Air Quality Analysis with Sensors, Satellites, and Models

Carl Malings

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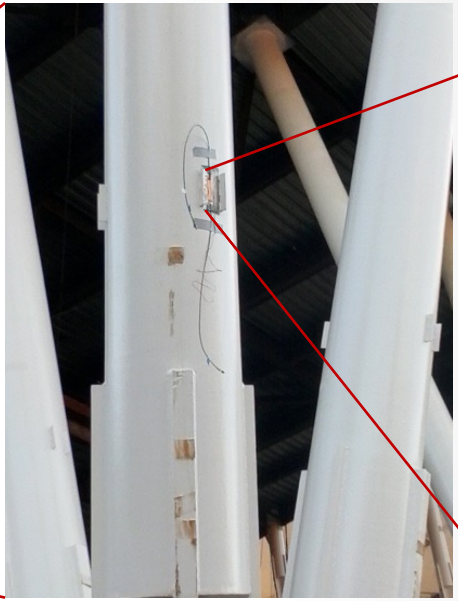
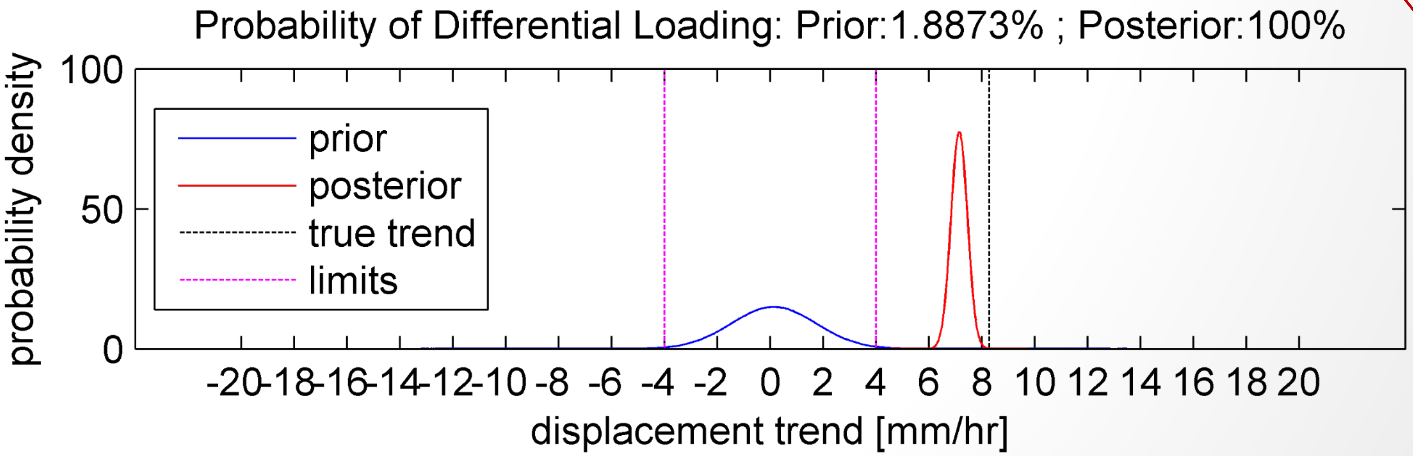
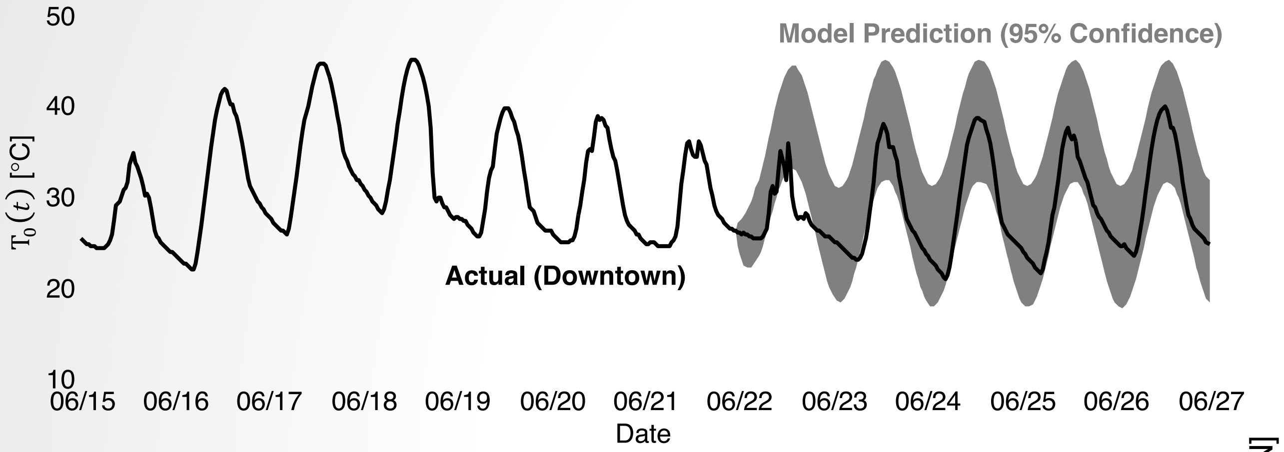
working in the Global Modelling and Assimilation Office (GMAO)
part of the Earth Sciences Division (ESD)
at the NASA Goddard Space Flight Center (GSFC)

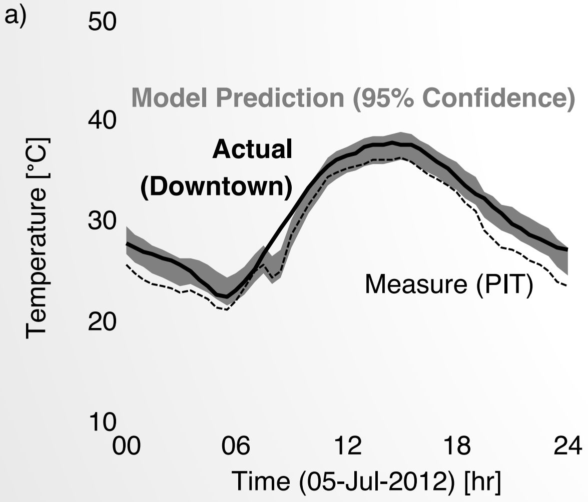
My background in Civil Engineering sensing optimization…

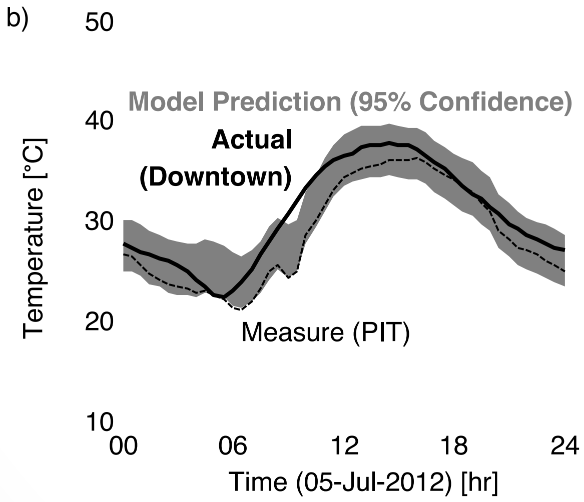


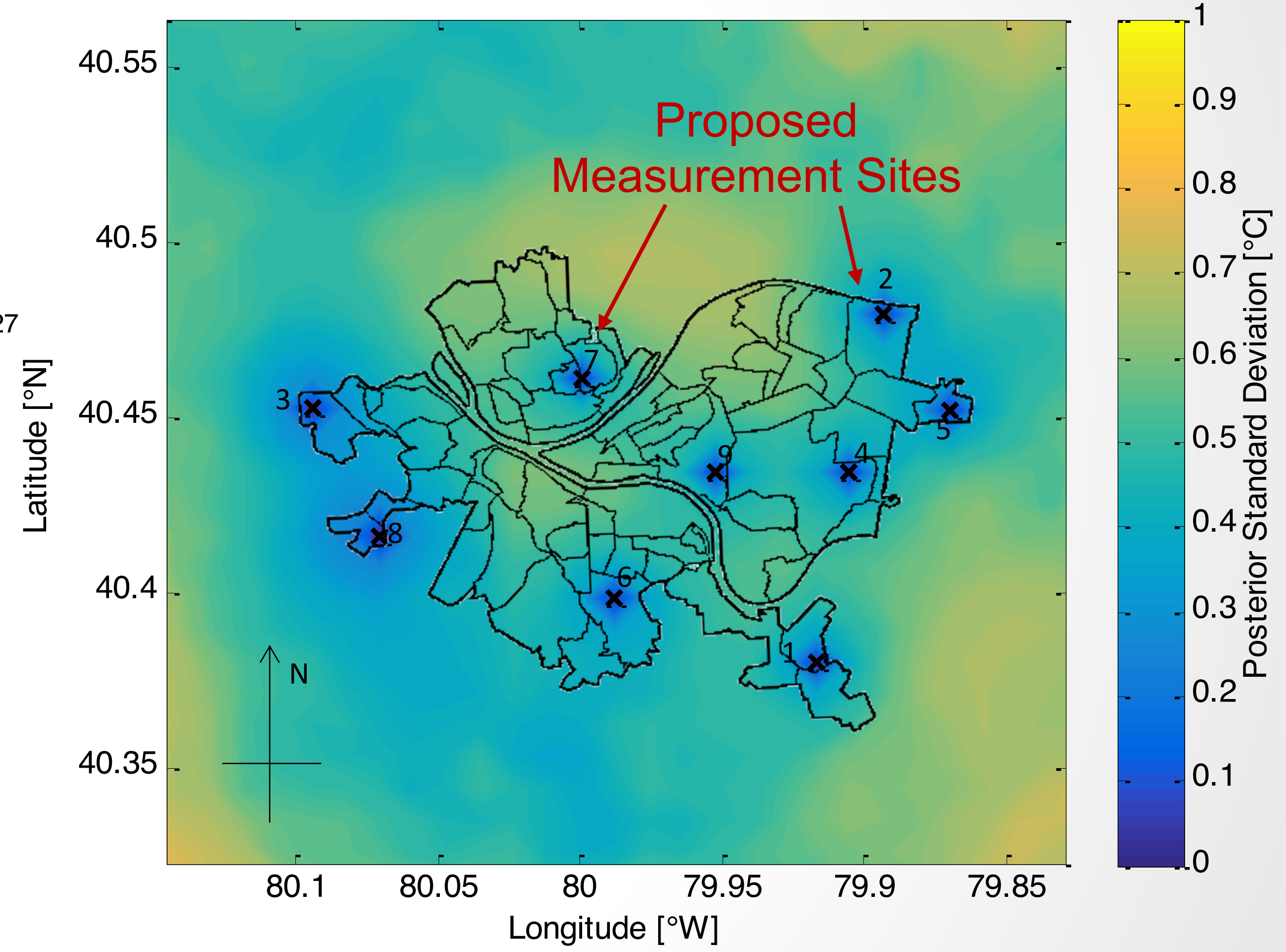


…and probabilistic random field modeling…





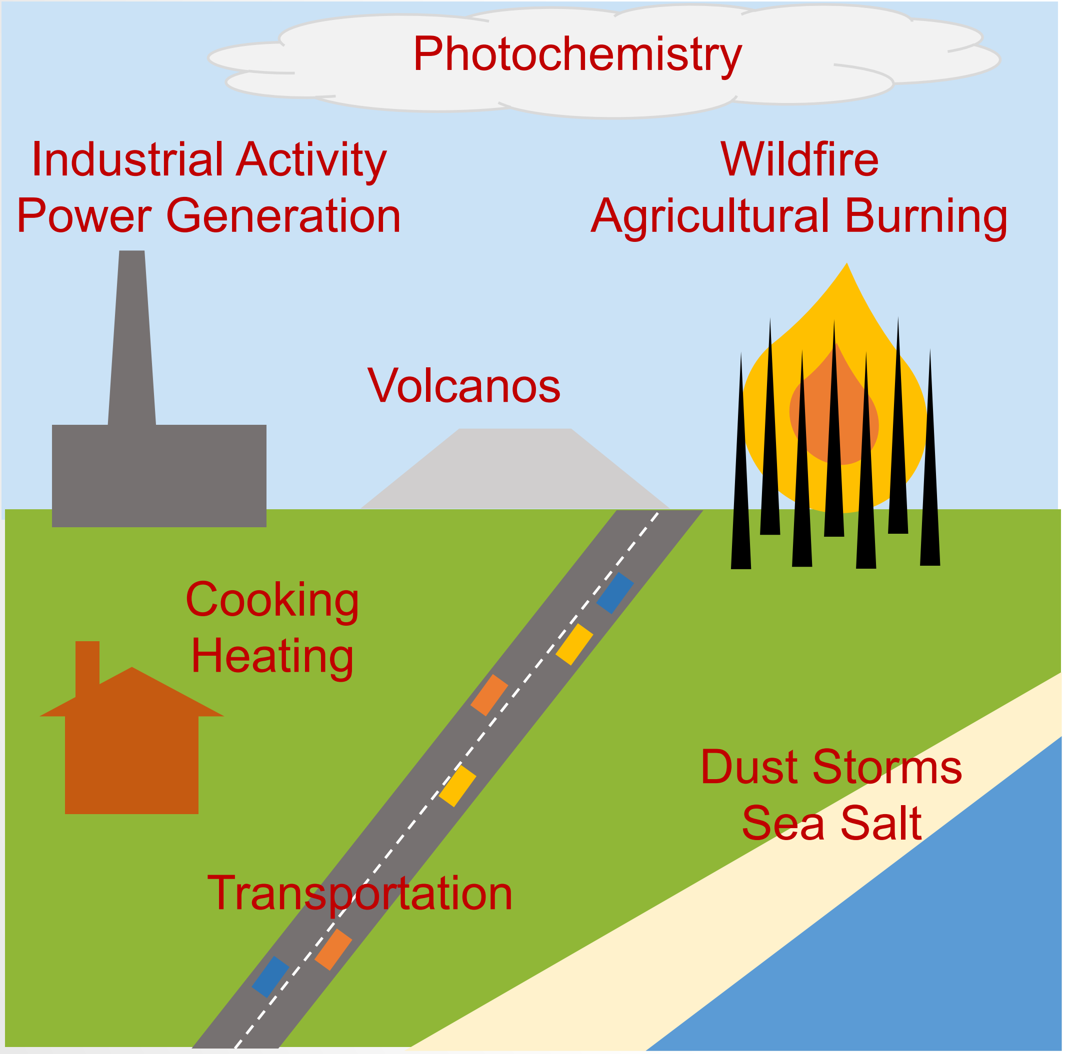




Source: Malings et al. (2018), "SHADE: Optimizing urban temperature monitoring" Building & Environment. DOI: 10.1016/j.buildenv.2018.05.059

…brought me to study Air Quality

What causes poor air quality, and how is it tracked?



US EPA Criteria Pollutants

Gases:
- NO_2 (Nitrogen Dioxide)
- O_3 (Ozone)
- CO (Carbon Monoxide)
- SO_2 (Sulfur Dioxide)

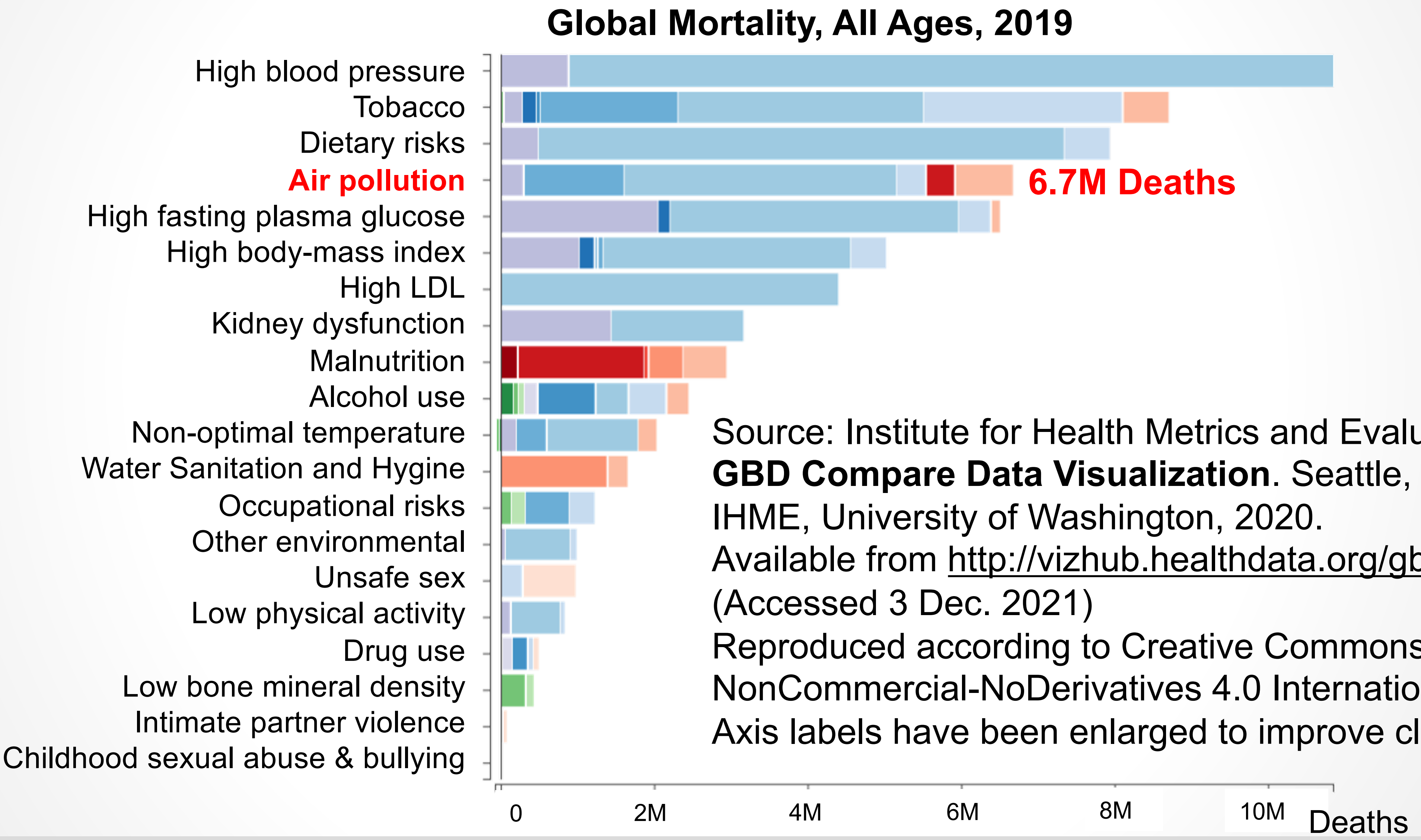
Particles:
- $PM_{2.5}$ (Fine Particulate Matter)
- PM_{10} (Coarse Particulate Matter)

