

Planning for Future Observing Systems Focused on Coupled Atmospheric Processes

Arlindo da Silva

NASA/GSFC, Global Modeling and Assimilation Office

arlindo.m.dasilva@nasa.gov

With contributions from many in GMAO, AOS Science Team, Angela Benedetti

US CLIVAR Reanalysis Webinars

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Focus of Presentation

Coupled Atmospheric Processes involving ...

Aerosols, Clouds, Convection and Precipitation

Outline

- ❑ What is in the horizon: models, observations, DA
- ❑ Highlights:
 - The Geostationary Constellation
 - EarthCARE
 - NASA's Atmosphere Observing System (AOS)
 - Issues in Aerosol Data Assimilation
- ❑ The 7 Questions

Atmospheric Models in 10 Years

- **Cloud/storm resolving models**
 - Regional models (short range) → **sub km to 1 km**
 - Global forecast models (extended range up to 10 days) → **~1-5 km**
- **Aerosol models**
 - Regional models (short range) → **sub km to 4 km**
 - Global forecast models (ext. range) → **~3-5 km**
- **Climate models:** (long-term, years) → **25 km**
- **Unified Models:** scalable from CRM to Regional to Climate
- **More coupling**
 - New components: composition, land, applications (fire/urban)
- **Advances in Model Physics**
 - New methods (Lagrangian, Bayesian), increased complexity
- **Advances in data assimilation/evaluation**
- **Processes more important as scales collapse**

BAMS Report



“Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances... but that is a dream.”

L. F. Richardson

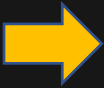
ACCP Modeling Workshop Workshop (BAMS 2021)



Major Advances in Observing Systems

Good News: The global observing systems for atmospheric composition are growing

Balloons
Airplanes
Satellites (LEO & GEO)
GLOBAL ATMOSPHERE WATCH
IAGOS
ACTRIS
AERONET
Ground-based stations
Ships
Low cost sensors



The dawn of a new era for atmospheric composition monitoring from space

The next few years will see an unprecedented amount of satellite instruments capable of monitoring a wide range of trace gases, key greenhouse gases and aerosols.

GEMS is the first of the of the geo instruments with air quality capabilities.

Coordination Group for Meteorological Satellites
WORLD METEOROLOGICAL ORGANIZATION
GLOBAL ATMOSPHERE WATCH
ECMWF
CGMS

CGMS-49-GUEST-WP-07, Date 27 April 2021

NASA AOS (ACCP)

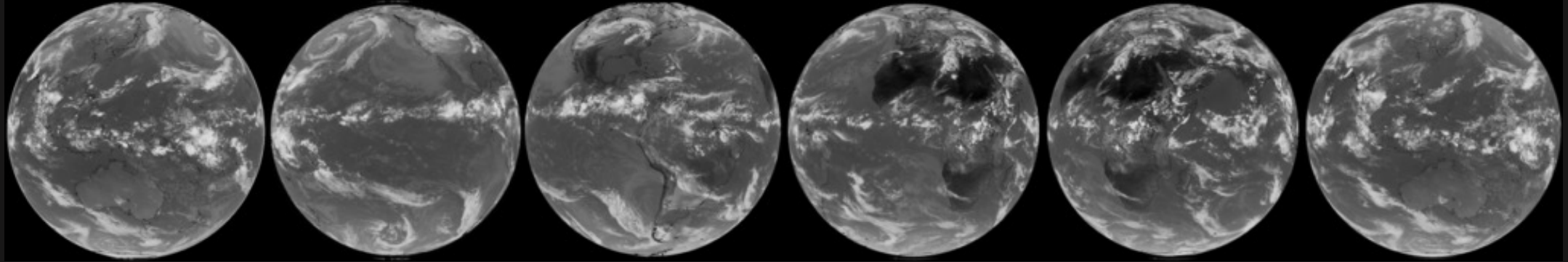
SSP-1: Ka & W Doppler Radar, Microwave Radiometer, HSRL Lidar, Polarimeter, LWIR-TIR Spectrometer, UV-VIS Spectrometer

