Capabilities, Limitations Information Gaps for Aerosols & AQ

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Factors Affecting the AOD-PM Relationship

Aerosol vertical profile:

- AOD is a remote-sensing optical measurement for the entire atmospheric column, whereas PM2.5 is an in-situ measurements of mass at the surface. -> **PM2.5 depends on aerosol vertical profile (including PBL or mixed layer height), while AOD corresponds to total aerosol amount in the atmospheric column**

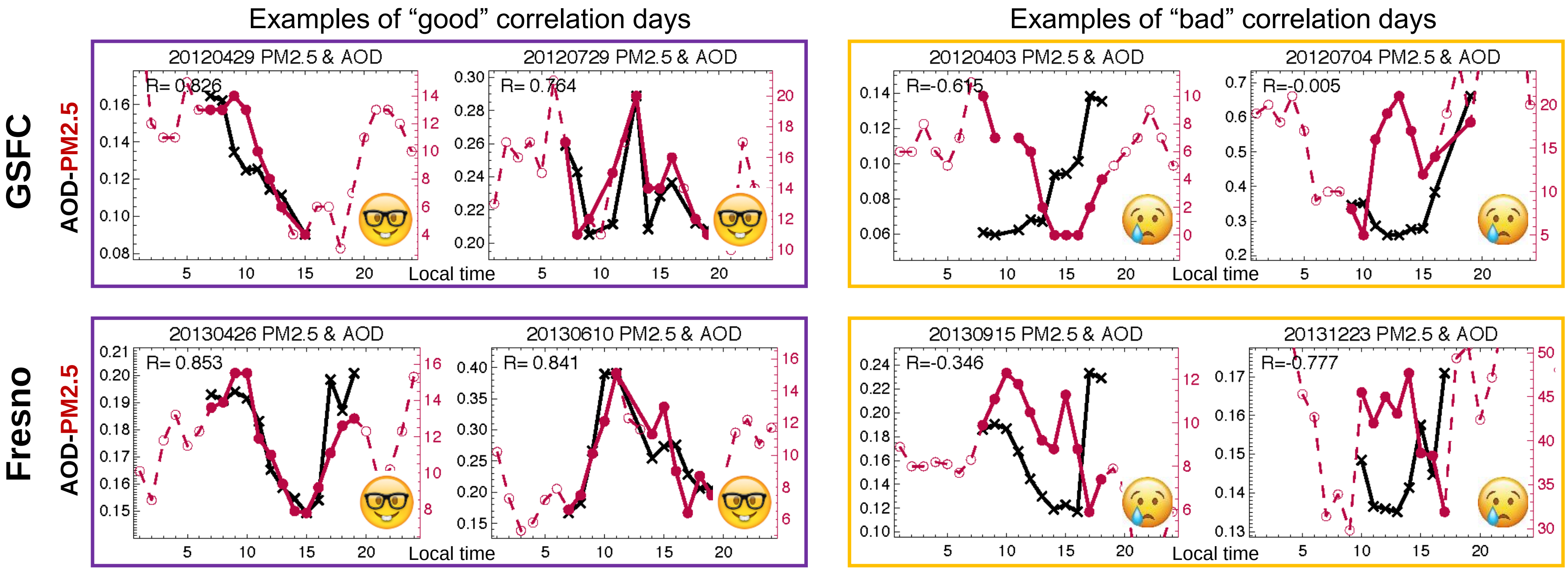
Relative humidity (or water vapor):

- AOD value increases with the increase of RH, whereas PM2.5 usually refers to the aerosol dry mass -> **AOD corresponds to RH but PM2.5 does not**

Aerosol composition and particle size:

