Satellites and Low-Cost Sensors

Advantages, Limitations, and Opportunities for Integration

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Outline

- Low-Cost Sensors (LCS)
  - Advantages
  - Limitations
- Satellites
  - Advantages
  - Limitations
- Examples for Integrating LCS and Satellite Information
  - Opportunities
  - Methods (high-level overview)
  - Case studies & results
  - Challenges

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Low-Cost Sensors (LCS): Overview

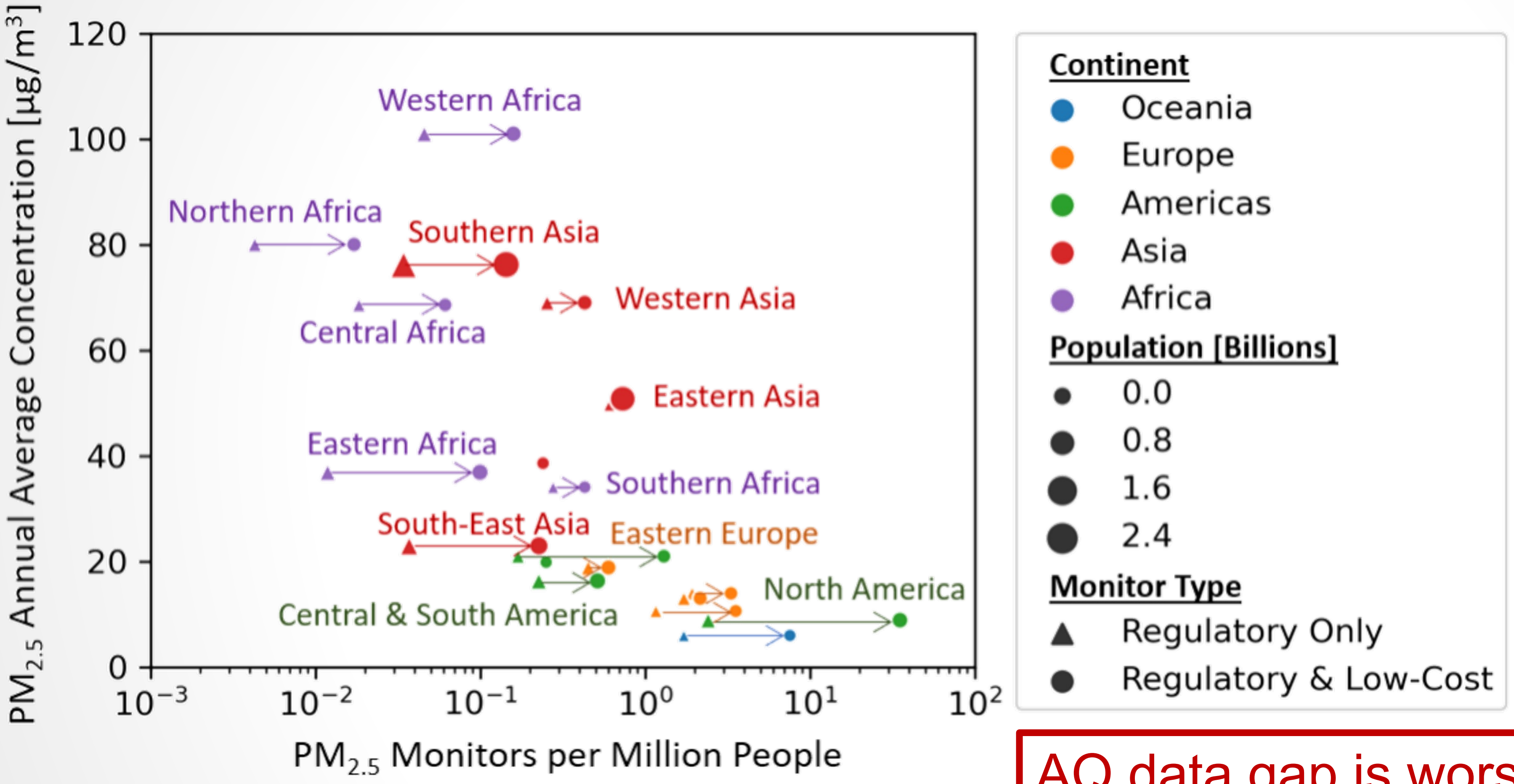
SENSIT RAMP: $PM_{2.5}$,
CO, NOx, O_3, SO_2, T, RH
gasleaksensors.com

PurpleAir: $PM_{2.5}$, T, RH
purpleair.com

Clarity Node S: for $PM_{2.5}$, NOx, T, RH
clarity.io

LCS allow relatively cheap AQ data
$PM_{2.5}$ (e.g., PurpleAir)
Multi-pollutant (e.g., RAMP, Clarity)

Low-Cost Sensors (LCS): Global Scope



Many regions (especially Africa & Asia) feature high $PM_{2.5}$ concentration but low per-capita $PM_{2.5}$ monitor density, leading to poor AQ data coverage.

Including low-cost sensors increases per-capita AQ monitor density by up to an order of magnitude in some regions (e.g., East Africa).

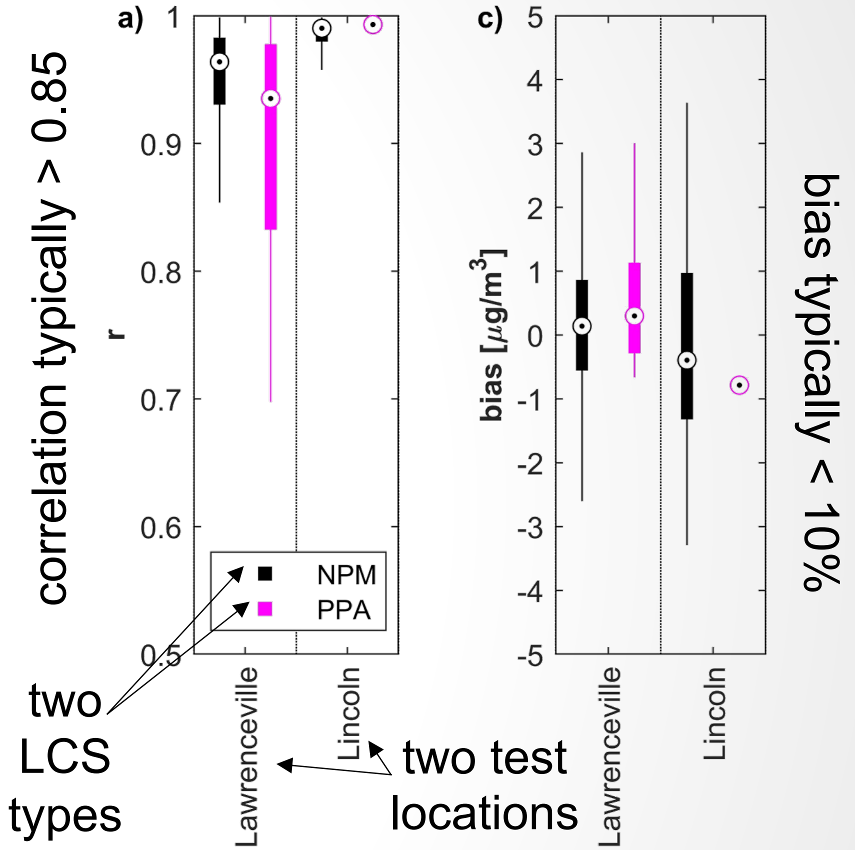
Source: Malings et al. (2020). "Application of low-cost fine particulate mass monitors to convert satellite AOD to surface concentrations in North America and Africa." *Atmospheric Measurement Techniques.* DOI: 10.5194/amt-13-3873-2020. With additional data from openAQ.org

AQ data gap is worst in Africa, Asia
LCS are filling in-situ AQ data gap
LCS adoption is increasing globally

Low-Cost Sensors (LCS): Advantages

- **10-100x less expensive** than reference-grade AQ monitors
- Relative **ease of installation** and operation (compared to reference-grade instruments)
- **Low power & infrastructure requirements** enable remote and “off-grid” deployment
- **Increased accessibility** of local AQ data allows the “democratization” of AQ monitoring
- **Fast data collection** and transmission: near-real-time AQ data
- **High inter-sensor consistency** for sensors of the same type

