.

A refined cluster analysis further characterized the upwind Central Valley conditions during Bay Area episodes. Two distinct inter-regional air flow patterns were associated with different types of Bay Area episodes. Most elevated PM days were associated with winds from the Sacramento Valley to the northeast entering the Bay Area through the Delta. Peak $PM_{2.5}$ levels typically occurred along the Delta and at San Jose for this type of episode. A minority of elevated PM days were associated with winds from the San Joaquin Valley from the southeast entering the Bay Area through the Delta. Peak $PM_{2.5}$ levels typically occurred along the Delta and in the East Bay (at Livermore, Concord, Vallejo or San Rafael, and to a lesser degree at Oakland and San Francisco) for this type of episode. The remaining relatively moderate episodes could not be associated with any distinct inter-regional transport pattern linking the Bay Area and surrounding air basins.

2. Observations and Data Analysis

2.1 Ambient Measurements

Both meteorological and air quality data have been continuously collected in the Bay Area and surrounding regions for many years. In 2016, there were twenty-six PM monitoring stations within the 1-km modeling domain - sixteen in the Bay Area and ten outside the region. Table 2.1 lists PM monitoring stations used in this study with their annual and quarterly average $PM_{2.5}$ values. Figure 2.1 shows the spatial distribution of monitored annual average $PM_{2.5}$ concentrations for 2016. A complete list of monitoring stations, types of measurements, and the purpose of their use in this study is provided in Appendix A. The air quality monitoring network plan published by BAAQMD (Knoderer et al., 2017) provides additional details on the District's monitoring network.

All ambient data used in this study were subjected to quality assurance checks and validated prior to being used. These data were used for the development of a conceptual model of PM formation in the region, establishment of relationships among emissions, meteorology and air quality, evaluation of models, and four-dimensional data assimilation (FDDA), in which meteorological observations are used by the meteorological model to "nudge" simulations toward observations.

Hourly average data are used for most analyses and model evaluation, but monthly, quarterly or annual averages are presented here for brevity.

2.2 Data Analysis

In 2016, the annual average $PM_{2.5}$ concentrations (Table 2.1) at two Bay Area air monitoring stations (Sebastopol and Gilroy) were between 5 $\mu g/m^3$ and 6 $\mu g/m^3$. These two sites captured the lowest $PM_{2.5}$ levels in the Bay Area. At three other air monitoring stations (Concord, Oakland and San Rafael), $PM_{2.5}$ concentrations were between 6 $\mu g/m^3$ and 7 $\mu g/m^3$, and at four other stations (Berkeley Aquatic Park, Livermore, San Francisco and Vallejo), they were between 7 $\mu g/m^3$ and 8 $\mu g/m^3$. At the remaining seven stations (Napa, San Pablo, Laney College, Oakland West, Redwood City, San Jose - Jackson and San Jose - Knox Avenue), $PM_{2.5}$ levels were above 8 $\mu g/m^3$. San Jose - Knox Avenue had the highest Bay Area annual average $PM_{2.5}$ concentration (9.2 $\mu g/m^3$).

Outside of Napa, the stations with annual average $PM_{2.5}$ concentrations above 8 $\mu g/m^3$ extend from the north Bay to the south Bay. Previous analyses showed that $PM_{2.5}$ levels at these locations were influenced by local sources and the transport of pollutants from the Central Valley. Elevated concentrations at Napa are mostly due to local residential wood burning and the transport of PM from both residential wood burning and wildfire emissions.

While $PM_{2.5}$ levels at several Bay Area stations, such as Laney College, West Oakland and Livermore, showed little change from one quarter to another, another set of stations (including Napa, Vallejo and San Francisco) had significant differences between quarters (Table 2.1). These stations are impacted by transport and seasonal changes in meteorology and/or emissions, such as wood burning.

Table 2.1: PM stations in the 1-km modeling domain with their annual and quarterly average $PM_{2.5}$ values.

Station Name	**$PM_{2.5}$ Averages ($\mu g/m^3$) for 2016**				
Stations in the Bay Area	**ANNUAL**	**QTR_01**	**QTR_02**	**QTR_03**	**QTR_04**
Berkeley Aquatic Park	7.2	--[a]	--[a]	7.7	6.6
Concord	6.2	6.0	4.3	4.6	9.4
Gilroy	5.7	5.9	6.1	6.8	4.1
Laney College	8.8	8.9	9.4	8.7	8.1
Livermore	7.6	7.4	7.2	8.4	7.3
Napa	8.9	6.5	7.2	10.4	11.1
Oakland	6.2	5.2	5.9	6.4	7.2
Oakland West	8.7	9.6	8.9	7.6	8.6
Redwood City	8.7	6.8	10.3	10.6	6.7
San Francisco	7.8	8.5	8.1	5.9	8.4
San Jose - Jackson	8.3	8.0	8.0	8.8	8.4
San Jose - Knox Avenue	9.2	9.0	8.6	9.9	9.2
San Pablo	8.1	7.6	8.9	7.8	8.2
San Rafael	6.6	7.0	6.1	5.9	7.1
Sebastopol	5.1	4.9	4.6	4.0	6.5
Vallejo	7.6	8.4	5.6	6.0	10.2
Stations outside the Bay Area					
Manteca	9.9	10.8	7.5	8.8	12.3
San Lorenzo Valley Middle School	5.3	5.4	5.2	4.7	5.8
Roseville - N Sunrise Ave	6.8	6.7	5.7	6.7	8.3
Sacramento Health Department - Stockton Blvd.	6.9	7.8	5.7	6.6	8.3
Sacramento - 1309 T Street	7.6	7.2	5.6	7.1	10.9
Sacramento - Bercut Drive	--[a]	--[a]	--[a]	--[a]	14.6
Sacramento - Del Paso Manor	8.7	8.6	6.1	7.2	13.2
Santa Cruz	5.4	5.8	5.9	5.3	4.5
Stockton - Hazelton	11.8	13.9	8.2	10.0	15.2
Woodland - Gibson Road	6.3	5.2	5.4	8.1	6.9

[a]Data missing or invalidated.