Satellites and Low-Cost Sensors

Advantages, Limitations, and Opportunities for Integration

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Outline

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

Low-Cost IoT Air Sensors (LCS): Overview

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

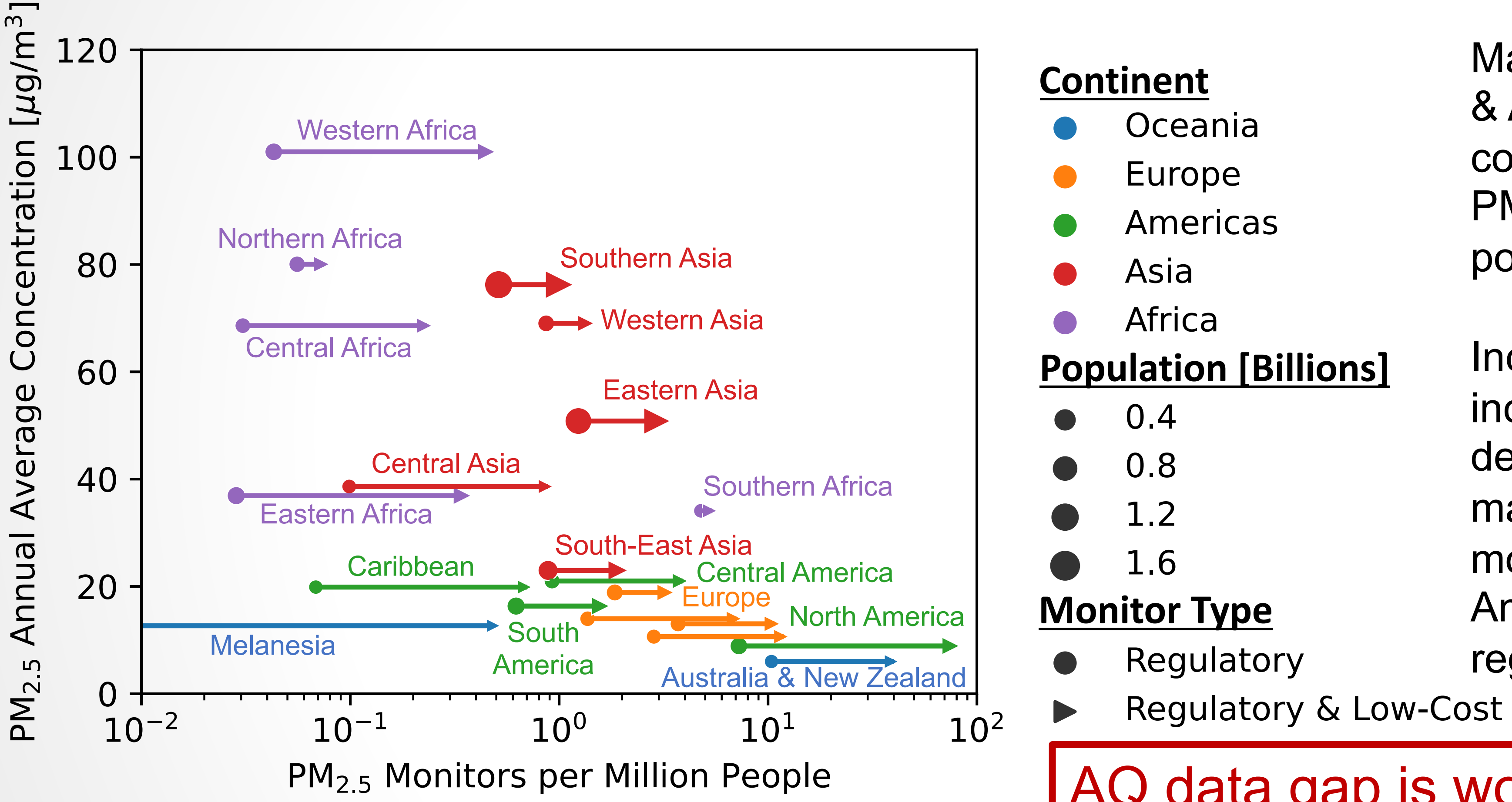
AirQo Binos: $PM_{2.5}$, PM_{10}, T, RH, P
airqo.net

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

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

LCS are an accessible tool to collect locally-relevant near-real-time AQ data
Local calibration & accuracy are issues

Low-Cost Sensors (LCS): Global Scope



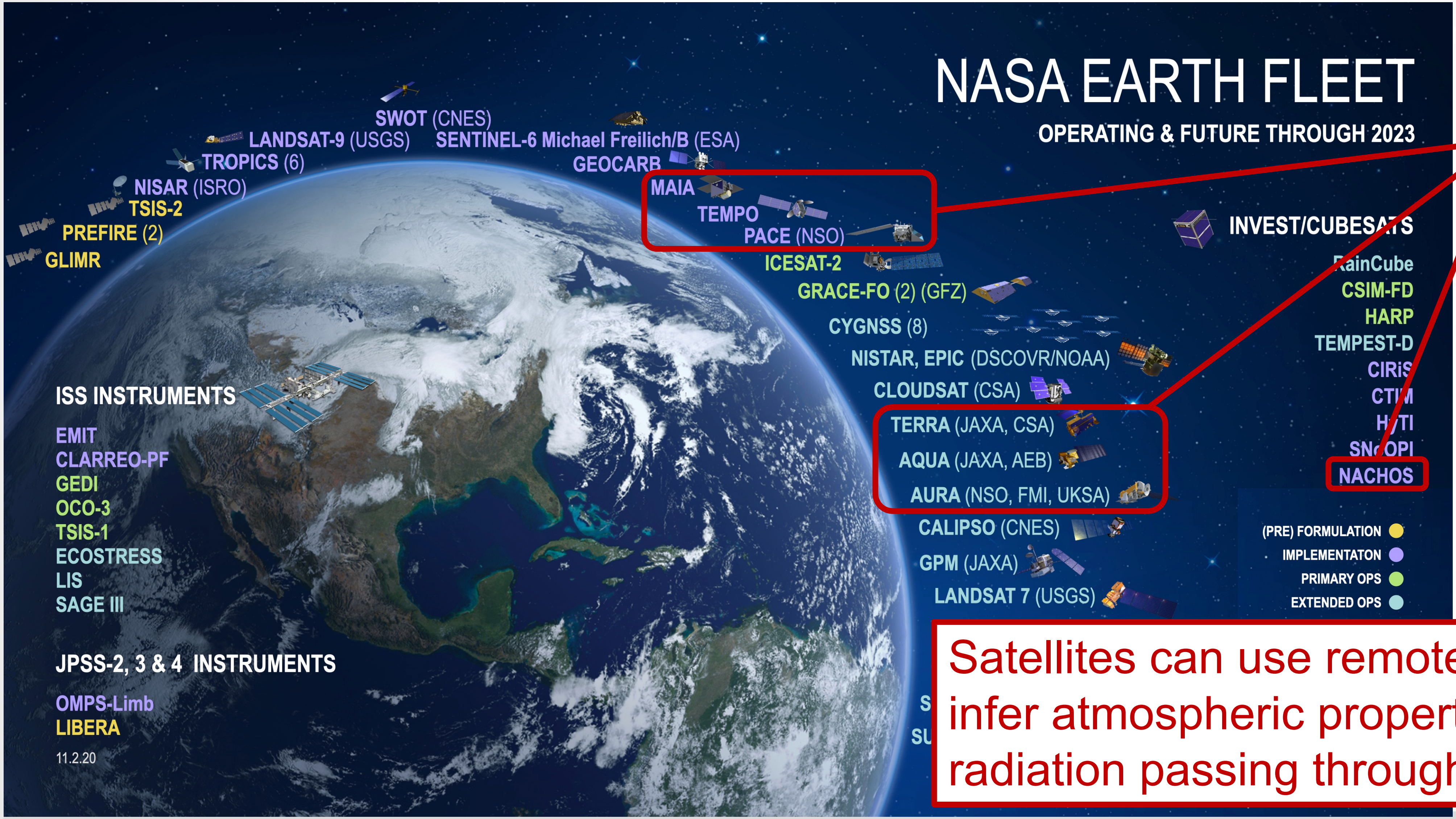
Many regions (especially Africa & Asia) feature high $PM_{2.5}$ concentration but low per-capita $PM_{2.5}$ monitor density, leading to poor AQ data coverage.

Including low-cost sensors increases per-capita AQ monitor density by up to an order of magnitude in both well-monitored regions (e.g., North America) and poorly monitored regions (e.g., East Africa).

Source: Malings et al. (2022). "Forecasting with the GEOS-CF System and Other NASA Resources to Support Air Quality Management." *Proceedings of the 2022 International Conference on Air Quality in Africa*.
Analysis based on openly available air quality data from https://openaq.org