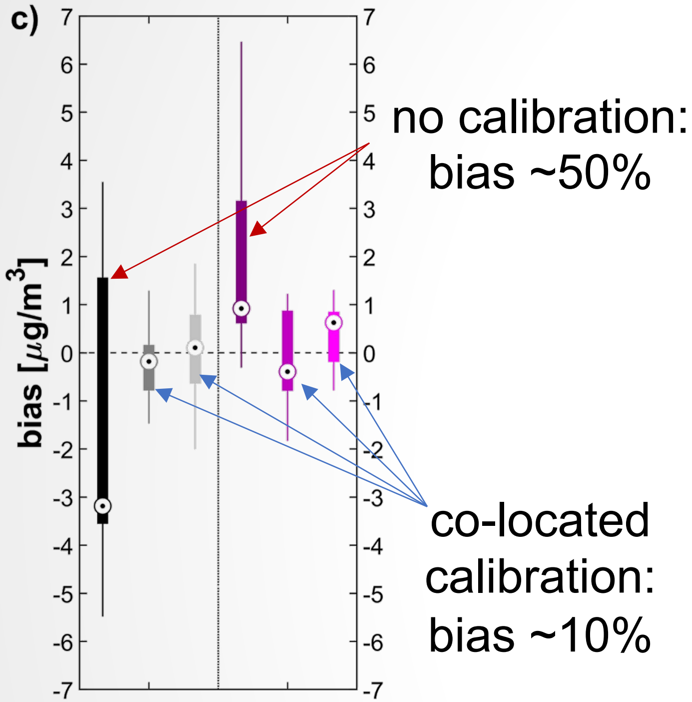
comparing batches of LCS



Source: Malings et al. (2020). “Fine particle mass monitoring with low-cost sensors: Corrections and long-term performance evaluation”. *Aerosol Science & Technology*, 54. DOI: 10.1080/02786826.2019.1623863.

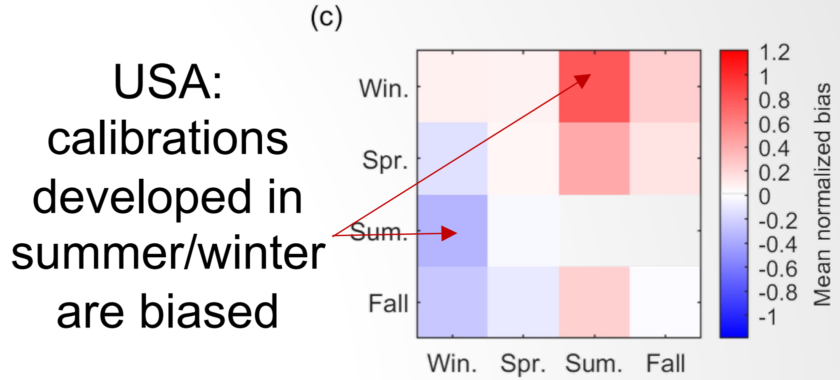
LCS allow more flexible deployment
LCS allow near-real-time data
LCS provide qualitative information

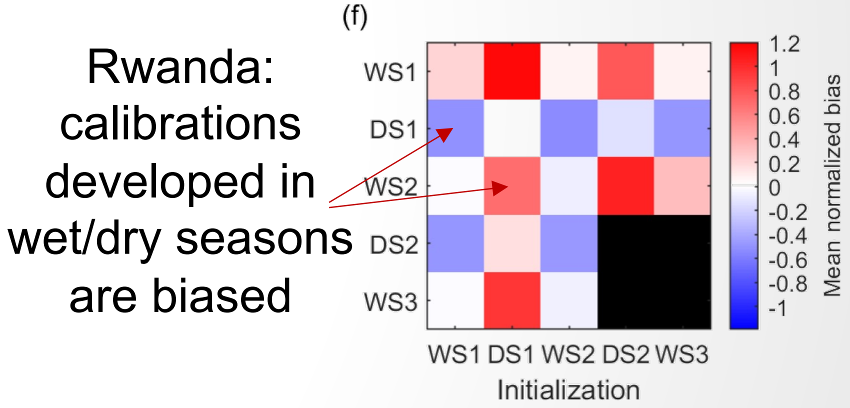
Low-Cost Sensors (LCS): Limitations



Two type of LCS

- **Low-cost is not no-cost**; access is still limited for some
- **Cross-sensitivity**; certain LCS may be highly sensitive to local humidity, other pollutants, and other ambient conditions
- **Calibration to reference monitors**: a locally-developed calibration against a trusted reference is needed.
- **Calibration may vary** seasonally as conditions change, and/or over time as sensor degrade





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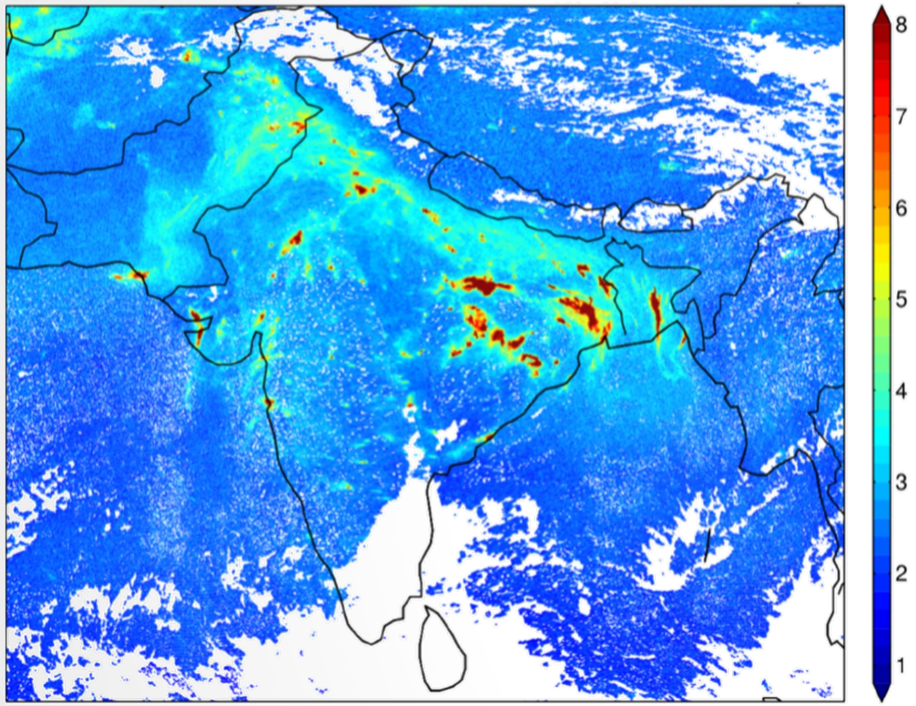
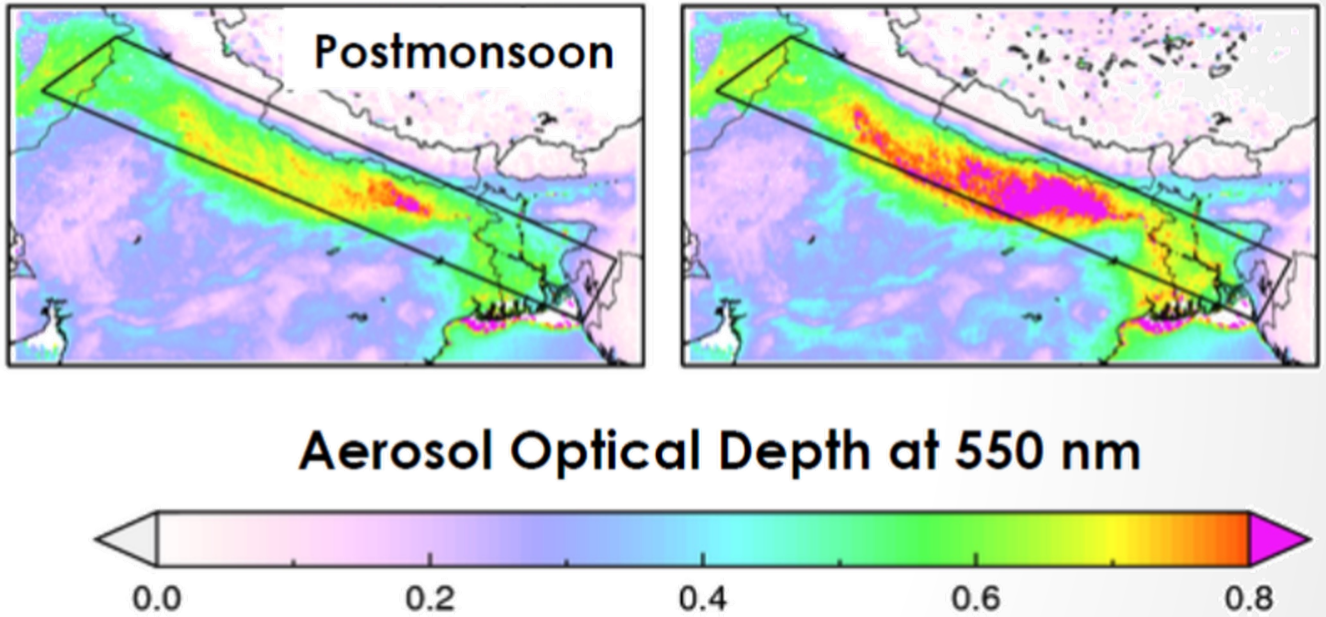
LCS have cross-sensitivities (T,RH,…)
Calibration depends on region, season
Calibration may drift over time