SSG-1: W & Ku Doppler Radar, Stereo Camera

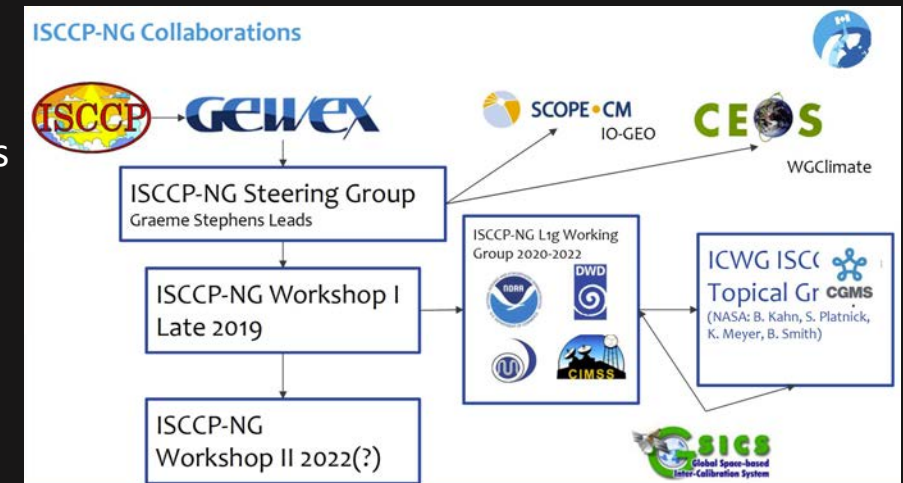
SSG-2: Backscatter Lidar, Microwave Radiometer, Polarimeter, Stereo Camera

Process oriented: aerosols, clouds, convection and precipitation

ISCCP Next Generation



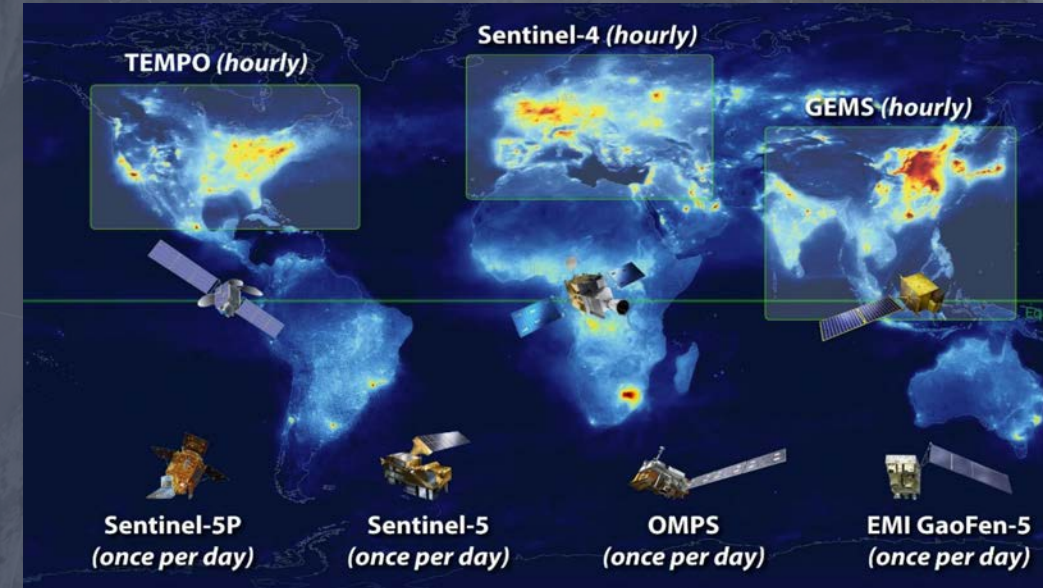
- With assumed launch of the [MTG in 2022](#), the entire equator is encircled by “advanced” geostationary imagers.
- This is our targeted start date for new cloud/aerosols property data records
- New sensors provide information absent from the original ISCCP:
 - **Cloud Dynamics**
 - **Cloud Microphysics**
 - **Aerosol**
 - **Diurnally consistent cloud climatologies**
- Maintaining these and the unimagined applications while sub-setting the data to a manageable size is the challenge.
- Consistency with past climatology for common information is achievable. Data rescue, new quality control, re-calibration, and uncertainty estimates for past sensor radiances improve historic estimates.



Courtesy: Andy Heidinger

The Atmospheric Composition Virtual Constellation (AC-VC)

- **Geostationary Air Quality (Geo-AQ)** constellation consists of geostationary satellite sensors with a strong focus on air quality.
 - hourly observations of key air pollutants over Asia, Europe, and North America.
- **GEO-AQ missions:**
 - GEMS (launched in 2020)
 - TEMPO (to launched in 2022)
 - Sentinel-4 (to launched 2023)
- Complemented by **LEO-AQ** missions providing daily global atmospheric composition observations.