Pb (Airborne Lead)

* Also covered by the WHO Global Air Quality Guidelines

Sources: https://www.epa.gov/criteria-air-pollutants/naaqs-table
https://apps.who.int/iris/handle/10665/345329

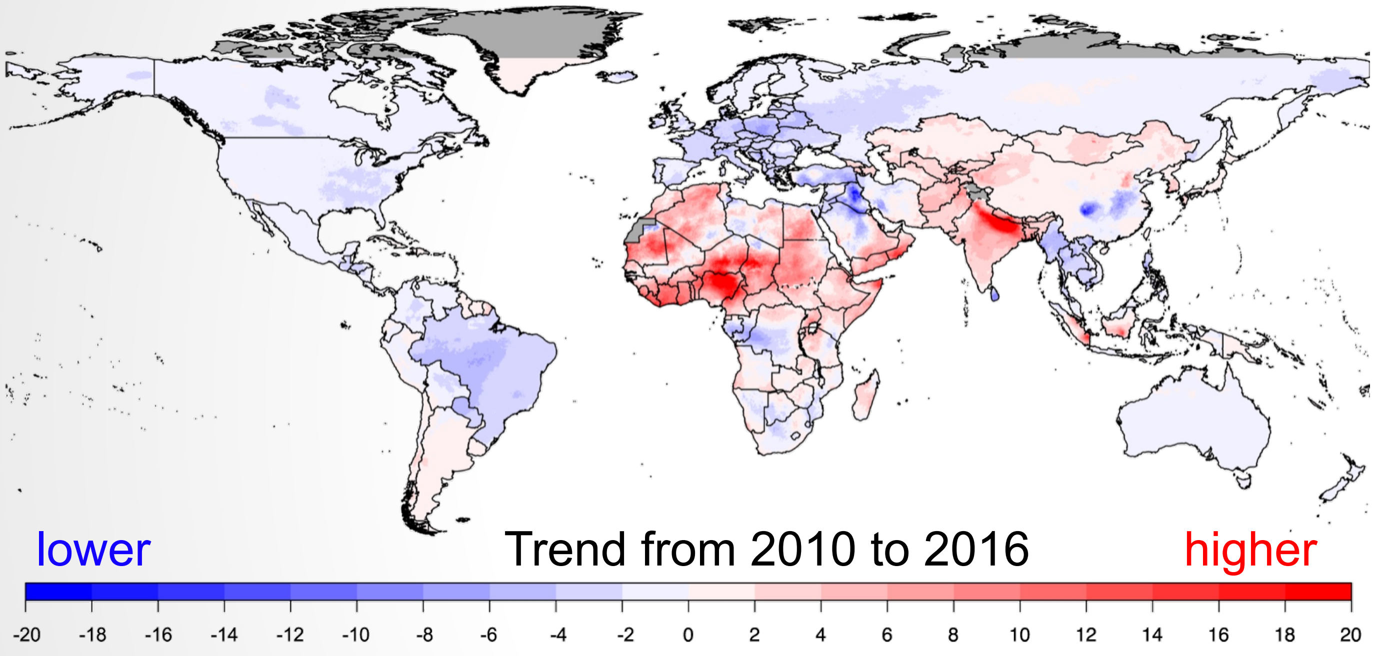
The global risks of poor air quality are severe…

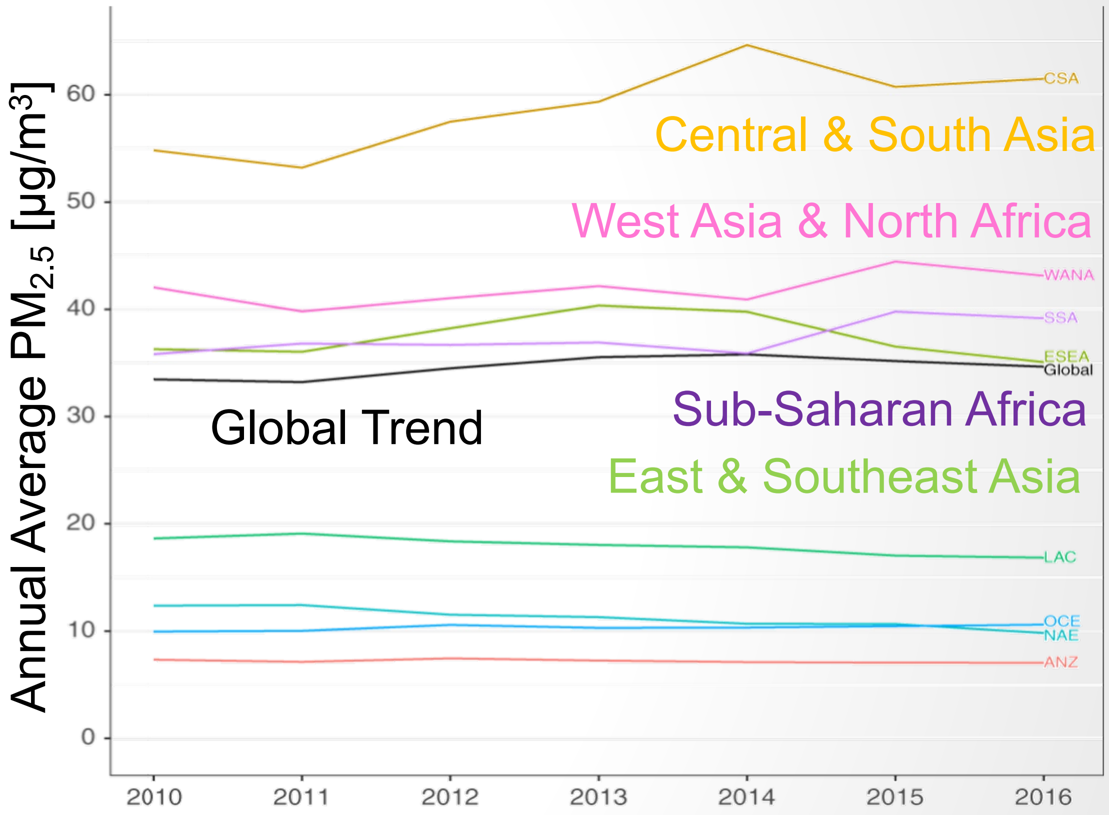


Source: Institute for Health Metrics and Evaluation (IHME). **GBD Compare Data Visualization**. Seattle, WA: IHME, University of Washington, 2020. Available from http://vizhub.healthdata.org/gbd-compare. (Accessed 3 Dec. 2021)

Axis labels have been enlarged to improve clarity.

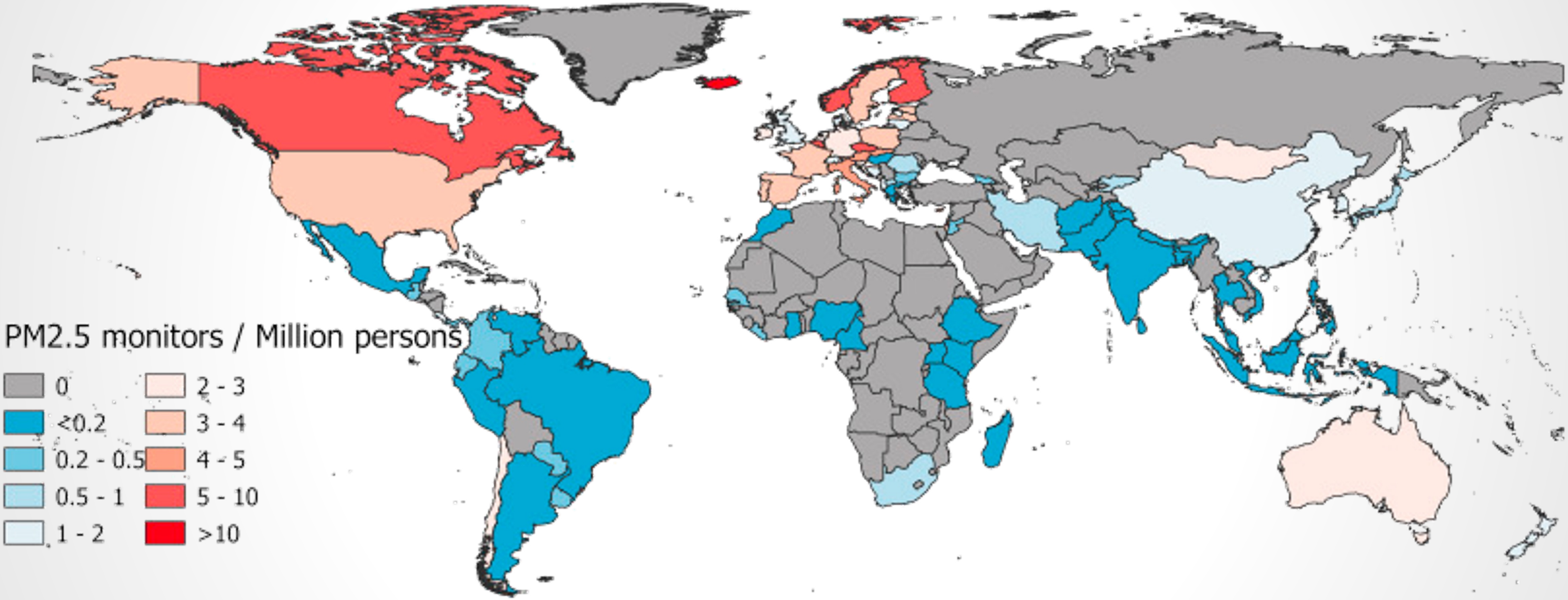
…and they are getting worse for many people…





Source: Shaddick et al. (2020), "Half the world's population are exposed to increasing air pollution" *Climate and Atmospheric Science*. https://doi.org/10.1038/s41612-020-0124-2

…but our knowledge of air quality is incomplete!



Source: Martin et al. (2019), "No one knows which city has the highest concentration of fine particulate matter" *Atmospheric Environment*. https://doi.org/10.1016/j.aeaoa.2019.100040

How do we measure and understand air quality?

traditional monitors

low-cost sensors

Ground Measurements

atmospheric observations

Air & Space Observations

Models

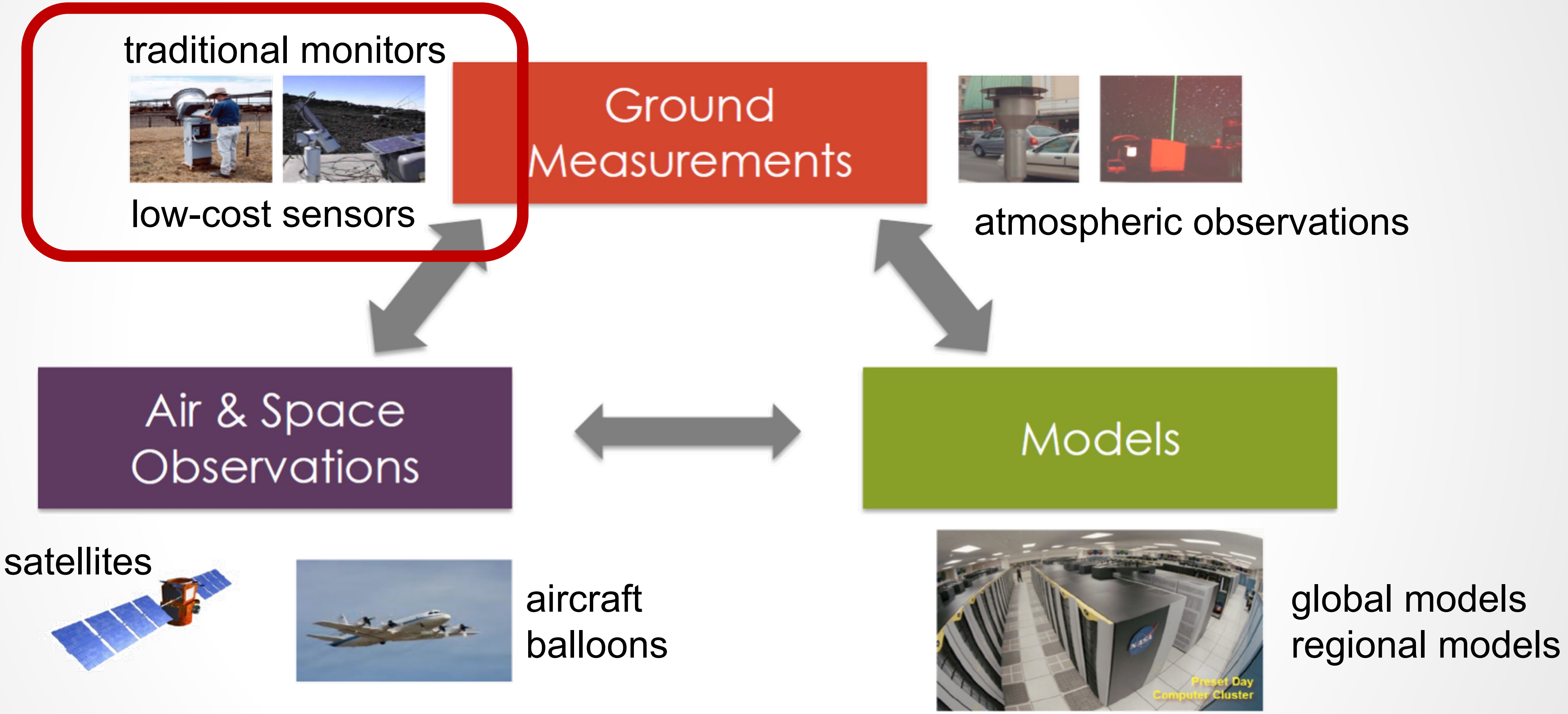
satellites

aircraft
balloons

global models
regional models

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

How do we measure and understand air quality?



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Traditional Regulatory Monitors

air quality monitoring trailer of the Houston Health Department, www.houstontx.gov/health/Environmental

MetOne BAM-1020 for Particulate Matter, metone.com

2BTech Model 405 for NOx, twobtech.com

+ accurate
- expensive
? representativity

These form the "backbone" of the monitoring system, but are relatively sparse (especially when taking a global view).

Low-Cost Air Quality Sensors

SENSIT RAMP multi-pollutant sensor, gasleaksensors.com

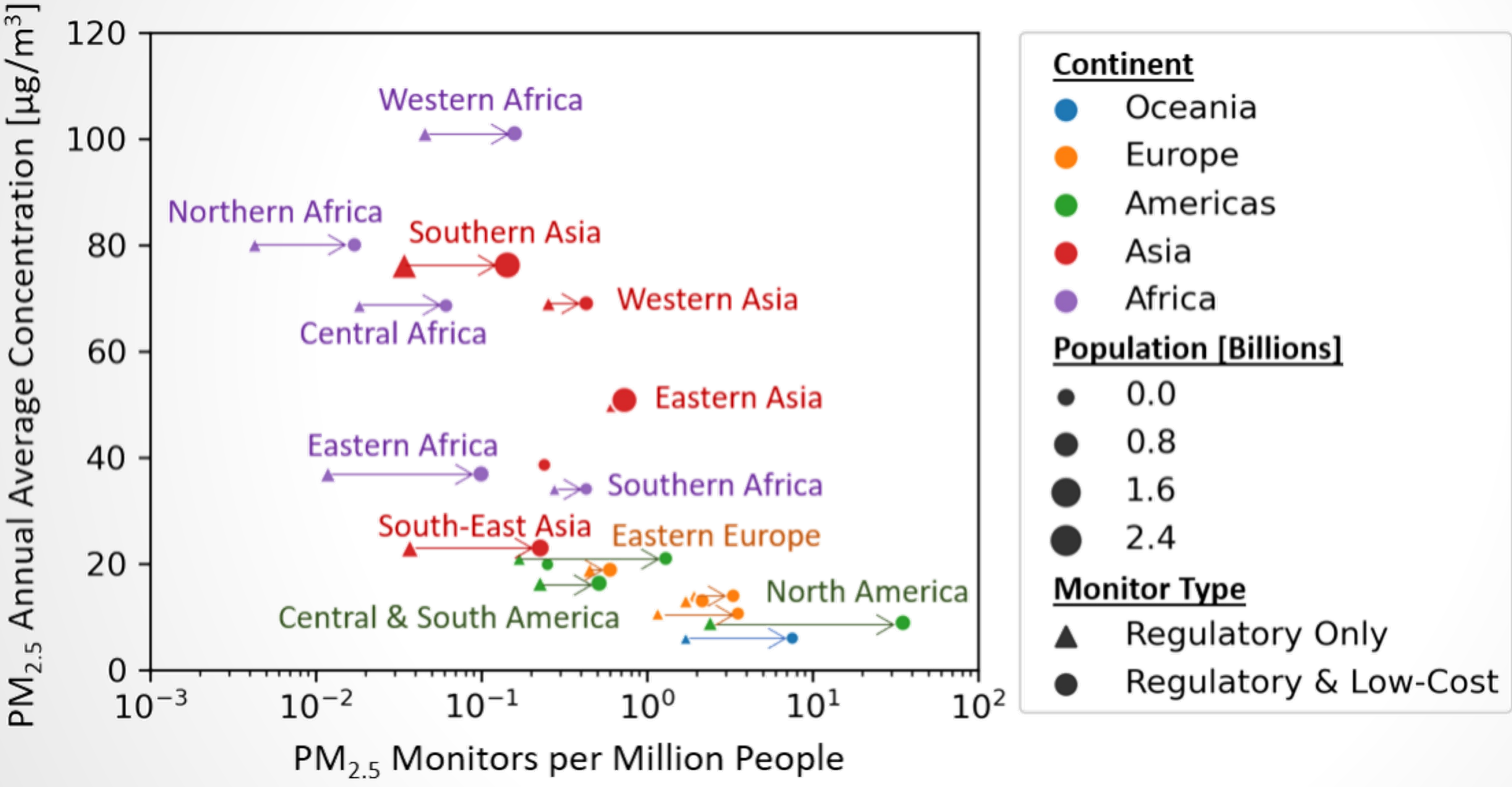
PurpleAir for Particulate Matter, purpleair.com