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

Satellites



key NASA missions for air quality

key non-NASA missions

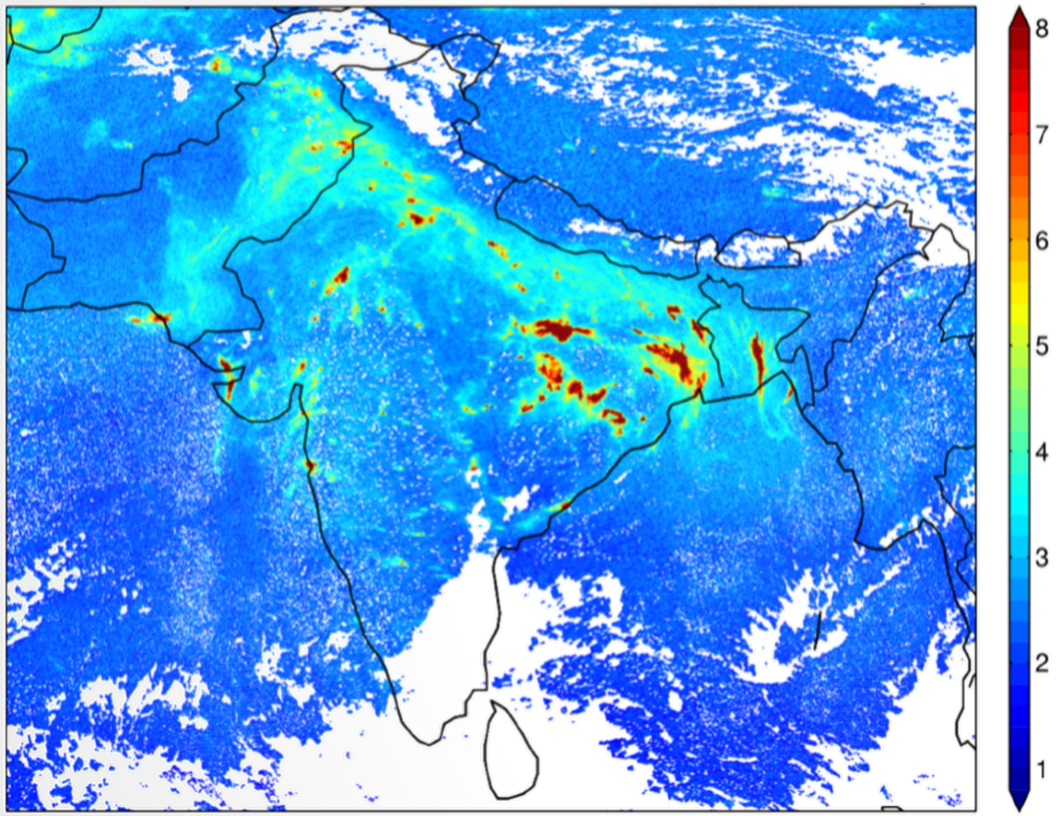
VIIRS (NOAA)
TROPOMI (ESA)
Meteosat (ESA)
GEMS (Korea)
Himawari (Japan)
& more…

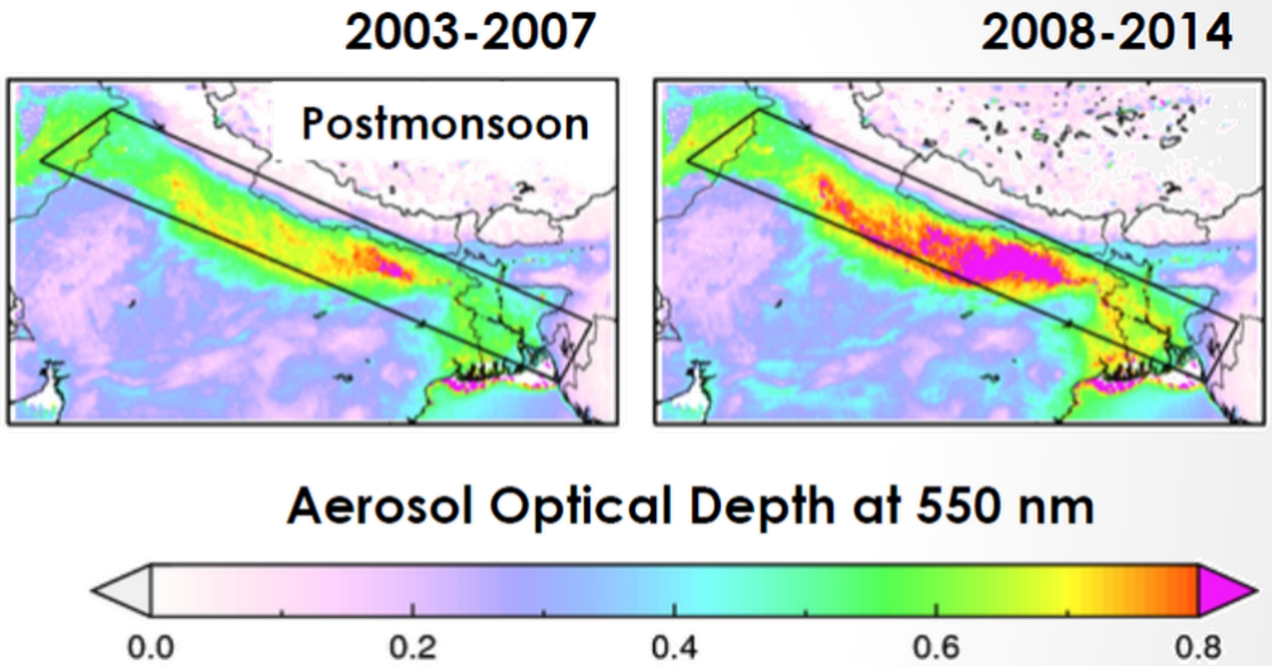
Source: [NASA Goddard Scientific Visualization Studio]

Satellites can use remote sensing to infer atmospheric properties from radiation passing through the air

What a satellite CAN do for air quality

TROPOMI NO_2 (Real Data)

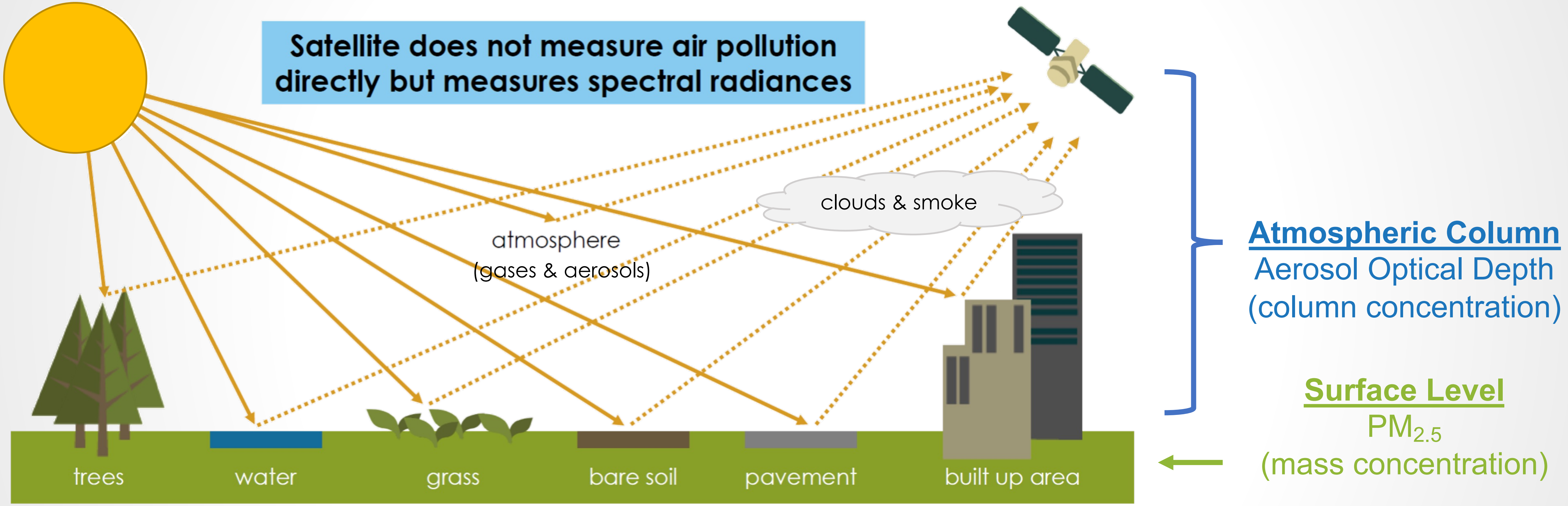




Source: Gupta, P.; Follette-Cook, M. (2018). Satellite Remote Sensing of Air Quality. NASA Applied Remote Sensing Training Program (ARSET). https://appliedsciences.nasa.gov/join-mission/training/english/arset-satellite-remote-sensing-air-quality

Satellites give wide global coverage
Can track regional transport and trends
Easy to "see for yourself" with maps

What a satellite CANNOT do for air quality

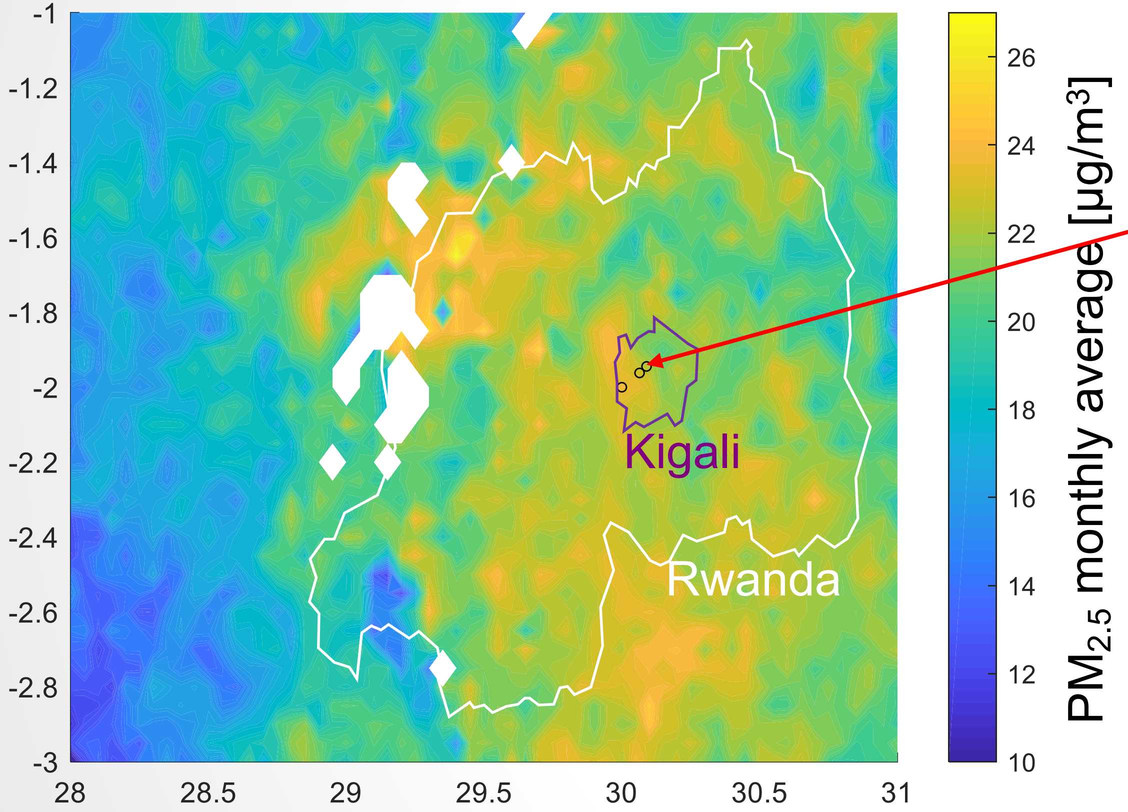


Source: Gupta, P.; Follette-Cook, M. (2018). Satellite Remote Sensing of Air Quality. NASA Applied Remote Sensing Training Program (ARSET). https://appliedsciences.nasa.gov/join-mission/training/english/arset-satellite-remote-sensing-air-quality