The **Geo-AQ** constellation is relevant for

- Providing measurements of aerosol precursor gases
- Providing UV and O₂-band channels for further constraining geostationary aerosol retrievals from the operational Geo Ring.

EarthCARE Satellite

Orbit:

- 393 km mean altitude
- Sun Synchronous frozen orbit
- 97° Inclination
- 14h00 DSN MLST
- 25-days repeat cycle

Lifetime:

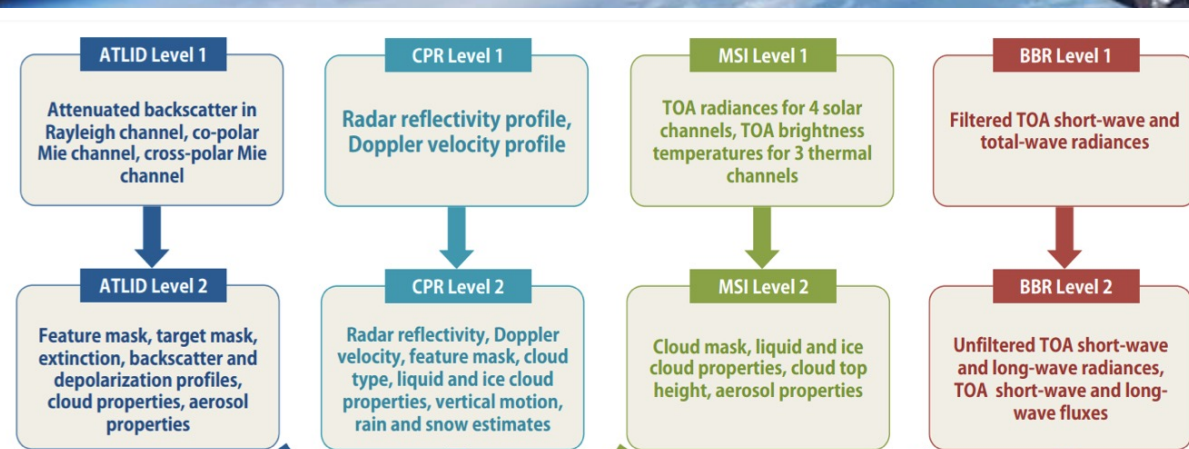
- 3 years + 1
(incl. 6-months commissioning)
- Launch: 2023

Satellite:

- 2350 kg (incl. 313 kg propellant)
- 3-axis stabilized / yaw-steering
- 1700W
- On-board data rates average:
<15 kbps (HKTM)
<2.5 Mbps (science)