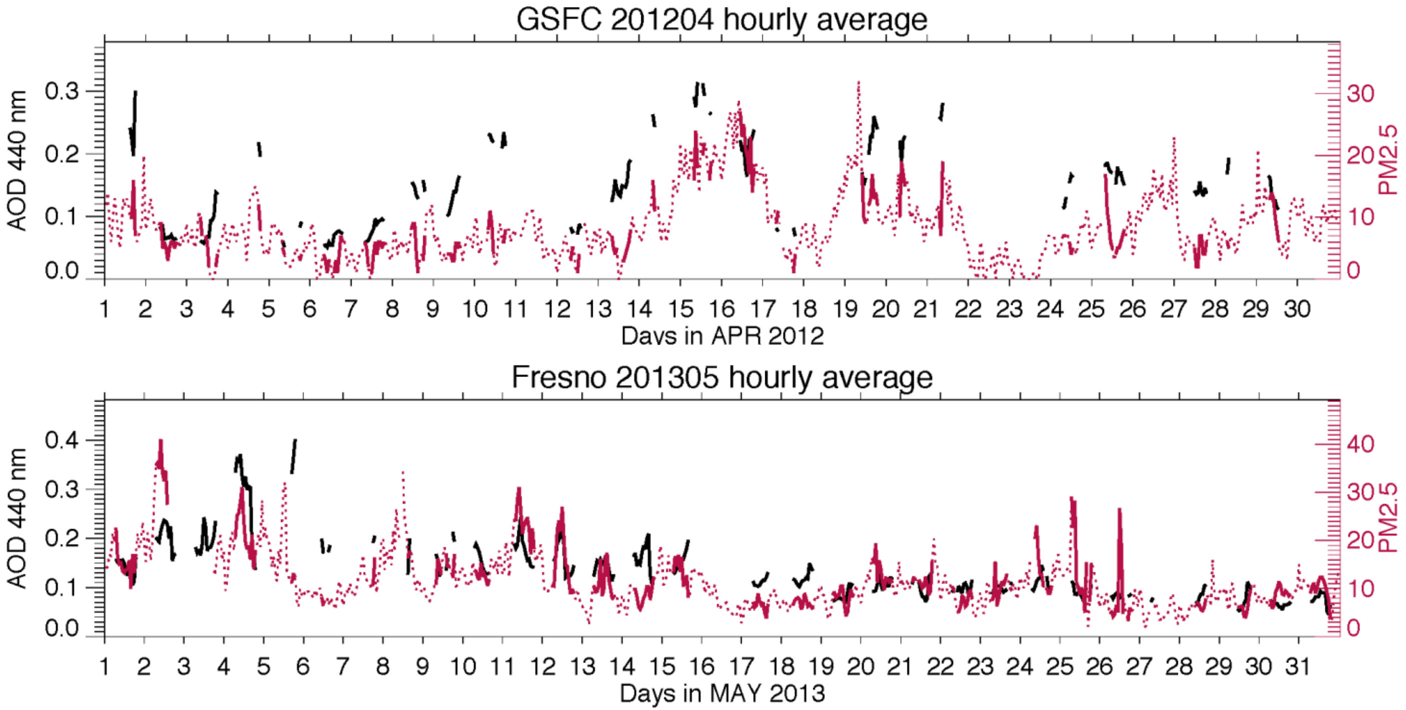
- Different aerosol species and size have different mass extinction efficiency -> even under dry conditions, **mass-to-extinction conversion depends on aerosol composition and particle size**

On hourly scale, AOD-PM2.5 are not well correlated for most of the time



At all the four locations in multiple years, we found that **only 13-22% days** the daytime AOD and PM2.5 are correlated with $R \geq 0.7$, **but 30-57% days** when daytime AOD and PM2.5 are negatively correlated with $R < 0$

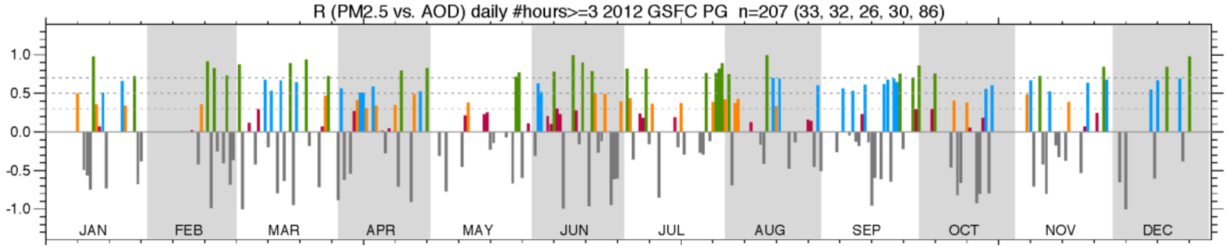
But on day-to-day basis, the variations of AOD and PM2.5 are mostly in-sync: Examples of hourly variations within a month