Satellites observe limited times of day
Satellites observe column quantities
May not relate to “nose-level” pollution

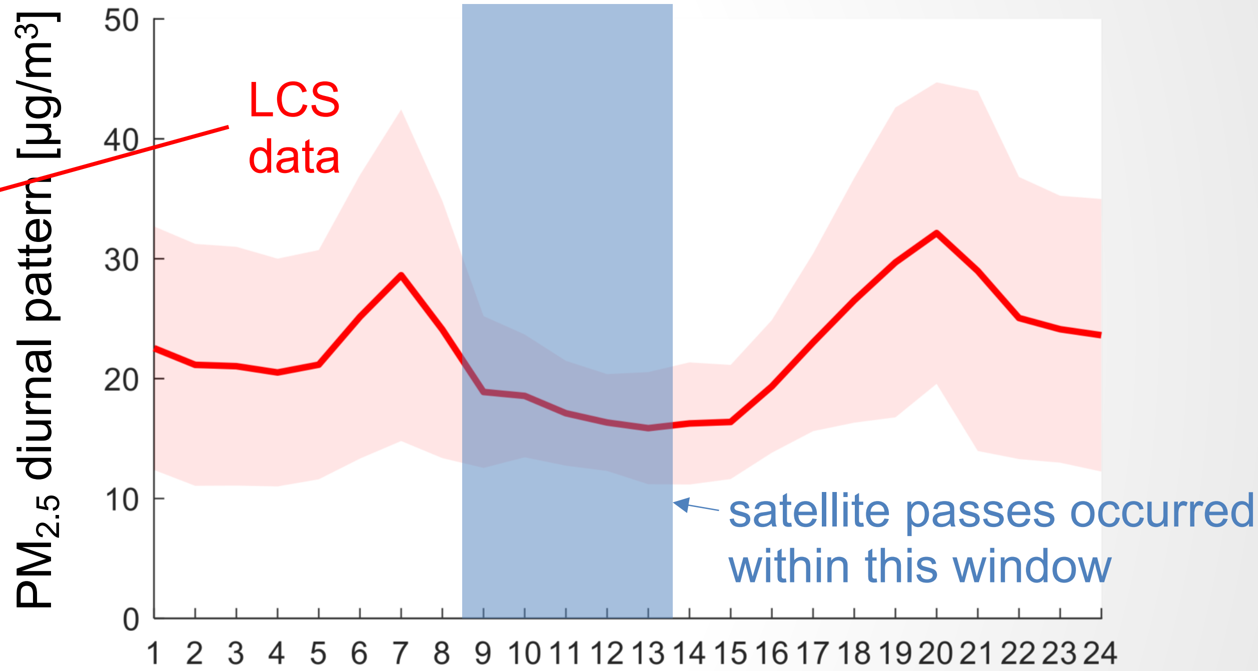
Satellites and LCS can be complementary

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

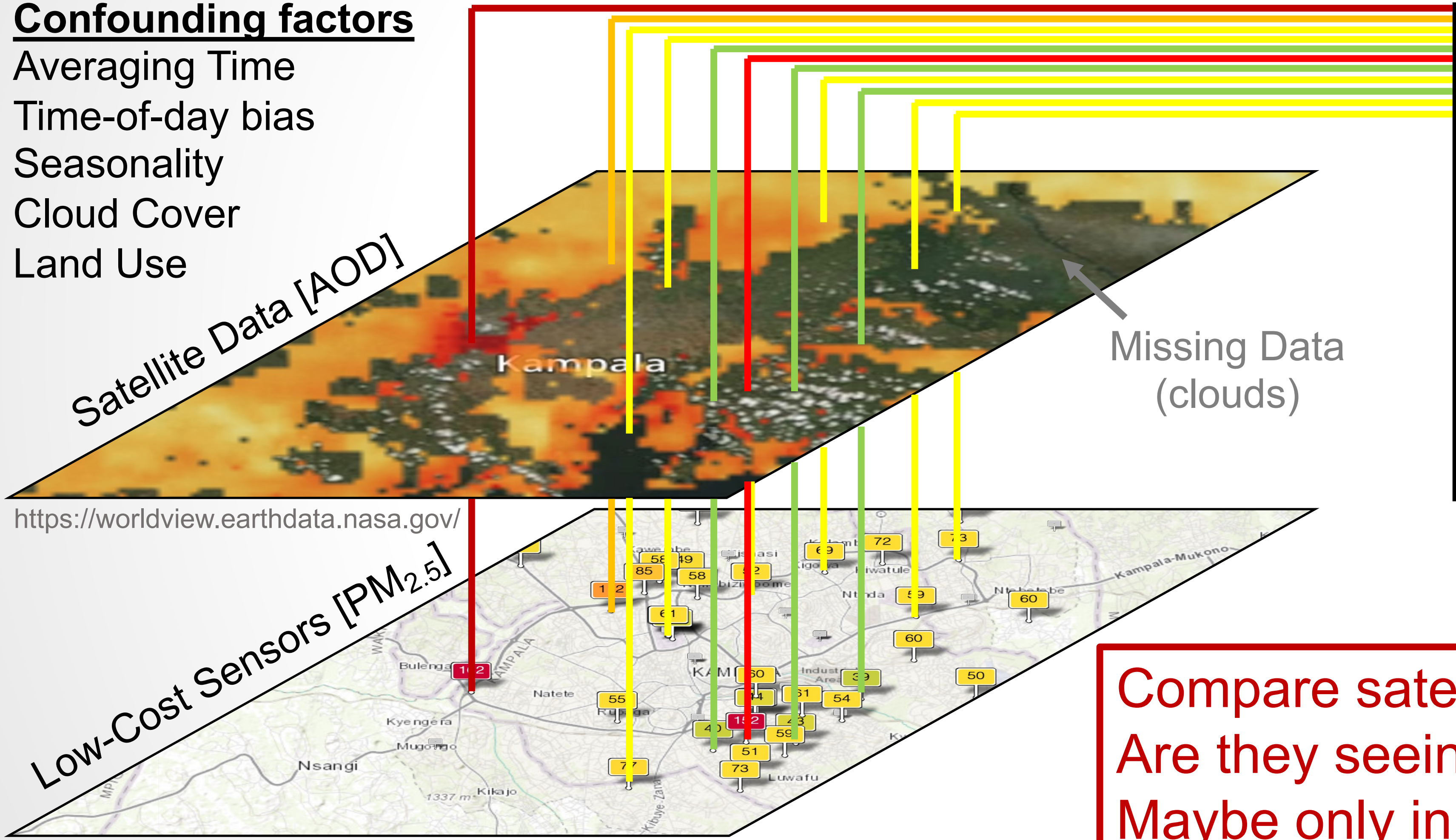
Integration of satellites and LCS with models and/or regulatory monitors for comprehensive AQ assessment

Harder

Spatial Correlations: do satellites capture patterns?

