# The future of urban air

## Clean air and climate protection



**Ronald C. Cohen**
**UC Berkeley**

**$ UC Berkeley, Koret Foundation**

# The future of urban air

**Clean air and climate protection require reducing emissions of chemicals into our atmosphere.**

# The future of urban air

Knowing that we are reducing emissions of chemicals into our atmosphere in the way we intend requires a sophisticated system of tools:

## Predictions/hypotheses

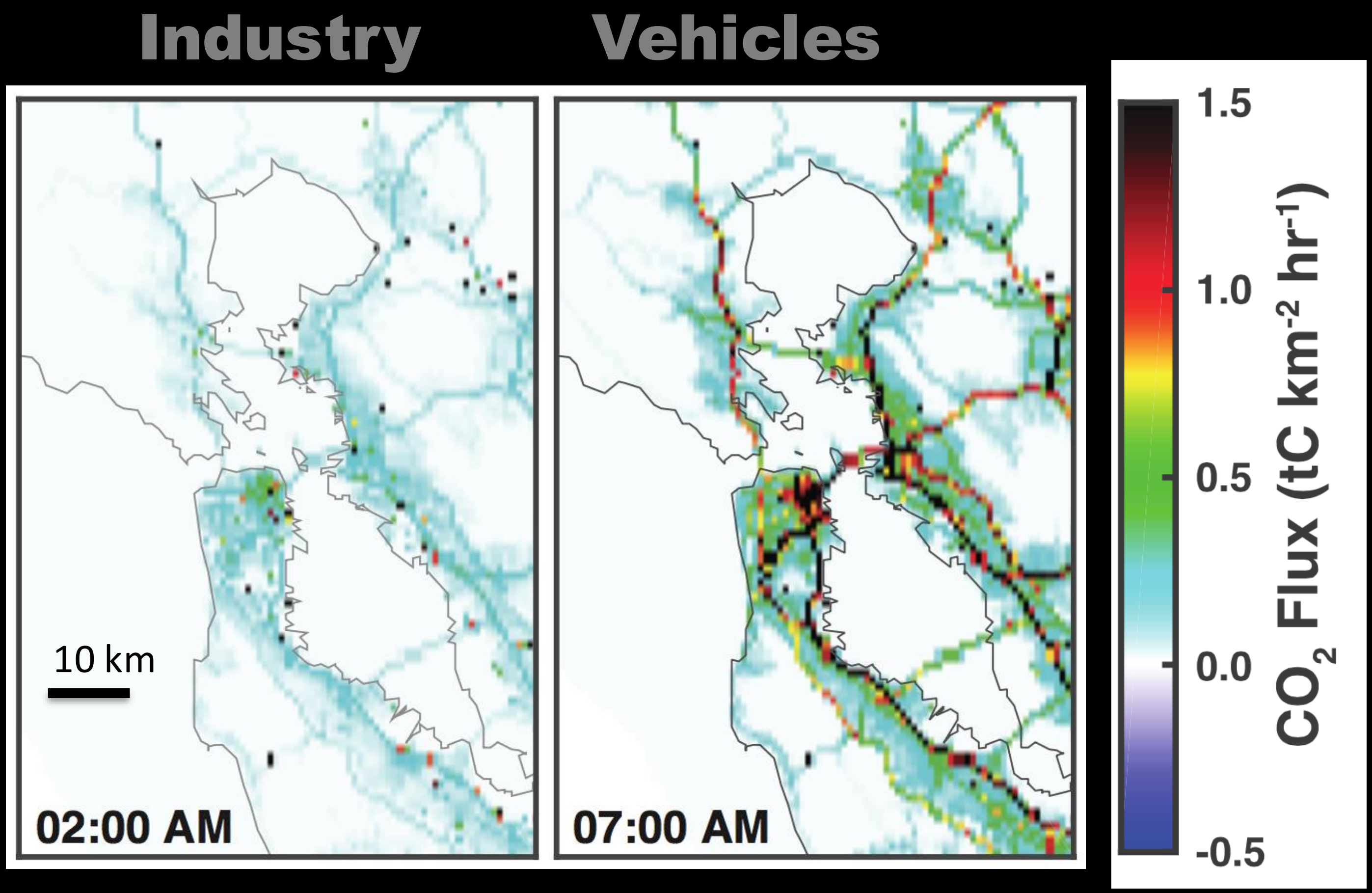
- economic and social data
- weather models with chemistry

## Tests

- observations of the atmosphere
- strategies for synthesis of available information

# The future of urban air

- economic and social data




Turner et al., ACP 2016

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- weather models with chemistry


$CO_2$ concentration, 1 km grid; 3 days

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## Tests

Lots of different ways we might observe the atmosphere and test the hypothesis.

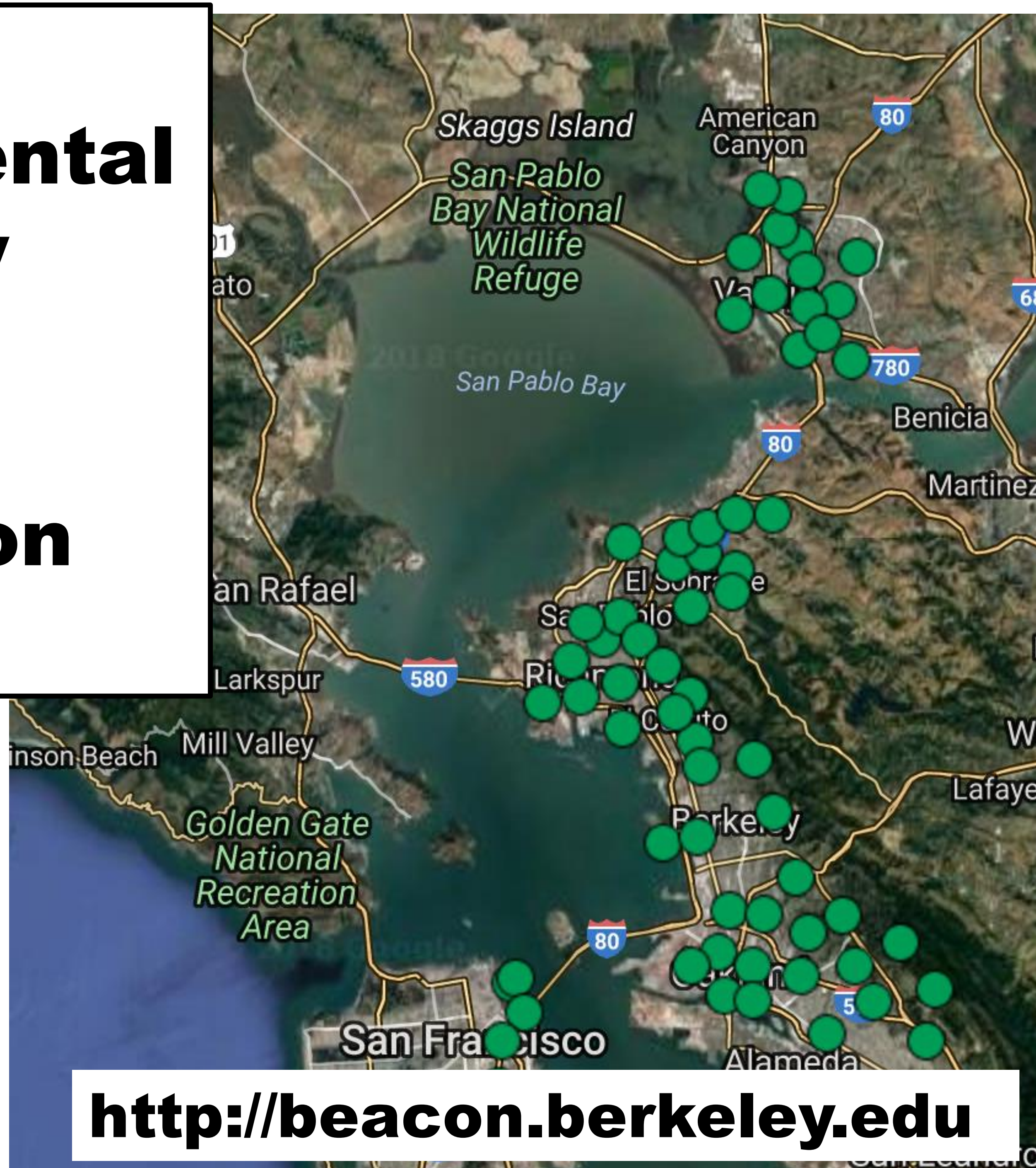
Average over time and space
- e.g. total annual emissions from a city

Separate by activity
- e.g. vehicles, industry, home heating, ...