Satellites: Advantages

TROPOMI NO_2 (Real Data)

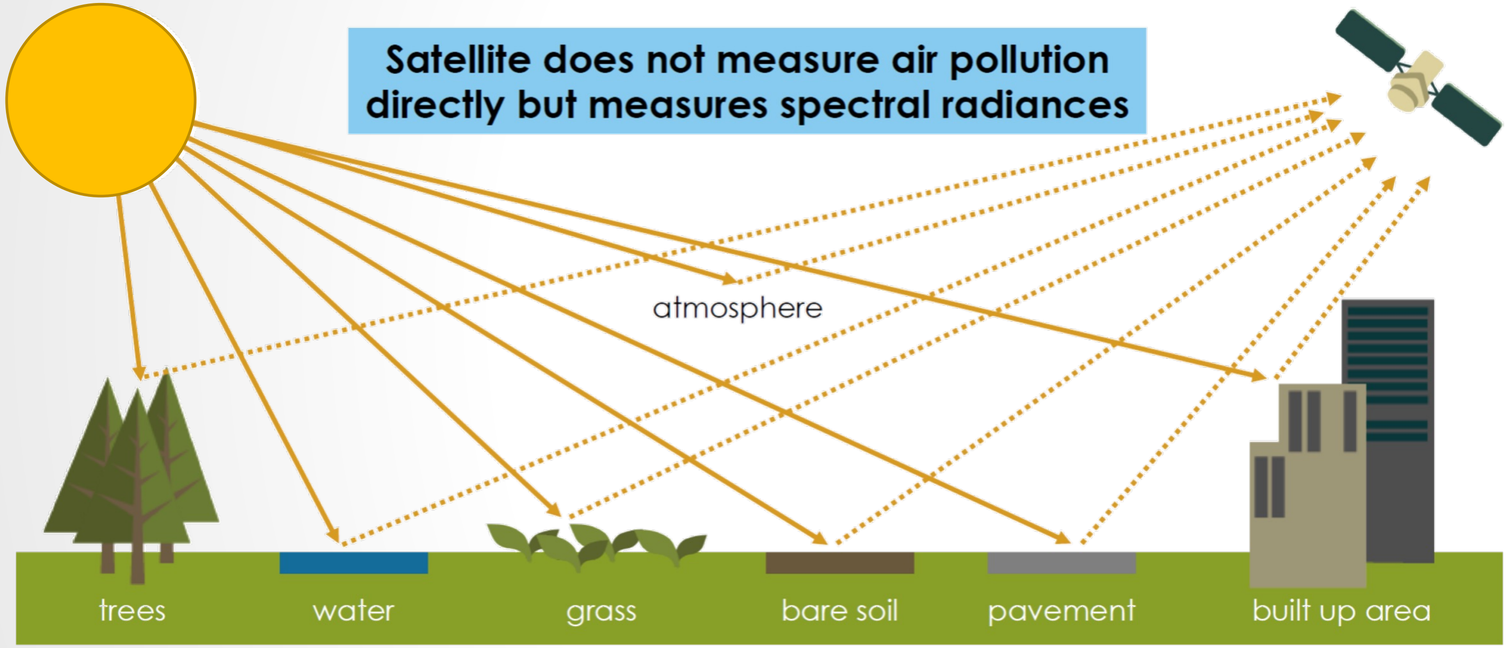


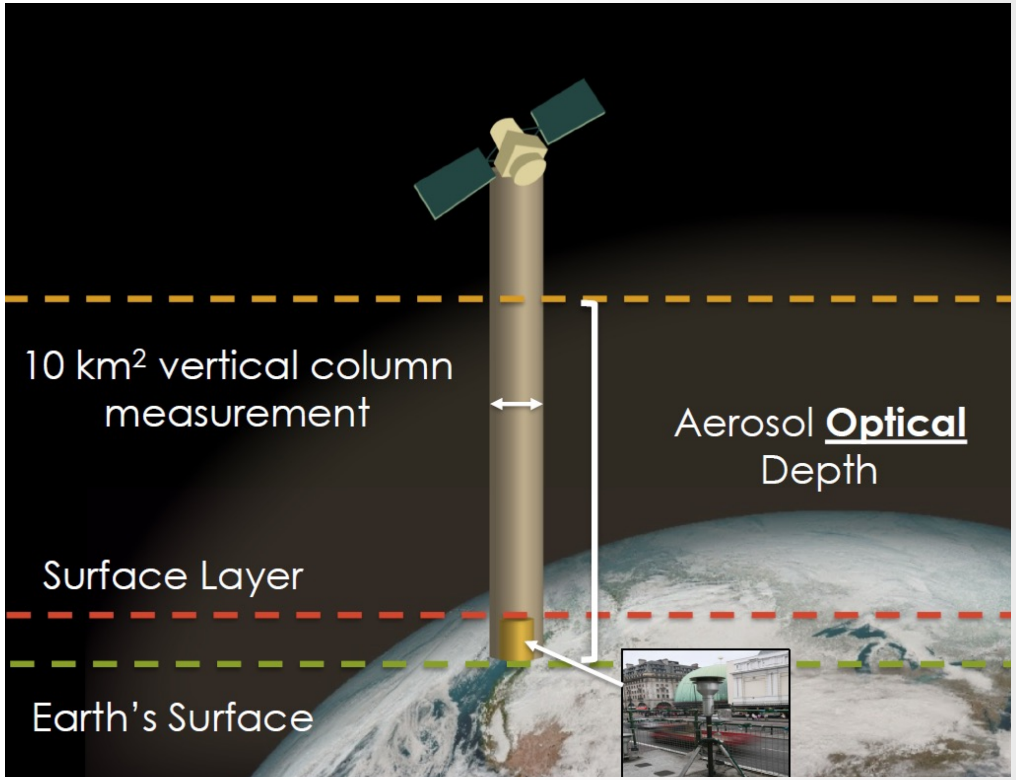


Source: Gupta, P.; Follette-Cook, M. (2018). Satellite Remote Sensing of Air Quality. NASA Applied Remote Sensing Training Program (ARSET). https://appliedsciences.nasa.gov/join-mission/training/english/arset-satellite-remote-sensing-air-quality

Satellites give wide global coverage
Satellites can track long-term trends
"A picture is worth a million datapoints"