Day-to-day co-variations of PM2.5 and AOD are driven mostly by the synoptic-scale meteorology. Geostationary observations increase the number of daily observations compared to the LEO satellite observation

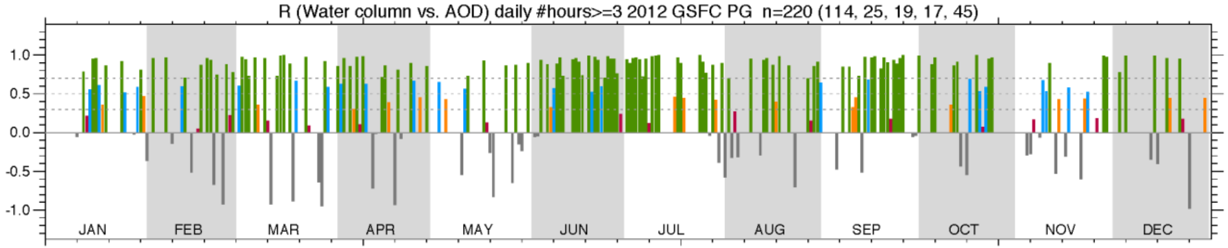
AOD varies more closely with column water vapor than with PM2.5 over the US – example at GSFC site

Daily correlation coefficients between AOD and PM2.5 in 2012, GSFC



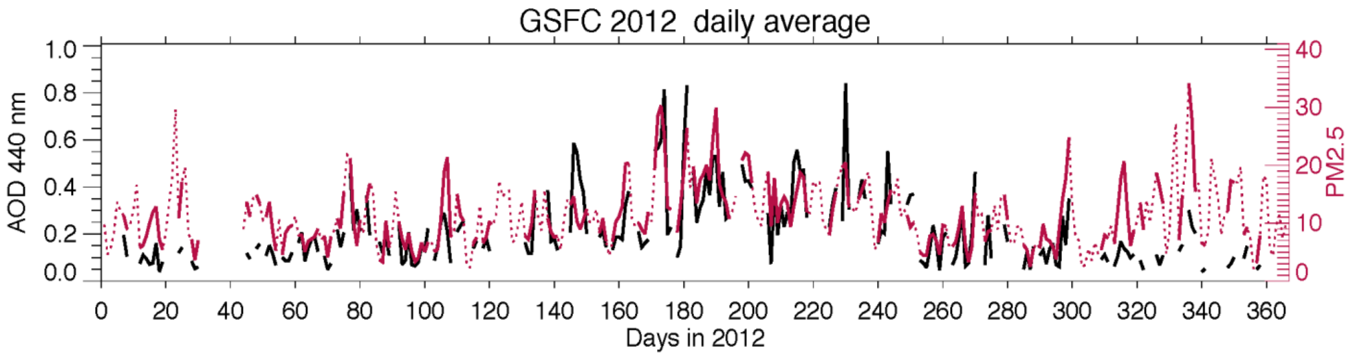
Total available days: 207
16% (33): R ≥ 0.7
42% (86): R < 0.0