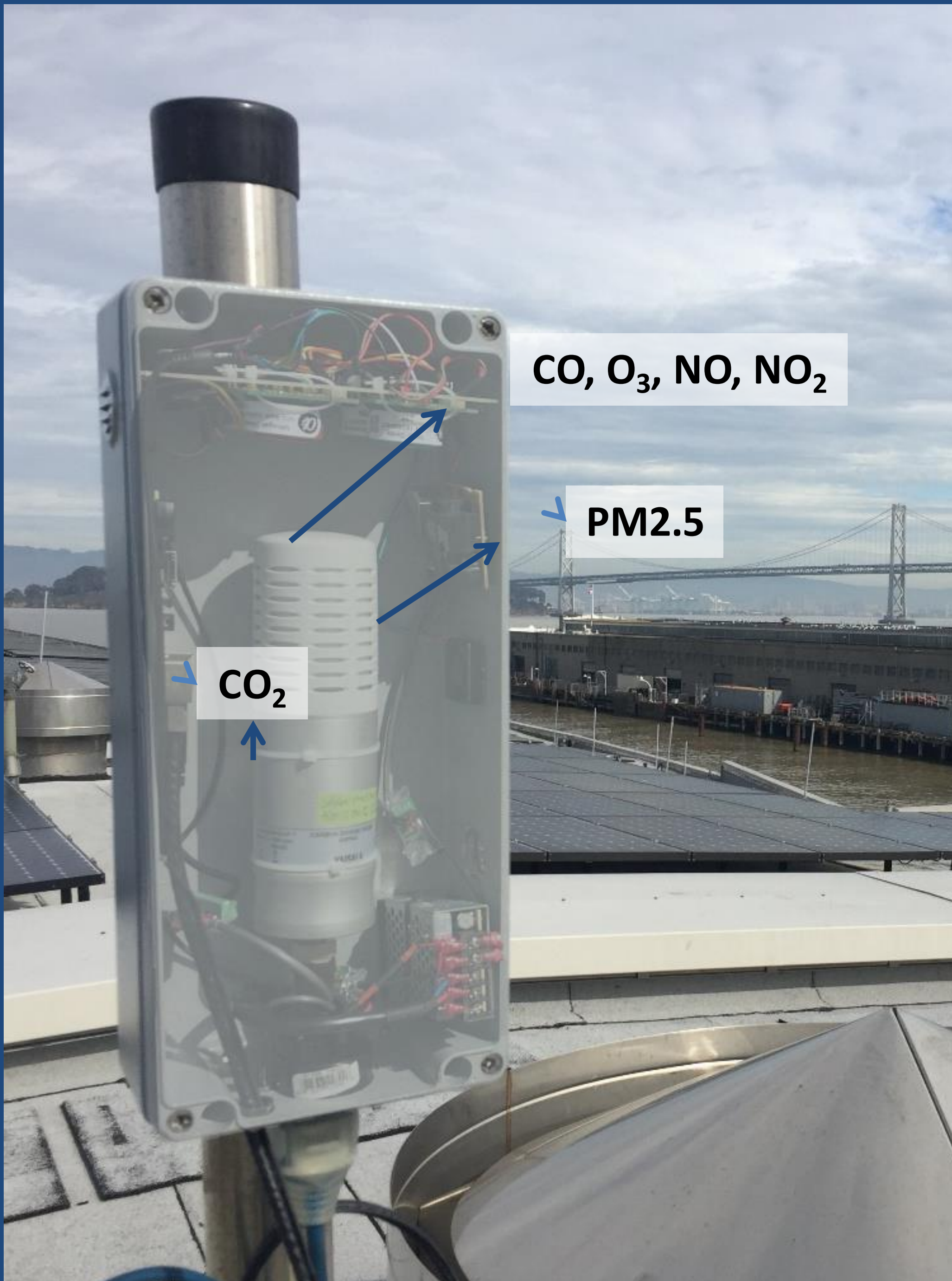
Maximum necessary space and time resolution
- e.g. ~1km and 1 hr

**Hypothesis: Dense networks of medium quality observations can be more cost effective and give more insight than a smaller number of state-of-the-art observations**