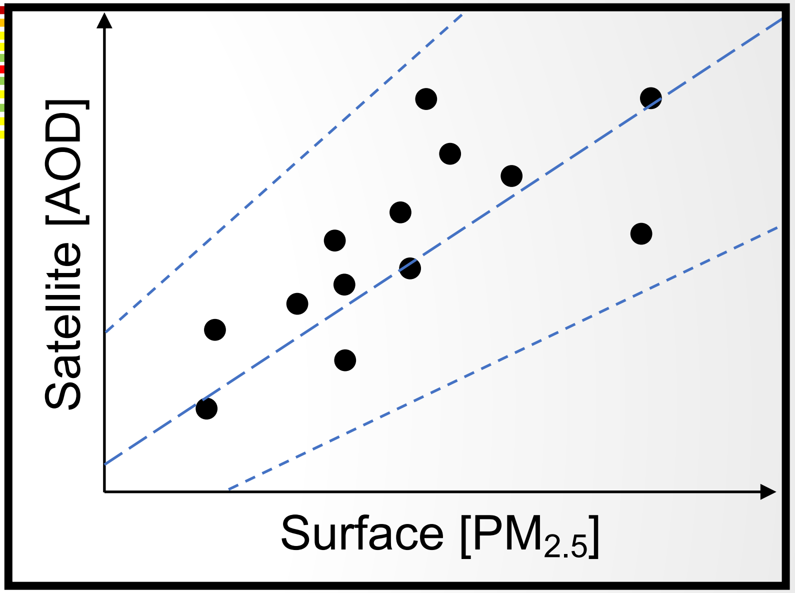
Confounding factors

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



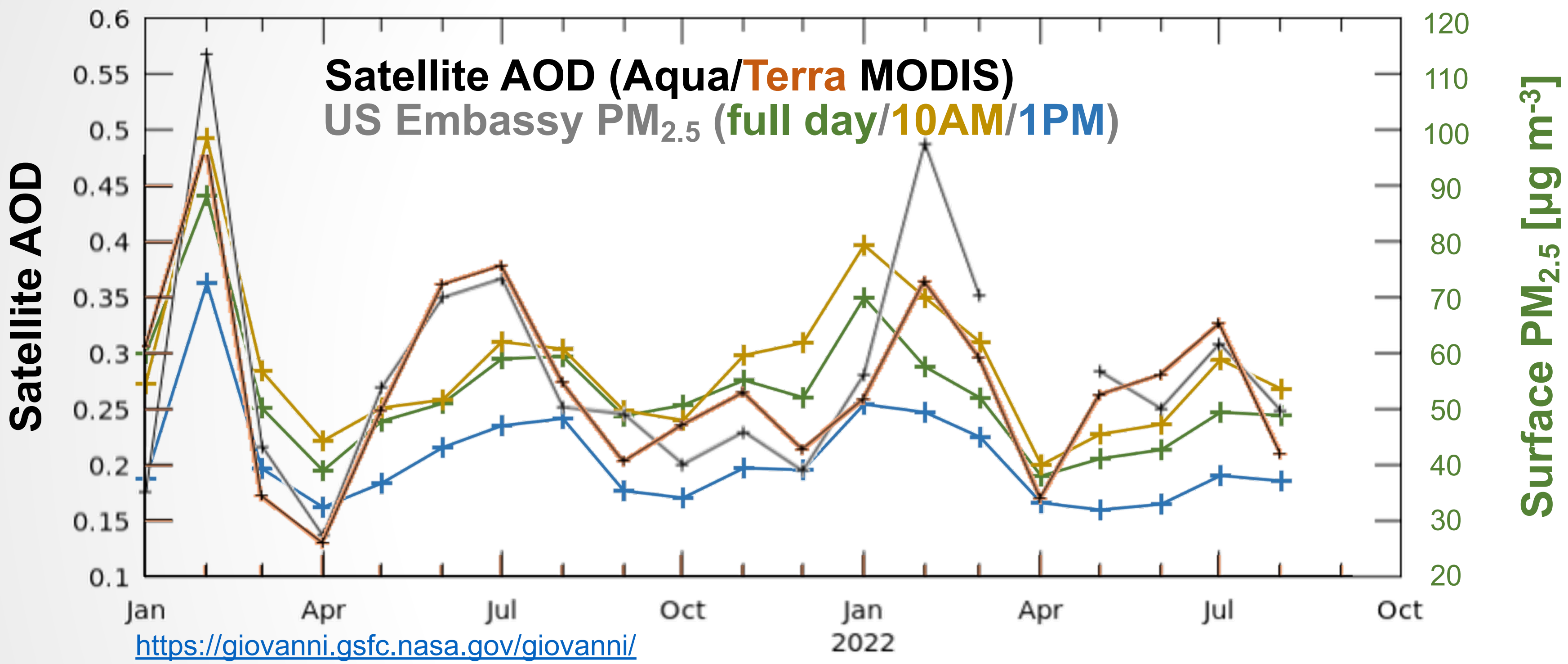
https://worldview.earthdata.nasa.gov/

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

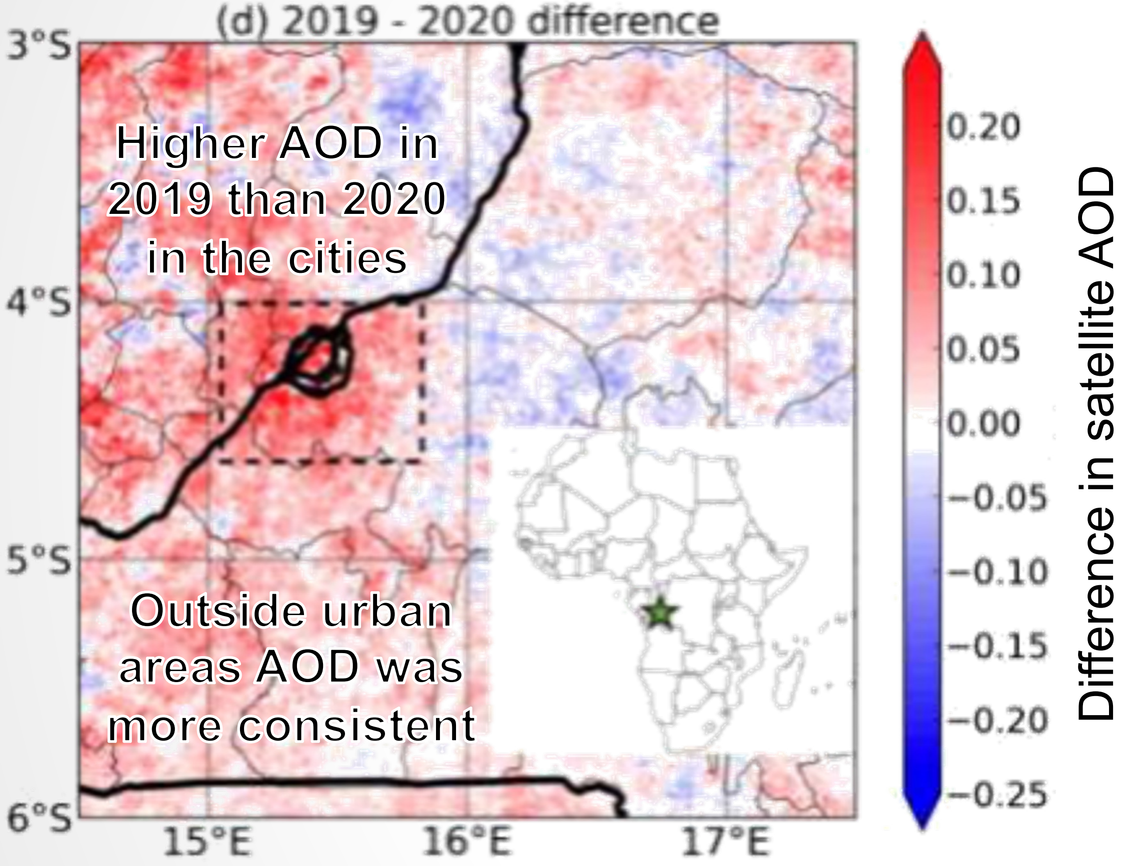
Averaging Area
Averaging Time
Time-of-day bias
Seasonality
Cloud Cover

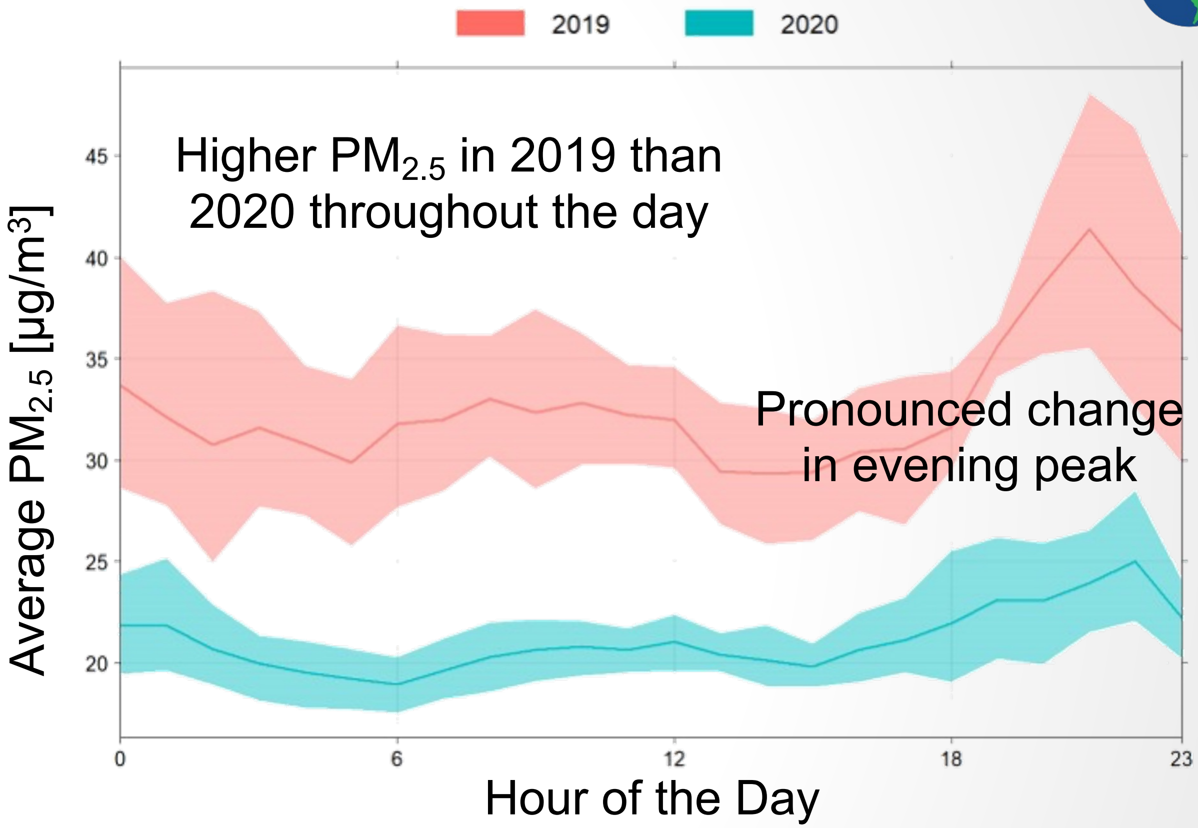
Example: trends in Kampala (0-1N,32-33E) for 1+ year