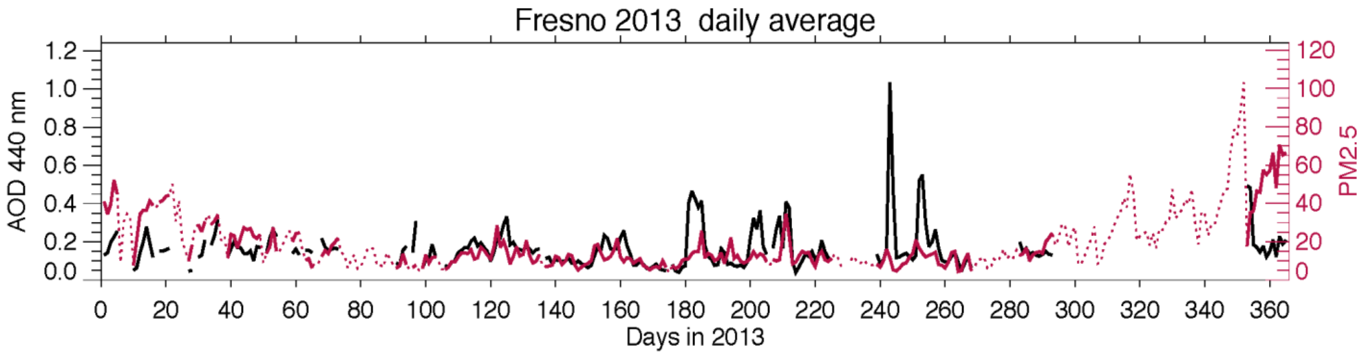
Daily correlation coefficients between AOD and column water vapor in 2012, GSFC

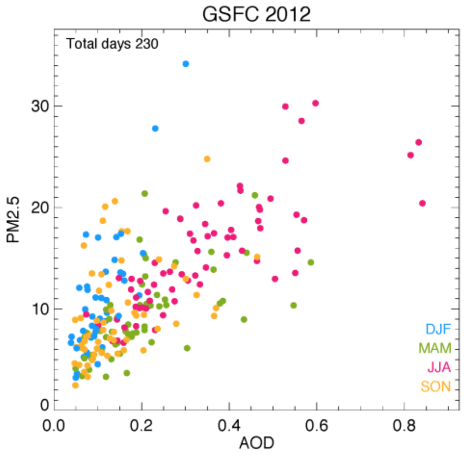


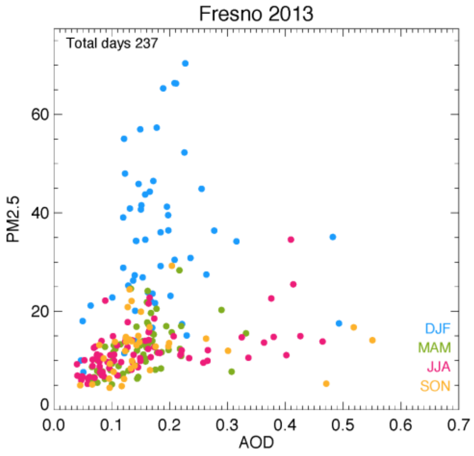
Total available days: 220
52% (114): R ≥ 0.7
20% (45): R < 0.0

However, the AOD-PM2.5 ratio changes with seasons; for the same PM2.5, AOD is higher in the summer and lower in the winter









Inferring PM via Data Assimilation

- **Using data assimilation to infer PM concentrations from satellite data**
  - Multi-spectral AOD
  - (Polarized) reflectances
  - Lidar attenuated backscatter, extinction (HSRL)
- **State estimations vs emission estimation? Which? Both.**
- **Goals:**
  - Prediction: air-quality forecasts
  - Analysis: gridded Level 4 products

Aerosol Data Assimilation

- **Several algorithms:**
  - 3D & 4D variational, ensembled-based, hybrid variational/ensemble
- **Even when PM data is not assimilated as an observable, each of these systems can produce PM gridded fields**
  - Quality depends on model parameterizations, in particular PBL, transport and aerosol processes, details of chemical processes for secondary aerosols, etc
  - Aerosol optical properties
  - Emissions are critical
- **Global or regional, take your pick (resolution vs. domain)**