**B**erkeley
**E**nvironmental
**A**ir Quality
and
$CO_2$
**O**bservation
**N**etwork




http://beacon.berkeley.edu

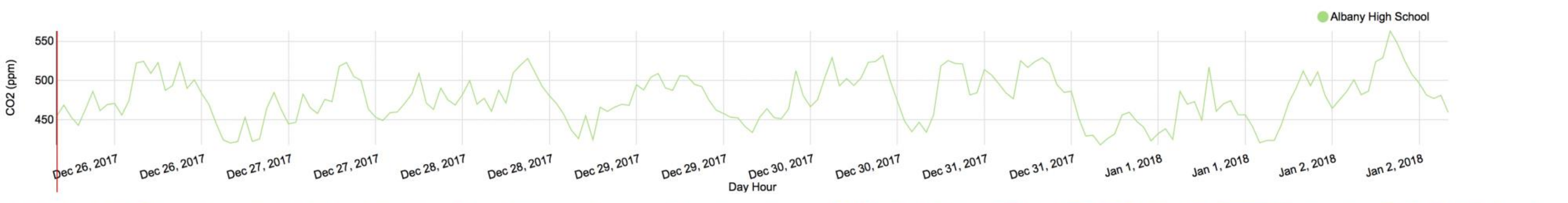



# Measure $NO_2$, NO, $O_3$, CO, $CO_2$, particles

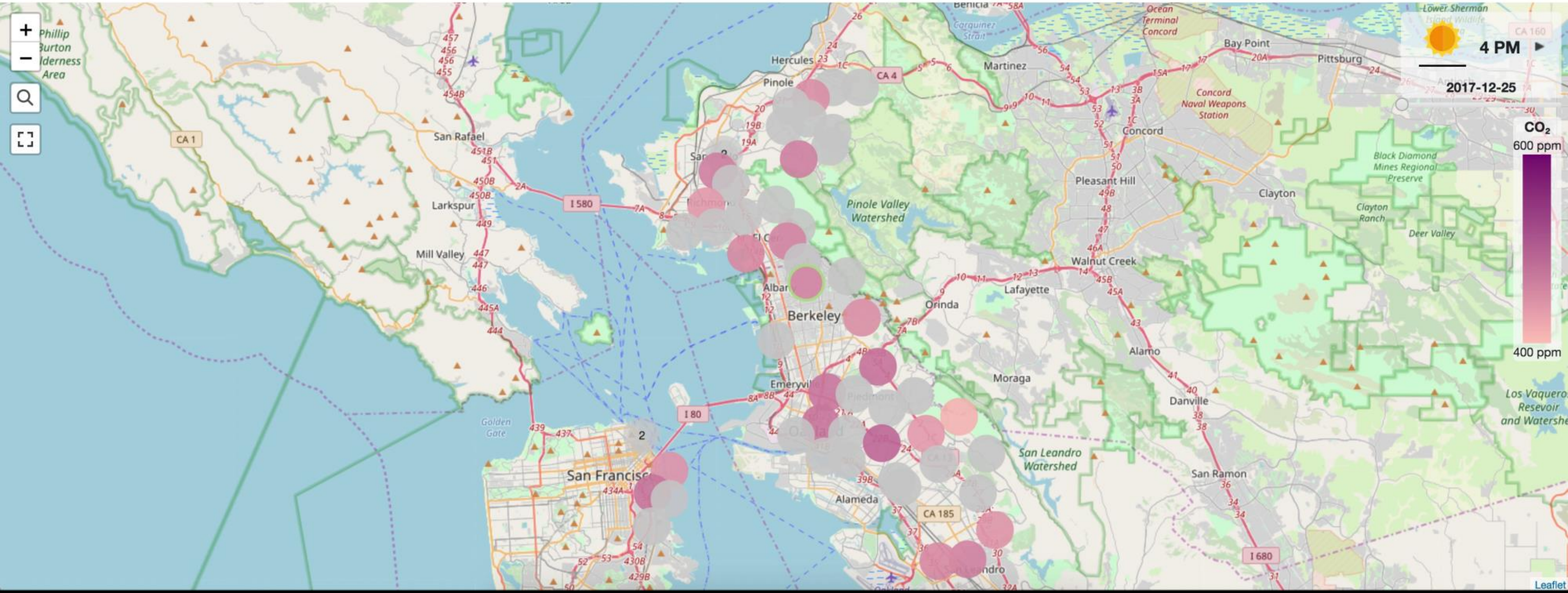
# Low cost: $6000/node

A.A. Shusterman, et al., Atmos. Chem. Phys., 2016

# $CO_2$

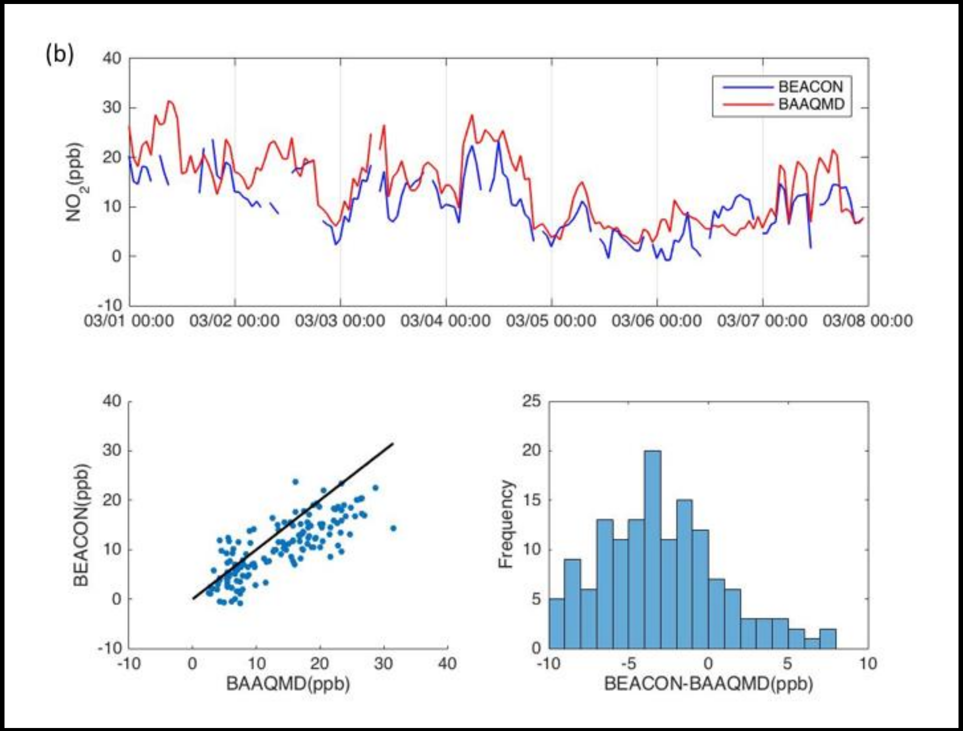


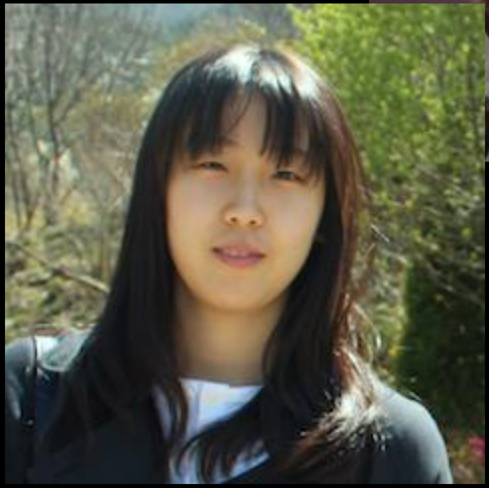
Albany High School
CO2 (ppm)
550
500
450
Dec 26, 2017
Dec 26, 2017
Dec 27, 2017
Dec 27, 2017
Dec 28, 2017
Dec 28, 2017
Dec 29, 2017
Dec 29, 2017
Dec 30, 2017
Dec 30, 2017
Dec 31, 2017
Dec 31, 2017
Jan 1, 2018
Jan 1, 2018
Jan 2, 2018
Jan 2, 2018
Day Hour

4 PM
2017-12-25
CO2
600 ppm
400 ppm
San Francisco
Berkeley
Oakland
Alameda
Emeryville
Richmond
Albany
Hercules
Pinole
Martinez
Concord
Pleasant Hill
Walnut Creek
Lafayette
Orinda
Moraga
Alamo
Danville
San Ramon
Clayton
Pittsburg
Bay Point
San Rafael
Larkspur
Mill Valley
Leaflet

# Calibrating sensors in <u>many</u> locations without gas standards, reference material, …



**A.A. Shusterman, et al.** ***The BErkeley Atmospheric $CO_2$ Observation Network: initial evaluation***, **Atmos. Chem. Phys., 2016.**

**J. Kim, et al.** ***The BErkeley Atmospheric $CO_2$ Observation Network: field calibration and evaluation of low-cost air quality sensors***, **Atmos. Meas. Tech., 2018.**

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## Example

**How much did $CO_2$ emissions drop in the early phase of the COVID-19 shelter-in-place and why?**

Turner et al., submitted 2020

# Systematic mathematical inversion

1) map every observation to the family of locations where the $CO_2$ emissions originated

2) weight by estimate of combined model and observation uncertainty

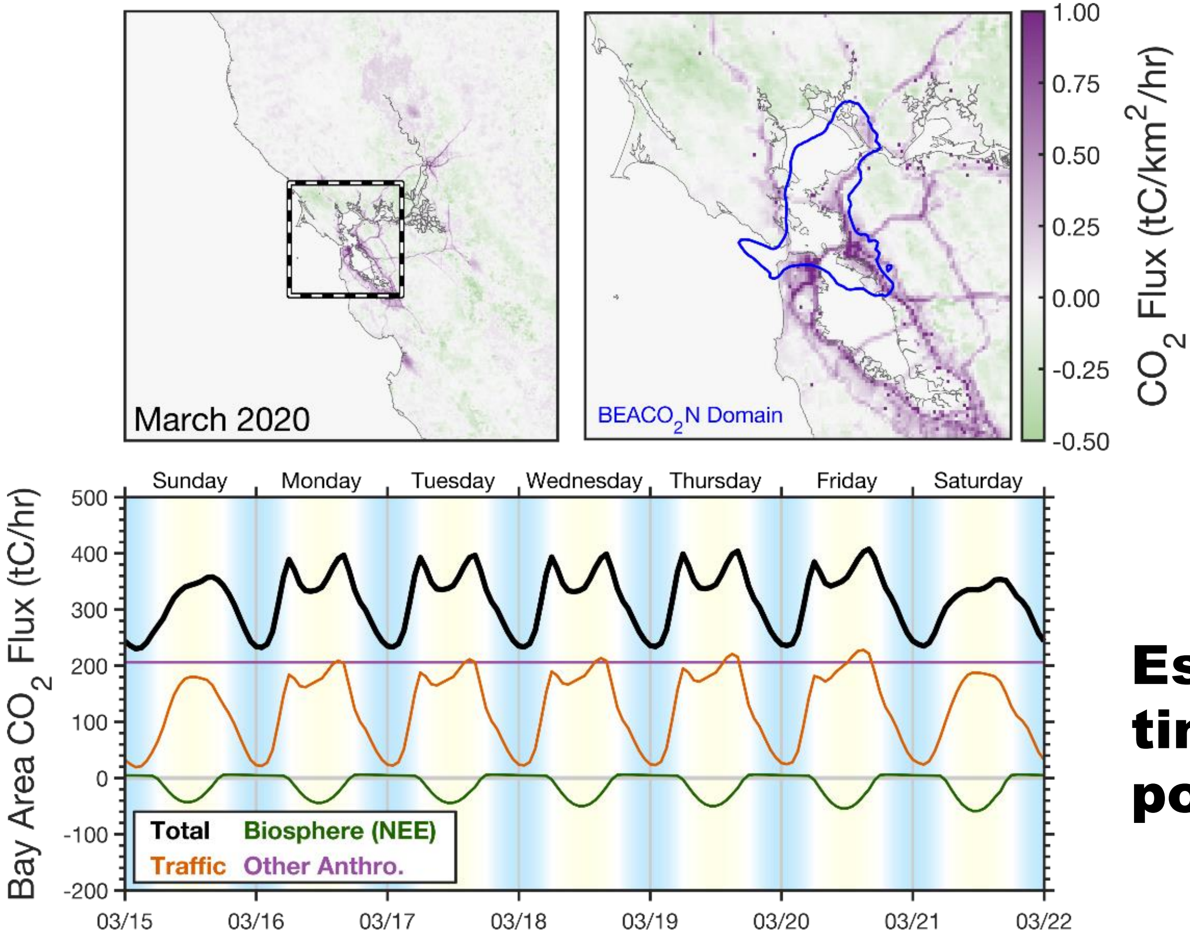
3) maintain physically reasonable solution by imposing correlations in space and time

4) adjust emissions to obtain best predictions of observations from network

Turner et al., submitted 2020

# Initial estimate of emissions adjusted by observations

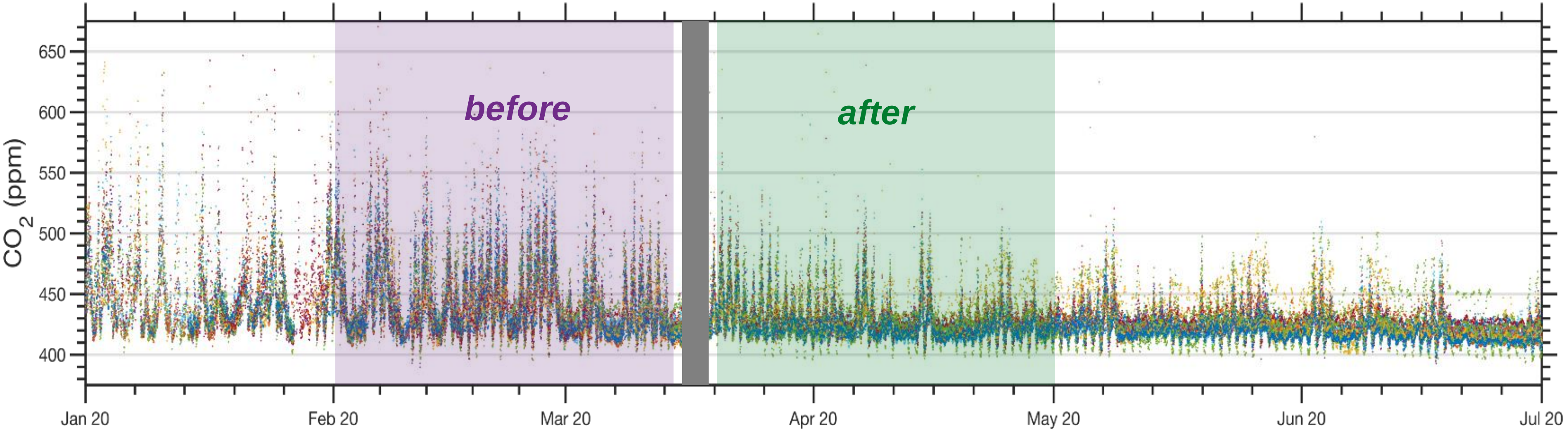
$$\hat{\mathbf{x}} = \underline{\mathbf{x_a}} + (\mathbf{HB})^T \left(\mathbf{HBH}^T + \mathbf{R}\right)^{-1} (\mathbf{y} - \mathbf{H}\underline{\mathbf{x_a}})$$