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

Qualitative: COVID-19 impact in Brazzaville & Kinshasa

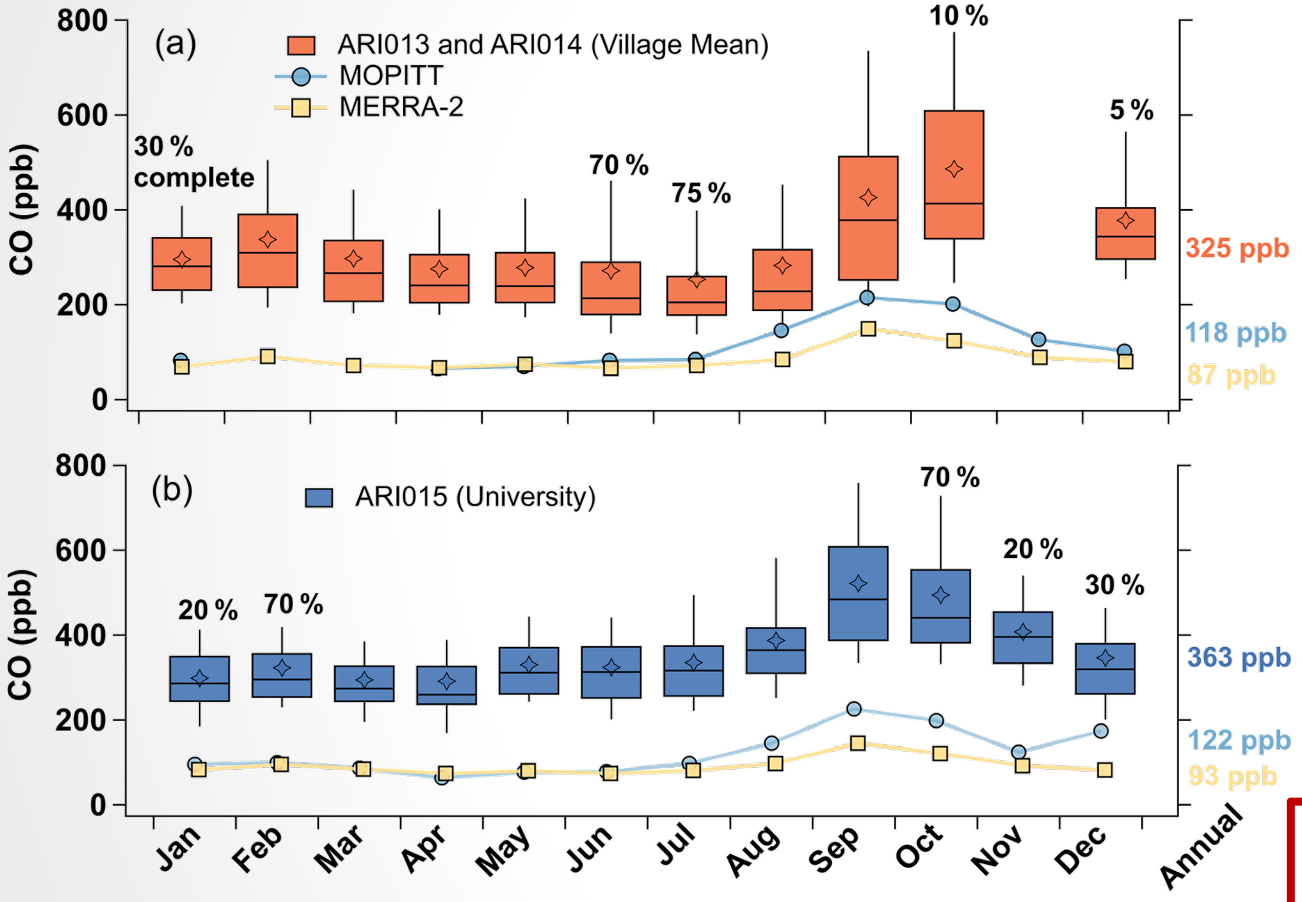




Source: McFarlane et al. (2021). "First Measurements of Ambient $PM_{2.5}$ in Kinshasa, Democratic Republic of Congo and Brazzaville, Republic of Congo Using Field-calibrated Low-cost Sensors." Aerosol and Air Quality Research, 21. DOI: 10.4209/aaqr.200619.

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)

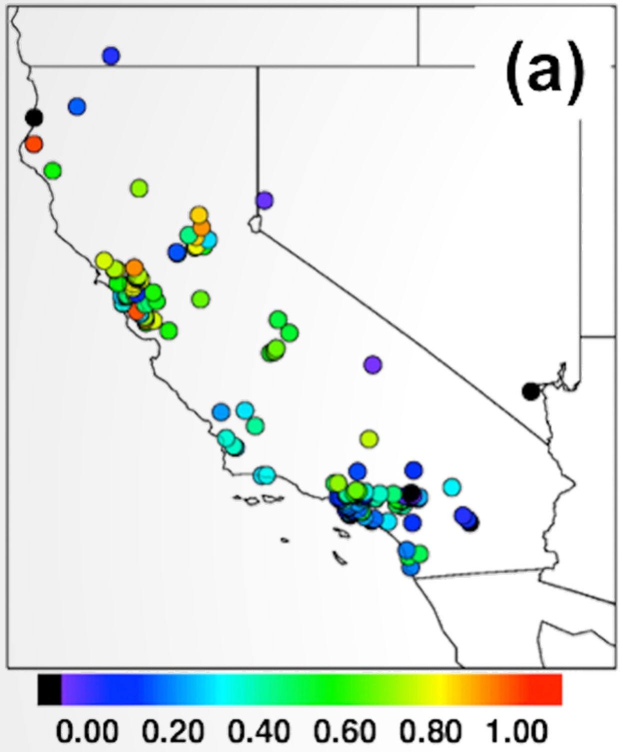
Data sources agree on trends
- Higher CO in urban than rural areas
- Higher CO in burning season (Aug-Nov)

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

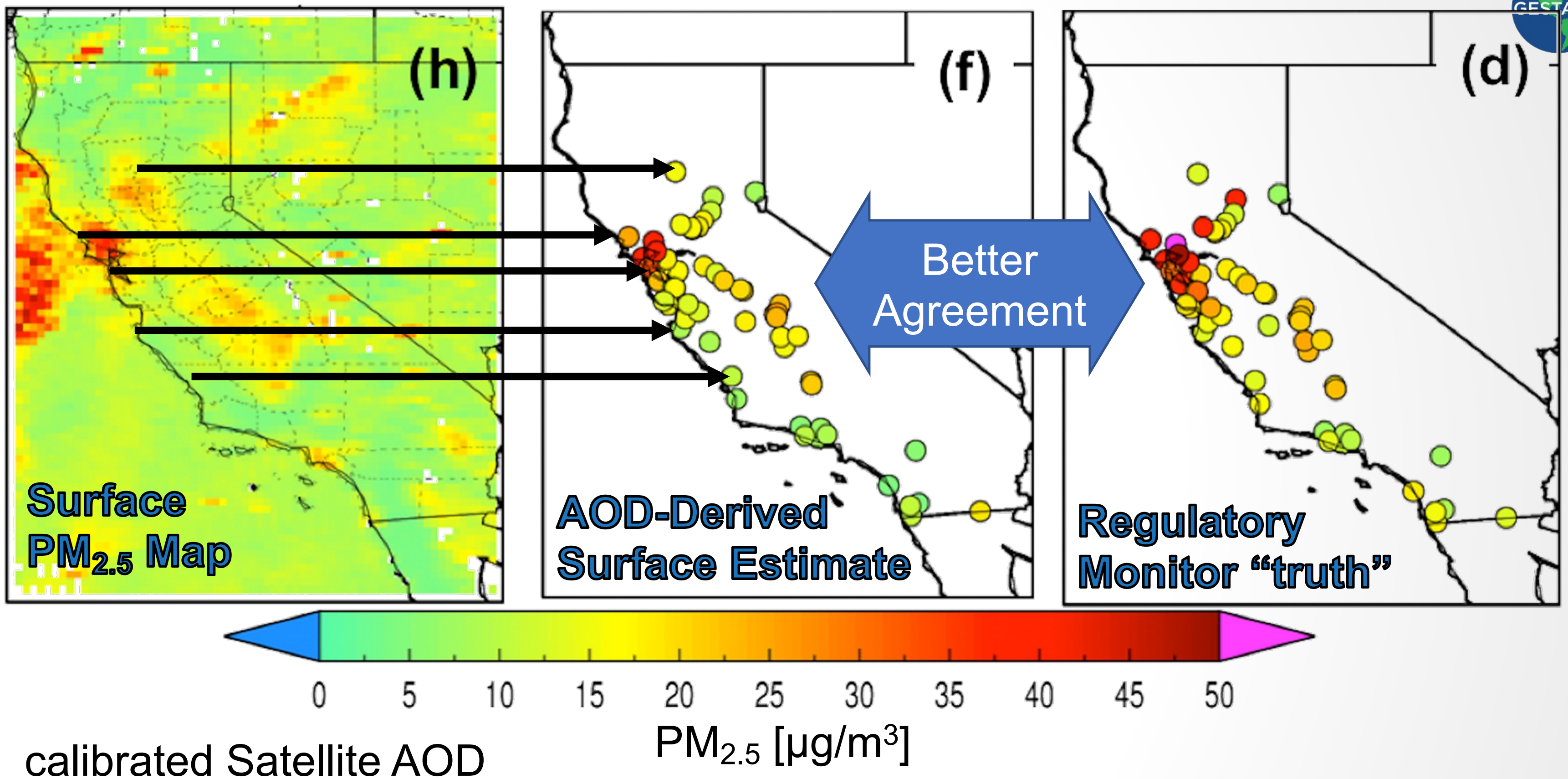
Numerous confounding factors
- No reference for region-specific LCS calibration
- Hyper-local sources (cooking, traffic)
- Once-daily MOPITT satellite passes