+ relatively inexpensive
+ dense and/or remote deployment
- greater noise and bias

Clarity Node for PM and NOx, clarity.io

calibration is an open issue, but leveraging network density can offset some of these shortcomings, and allows greater access to air quality monitoring technologies

Global Monitoring of Air Quality (surface monitors)



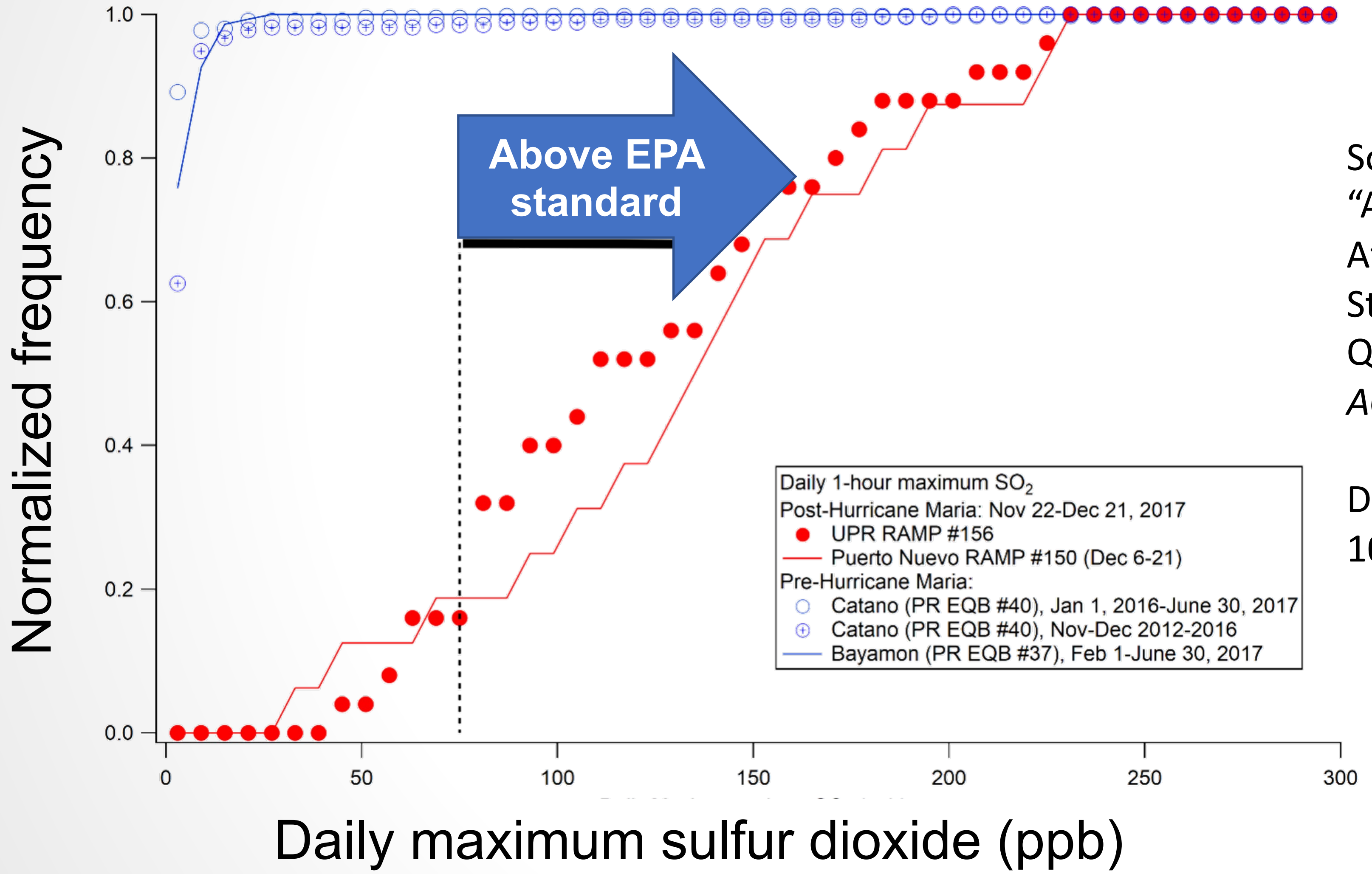
Source: Malings et al. (2020), "Application of low-cost fine particulate mass monitors to convert satellite AOD to surface concentrations in North America and Africa" *Atmospheric Measurement Techniques*

DOI: 10.5194/amt-13-3873-2020

With additional data from openAQ.org

RAMP Deployment

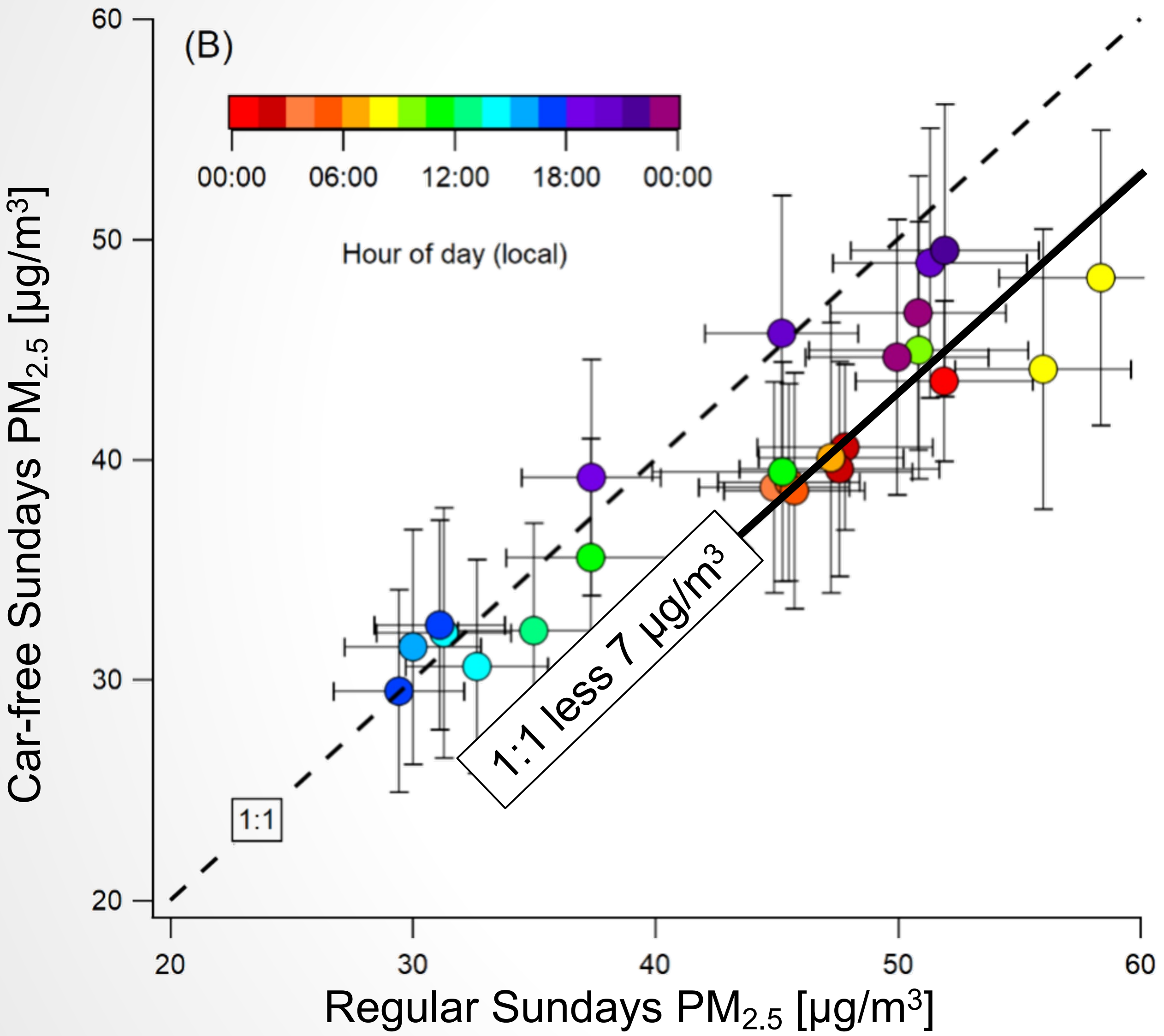
Puerto Rico: Ambient SO_2 appears to exceed EPA limits following Hurricane Maria due to diesel use



Source: Subramanian et al. (2018), “Air Quality in Puerto Rico in the Aftermath of Hurricane Maria: A Case Study on the Use of Lower Cost Air Quality Monitors”
ACS: Earth & Space Chemistry

DOI: 10.1021/acsearthspacechem.8b00079

Kigali, Rwanda: Car-free Sunday improves AM AQ



Source: Sumbramanian et al. (2020),

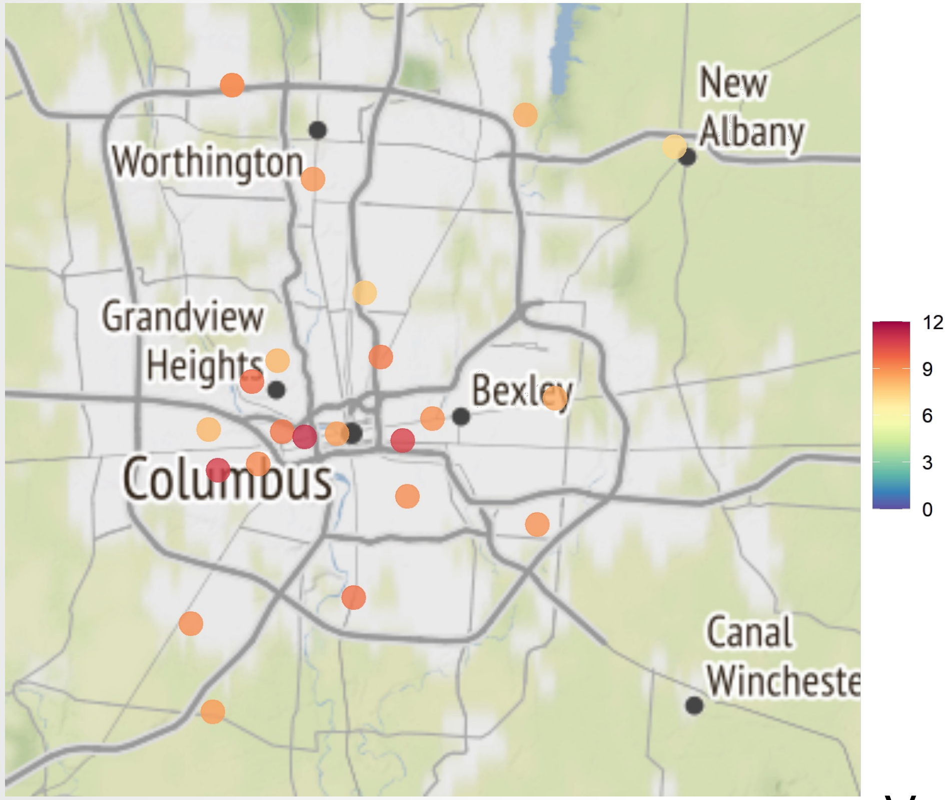
"Air pollution in Kigali, Rwanda using lower-cost RAMP monitors: Spatial and temporal variability, contribution of regional and local sources, and evaluation of car-free Sundays"

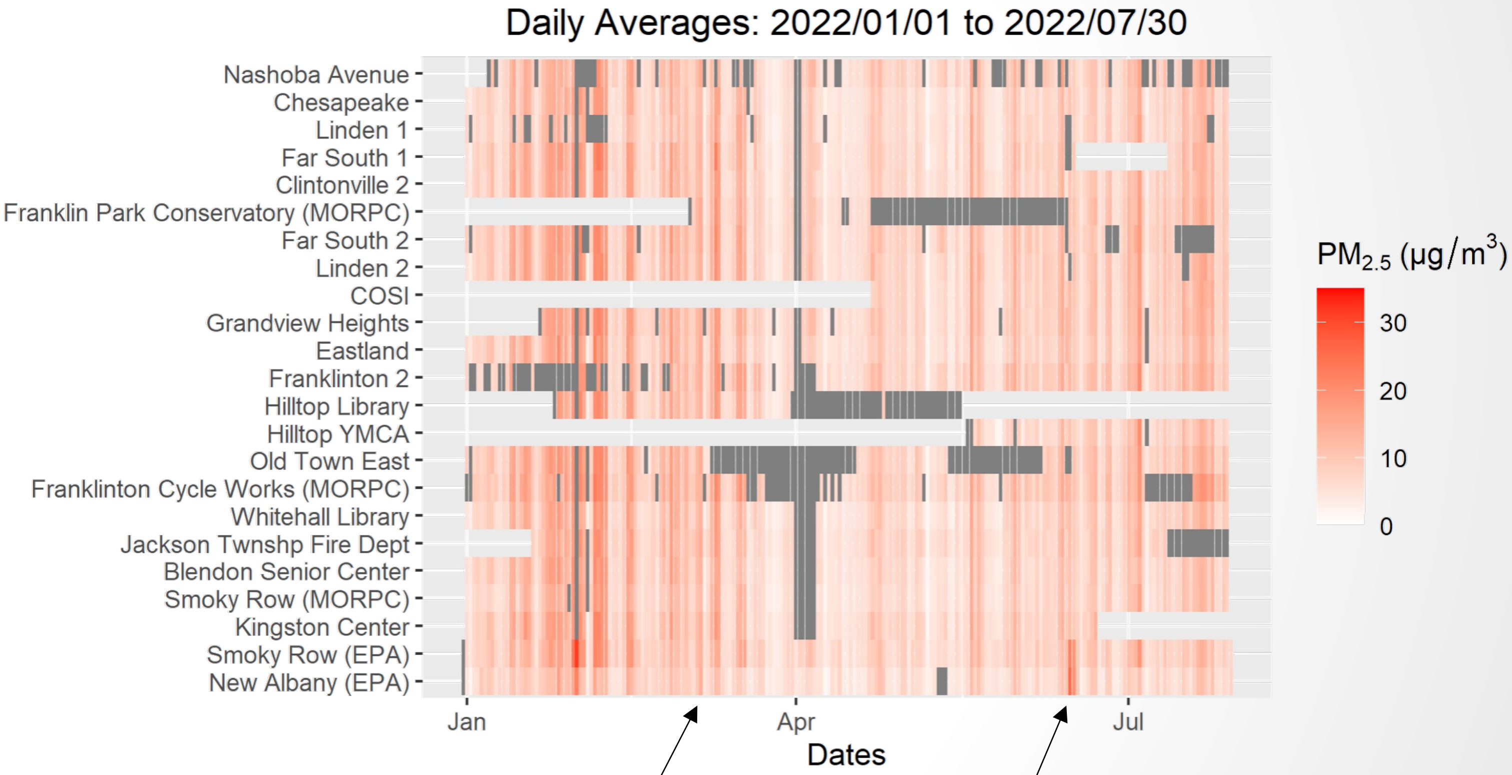
Clean Air Journal

DOI: 10.17159/caj/2020/30/2.8023.