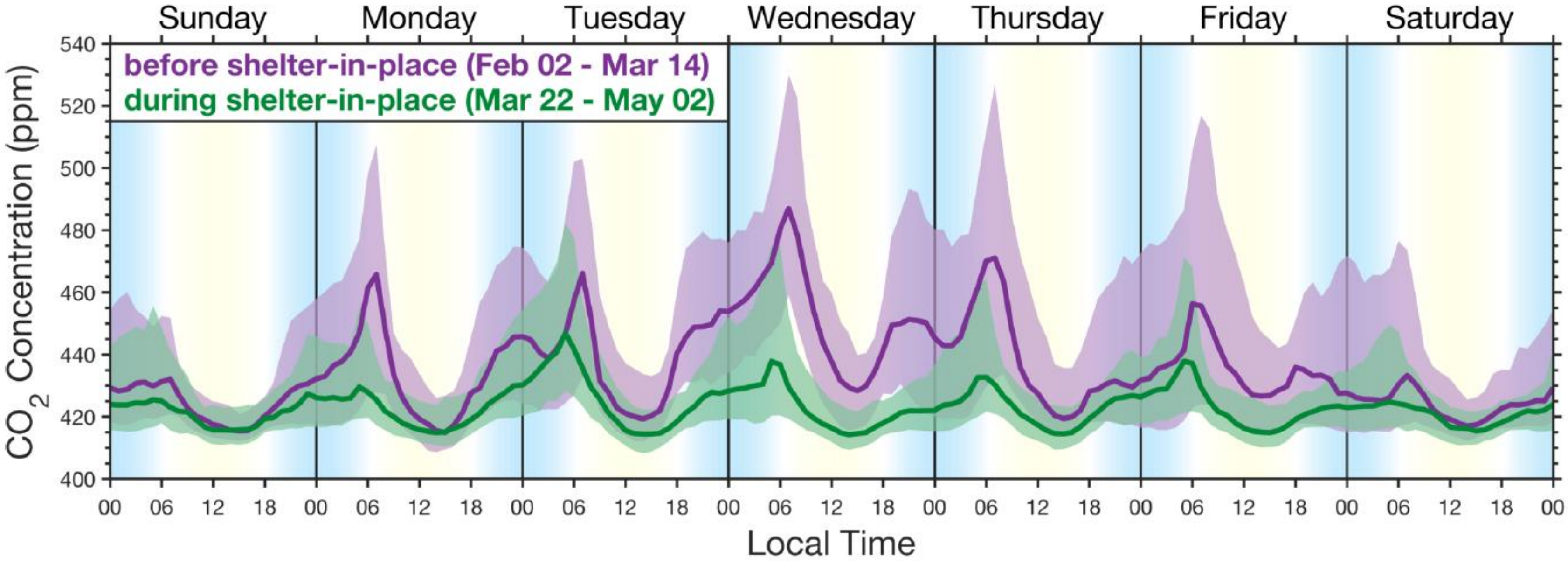



**Estimated space and time variation at every point**

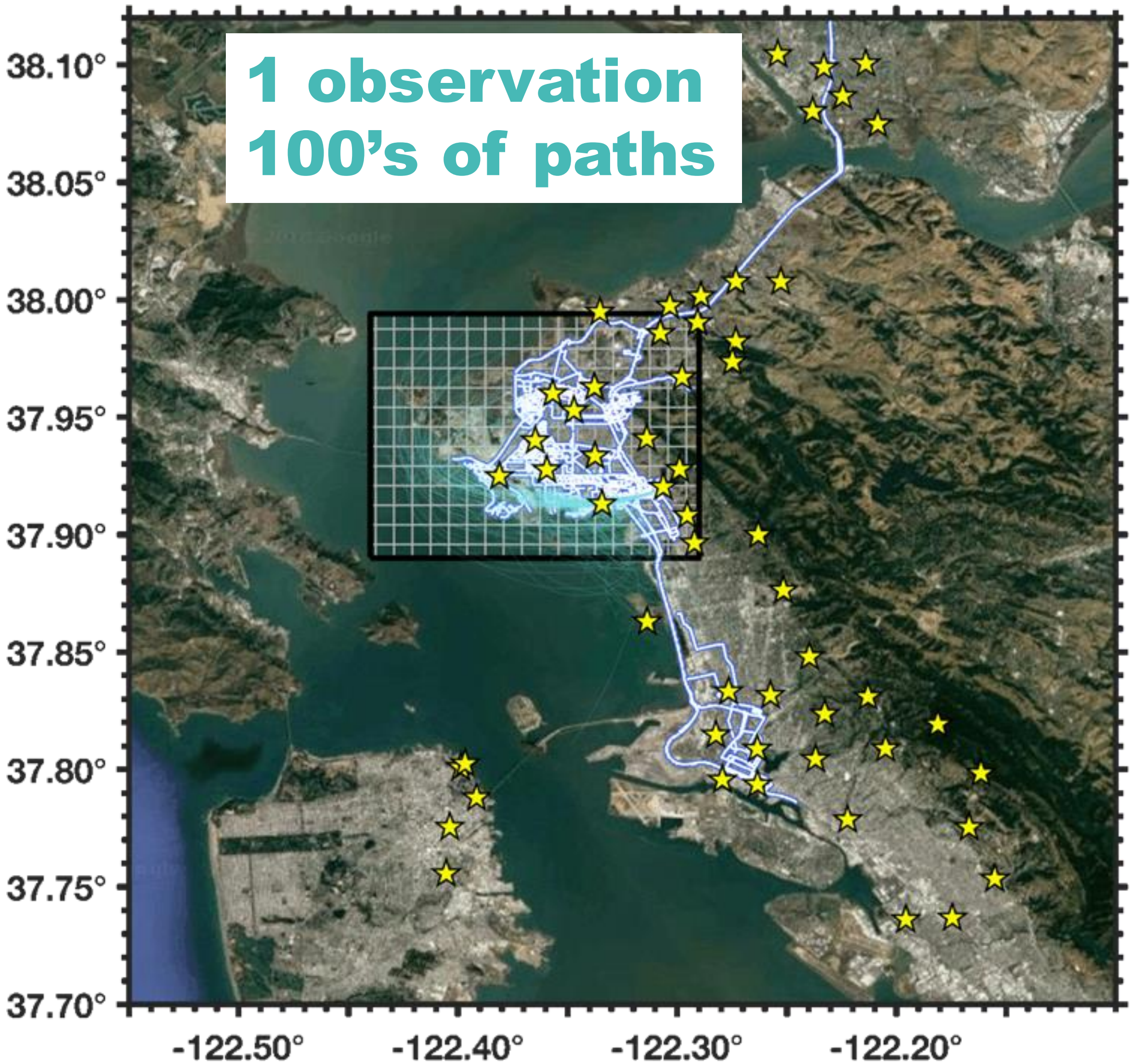
# BEACO$_2$N observations

$$\hat{\mathbf{x}} = \mathbf{x_a} + (\mathbf{HB})^T \left(\mathbf{HBH}^T + \mathbf{R}\right)^{-1} (\underline{\mathbf{y}} - \mathbf{Hx_a})$$



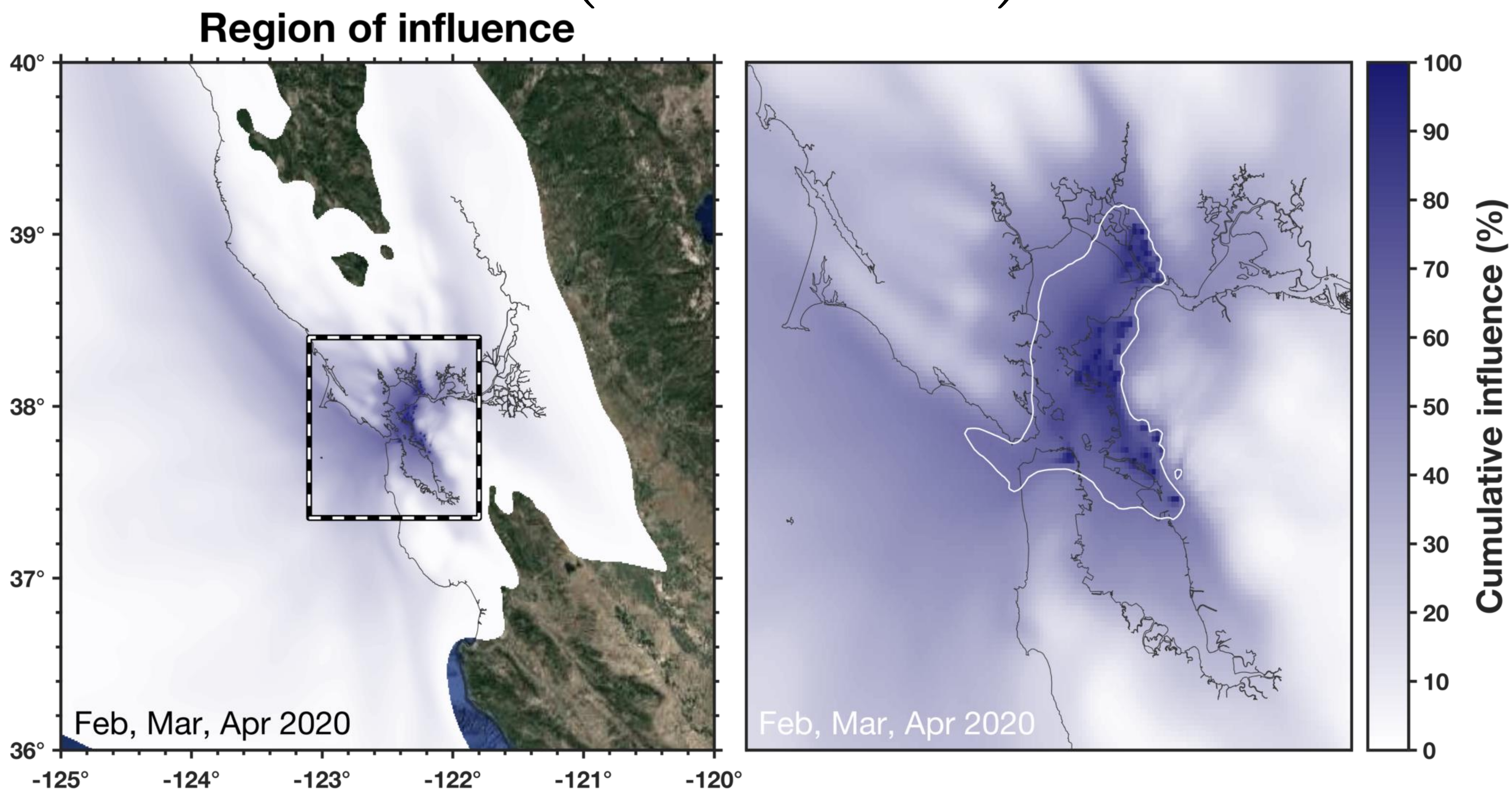

Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
before shelter-in-place (Feb 02 - Mar 14)
during shelter-in-place (Mar 22 - May 02)
CO2 Concentration (ppm)
540
520
500
480
460
440
420
400
00
06
12
18
Local Time