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



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

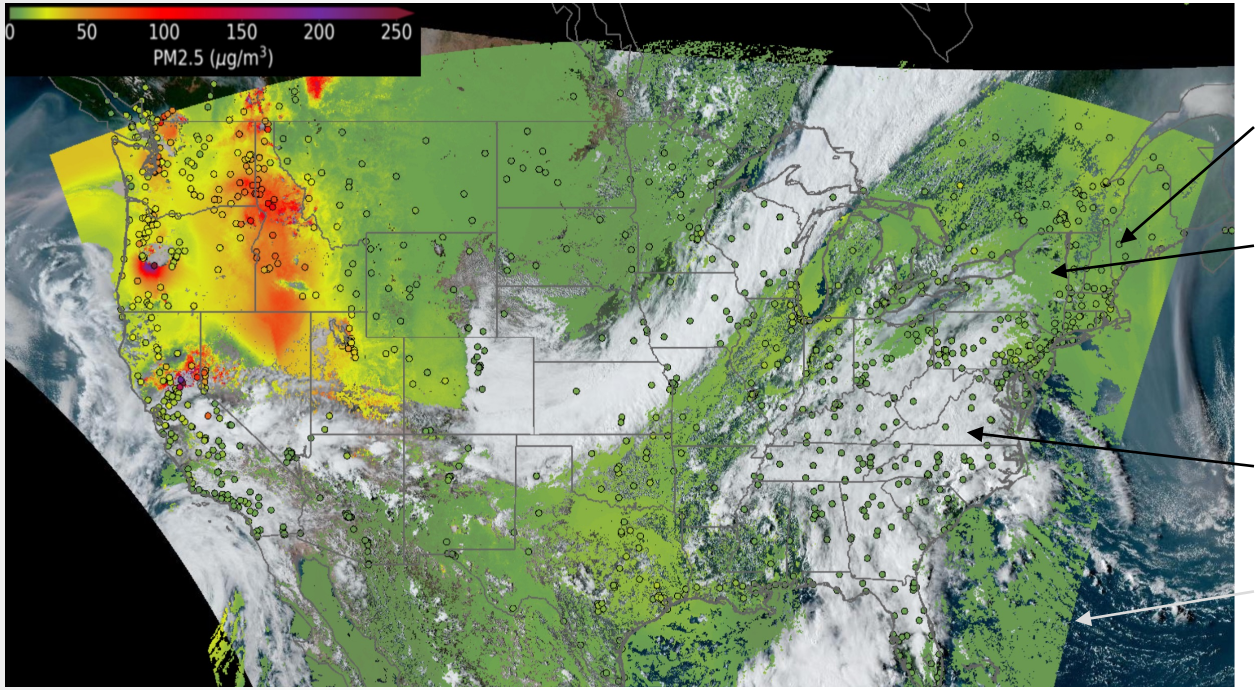


calibrated Satellite AOD with LCS over the region

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.

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

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

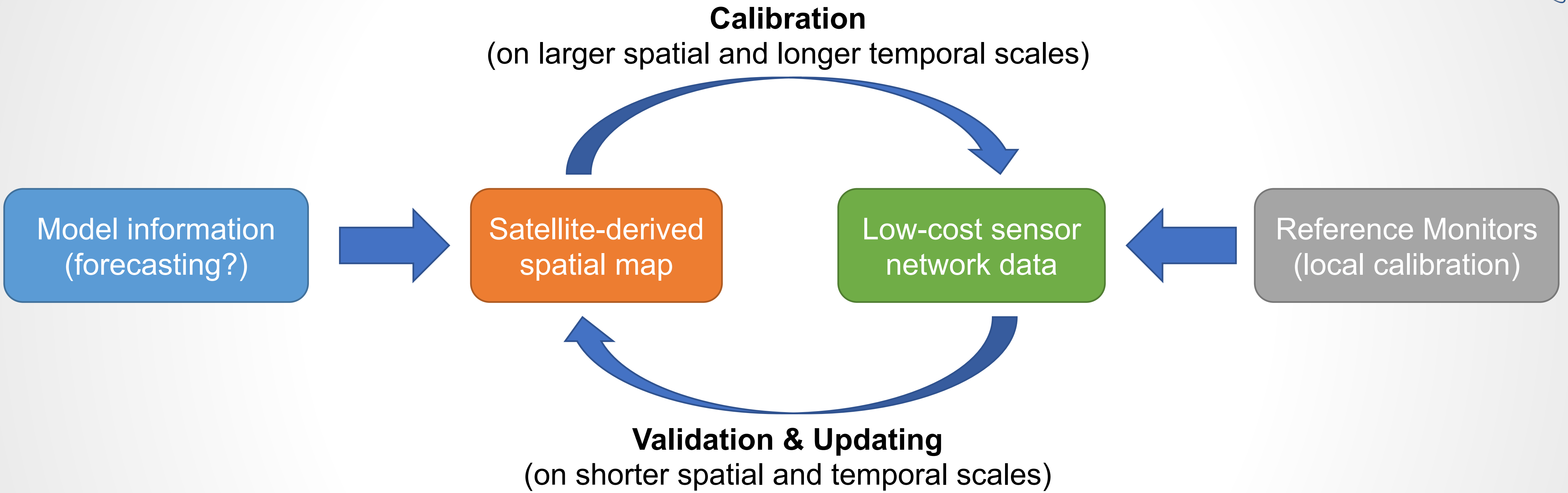
Screenshot of NOAA AerosolWatch (implemented for CONUS only)
https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/

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

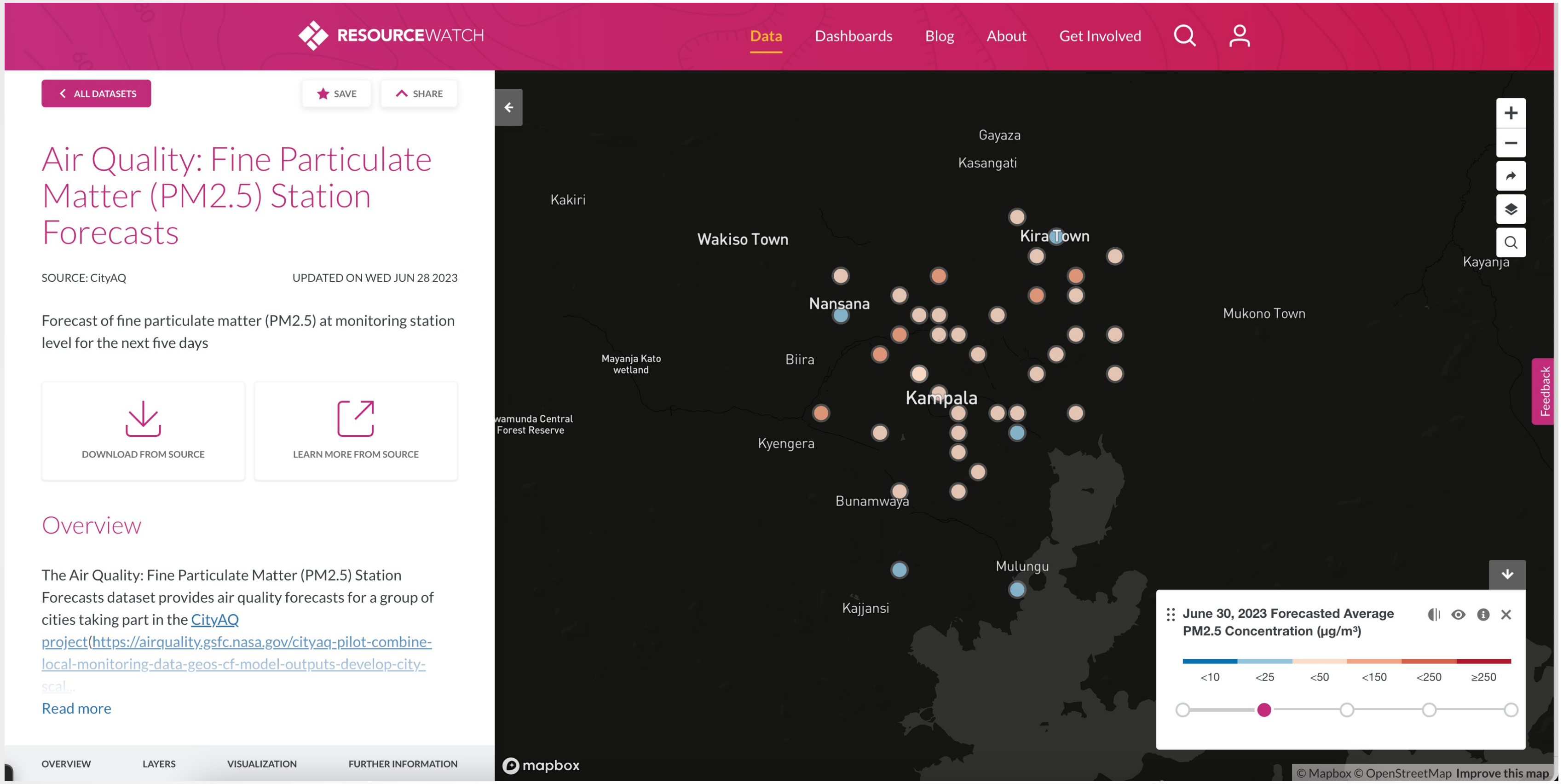
Integrating LCS into larger air quality assessments

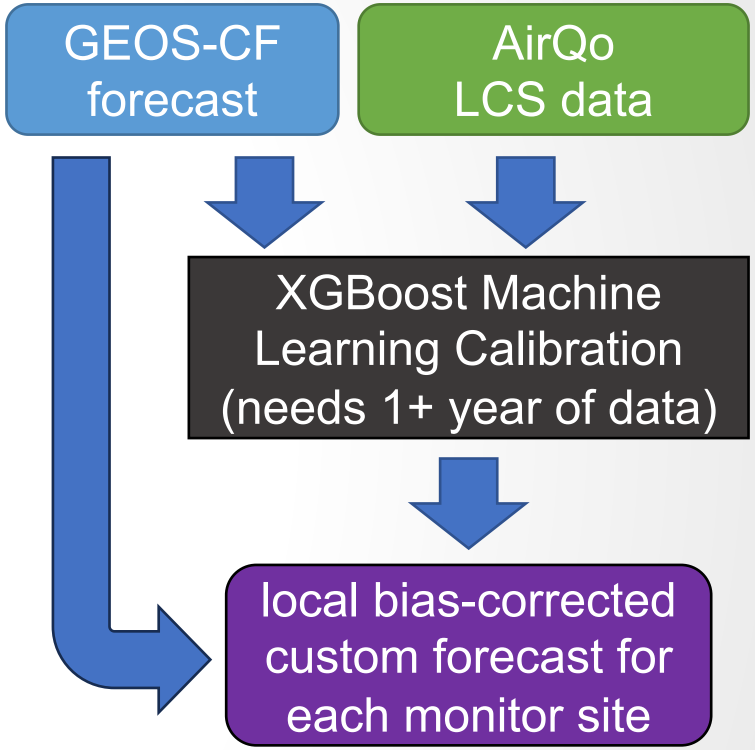


Source: Malings, C., Knowland, K. E., Keller, C. A., Cohn, S. E. (2021). “Sub-city scale hourly air quality forecasting by combining models, satellite observations, and ground measurements.” *Earth and Space Science*, 8, e2021EA001743. DOI: 10.1029/2021EA001743