AGU Thriving Earth Exchange Community Air Quality Monitoring Project for Columbus, OH

Long-term average $PM_{2.5}$ [μg/m³]

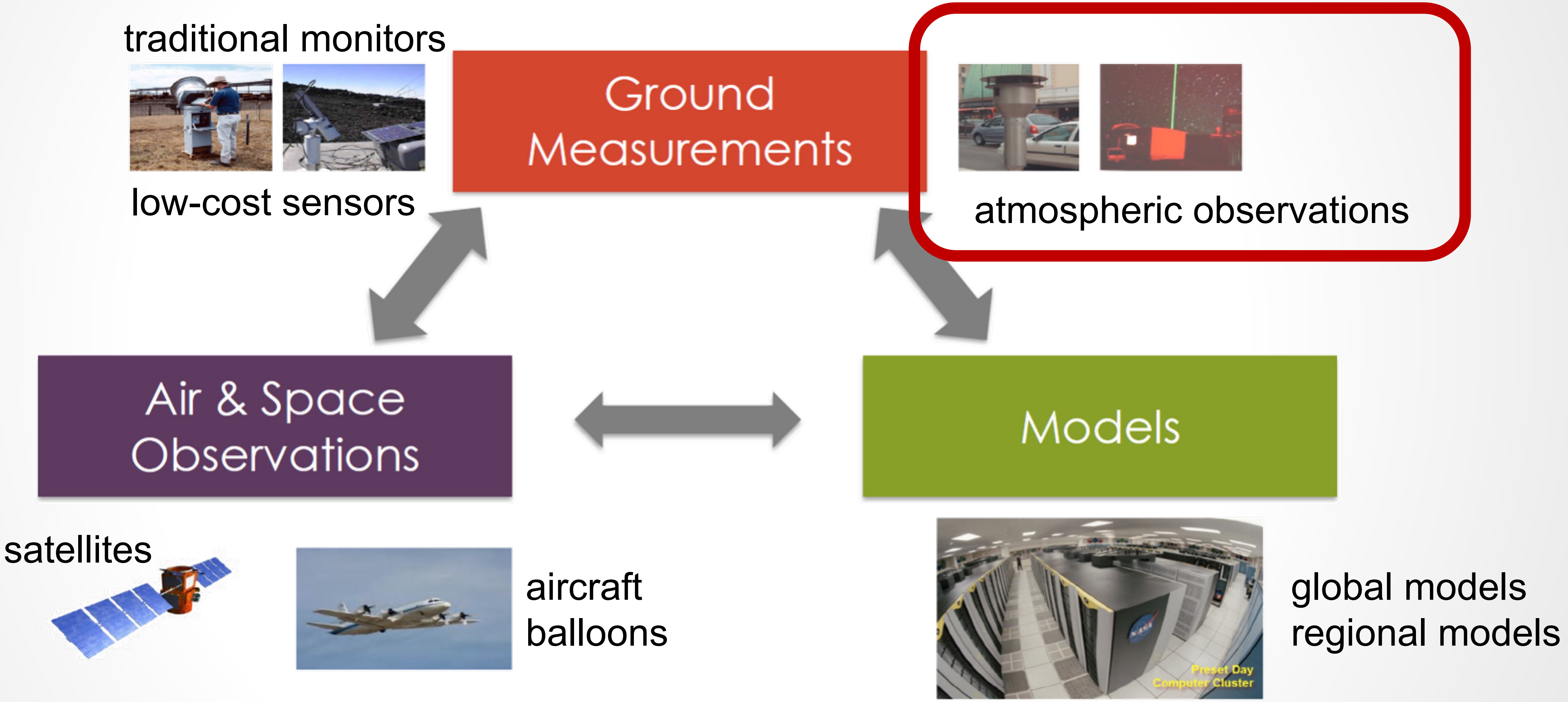




Vertical bands: most air quality events are regional

Saharan Dust Event: a-typical particles not well captured with low-cost sensors

How do we measure and understand air quality?



Source: Gupta, P.; Follette-Cook, M. (2018). Satellite Remote Sensing of Air Quality. NASA Applied Remote Sensing Training Program (ARSET).
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Ground-based atmospheric column observations

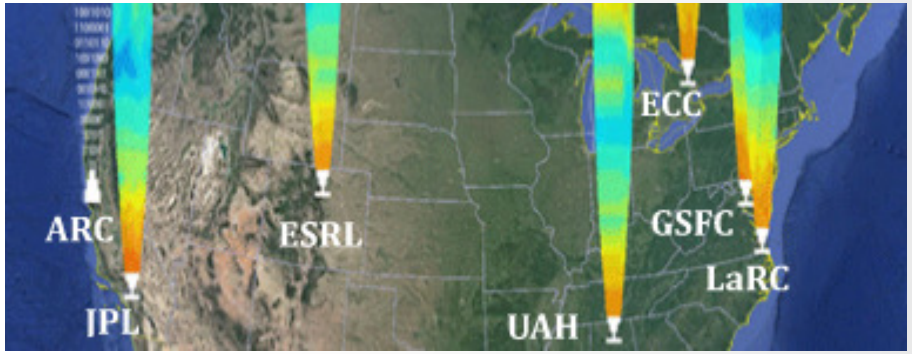
AERONET
aerosol optical depth
(relevant to PM)

Source: https://aeronet.gsfc.nasa.gov/

Source: https://pandora.gsfc.nasa.gov/

PANDORA
atmospheric gases
(NO_2, Ozone)

TOLNET
LIDAR measurements
of Ozone profiles



Source: https://www-air.larc.nasa.gov/missions/TOLNet/index.html

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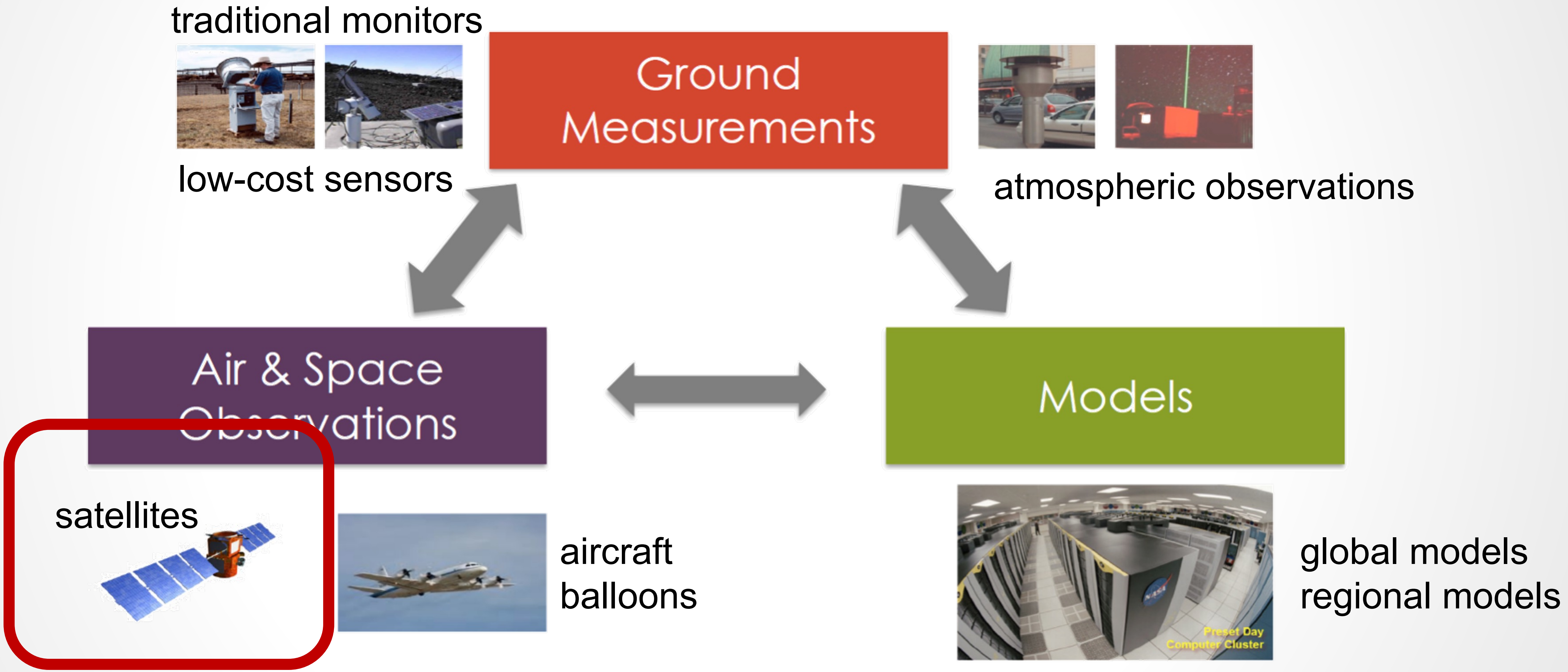

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Satellite instruments and retrievals

Geophysical Parameters (useful data product)

↑

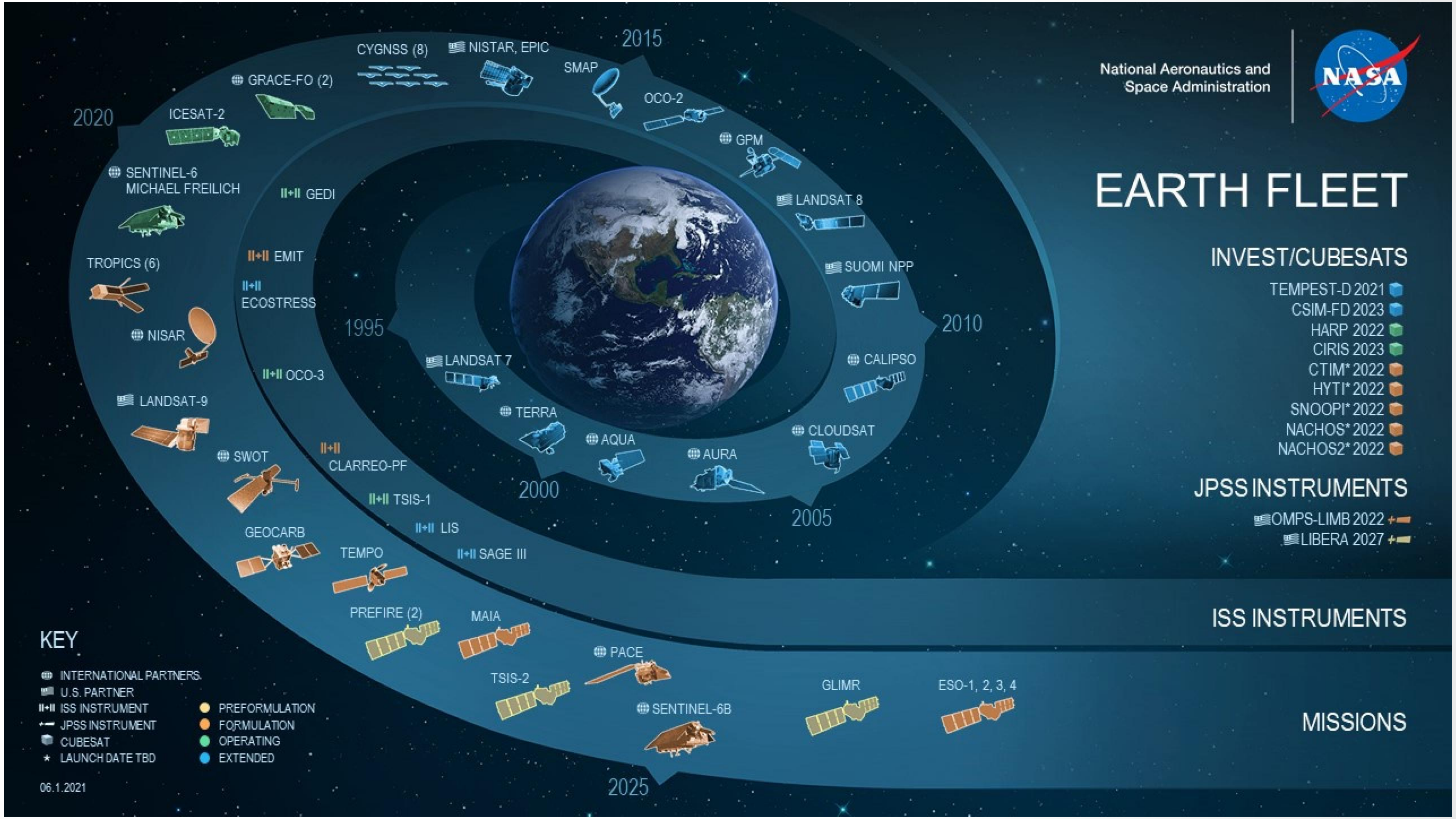
Retrieval Algorithm (data processing)

↑

Radiative Transfer Theory (physics)

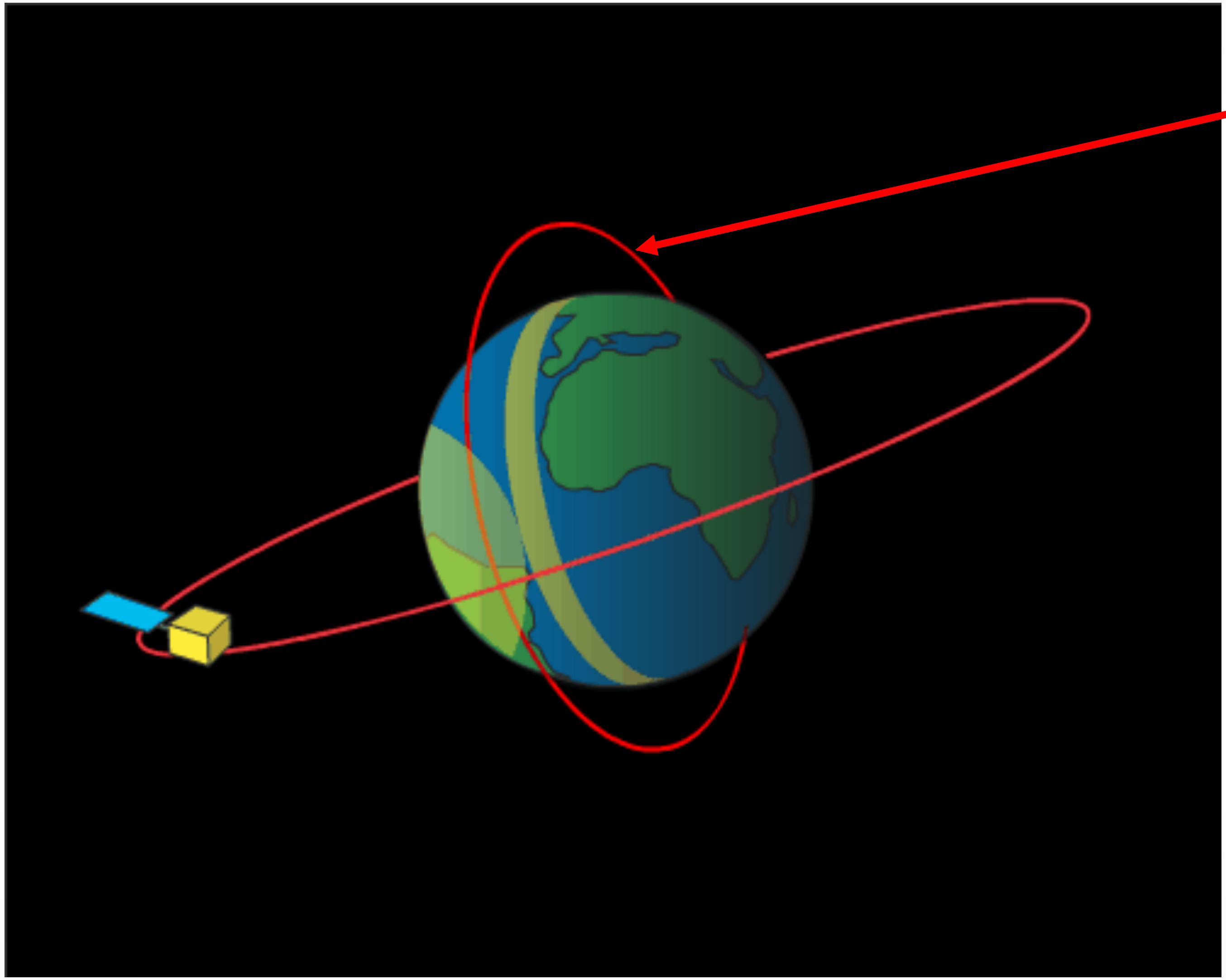
↑

Spectral Radiance (instrument)



Source: NASA Earth Science https://science.nasa.gov/earth-science

Common types of orbits for air quality satellites



Polar Orbit

Observes a location about once a day (weather permitting)

Observes at about the same time of day (sun-synchronous)