# Mapping emissions to observations based on transport by winds and acknowledging unresolved turbulence



# Matrix representing emission weighted source for all observations

$$\hat{\mathbf{x}} = \mathbf{x_a} + (\underline{\mathbf{H}}\mathbf{B})^T \left(\underline{\mathbf{H}}\mathbf{B}\underline{\mathbf{H}}^T + \mathbf{R}\right)^{-1} (\mathbf{y} - \mathbf{H}\mathbf{x_a})$$




*NOAA HRRR meteorology, 72 hour back trajectories with 1000 particles (STILT)*

# Matrix representing model-data mismatch and error covariance

$$\hat{\mathbf{x}} = \mathbf{x_a} + (\mathbf{HB})^T \left(\mathbf{HBH}^T + \underline{\mathbf{R}}\right)^{-1} (\mathbf{y} - \mathbf{Hx_a})$$

$$\mathbf{R} = \mathbf{R}_I + \mathbf{R}_B + \mathbf{R}_M$$

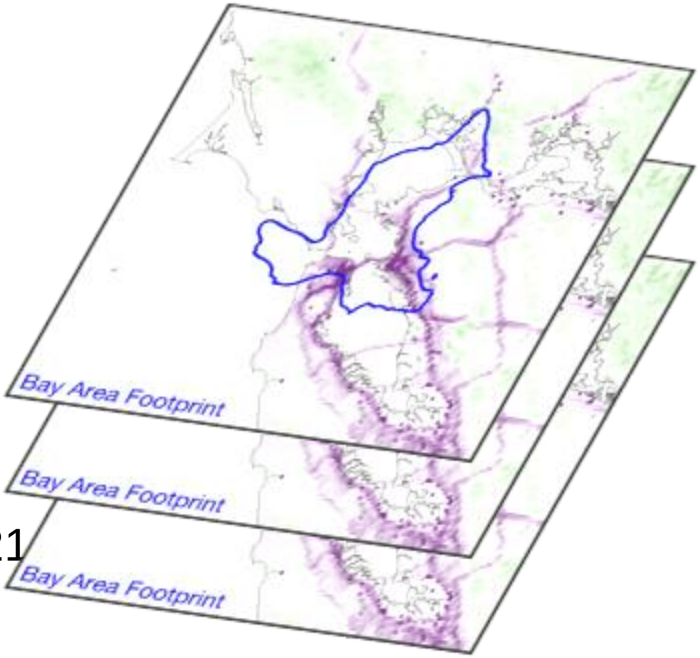
*instrument error* — $\mathbf{R}_I$

*background error* — $\mathbf{R}_B$

*model error* — $\mathbf{R}_M$

# The system of equations

## For hourly fluxes at ~1km for 15 days

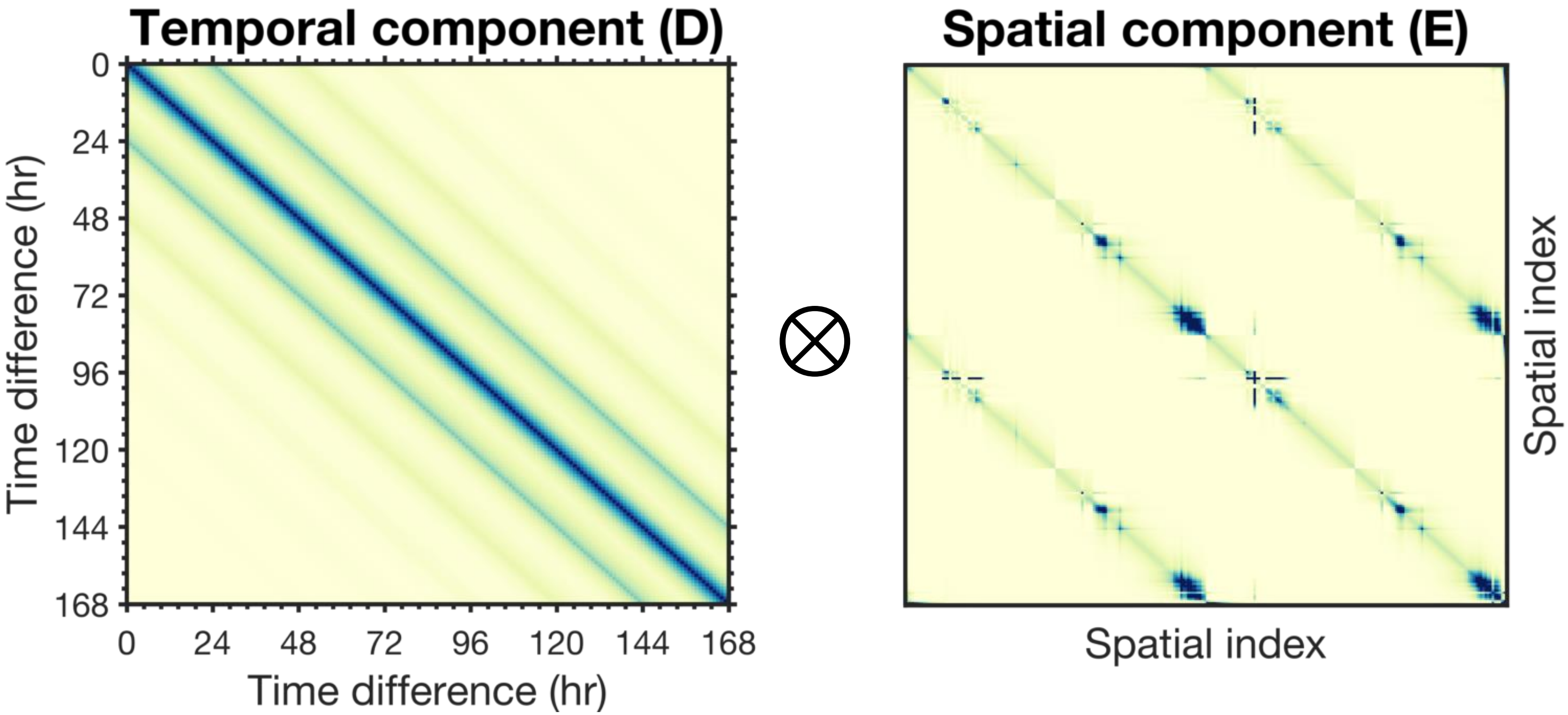



- Horizontal grid is $n_x \times n_y$ where $n_x$ = 157 and $n_y$ = 121
- 15 days of hourly fluxes: $n_t$ = 360
- ($m = n_x n_y n_t$ = 6,338,920 parameters): **55 Mb***!

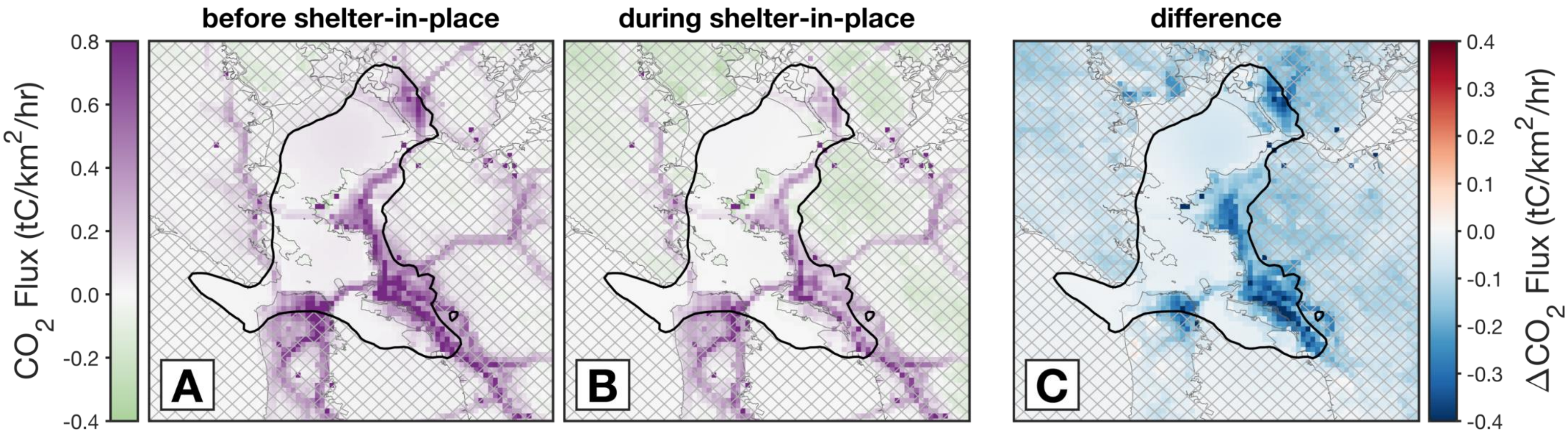
**Assuming double precision: 8 bytes per element*