Satellites: Limitations



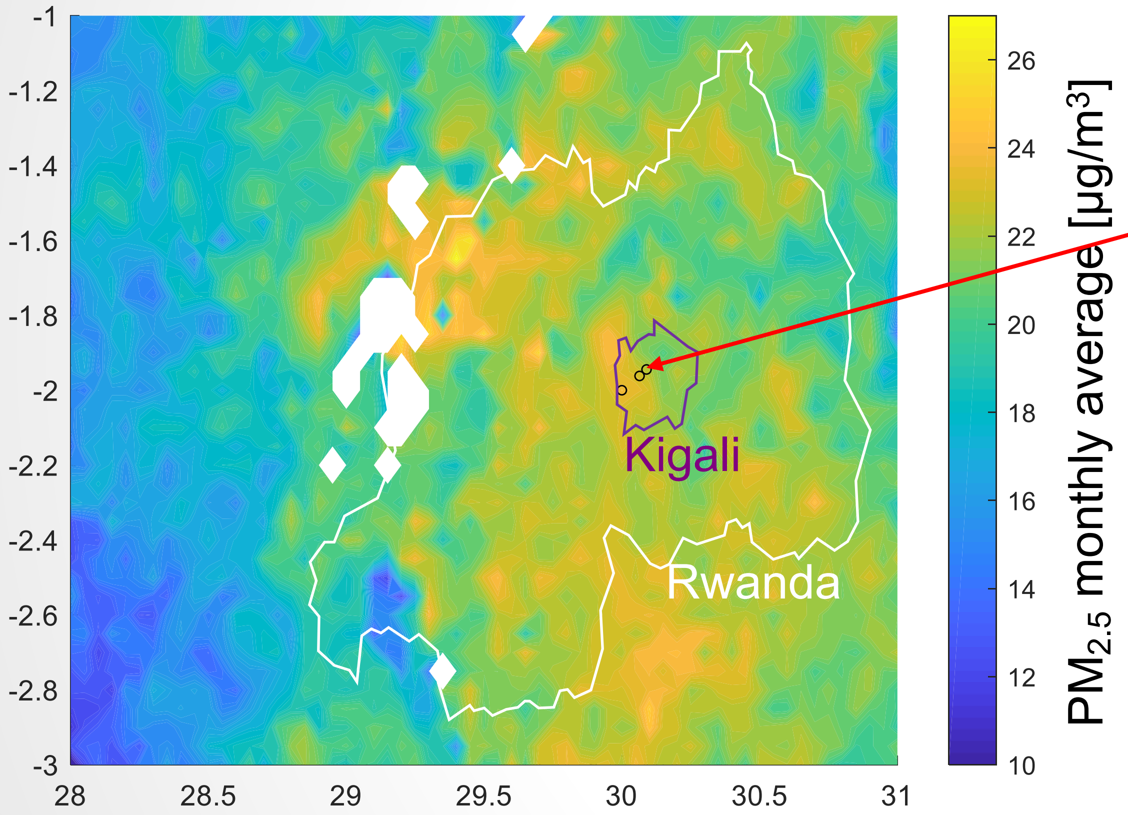


Source: Gupta, P.; Follette-Cook, M. (2018). Satellite Remote Sensing of Air Quality. NASA Applied Remote Sensing Training Program (ARSET). https://appliedsciences.nasa.gov/join-mission/training/english/arset-satellite-remote-sensing-air-quality

Satellites aren't always overhead
Satellites observe column quantities
Clouds & smoke can block the view

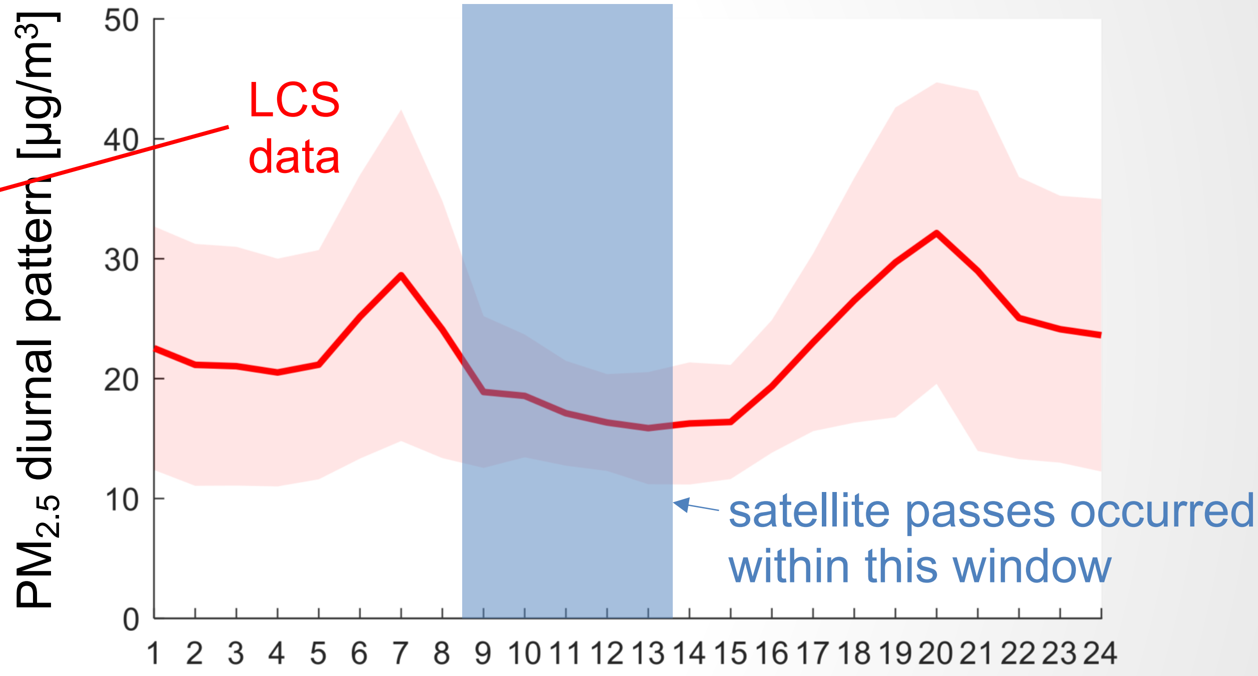
Satellites and LCS can be complementary

Spatial Coverage (satellite)



Source: Malings et al. (2020), "Application of low-cost fine particulate mass monitors to convert satellite AOD to surface concentrations in North America and Africa" *Atmospheric Measurement Techniques.* DOI: 10.5194/amt-13-3873-2020

Temporal Coverage (LCS)



Satellite gives wide-area map
Satellite only observed near mid-day
LCS measures daily cycle (and peaks)

Opportunities for Integrating Satellites and LCS

Easier

Use satellite data products to locate potential “hotspots” for monitoring with LCS

Qualitative comparisons of satellites and LCS spatial patterns and trends

Source apportionment distinguishing local sources (LCS only) from regional sources (visible in satellite)

Validation of Satellite data products with LCS

In-situ calibration of LCS with satellite data products

Integration of satellites and LCS with models and/or regulatory monitors for comprehensive AQ assessment

Harder

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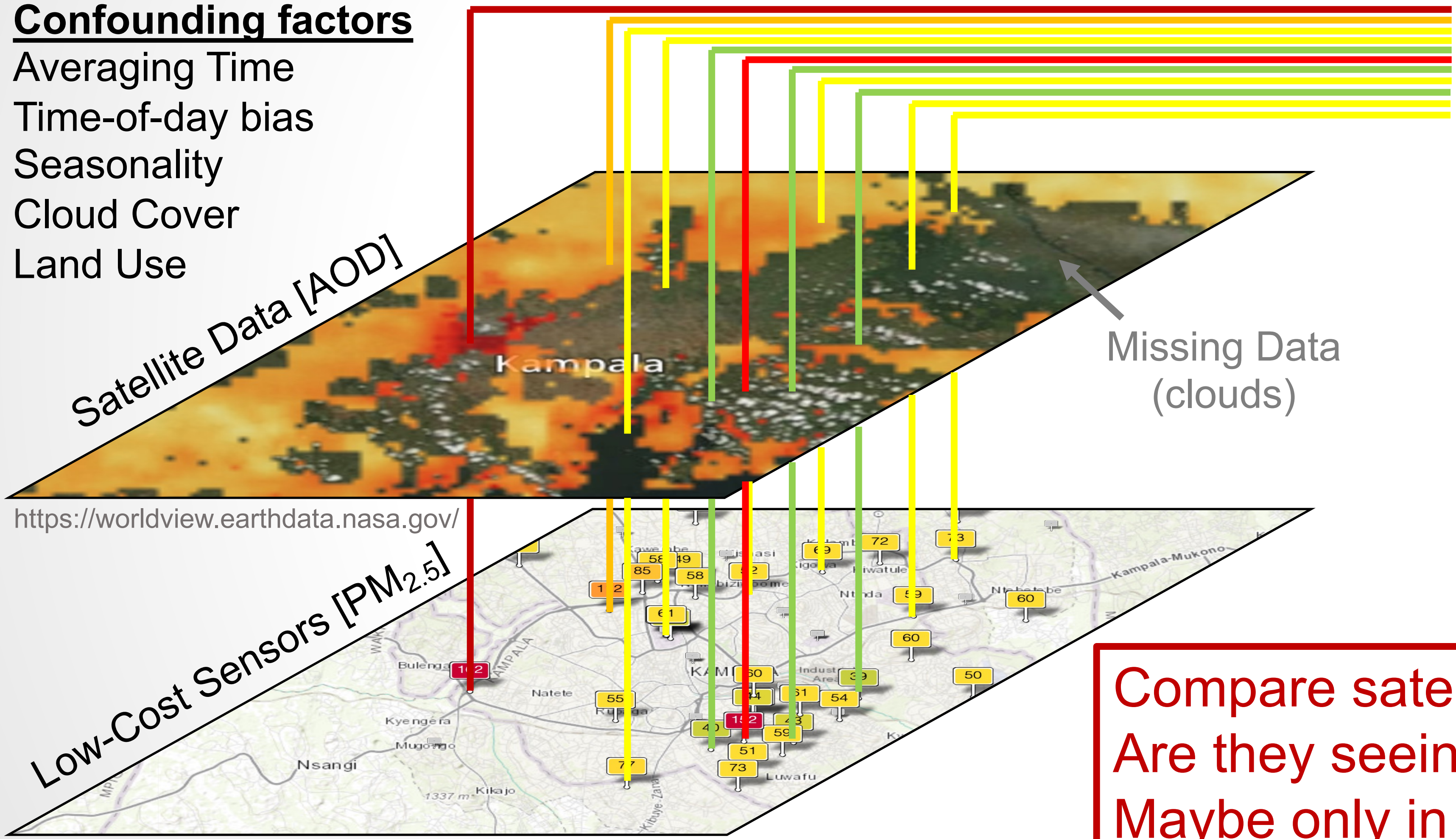
Spatial Correlations: do satellites capture patterns?