Challenges of Aerosol Data Assimilation

- **State representation:**
  - Multiple 3D concentrations
    - ✓ Mass
    - ✓ Number (modal schemes)
    - ✓ Bin sizes (sectional schemes)
  - Number of tracers: tens to hundreds
- **Emissions:**
  - ✓ Dynamic: dust, marine, biogenic aerosols
  - ✓ Remotely sensed: biomass burning
  - ✓ Inventories: anthropogenic
- **Observation operators**
  - Intrinsic aerosol optical properties needed for remotely sensed data:
    - ✓ Mass extinction coefficient, single scattering albedo, phase matrix
    - ✓ These are often poorly known but assumed to be known due to identifiability issues:

$$\tau = \beta \bullet \mathbf{M}$$

Aerosol Observables

- **Aerosol Optical Depth (AOD) is the most commonly available observable**
  - Vertically integrated mass weighted by extinction coefficient, summed over multiple species: low observability
  - Multi-spectral AOD measurements
- **Radiance Assimilation:**
  - Vector scattering calculations needed for UV-VIS measurements are not cheap
  - Surface BRDF/BPDF characterization is a challenge
- **Surface PM 2.5**
  - Single level
  - Often plagued by representativeness
- **Lidars provide vertical profiles**
  - Spatially coverage is poor (pencil thin)
  - Attenuated backscatter again requires optical assumptions which are not directly measured
  - HSRL makes a more direct measurement of aerosol extinction
    - Ground base and airborne demonstrations
    - Being considered by NASA’s ACCP Decadal mission

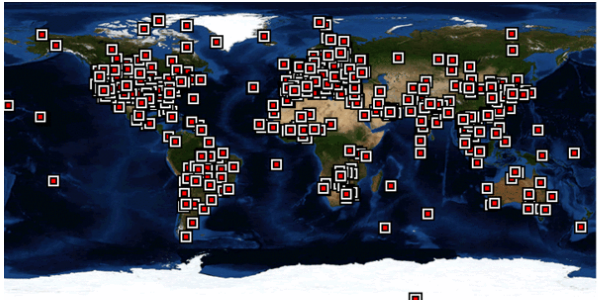
Current (NRT)

AEROSOL PROGRAM OF RECORD

Aerosol Observing System

AERONET

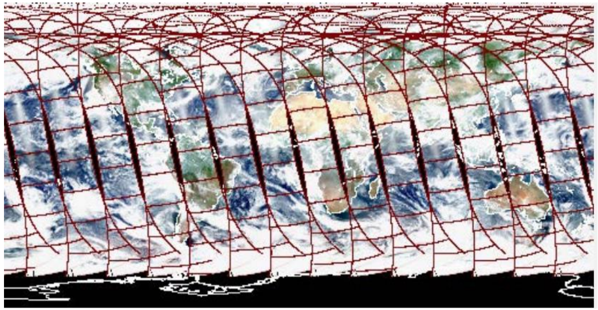
- Ground-based Sun photometers globally distributed
- Direct measurements of multi-spectral Aerosol Optical Depth
- AERONET measurements are considered the reference
- observation and are generally used to perform validation



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

MODIS Instruments on AQUA and TERRA satellites

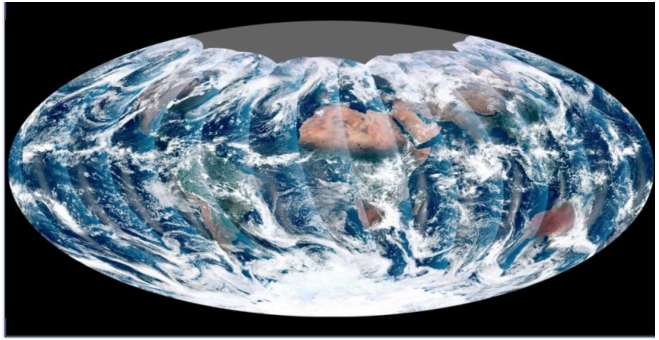
- TERRA (20 years) and AQUA (18 years) may last until 2023
- Temporal resolution: **Daily coverage of the globe**
- Spatial Resolution: 250m, 500m, 1000m depending on bands
- Several AOD algorithms available:
  - Dark target
  - Deep Blue
  - MAIAC