# Prior error covariance matrix

- Matrix is m x m = **$4.7 \times 10^{13}$** elements (naïve storage requirement: **374 Tb**)
- Can describe as a Kronecker product ($\otimes$) of two sub-matrices

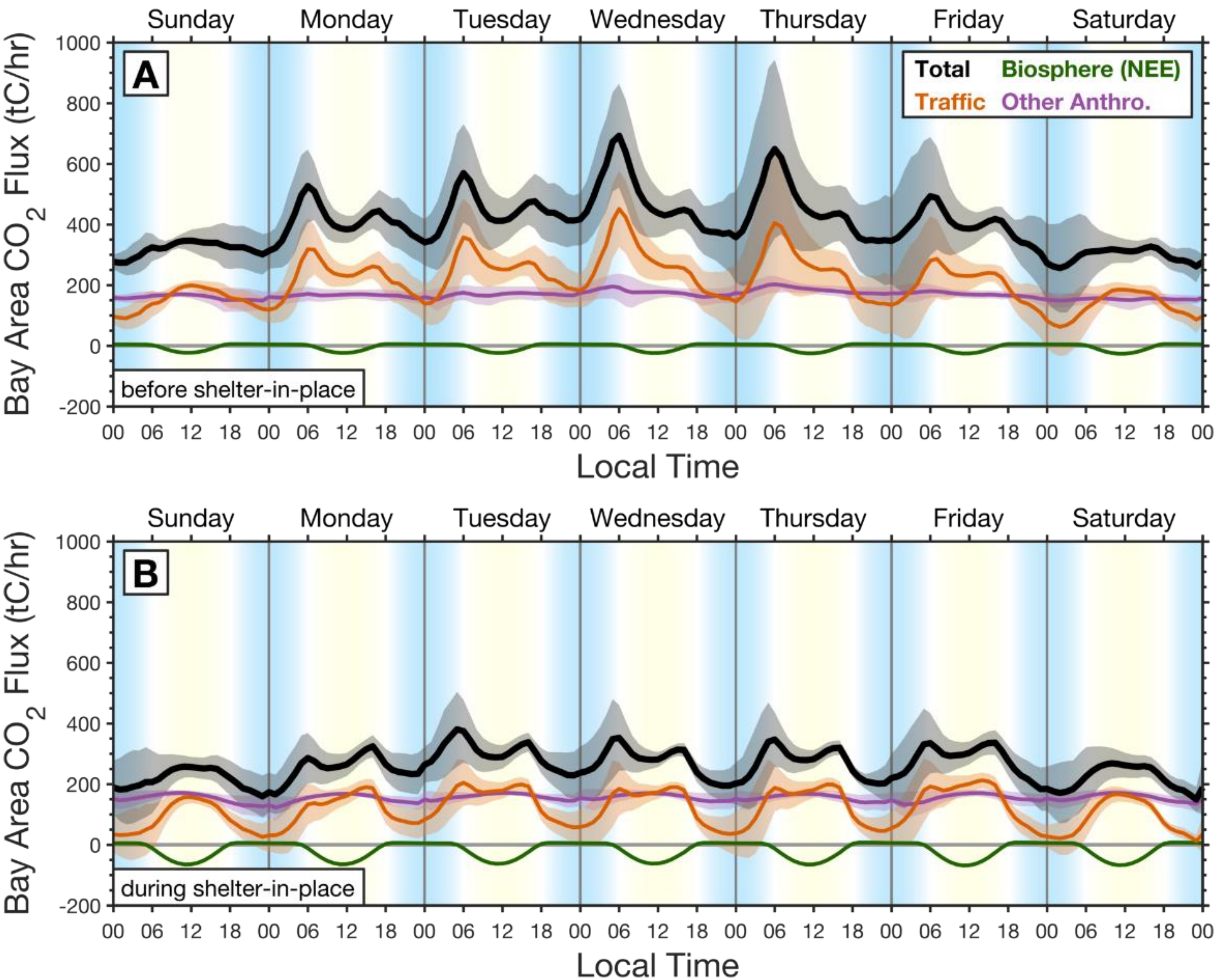


# Results



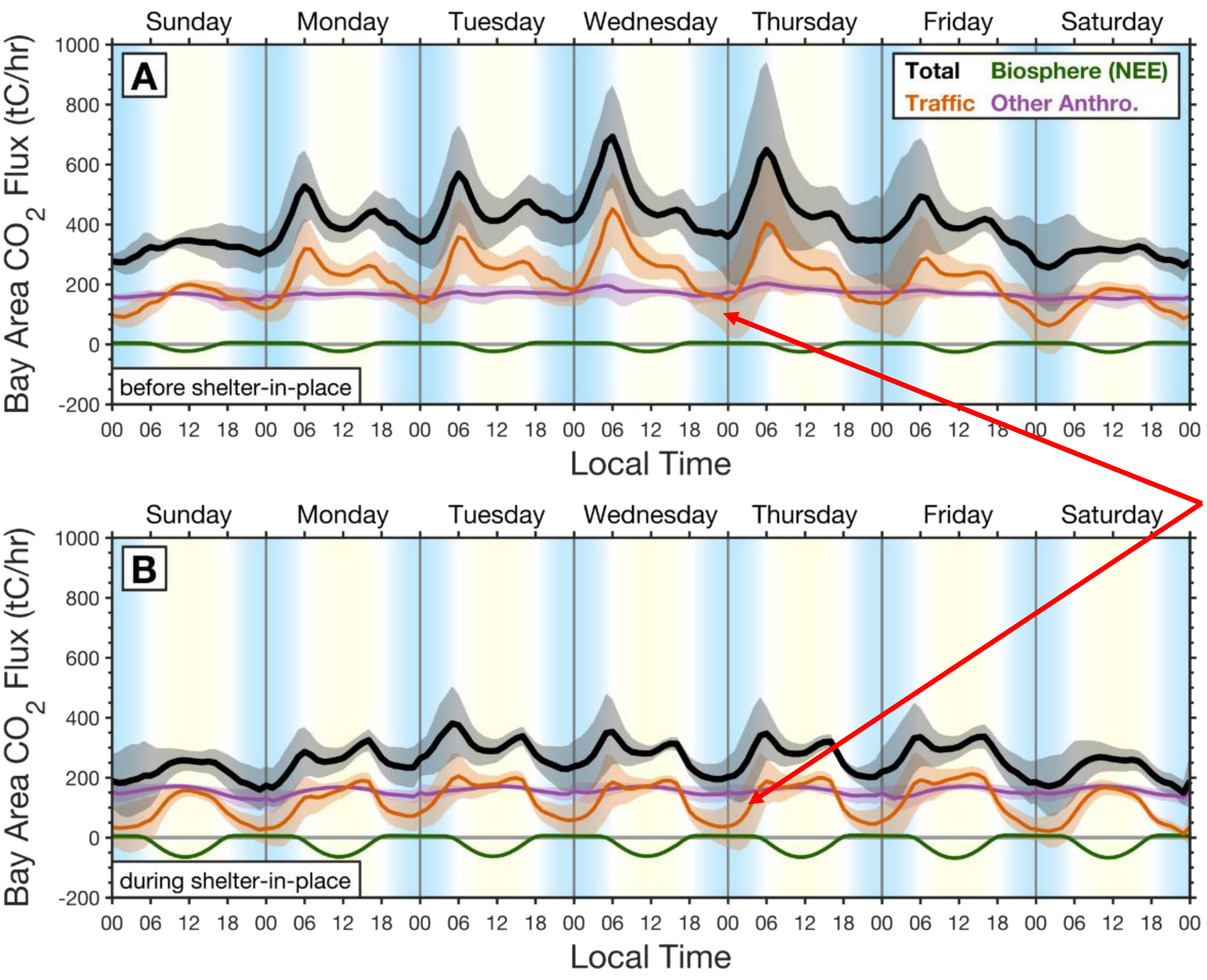

- **The emissions are best constrained inside the black line (where the footprints are most influential)**
- **Largest changes on freeways**

# Results




- **45% decrease** in traffic emissions
- **7% decrease** from other anthro.
- Biosphere constrained by satellite obs