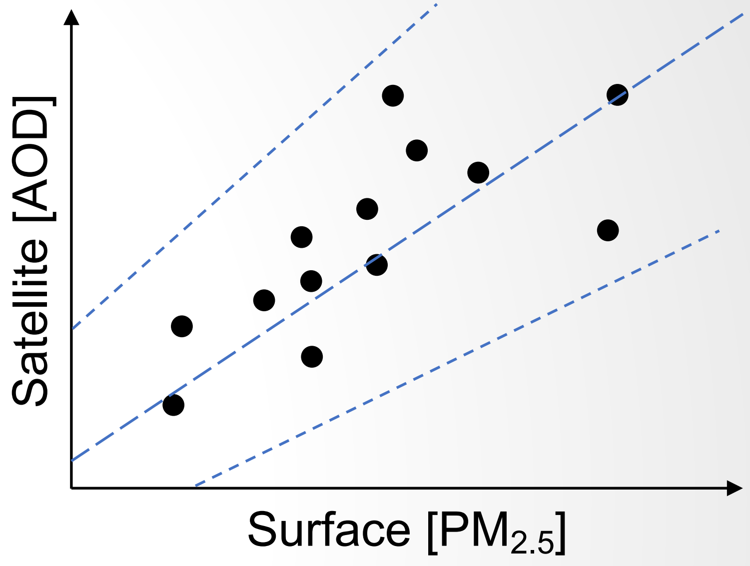
Confounding factors

Averaging Time
Time-of-day bias
Seasonality
Cloud Cover
Land Use



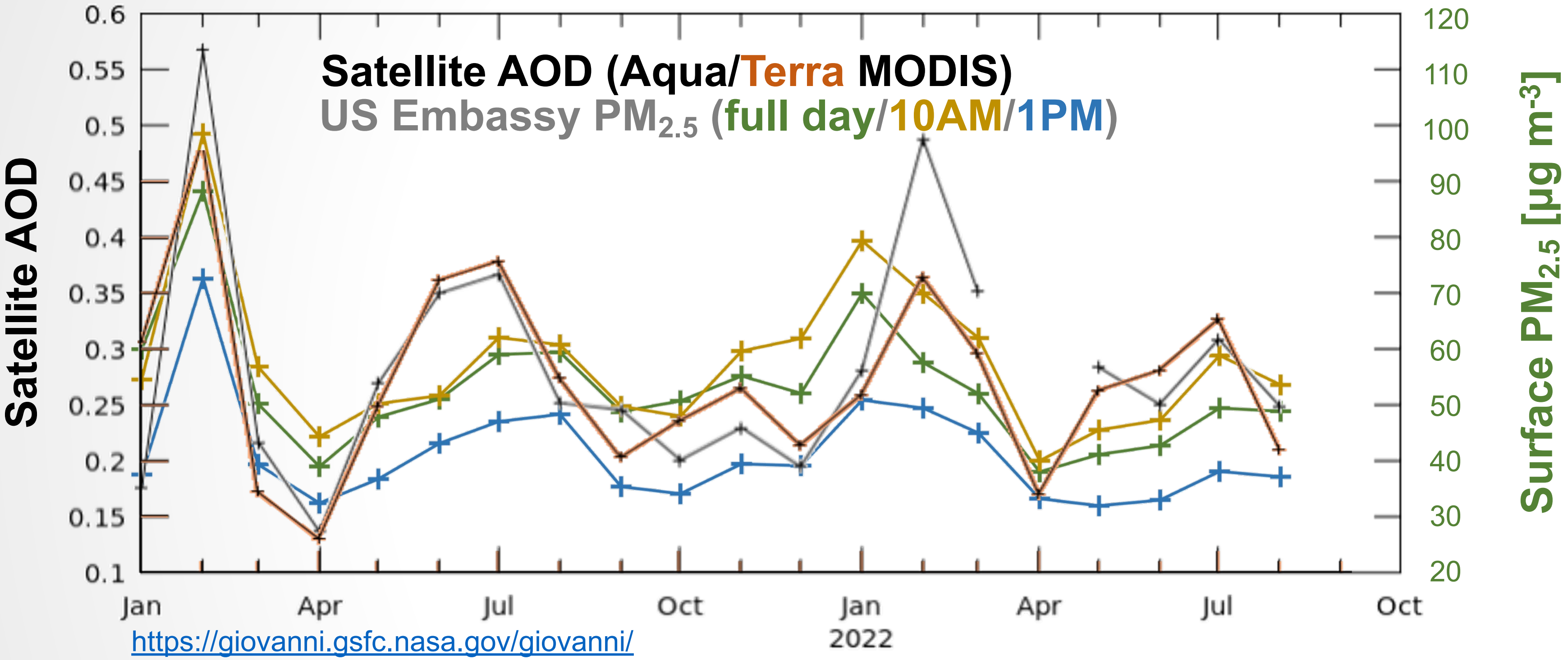
https://worldview.earthdata.nasa.gov/

https://aqicn.org/station/network/airqo



Compare satellite and LCS maps
Are they seeing the same "pattern"?
Maybe only in some areas or times

Temporal Correlations: do satellites capture trends?



https://giovanni.gsfc.nasa.gov/giovanni/
https://www.airnow.gov/international/us-embassies-and-consulates/

Comparing at different times of day

Full Day Average
Morning ↔ Terra
Afternoon ↔ Aqua

Confounding factors

Averaging Area
Averaging Time
Time-of-day bias
Seasonality
Cloud Cover

Example: trends in Kampala (0-1N,32-33E) for 1+ year

Trends at US embassy may not represent city-wide trends

Compare satellite and LCS timeseries
Are they seeing the same "trend"?
Maybe in some seasons or regions