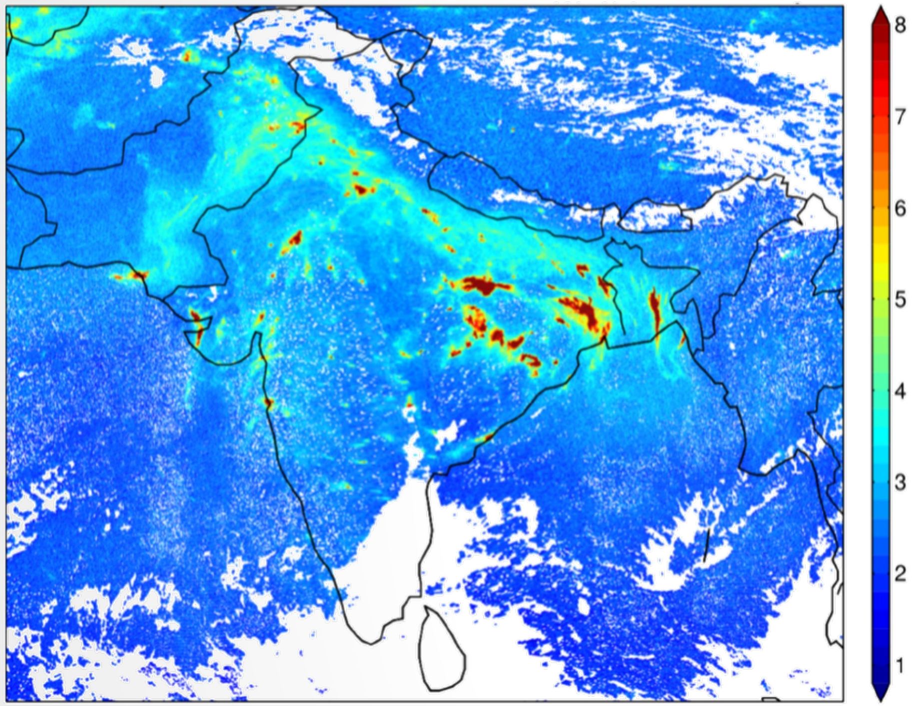
Geostationary Orbit

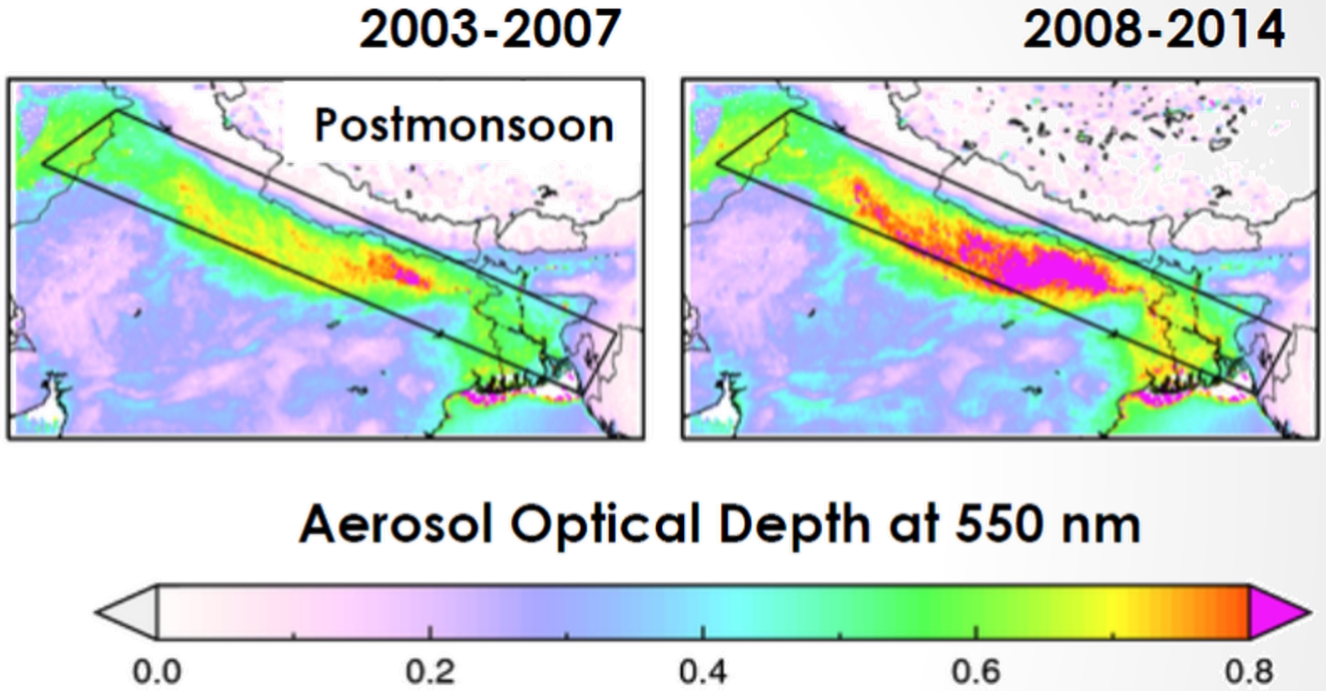
Observes the same area all the time

Observes throughout the day (weather and light permitting)

source: NOAA
https://scijinks.gov/orbit/

What a satellite CAN do for air quality





- **Examine a large area**: where are the hotspots? how is long-range transport happening?
- **Track changes over time:** how much has the average concentration over an area changed over time?
- **A picture is worth a million datapoints:** Anyone can understand a satellite photo of a smoke plume.

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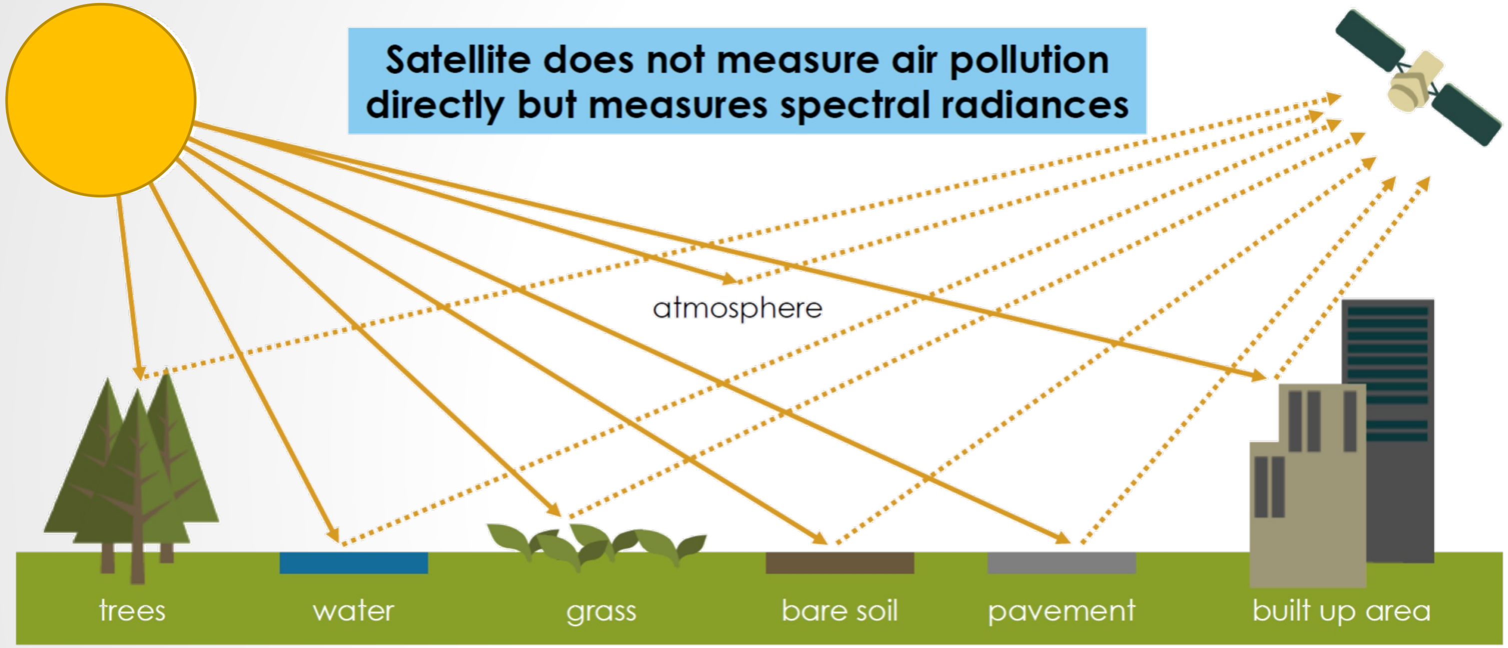
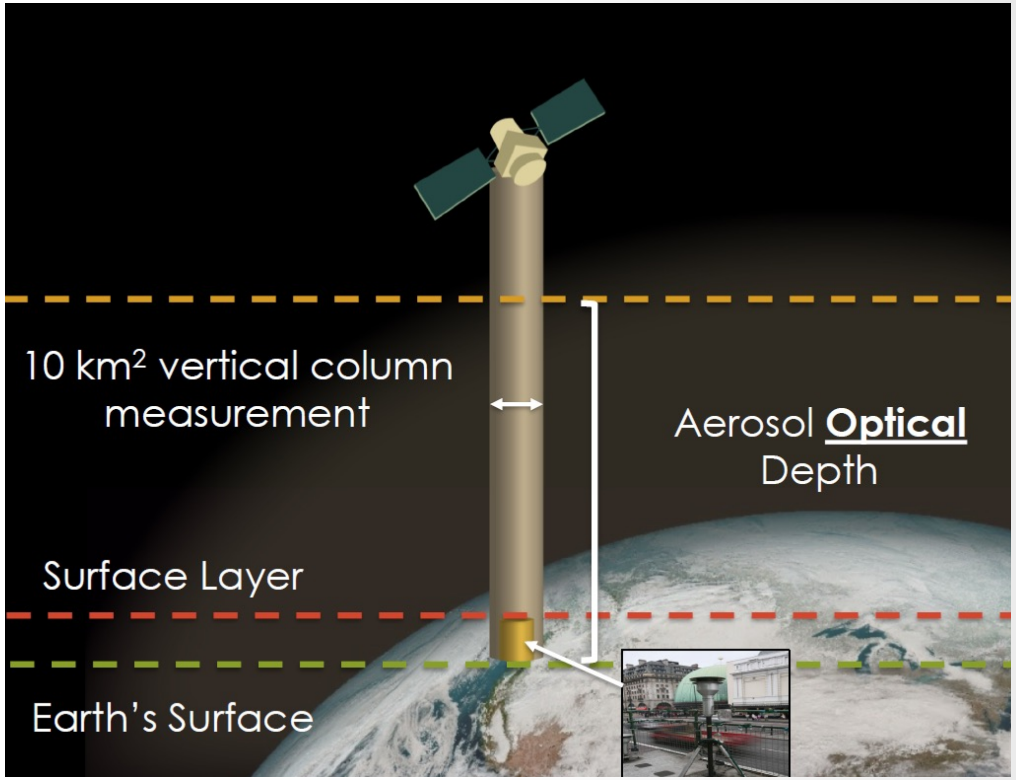
What a satellite CANNOT do for air quality



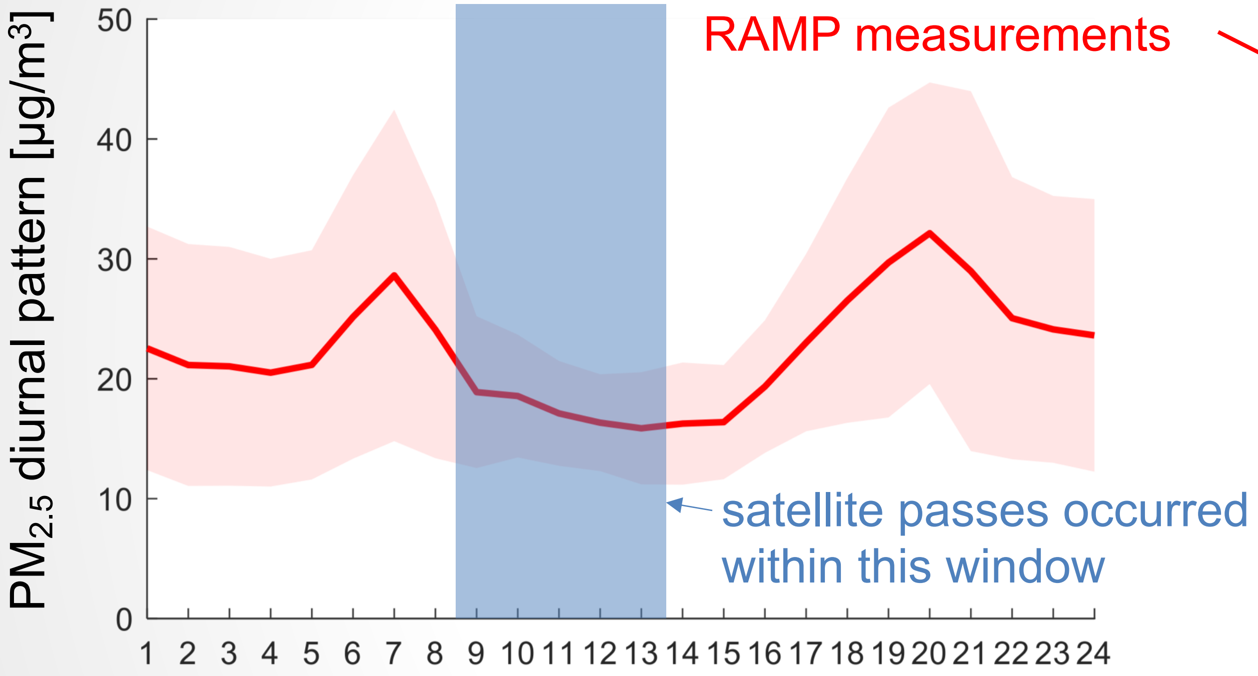


- **See at night:** satellites measure the properties of reflected sunlight passing through the atmosphere.
- **See through clouds:** most satellite measurements are blocked by cloud cover.
- **See what is happening at "nose level":** satellites measure quantities in the whole atmosphere.
- **See at different times of day:** most satellites will observe a location once per day.

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

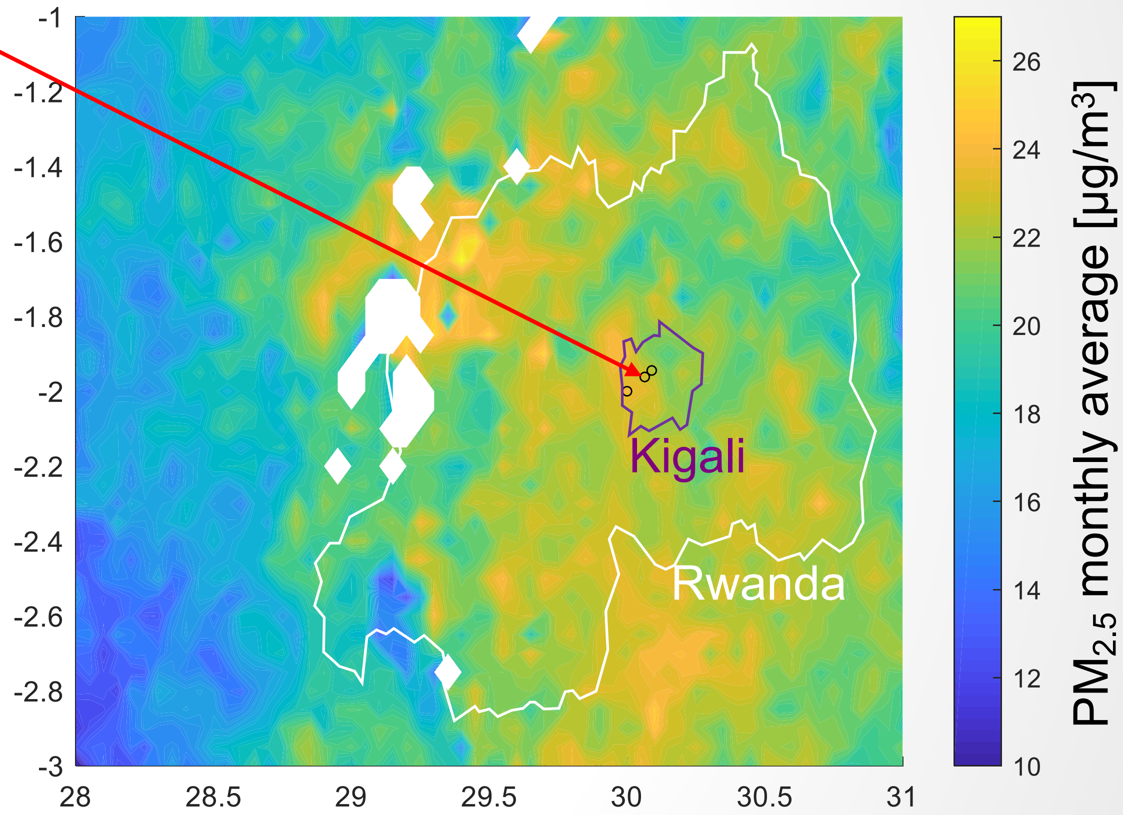
Satellites and surface sensors are complementary

Temporal Coverage (local measurements)



passes during low-concentration periods may bias long-term averaging

Spatial Coverage (satellite)



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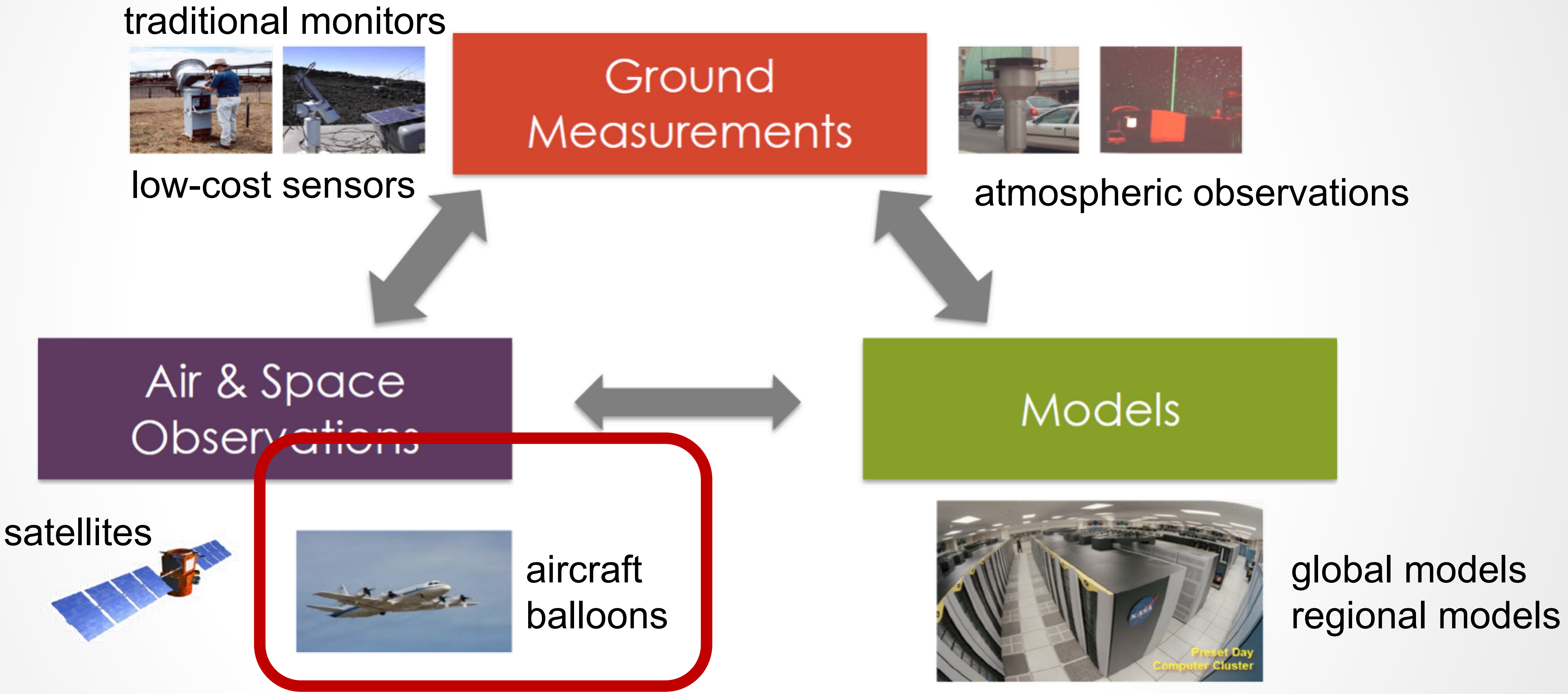
How do we measure and understand air quality?