https://modis.gsfc.nasa.gov/

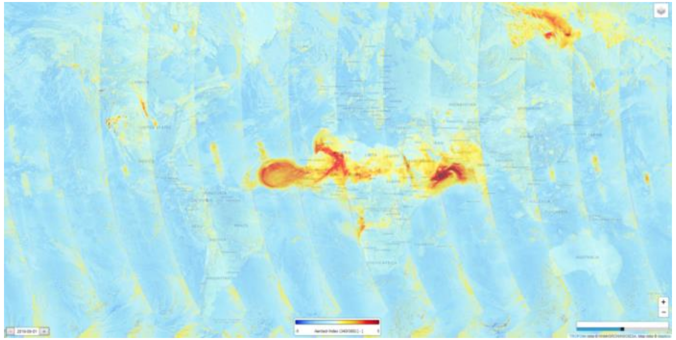
Aerosol Obs System: LEO Satellites

- **VIIRS onboard Suomi-NPP satellite:**
  - Launched in 2011
  - Temporal resolution: **Daily coverage of the globe**
  - Spatial Resolution: ~750m for aerosol retrieval
  - Several algorithms:
    - NOAA/NESDIS/STAR algorithm
    - ✓ NASA Deep Blue algorithm



https://ncc.nesdis.noaa.gov/VIIRS/

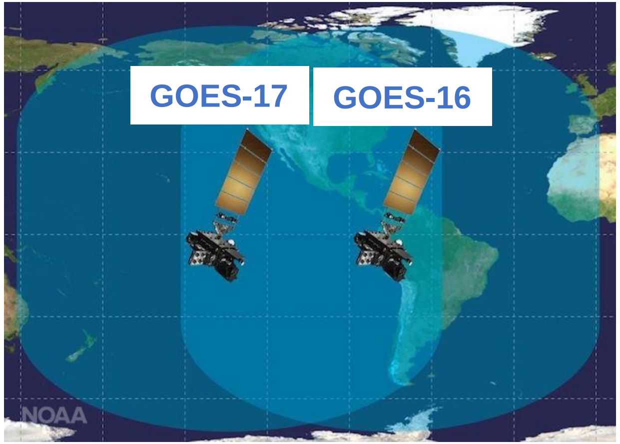
- **TROPOMI onboard SENTINEL-5P**
  - Launched in 2017
  - Temporal resolution: **Daily coverage of the globe**
  - Spatial Resolution: ~7km
  - Spatial resolution is a challenge: cloud contamination
  - Reflectance measurements over the UV-SWIR spectral range



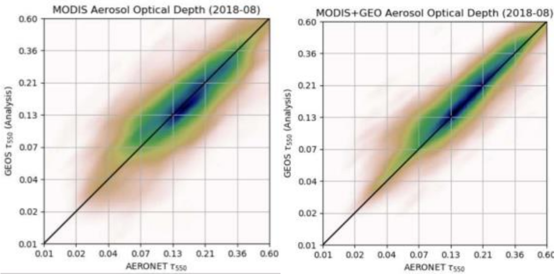
http://www.tropomi.eu/

Aerosol Obs System: GEO satellites

- **Advanced Baseline Imager (ABI) onboard GOES satellites**
  - GOES-R or 16 launched in 2016
  - GOES-S or 17 launched in 2018
  - ABI has 16 spectral bands vs. 5 on the legacy GOES Imager
  - Spatial resolution: 500m to 2km
  - New products with higher accuracy and higher spatial resolution
  - Faster scan rate compared to the legacy GOES imager
    - **Full disc image** every 10 min (default mode)
    - More frequent observations (higher temporal resolution)
  - Several Algorithms:
    - NOAA Algorithm
    - ✓ NASA Dark Target (MODIS heritage)



Credit: https://www.noaa.gov/media-release/noaa-s-newest-geostationary-satellite-will-be-positioned-as-goes-east-fall



Aerosol Obs System: GEO Satellites

Advanced Himawari Imager (AHI) over ASIA on HIMAWARI satellite

- Himawari-8 launched in 2014
- AHI has 16 spectral bands
- Spatial resolution: 500m to 2km
- Temporal resolution:
  - Full disc image every 10 min
- Several algorithms:
  - JAXA algorithm
  - ✓ NASA Dark Target (MODIS heritage)
  - Yonsei aerosol algorithm
  - etc