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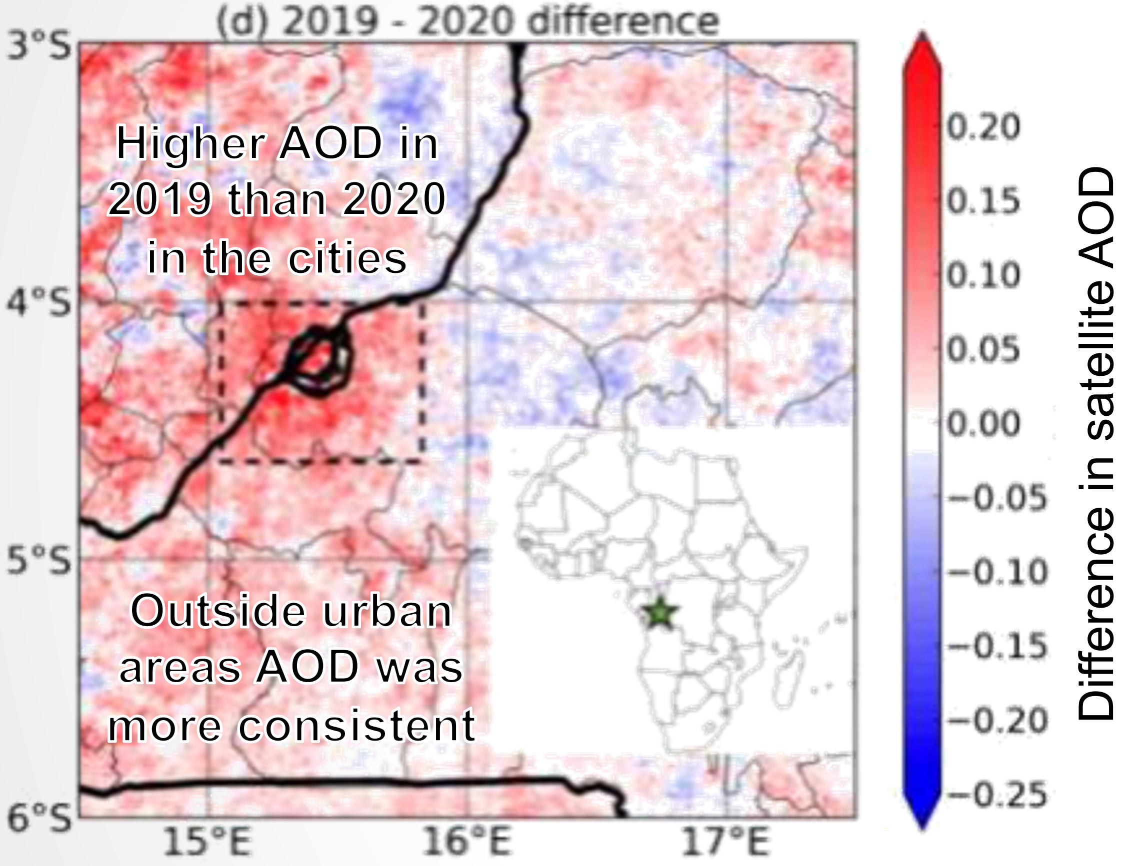
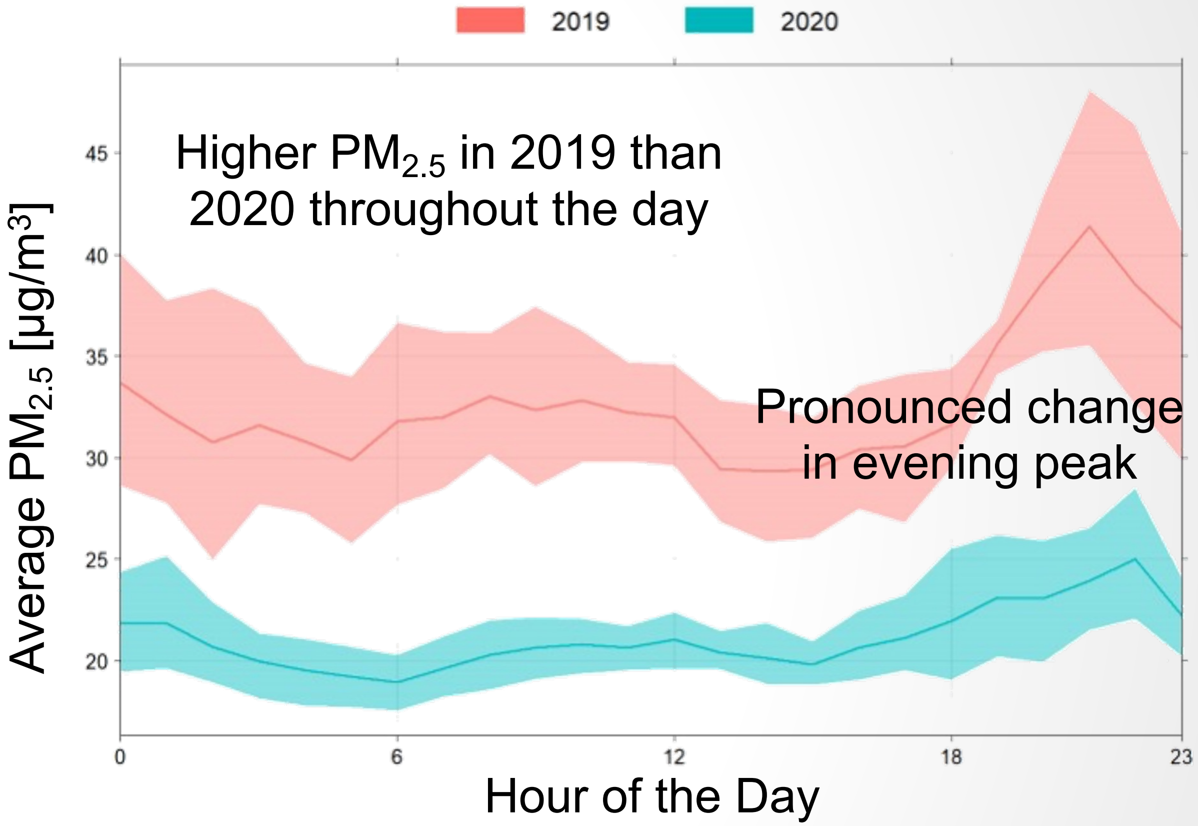
Qualitative: COVID-19 impact in Brazzaville & Kinshasa

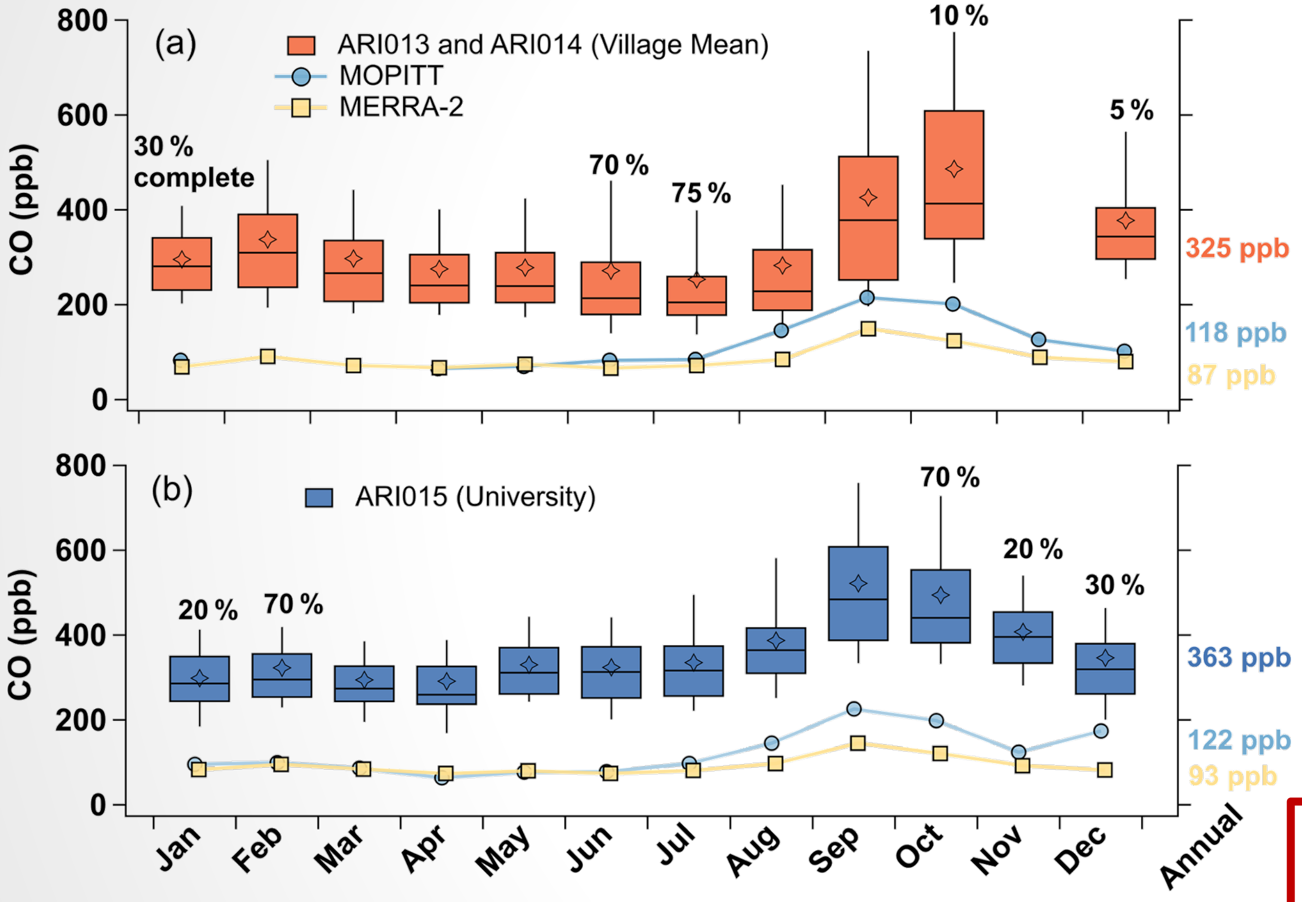




Source: McFarlane et al. (2021). "First Measurements of Ambient $PM_{2.5}$ in Kinshasa, Democratic Republic of Congo and Brazzaville, Republic of Congo Using Field-calibrated Low-cost Sensors." Aerosol and Air Quality Research, 21. DOI: 10.4209/aaqr.200619.