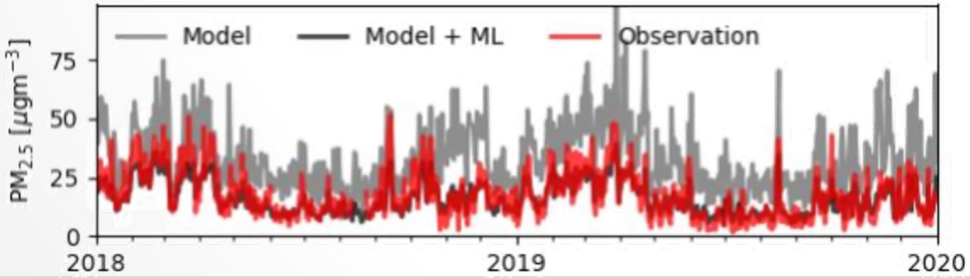
Global Data (models & satellites) +
Local Data (references & LCS) =
Iterative comparison & calibration

WRI CanAIRy Alert: bias-corrected model forecasts



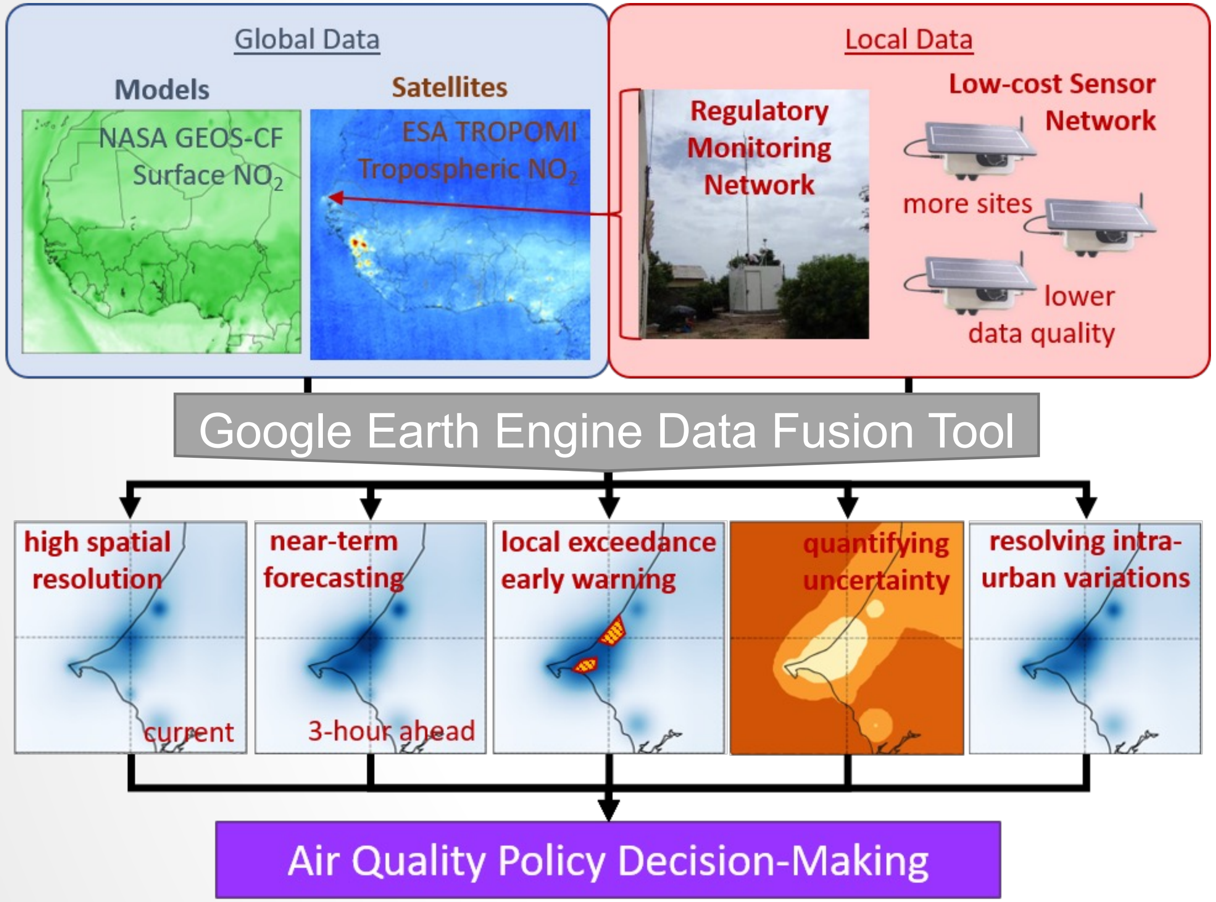


Source: World Resources Institute CanAIRy Alert https://www.wri.org/initiatives/canairy-alert



Global Model (GEOS-CF) forecast + Local LCS (AirQo) + XGBoost ML = bias-corrected local air quality forecast

Related ongoing work funded by NASA



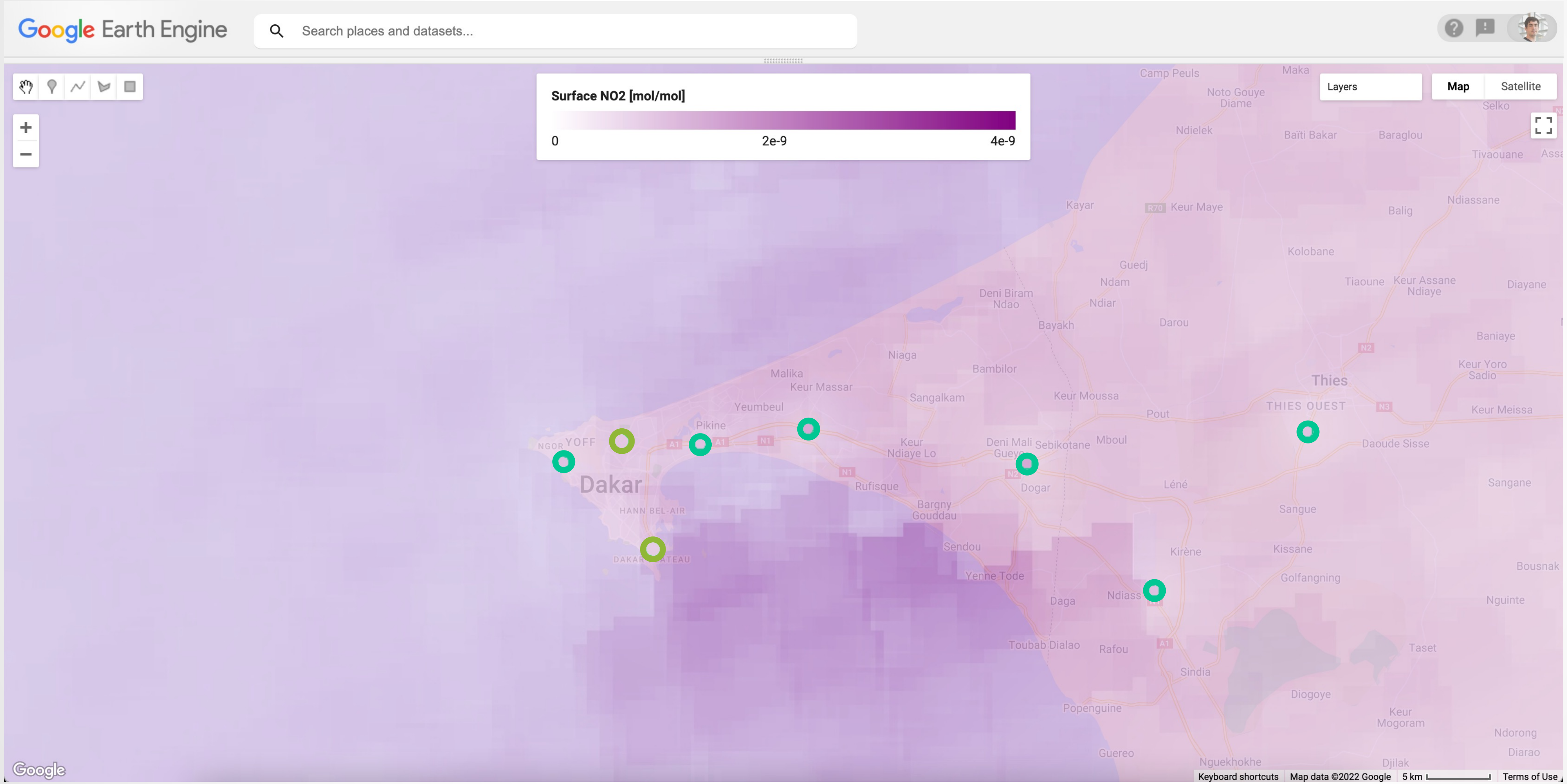
NASA Earth Science Applications: Health and Air Quality

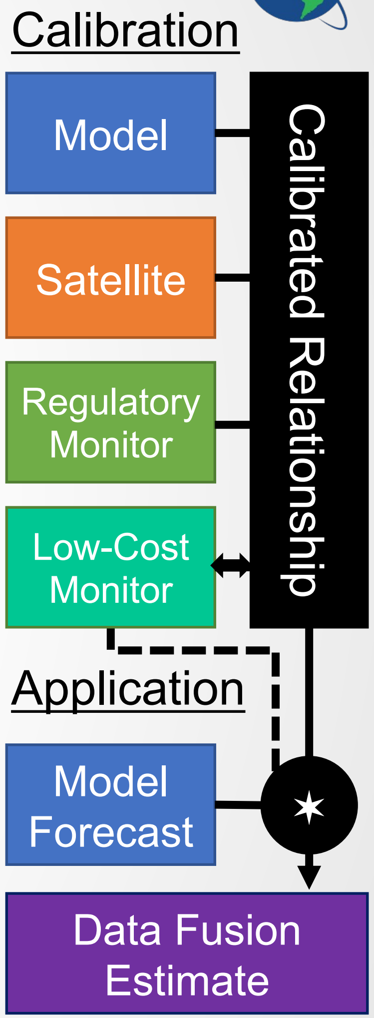
Supporting local government public health and air quality decision-making with a sub-city scale air quality forecasting system from data fusion of models, satellite, in situ measurements, and low-cost sensors.