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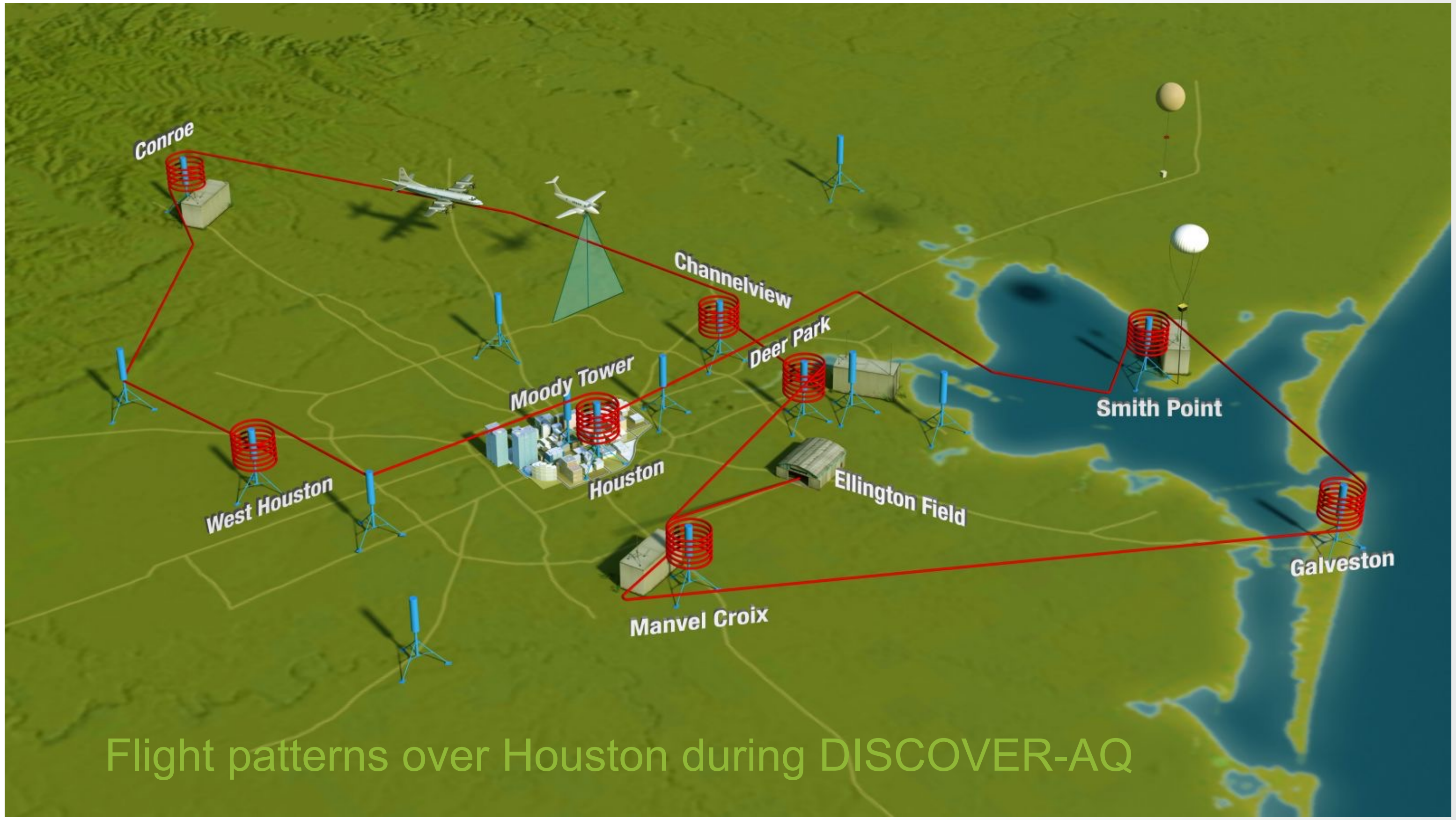
A few airborne air quality campaigns

Typically, these campaigns gather data to improve satellite retrieval algorithms and models.

Instruments aboard NASA DC-8 Aircraft (photo credit: Pedro Campuzano-Jost)



Flight patterns over Houston during DISCOVER-AQ

Source: https://espo.nasa.gov/firex-aq/content/FIREX-AQ

Source: https://www.nasa.gov/mission_pages/discover-aq/index.html

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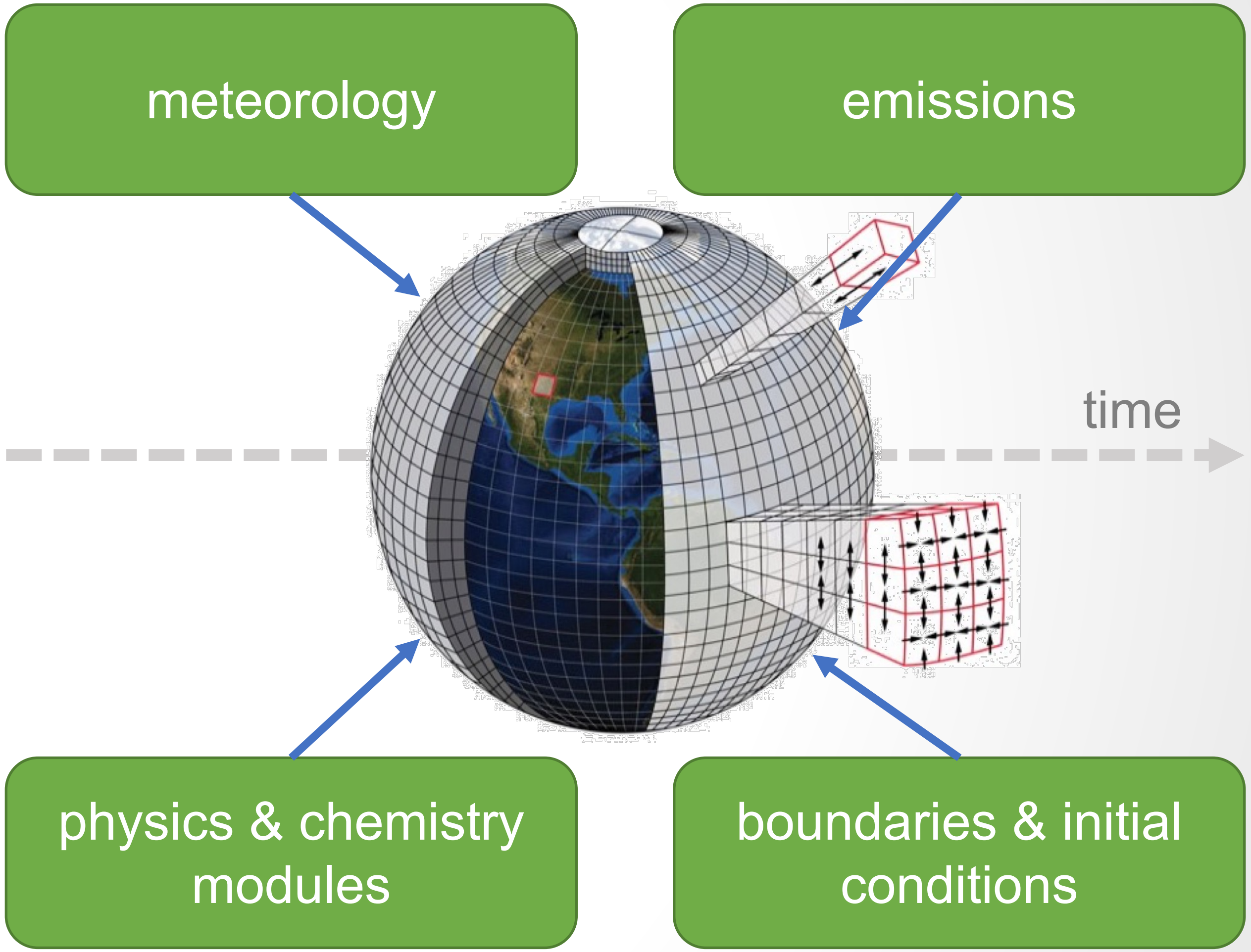
Atmospheric transport & chemistry models

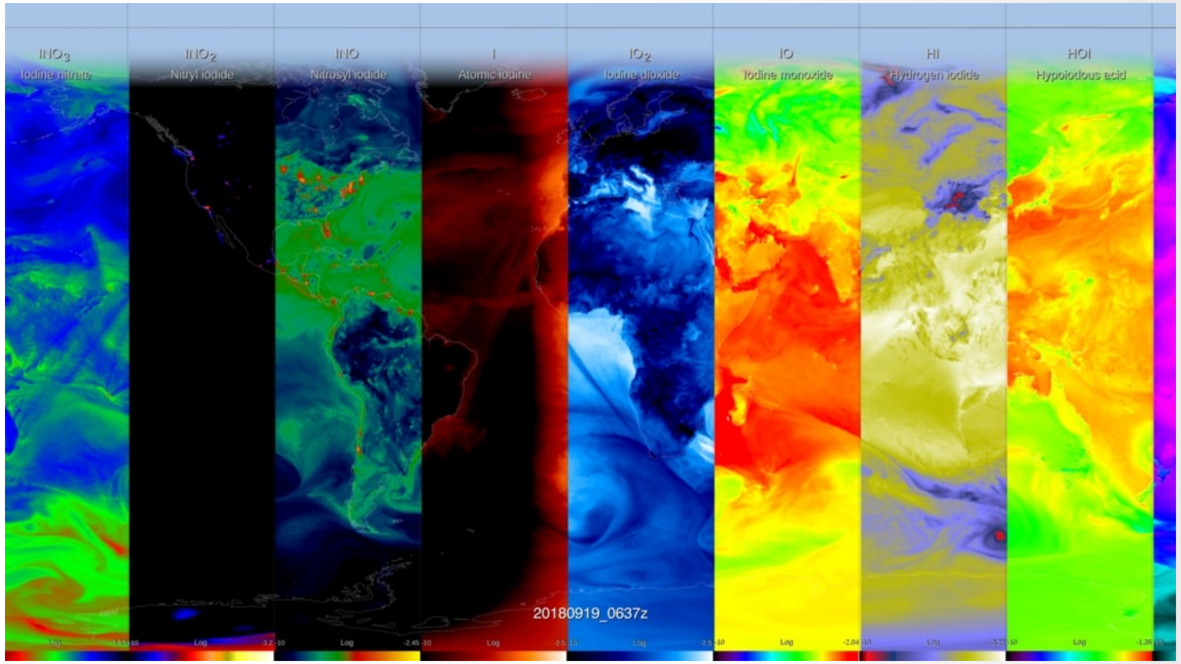
- **Mathematically represent the processes which influence air quality** (emission, transport, diffusion, transformation, removal)
- Operate on a **4D grid** with a specified resolution (horizontal, vertical, temporal)
- Can be part of an **Earth Systems Model** simulating the atmosphere, hydrosphere, geosphere, biosphere, etc.
- Models require decades of research and development; **updates integrate the latest science**, but make it harder to compare between different versions of the model
- **Different models use different approaches**, and so give different results.



Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

Advantages of air quality models

- Simulate physical and chemical processes which affect air quality; **data are self-consistent**.
- Applicable to **many space & time scales**.
- **No “missing data”**. The model grid is complete.
- Can forecast **future conditions**.
- Can utilize measurements (through data assimilation), but do not require measurements; this makes models **useful in data-sparse regions**.
- **Freely available** global models are run by various groups (including NASA), whose outputs can be used by anyone around the world for free.
- Simulations can **identify sources** of pollution and their relative importance to local air quality.



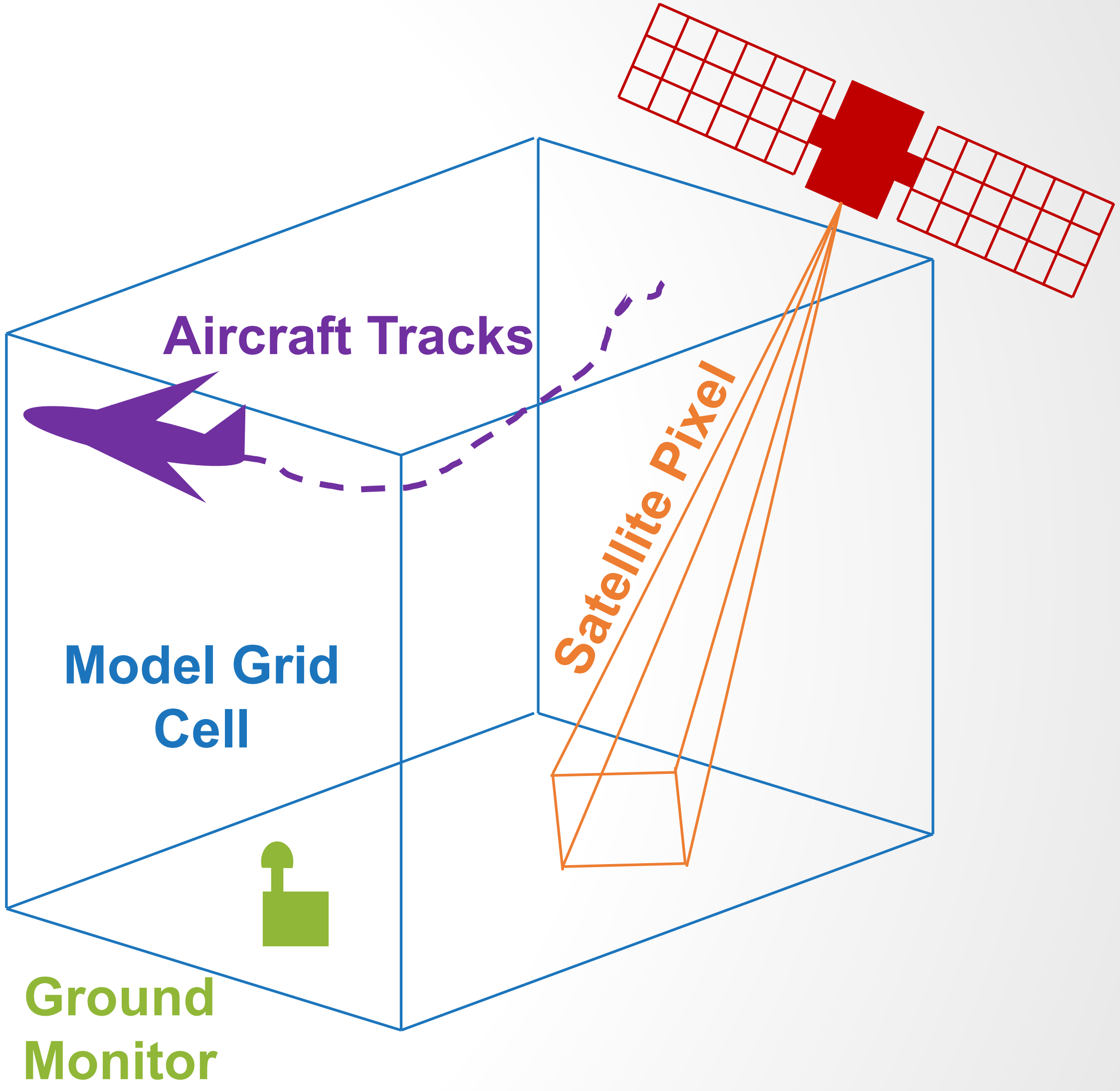
Visualization of several outputs from the NASA GEOS atmospheric chemistry model system.

Source: https://svs.gsfc.nasa.gov/4754

Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

Weaknesses of air quality models

- **"garbage in, garbage out"**; model outputs are only as good as the emissions data, model assumptions, and initial conditions that are used.
- **Out of date** and/or **coarse resolution emissions inventories** cause uncertainty.
- **Model outputs are not directly comparable to ground or other data sources** due to the scale mis-match; the model estimates average concentrations across its grid, which are not the same as measurements at specific locations.
- Models are difficult and **computationally intensive** to run.
- **Large amount of data** requires expertise & software to interpret and visualize.



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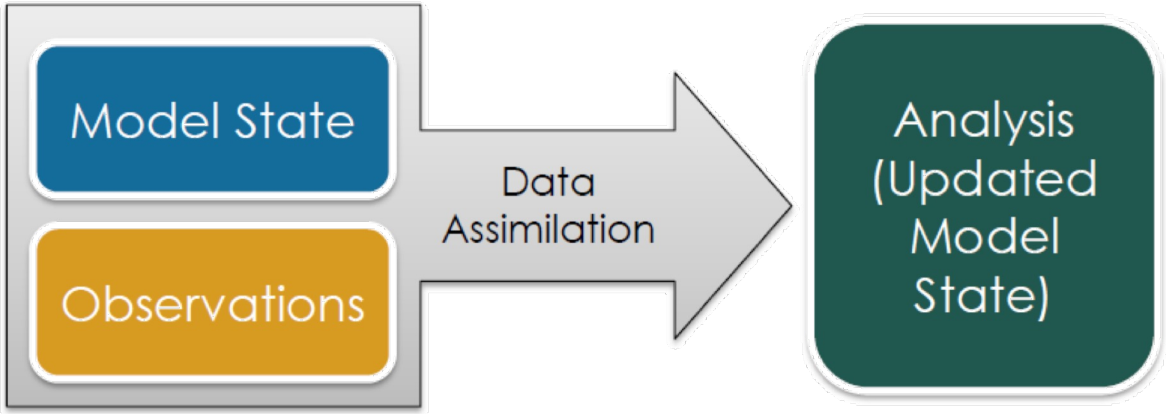
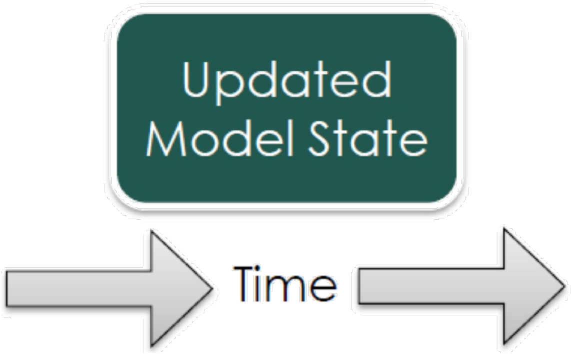
Assimilation, analysis, reanalysis & forecasting

Data assimilation describes the process of assimilating, or incorporating, observations into a model state to produce the best estimate of the atmosphere, land, and ocean conditions.