PM decreases in Satellite & LCS data
Satellite gives spatial extent of change
LCS give time-of-day changes locally

Quantitative Comparison & Validation: CO in Malawi



Source: Bittner et al. (2022) "Performance characterization of low-cost air quality sensors for off-grid deployment in rural Malawi." Atmospheric Measurement Techniques. 15:11. DOI: 10.5194/amt-15-3353-2022

ARISENSE Low-Cost Sensor Package
MOPITT Satellite
MERRA-2 Reanalysis (Model + Satellite)

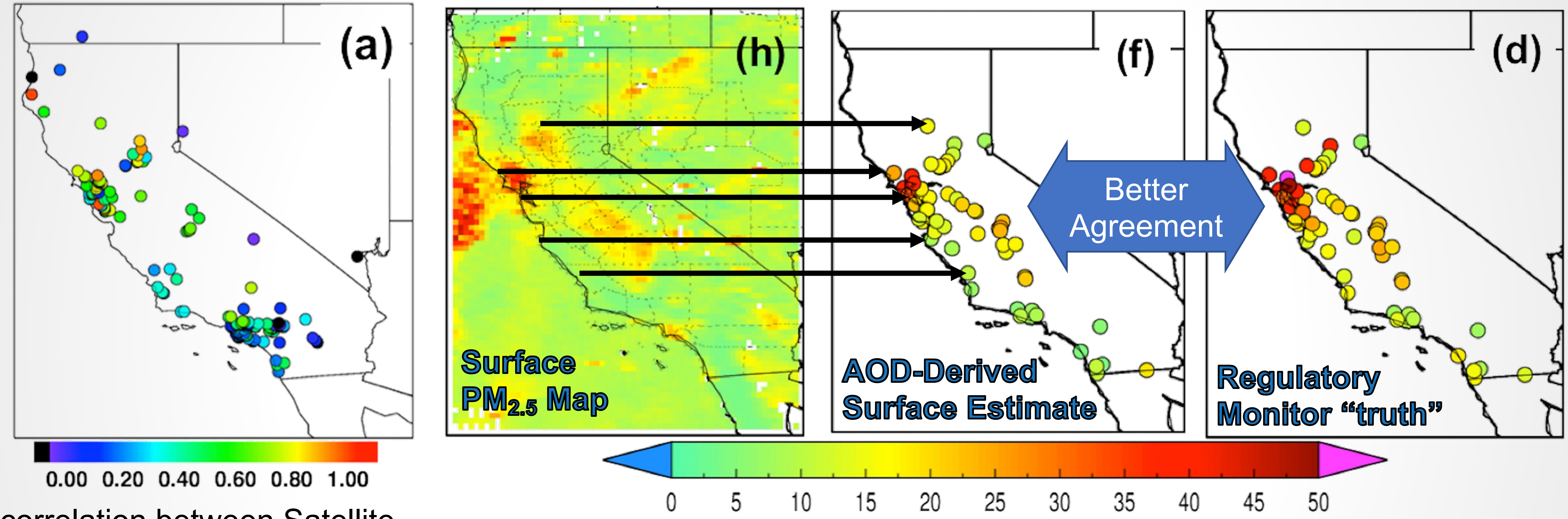
Data sources agree on trends
- Higher CO in urban than rural areas
- Higher CO in burning season (Aug-Nov)

Data sources disagree on magnitudes
- Satellite ~30% higher than model during peaks
- LCS 2-4x higher than model or satellite

Numerous confounding factors
- No reference for region-specific LCS calibration
- Hyper-local sources (cooking, traffic)
- Once-daily MOPITT satellite passes

Satellite and LCS see similar trends
Disagreement on magnitude
What is the ground truth? Unclear.

Surface $PM_{2.5}$ from Satellite AOD with LCS during Fires



$PM_{2.5}$ [μg/m^3]

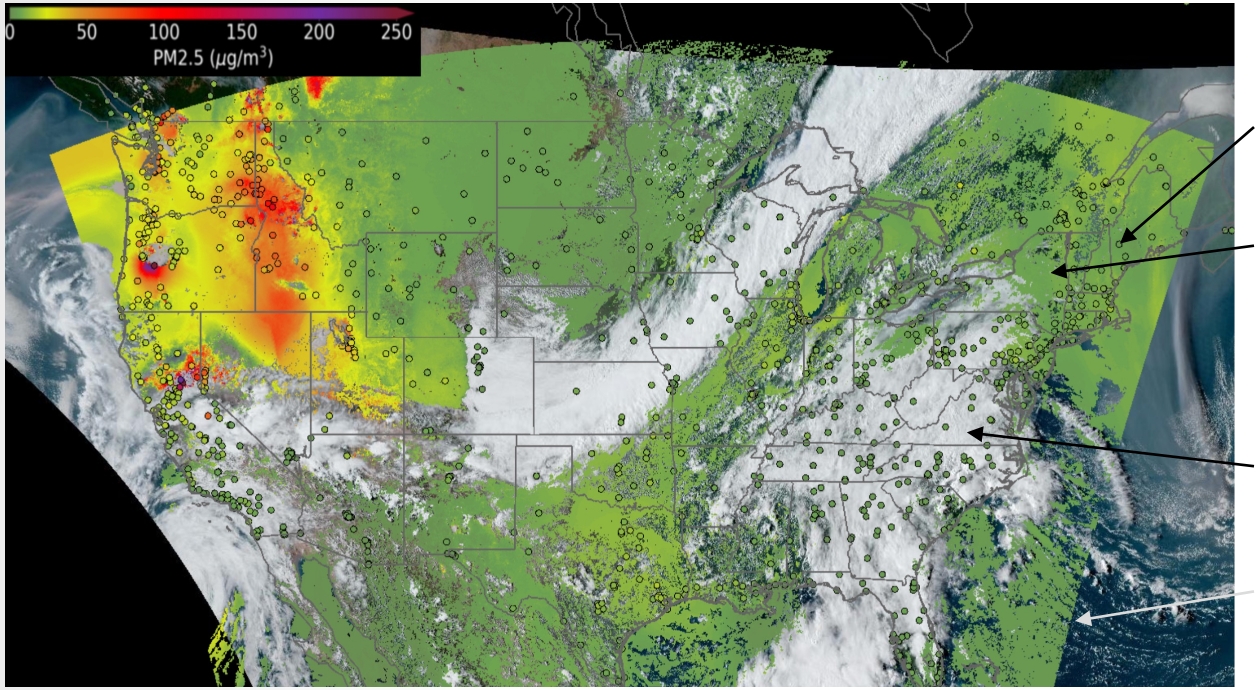
correlation between Satellite AOD and individual LCS $PM_{2.5}$ Mostly Poor ($R < 0.6$)

calibrated Satellite AOD with LCS over the region

Poor individual LCS to AOD agreement
Regional LCS and AOD more useful
AOD+LCS PM agrees with EPA data

Source: Gupta et al. (2018). "Impact of California Fires on Local and Regional Air Quality: The Role of a Low-Cost Sensor Network and Satellite Observations". GeoHealth 2:6. DOI: 10.1029/2018GH000136.