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

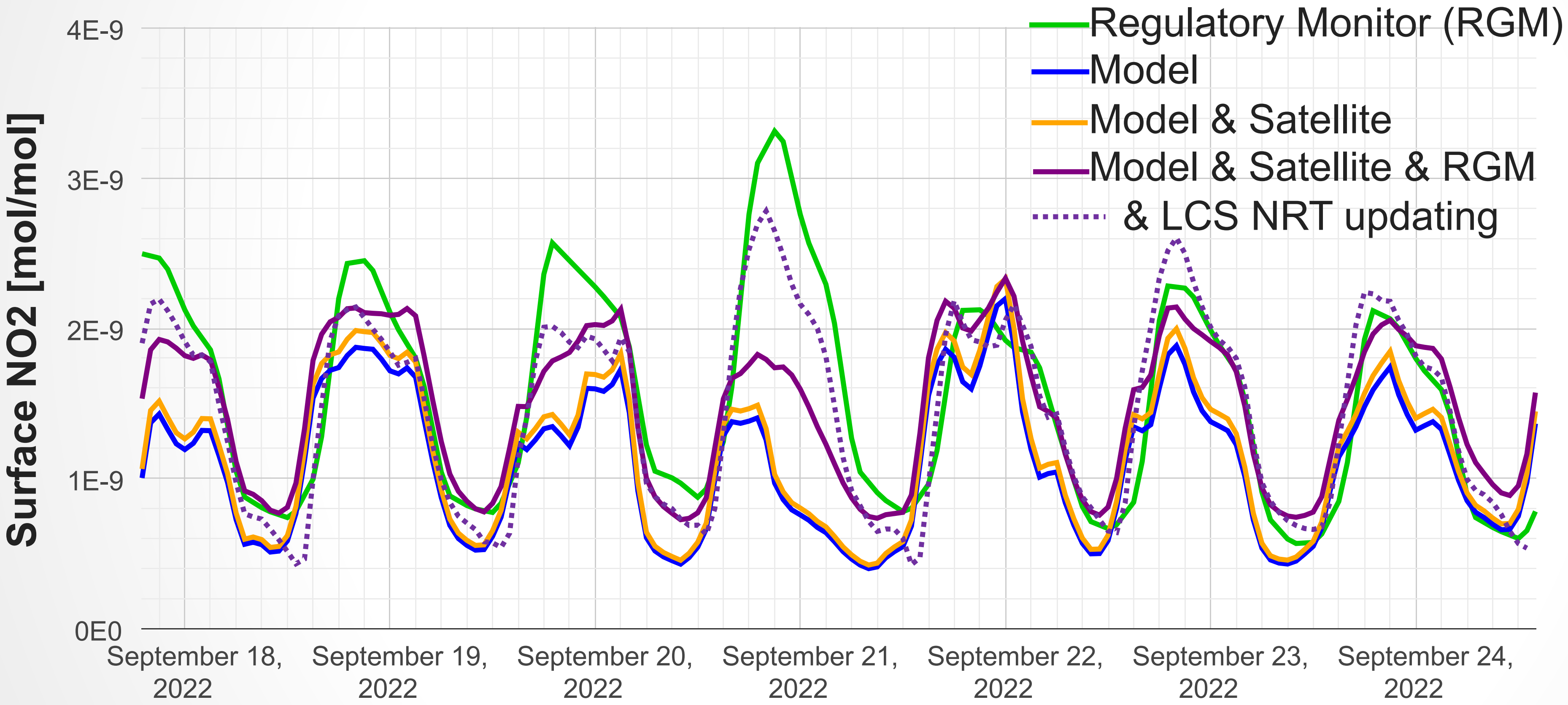
Data Fusion in Google Earth Engine (Prototype)

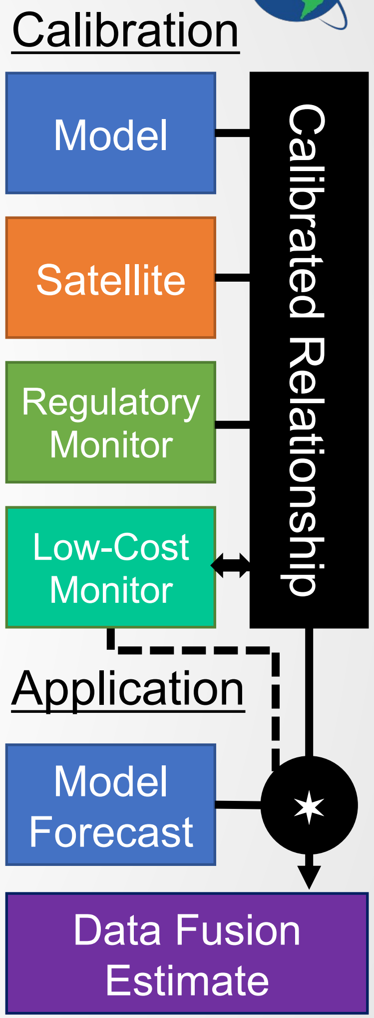




Data Fusion in Google Earth Engine (Prototype)

Comparison during Calibration Period





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

NASA Applied Remote Sensing Training (ARSET)

https://appliedsciences.nasa.gov/arset

ARSET provides accessible, relevant, and cost-free training on remote sensing satellites, sensors, methods, and tools.

Our trainings are:

- Online and in-person
- Open to everyone
- Live, instructor-led, or self-guided
- Provided at no cost, with materials and recordings available from our website
- Often multi-lingual
- Tailored to those with a range of experience in remote sensing, from **introductory** to **advanced**

APPLIED REMOTE SENSING TRAINING PROGRAM
TRAIN - EMPOWER - ADVANCE

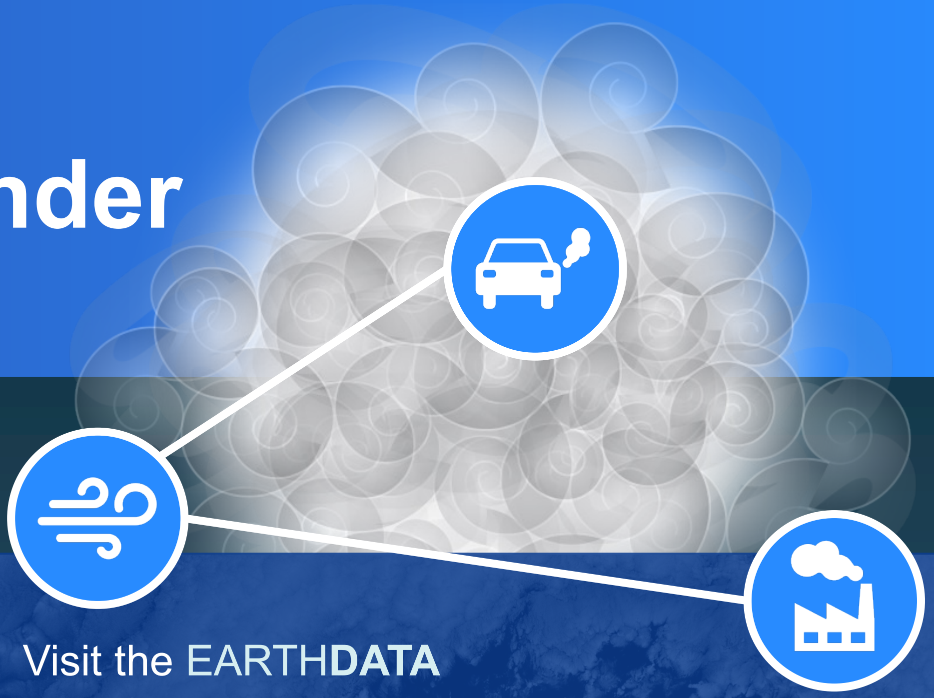
ARSET offers trainings for:

- Disasters
- Health & Air Quality
- Land Management
- Water Resources
- Climate

EARTH**DATA** Offers

The Air Quality Data Pathfinder

for Your Research & Applications



Air pollution is one of the largest global environmental and health threats. NASA provides data resources to better understand the movement of pollutants and the impact of events leading to poor air quality. This Pathfinder helps you access, and leverage data acquired from NASA's satellite, airborne, and ground-based missions and campaigns.

Available Data Types:

- Aerosols
- Trace Gases (e.g., Nitrogen Dioxide, Sulfur Dioxide, Carbon Monoxide, etc.)
- Weather (e.g., Air Temperature, Clouds, Precipitation, etc.)
- Land Surface (e.g., Soil Moisture, Surface Reflectance, Topography, etc.)
- Human Dimensions

Data are from satellites, airborne and ground-based platforms, and models, including:

- AIRS
- AMSR2
- GPM
- MODIS
- OLI/TIRS
- OMI
- OMPS
- SMAP
- TROPOMI
- VIIRS
- GEOS
- MERRA-2

Visit the EARTH**DATA**
Air Quality Data Pathfinder
for more information:

- Commonly Used Datasets for Air Quality Research and Applications
- Tools for Using Data
- Resources for Applying and Connecting NASA Data
- GIS Resources
- Tips for Getting Help and Connecting with NASA experts
- Tutorials and more!

Health and Air Quality Applied Science Team (HAQAST)

https://haqast.org/

"Our goal is to use NASA's data and satellites to pursue cutting edge applied research in order to keep you healthy and safe."

- Use NASA satellite & other data to help solve real-world public health and air quality problems.
- Work around the world on diverse issues related to health and air quality.
- Collaborate with public stakeholders to help guide long-term research.
- "Tiger Teams" pursue short-term, high-impact projects in small groups.

HAQAST

Getting started with NASA satellite data for health and air quality:
https://haqast.org/getting-started/

Thank You!