An **analysis** is the blend of the model and observations.

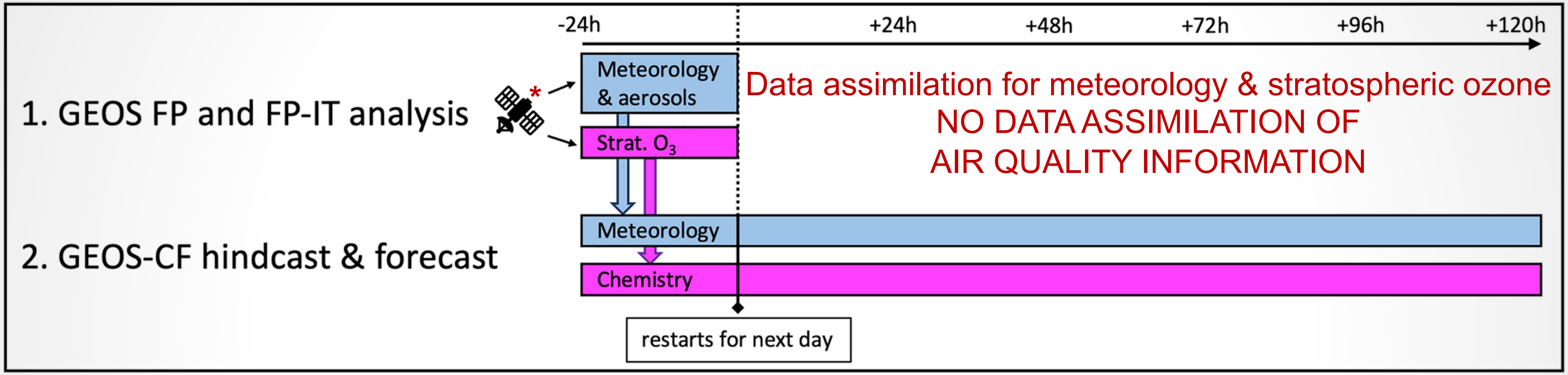
A **reanalysis** blends observations with model simulations of the past using a single model version.

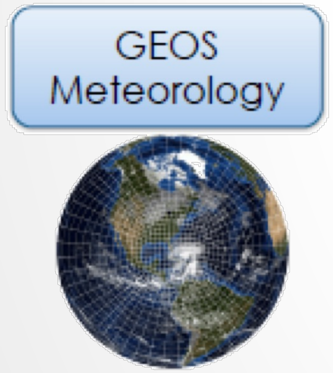


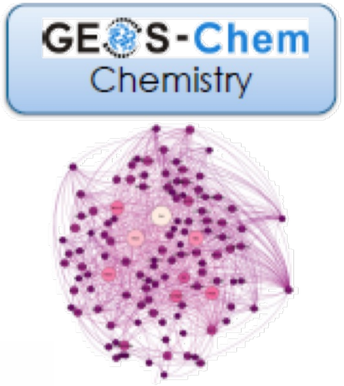
A **forecast** is a model simulation run forward in time to predict a future state.

Source: Gupta, P.; Follette-Cook, M.; Parrington, M.; Stewart, C. (2021). *Introduction and Access to Global Air Quality Forecasting Data and Tools*. NASA ARSET. https://appliedsciences.nasa.gov/join-mission/training/english/arset-introduction-and-access-global-air-quality-forecasting-data-and

GEOS Composition Forecast (GEOS-CF)







- Combine GEOS meteorology with GEOS-Chem chemistry
- 250 chemical species
- Hourly temporal resolution
- 0.25 degree (25 km) spatial resolution
- Global coverage
- Daily 1-day hindcast and 5-day forecast

Source: Keller, C., et al. (2021) “Description of the NASA GEOS Composition Forecast Modeling System GEOS-CF v1.0”. *Journal of Advances in Modeling Earth Systems*, 13:4. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020MS002413

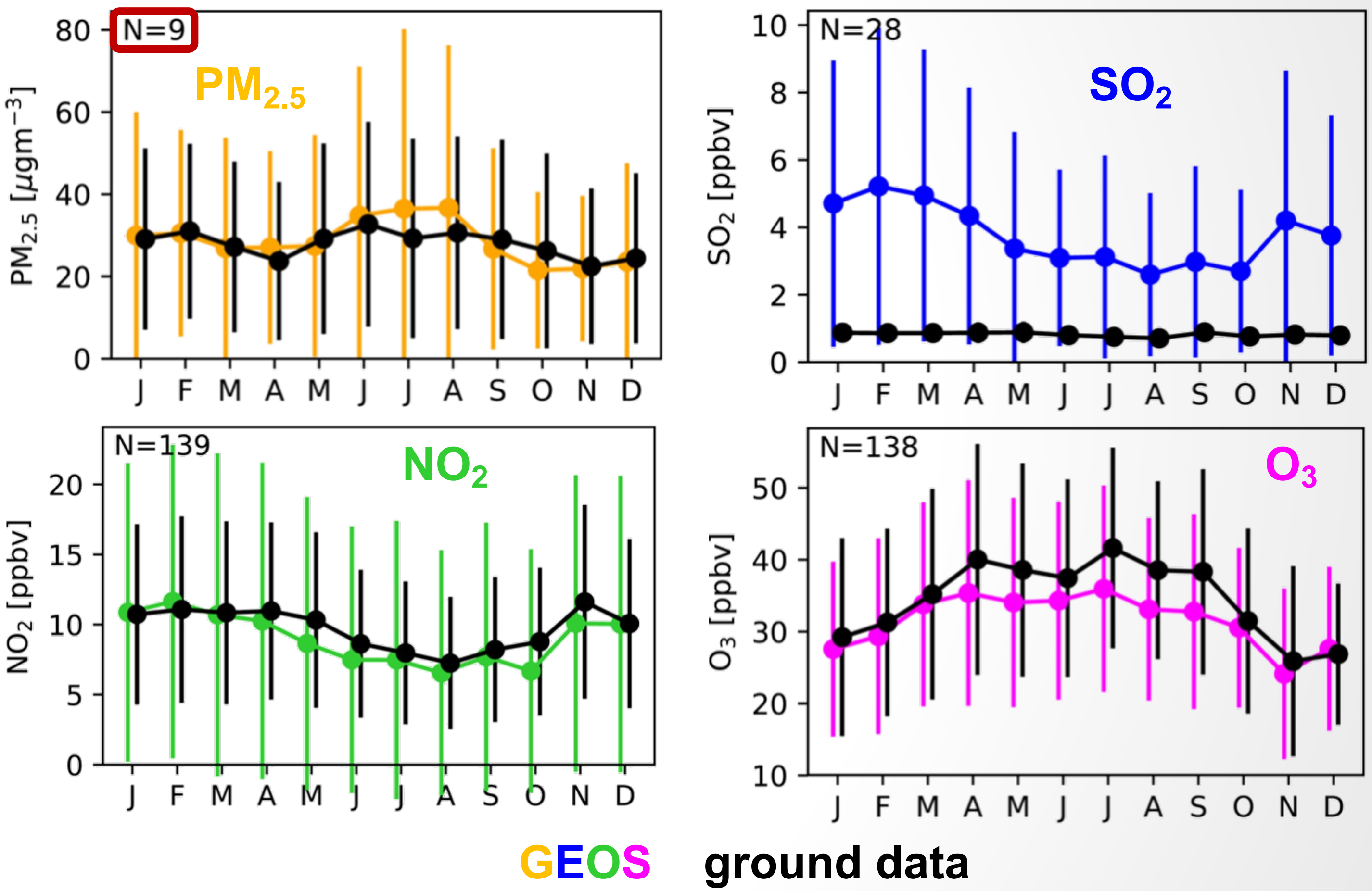
GEOS-CF performance evaluation

In general, GEOS-CF estimates and forecasts agree well with ground-based data for air quality relevant quantities.

HOWEVER:

- Agreement can vary annually, seasonally and by region.
- There can be high bias at individual locations due to local impacts.
- Many regions have limited ground data for verification.
- Some pollutants are not well represented yet (SO_2 is biased high globally).

Monthly average concentrations at sites in Africa



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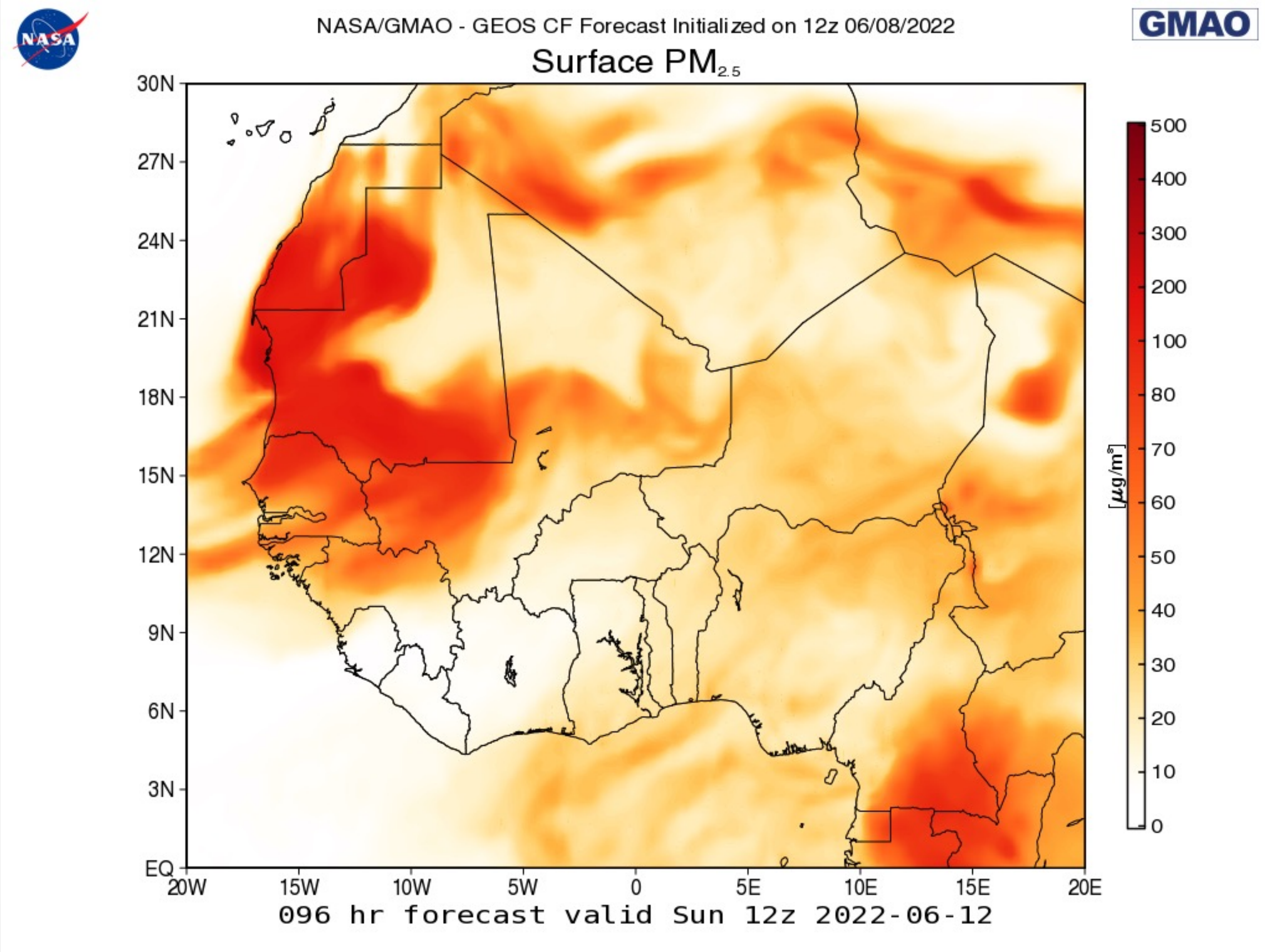
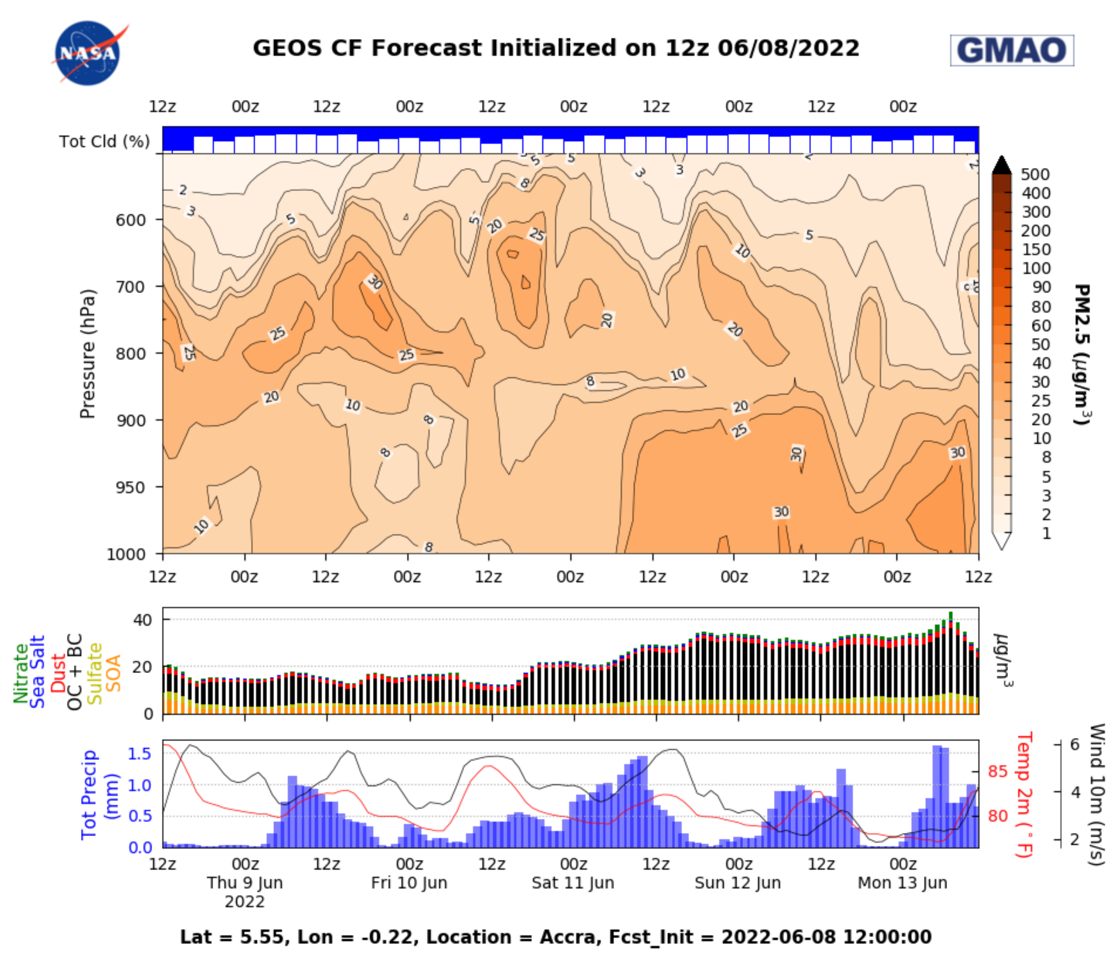
Examples of FLUID online visualizations