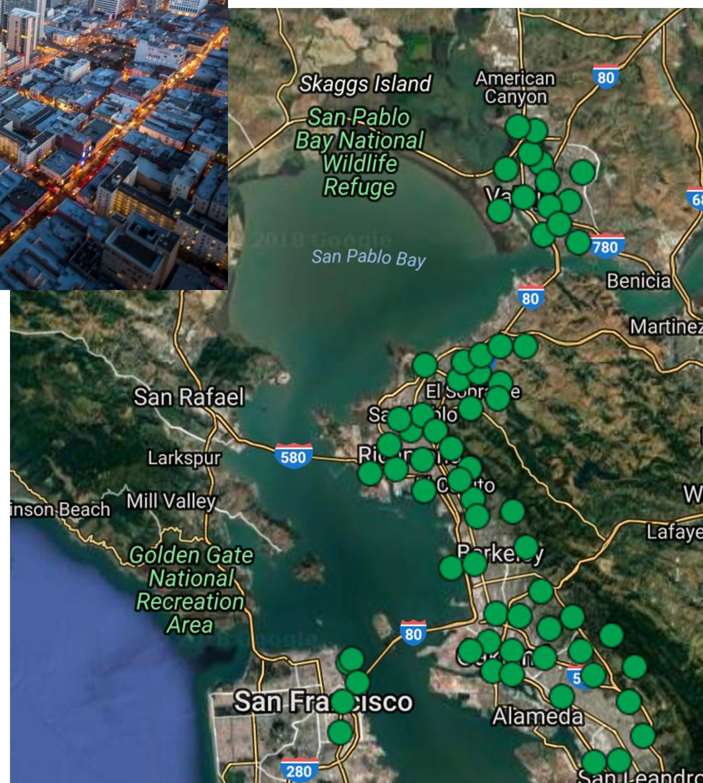
# Results



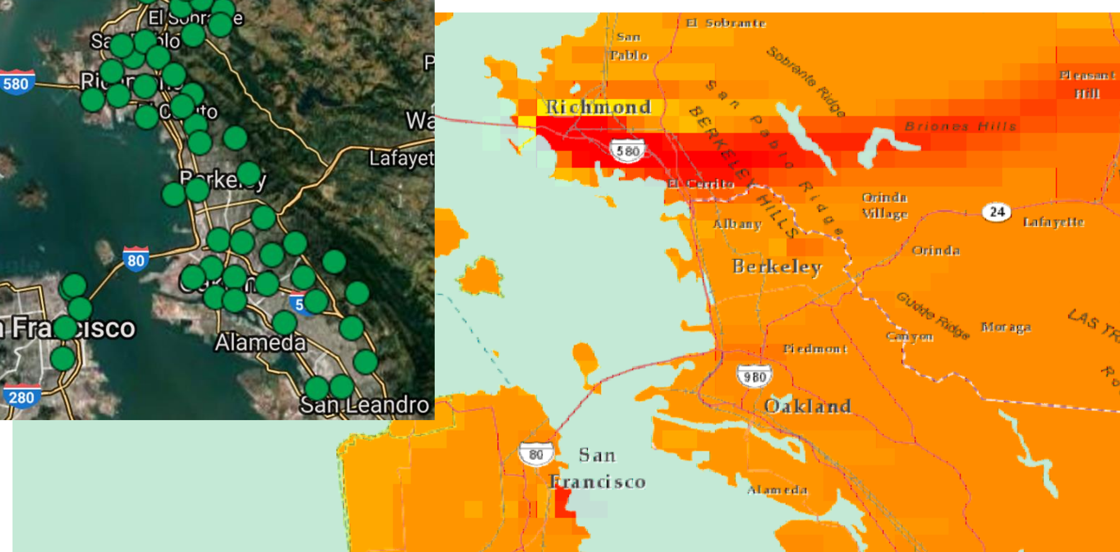

- **Nighttime emissions almost completely gone**
- **Changes supported by traffic counts**

# Neighborhood emissions

# Dense Observing Networks



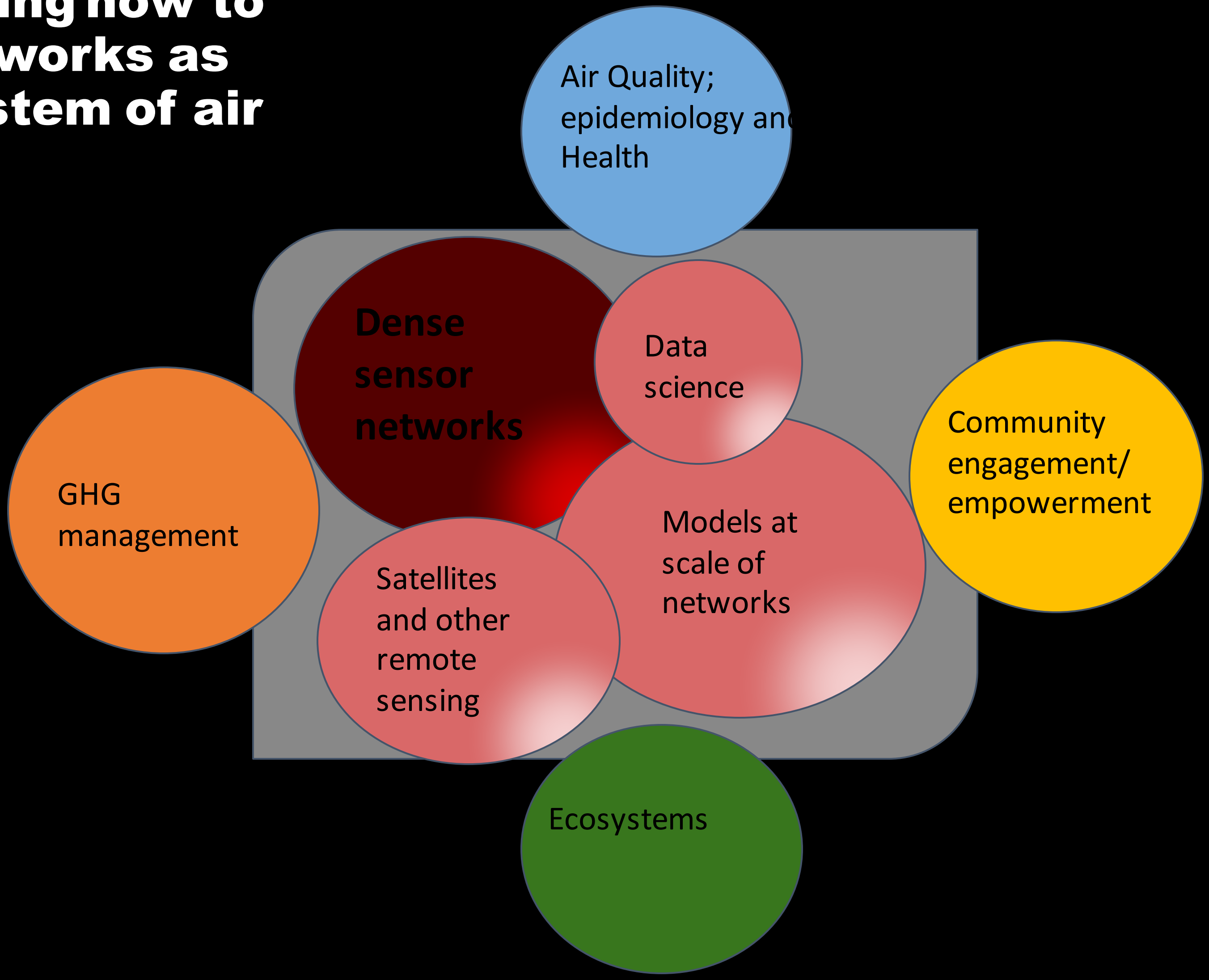

# Direct analysis, inverse models and data assimilation



# Dense networks

# Dense networks

**We are at the beginning of understanding how to use dense networks as part of our system of air management.**



# From research to operations

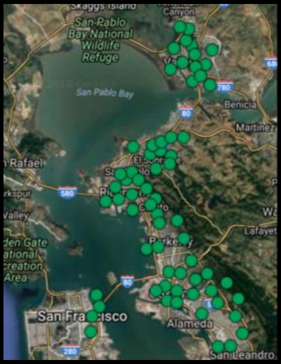
- Network design
- Instrument selection
- Test and evaluation
- Analysis

A routine emissions, exposure and policy efficacy assessment by government agencies (e.g. EPA) or the commercial sector.

# From research to operations

# Multiple points where there are loops and feedback along this sequence.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hardware | Calibration and maintenance | System for routinely representing emissions, concentrations and trends. | Display of emissions and obs.<br><br>Public access. | Analysis<br><br>inverse model<br><br>Simpler regression/ data science approaches | Interpretation and Communication | Education<br><br>Workforce development | Scaling from a few pilot cities to widespread adoption.<br><br>Commercial entities or government agencies manage system. |