AHI RGB image

Emerging

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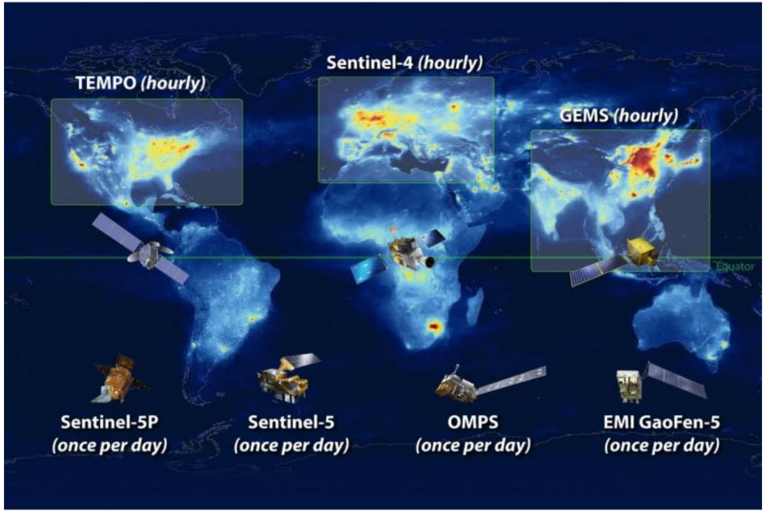
Geostationary (Virtual) Constellation

International constellation with a strong focus on air quality with TEMPO (U.S.), Sentinel-4 (Europe) and GEMS (Asia) → **hourly but regional coverage**

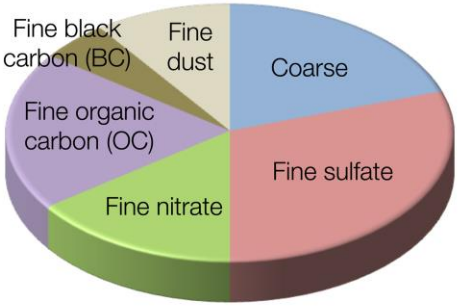


- **TEMPO**
  - UV/Vis spectrometer
  - Launch planned for 2022
  - Spatial resolution: 2 x 4.5 km^2
- **Sentinel-4**
  - UV/Vis/NIR spectrometer
  - Launch planned for 2023
  - Spatial resolution: 8 x 8 km^2
- **GEMS**
  - UV/Vis spectrometer
  - Launched on Feb 2020
  - Spatial resolution: 3.5 x 8 km^2 (over Seoul for aerosols)

- **METEOSAT 3rd generation**
  - Launch planned in 2021, 2025, 2029, 2032
  - Multipurpose VIS/IR radiometer with a spatial resolution from 500m to 2km

MAIA: Speciated PM heath impacts

PI: David Diner



MAIA
Multi-Angle Imager for Aerosols

- MAIA’s primary objective is to link exposure to different types of PM—mixtures of particles of various sizes, shapes, and compositions—with human health
- Globally distributed observations of major cities will provide large sample sizes to conduct statistically robust epidemiological studies
- Secondary targets will also be observed to enable other types of aerosol and cloud investigations