Surface $PM_{2.5}$ from Satellite AOD with GWR method



Surface $PM_{2.5}$ monitor data (ground truth)

Daily-average $PM_{2.5}$ map derived from geostationary satellite AOD information using Geographically Weighted Regression (GWR) method (van Donkelaar et al. 2015)

Gaps in $PM_{2.5}$ estimates due to dense smoke or clouds

Limit of geostationary satellite AOD observation area

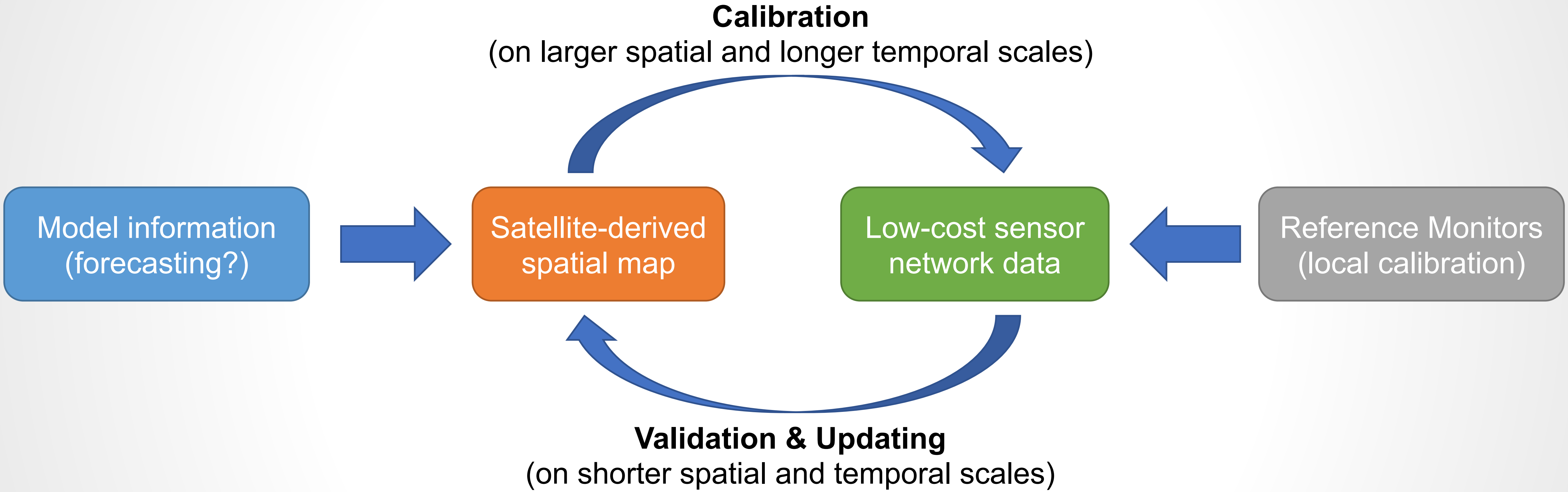
Screenshot of NOAA AerosolWatch (implemented for CONUS only)
https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/

Source: van Donkelaar, A., et al. (2015). "High-Resolution Satellite-Derived $PM_{2.5}$ from Optimal Estimation and Geographically Weighted Regression over North America." Environmental Science & Technology. DOI: 10.1021/acs.est.5b02076.

Zhang, H. & Kondragunta, S. (2021). "Daily and Hourly Surface $PM_{2.5}$ Estimation from Satellite AOD." Earth and Space Science. DOI: 10.1029/2020EA001599.

Geographic Weighted Regression
Requires reliable in-situ $PM_{2.5}$ data
Well-calibrated LCS *might* be used too

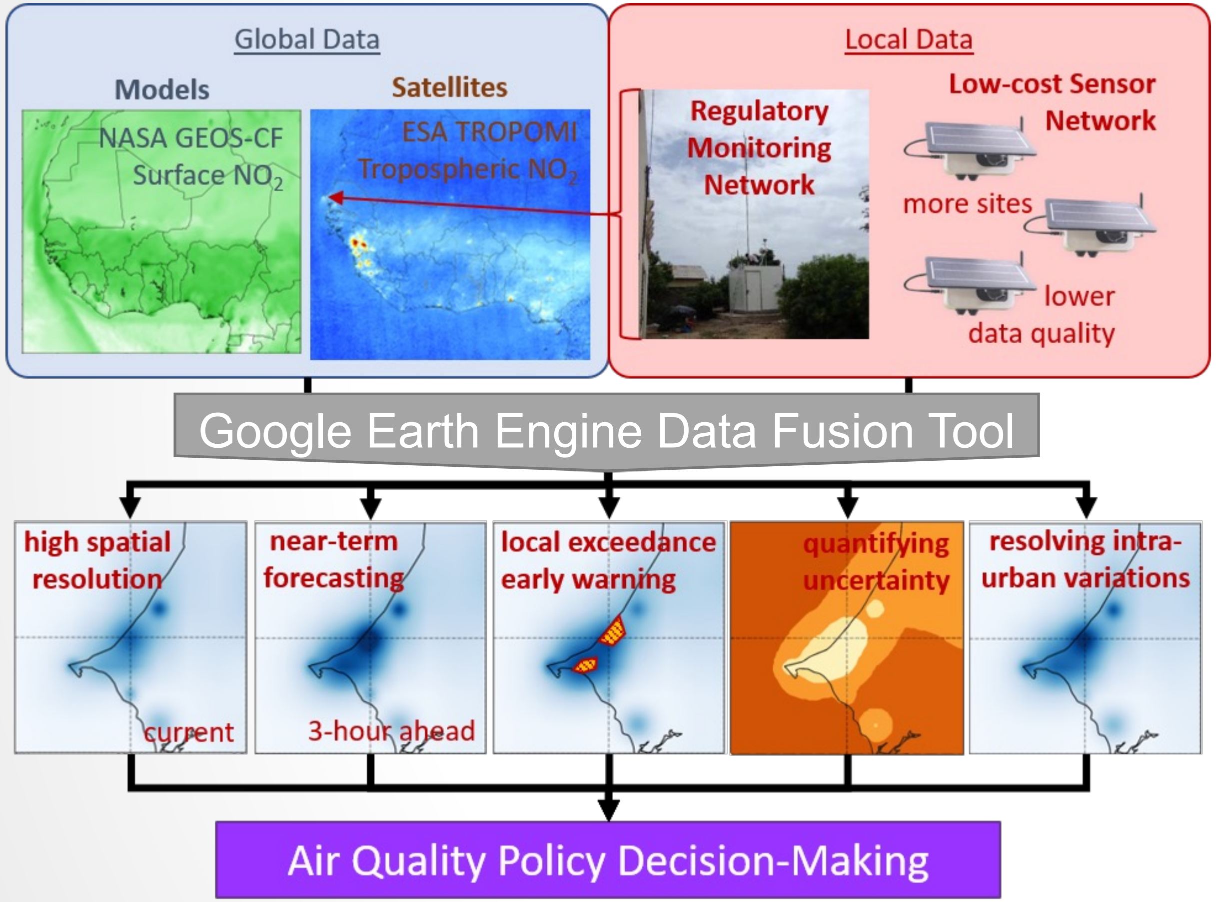
Integrating LCS into larger air quality assessments



Source: Malings, C., Knowland, K. E., Keller, C. A., Cohn, S. E. (2021). "Sub-city scale hourly air quality forecasting by combining models, satellite observations, and ground measurements." *Earth and Space Science*, 8, e2021EA001743. DOI: 10.1029/2021EA001743

Global Data (models & satellites) +
Local Data (references & LCS) =
Iterative comparison & calibration

Related ongoing work funded by NASA



NASA Earth Science Applications: Health and Air Quality

Supporting local government public health and air quality decision-making with a sub-city scale air quality forecasting system from data fusion of models, satellite, in situ measurements, and low-cost sensors.

Cities:
Dakar, **Senegal**
Rio de Janeiro, **Brazil**
Charleston, Denver, Boulder, Gulfport, Portland, **USA**

Collaborators:
US EPA
UN Environment Programme
Sonoma Technology, Inc.
Clarity Movement, Co.
Columbia University, WUSTL

Summary

- Low-Cost Sensors (LCS)
  - Advantages – increasing local high-time-frequency data availability around the world
  - Limitations – need for localized calibrations lead to uncertain and variable data quality
- Satellites
  - Advantages – global coverage with consistent long-term datasets
  - Limitations – once-a-day observations (from most satellites) of column (not surface) quantities
- Examples for Integrating LCS and Satellite Information
  - Opportunities – finding and classifying hotspots, trends, and sources, calibration, integration
  - Methods – qualitative and quantitative intercomparisons, regression, data fusion or assimilation
  - Case studies & results – COVID impacts, rural & urban disparities, wildfire smoke impacts
  - Challenges – data at different space and time scales, unknown "ground truth" in many cases

Thank You!

Questions & Comments?

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