Catherine Newman

Alexis Shusterman

Jinsol Kim

Kevin Worthington

Alex Turner

Paul Wooldridge

Helen Fitzmaurice

Pietro Vannucci

Naomi Asimow

Yishu Zhu

# Thank you

# The future of urban air

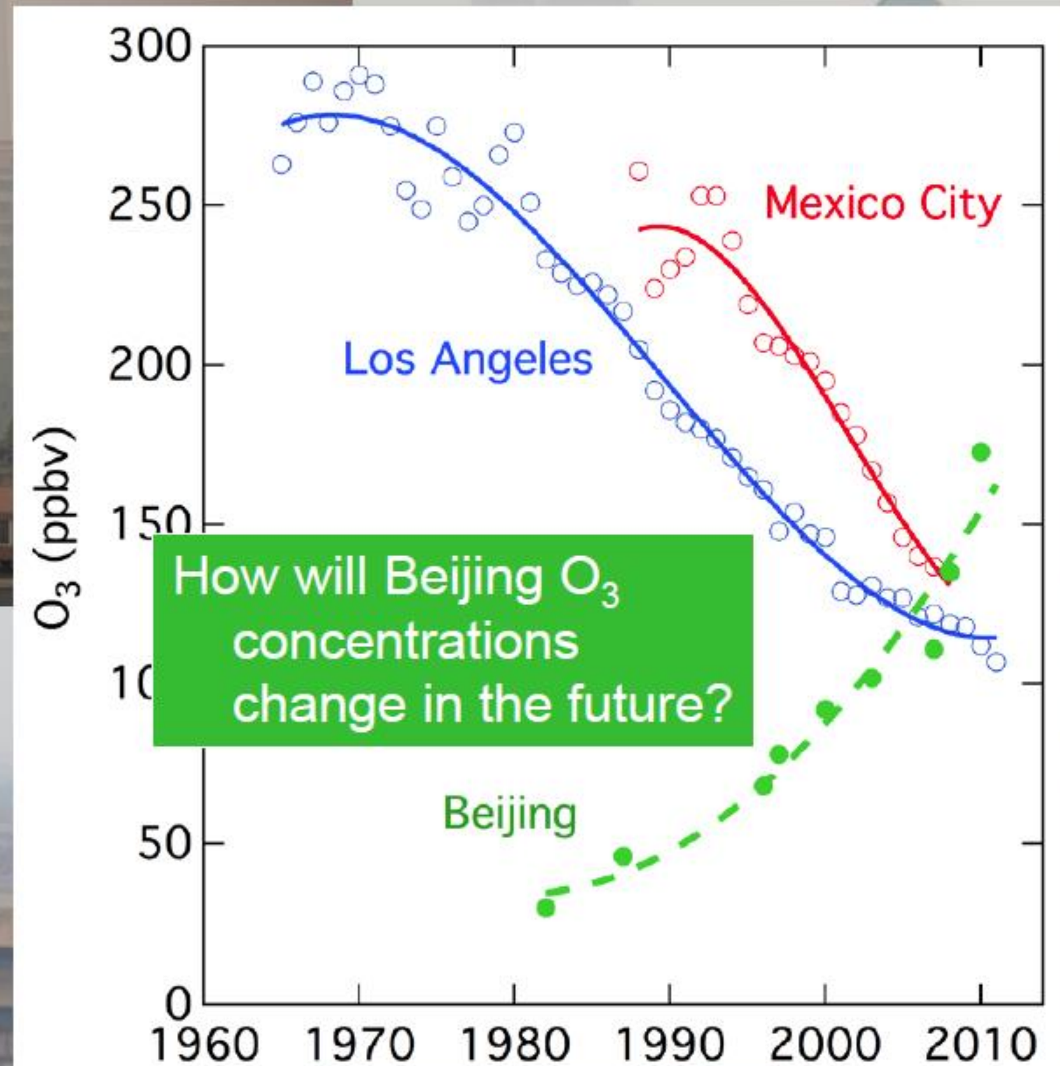

What are the local contributions to $CO_2$ and other greenhouse gases? Are management strategies working as expected? (Scope 1)

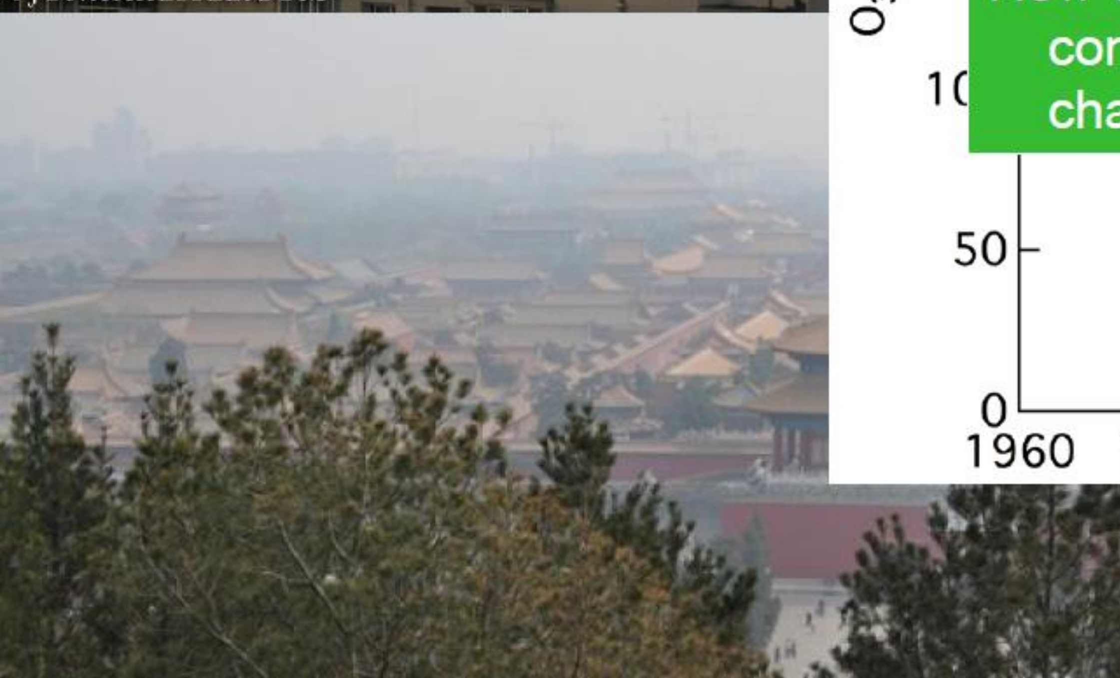
What are human (and plant, animal) exposure to toxic airborne chemicals? What strategies are available to reduce exposure?

Optimal strategies for climate and air quality?

# 50 years of urban $O_3$ concentrations

Beijing: A rapidly developing mega-city with serious air quality issues

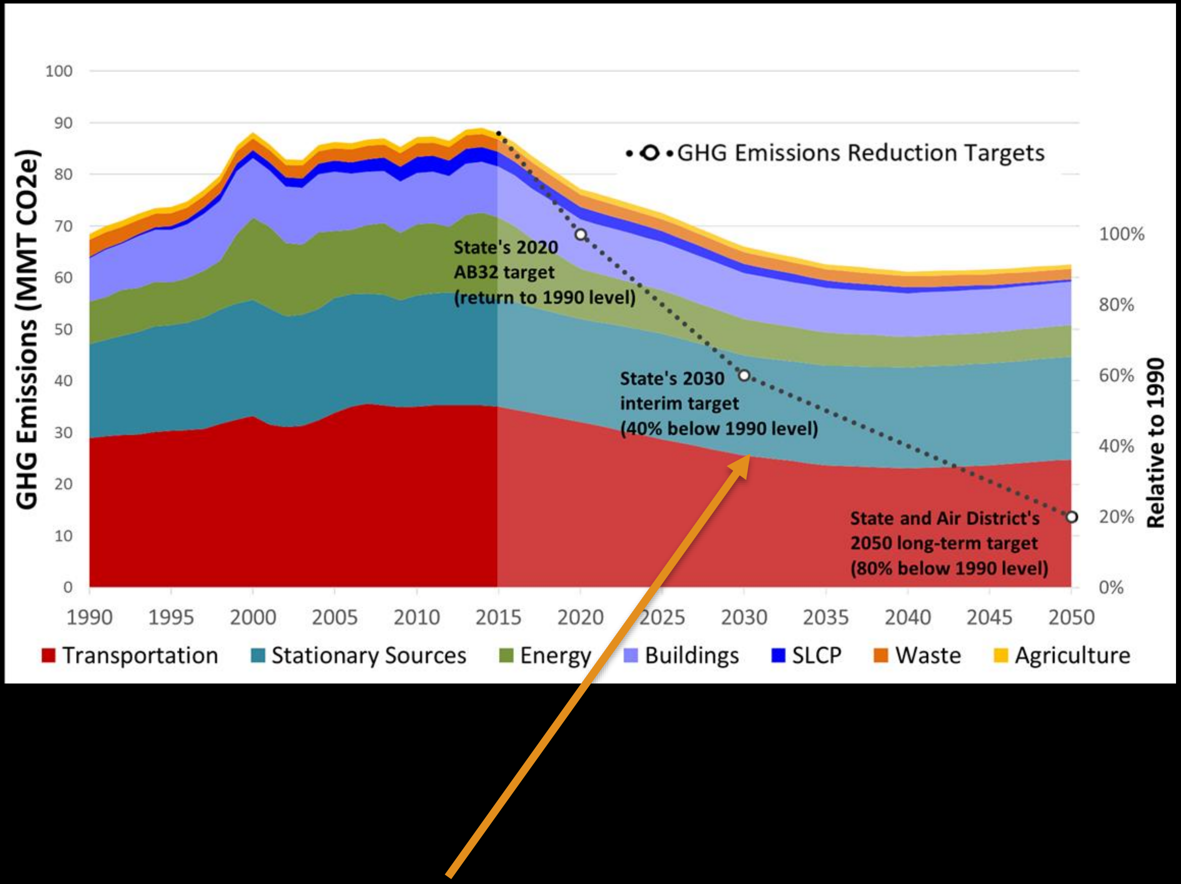



Slide courtesy of David Parrish (NOAA)

# California Greenhouse Gas policy

**One piece of a multi-tiered policy:**

**50% reduction in petroleum use in cars and trucks by 2030.**



# Greenhouse gases (GHGs) and health

GHGs: Could cities get industry funding to reduce their emissions in a cap and trade program?

AQ: Aerosol are the #1 environmental health problem in the world--asthma, cardiovascular problems, …? What options are available to improve health?

AQ: $O_3$ is not improving as fast as we would like in cities? What options would put us back on a better path?

AQ: Why are some neighborhoods more polluted than others?

GHGs&AQ: What are the win:wins for reducing our climate impact and breathing cleaner air?

# Examples of science questions to support policy

GHGs: What are the patterns and trends of $CO_2$ emissions/uptake: vehicles, homes, industry, biosphere. We know these vary at ~1km scales. Observations and analyses of them to date mostly focus on integrating across a whole city, not on detailed space and time allocation. Models becoming available at this resolution (see Kevin Gurney's talk tomorrow). Also $CH_4$.

AQ: 10 years ago $NO_x$ emissions were assumed to follow miles traveled and be mostly on highways. Today, catalytic convertors are thought to be so effective that cold start (first few miles near homes) might be the dominant source of $NO_x$, VOC, … ; if so what changes in spatial pattern have occurred; are occurring? (e.g. Saliba, et al. ES&T 2017)

AQ: Are emissions of household organics (e.g. terpenes from cleaners, solvents from paint) competitive with emissions from vehicles as source of urban reactive carbon? (and therefore urban aerosol?) (McDonald et al. Science 2018)