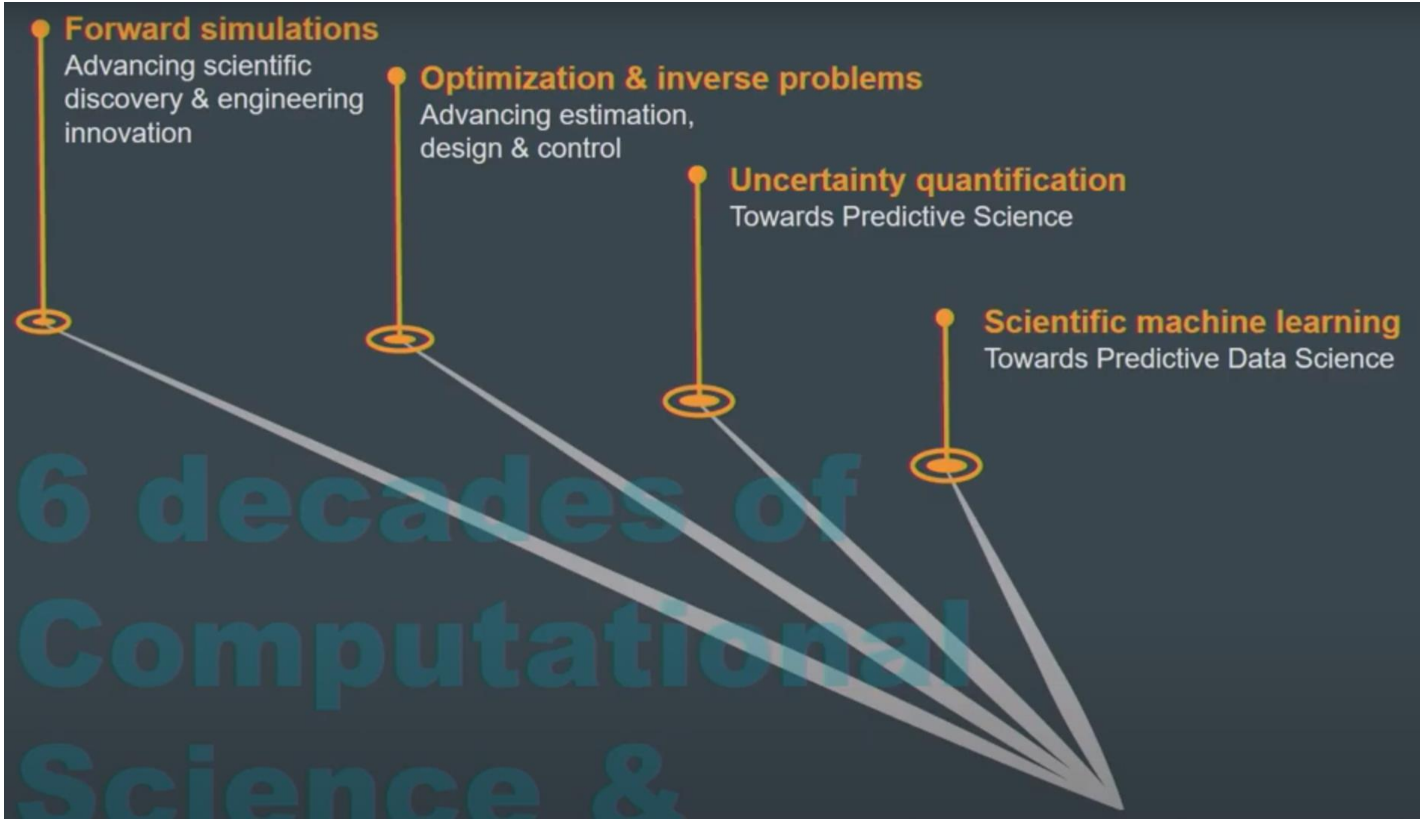
Aerosol Obs System: LEO Satellites

- **OCI and MAPs on PACE**
  - Launch planned in Fall 2022
  - A spectrometer and a pair of multi-wavelength, multi-angle polarimeters that will measure aerosol characterization from UV to SWIR -> UV channels allows retrieval of aerosol absorption
  - Global coverage every two days
  - Spatial resolution: 1 km
- **3MI on METOP-SG**
  - Launch planned in 2023
  - Multi-viewing Multi-channel Multi-polarisation Imager
  - Spatial resolution: 4km at nadir
- **EarthCARE**
  - Launch planned 2022
  - Lidar and a Multi-Spectral Imager (MSI)

    → Vertical profiles of aerosol extinction
- **ACCP**
  - Date planned: 2029
  - Polarimeter and a lidar

Earthcare

Scientific Machine Learning



Concluding Remarks

- **To date, data-driven (supervised) ML algorithms has shown skill deriving PM from space observations + *local ancillary information***
- **PM from models/DA systems at specific locations are plague by errors of representativeness – even if models are perfect**
  - Estimation at different scales
- **For those regions that are well served by ground monitors, machine learning/statistical methods can be used to *customize* analysis and forecasts to specific stations**
  - What else can we do when ground monitors are not available?
  - Universal MOS that do not depend on location? Doubtful, mainly because of emission uncertainties