https://fluid.nccs.nasa.gov/cf/

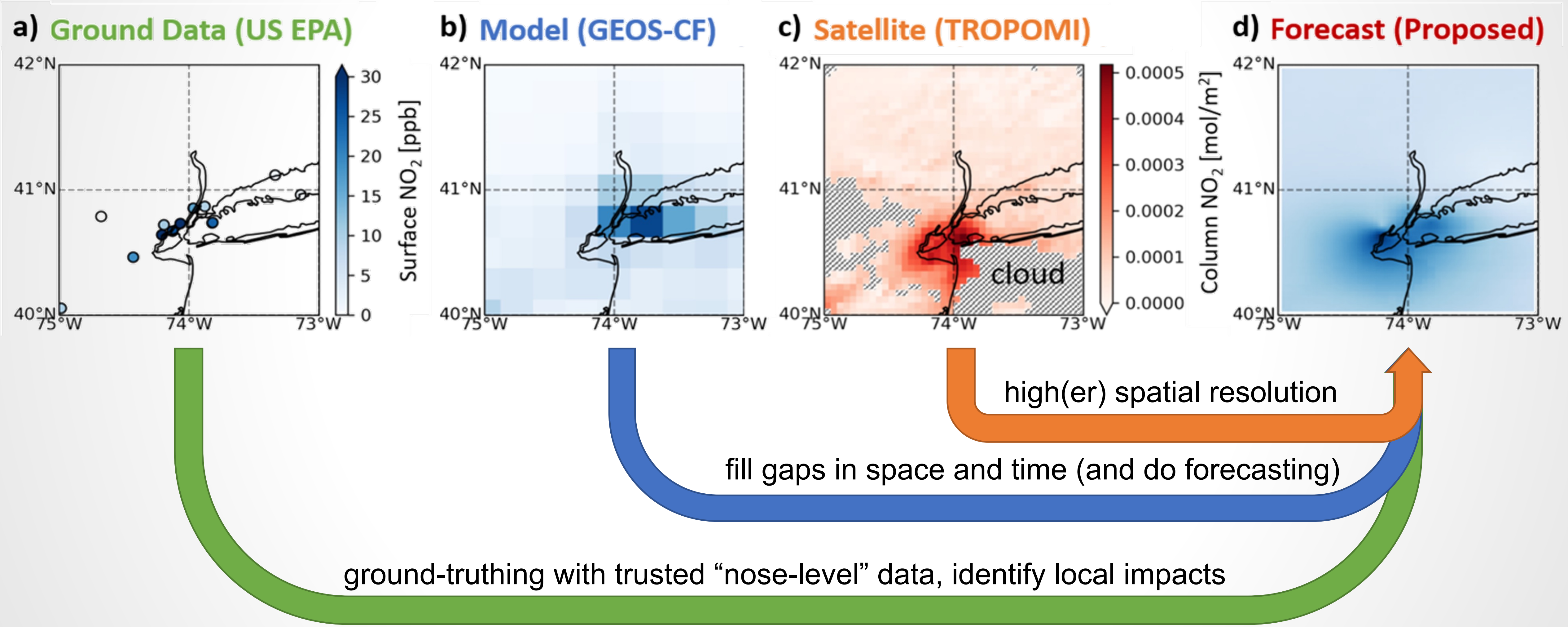


Surface Concentration Map

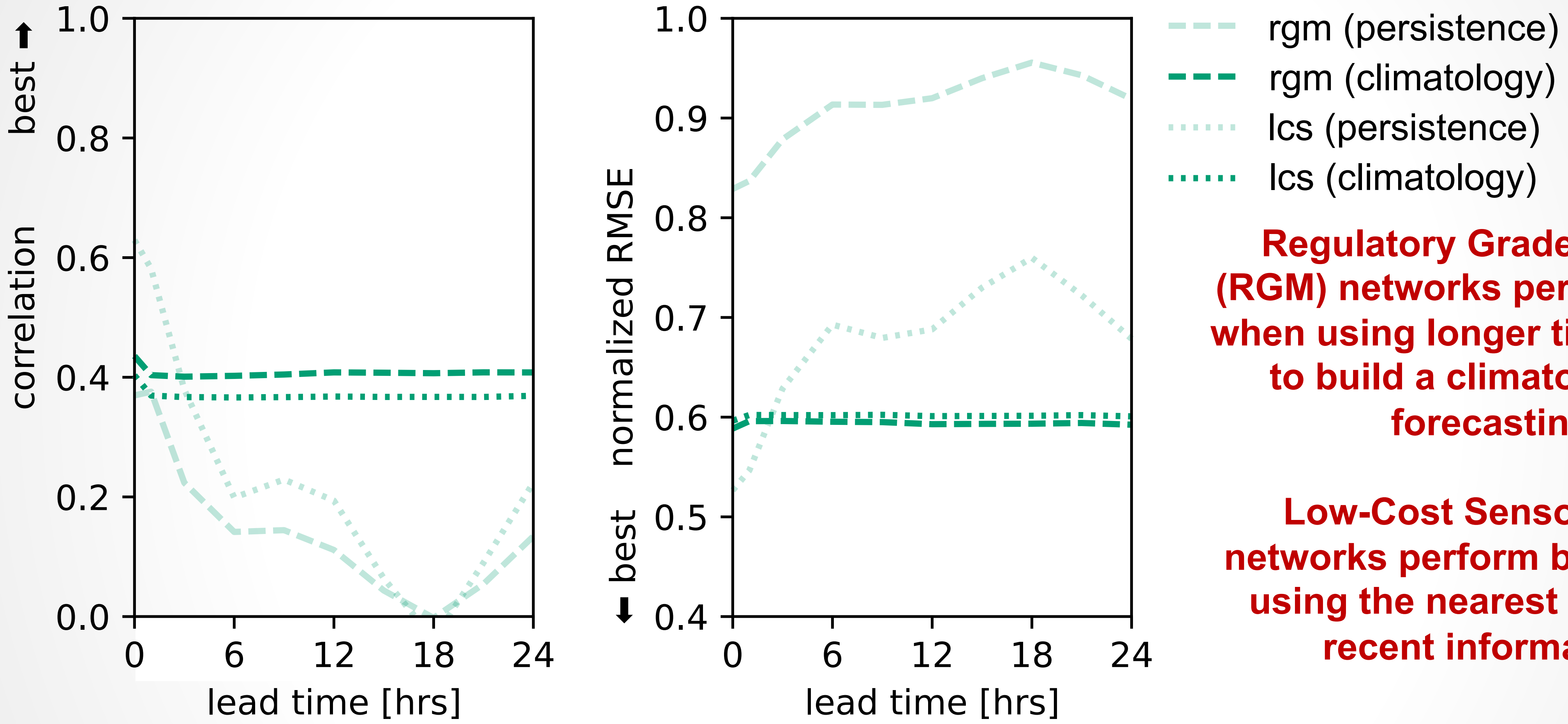


Datagrams

Data Fusion


a) Ground Data (US EPA)
b) Model (GEOS-CF)
c) Satellite (TROPOMI)
d) Forecast (Proposed)
42°N
41°N
40°N
75°W
74°W
73°W
30
25
20
15
10
5
0
Surface NO2 [ppb]
cloud
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
Column NO2 [mol/m2]
high(er) spatial resolution
fill gaps in space and time (and do forecasting)
ground-truthing with trusted "nose-level" data, identify local impacts

Case Study in London: Using local data only performs okay

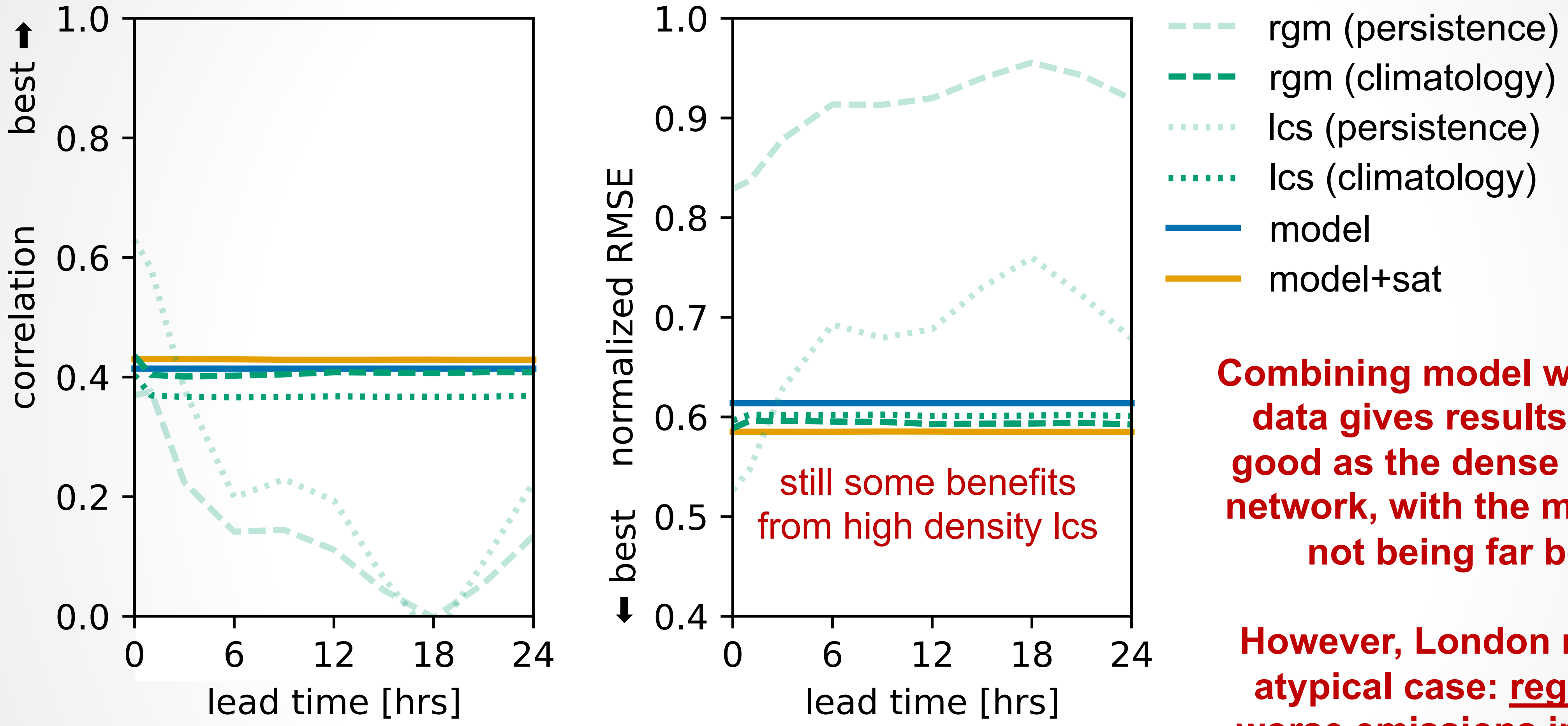


forecasting results for **NO_2** in ***London, October & November 2019***
cross-validation: leave-one-site-out, considering only regulatory sites
plotted results represent ***average metrics*** across validation sites

Regulatory Grade Monitor (RGM) networks perform better when using longer time periods to build a climatology for forecasting

Low-Cost Sensor (LCS) networks perform better when using the nearest and most recent information.

Case Study in London: Model and satellite is about as good

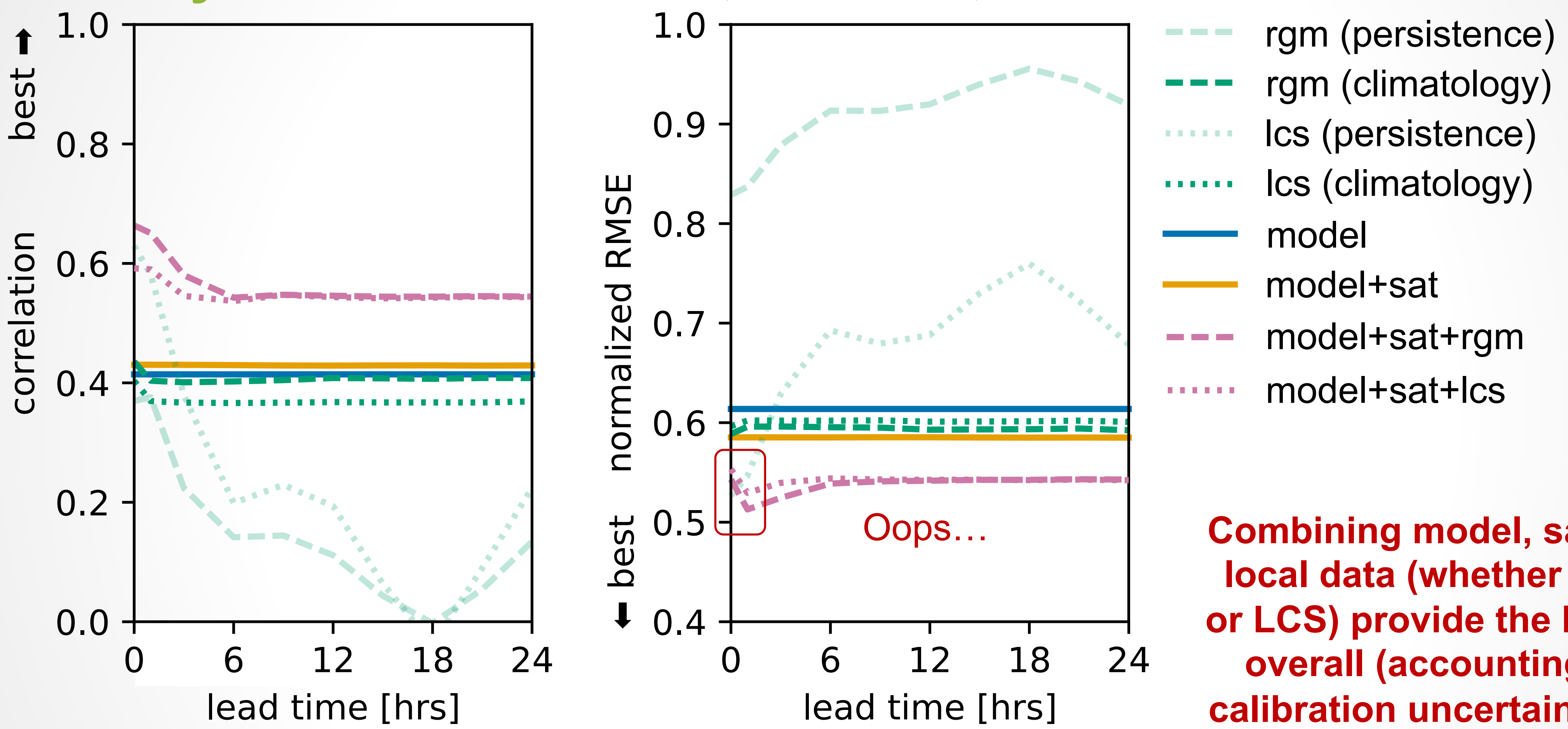


forecasting results for **NO_2** in ***London, October & November 2019***
cross-validation: leave-one-site-out, considering only regulatory sites
plotted results represent ***average metrics*** across validation sites

Combining model with satellite data gives results about as good as the dense local RGM network, with the model alone not being far behind.

However, London may be an atypical case: <u>regions with worse emissions inventories may be more poorly represented by the model!</u>

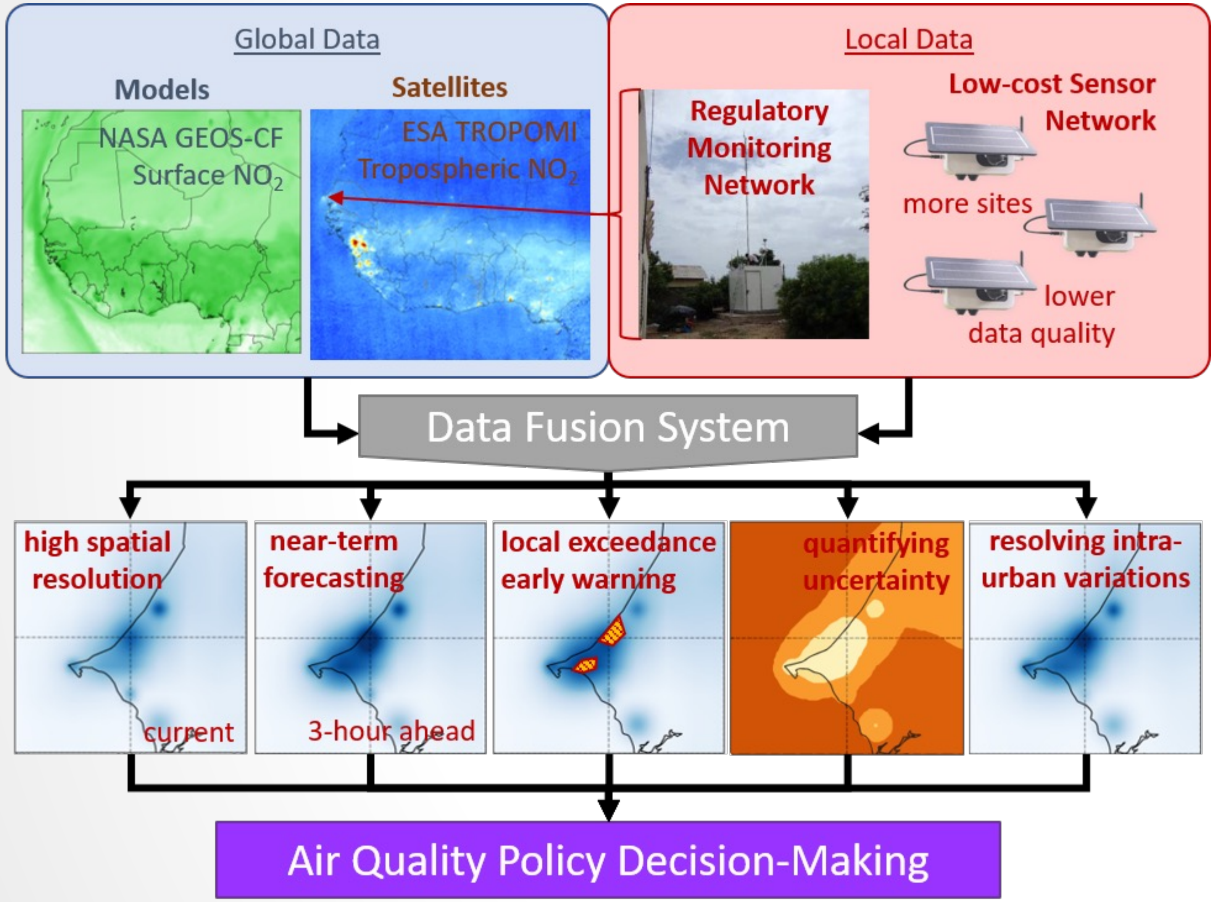
Case Study in London: Model, satellite, and local data are best



forecasting results for **NO_2** in ***London, October & November 2019***
cross-validation: leave-one-site-out, considering only regulatory sites
plotted results represent ***average metrics*** across validation sites

Combining model, satellite, and local data (whether from RGM or LCS) provide the best results overall (accounting for LCS calibration uncertainty properly is still work-in-progress).

Upcoming work



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

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.

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

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

Thank You!