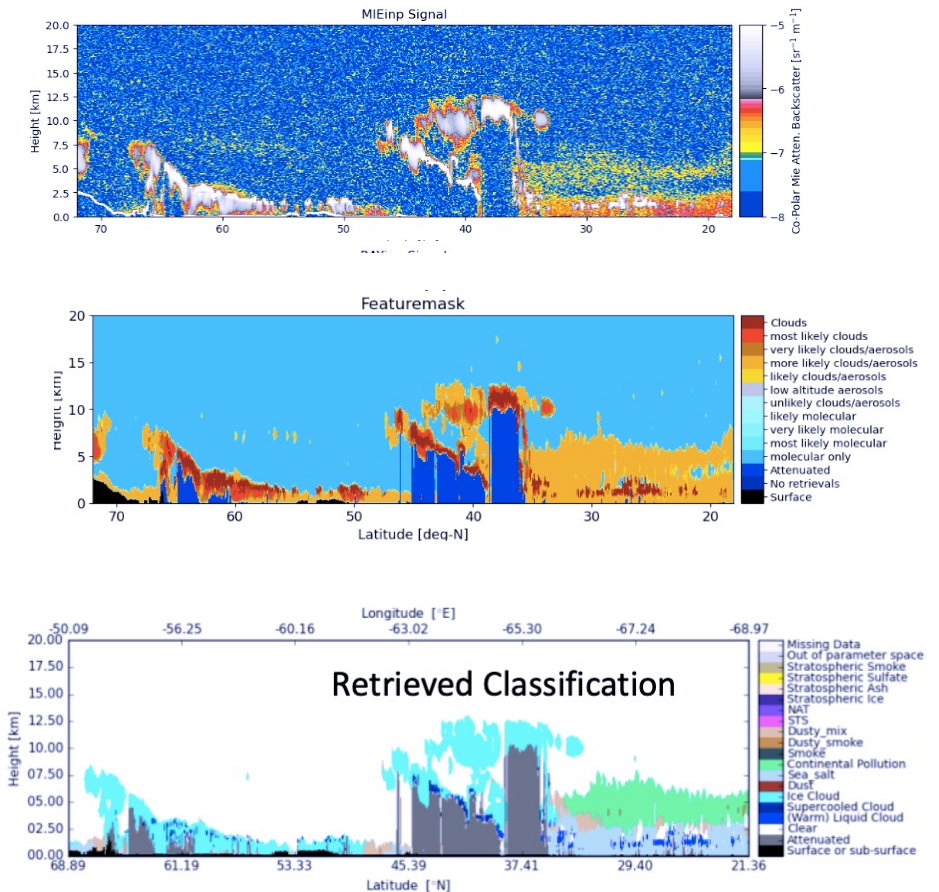
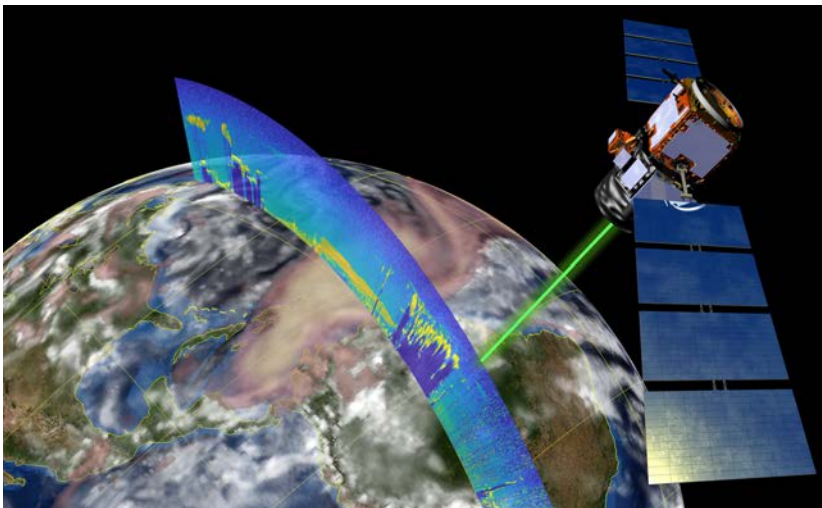
Payload:

- 2 active instruments (ATLID & CPR)
- 2 passive instruments (BBR & MSI)



Preparations for Synergistic Assimilation of Active Cloud and Aerosol Measurements

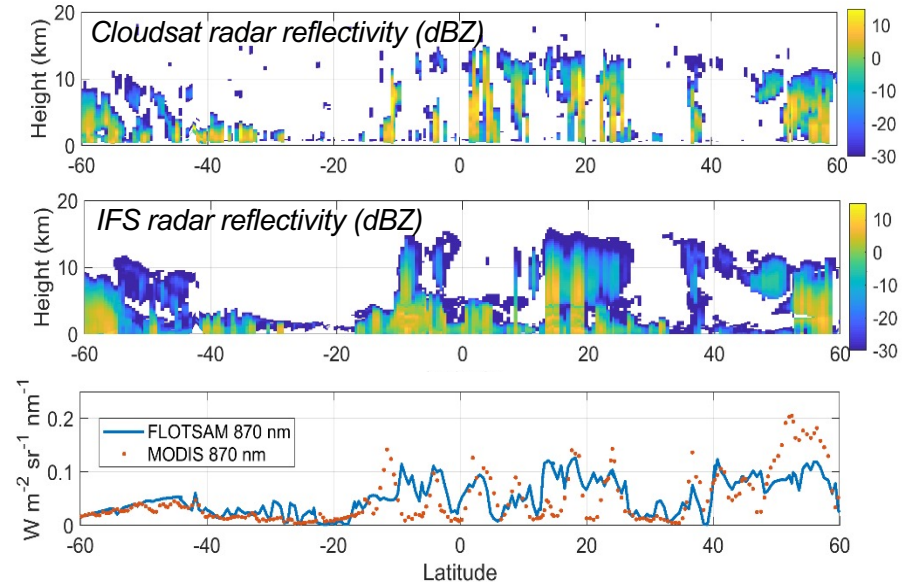
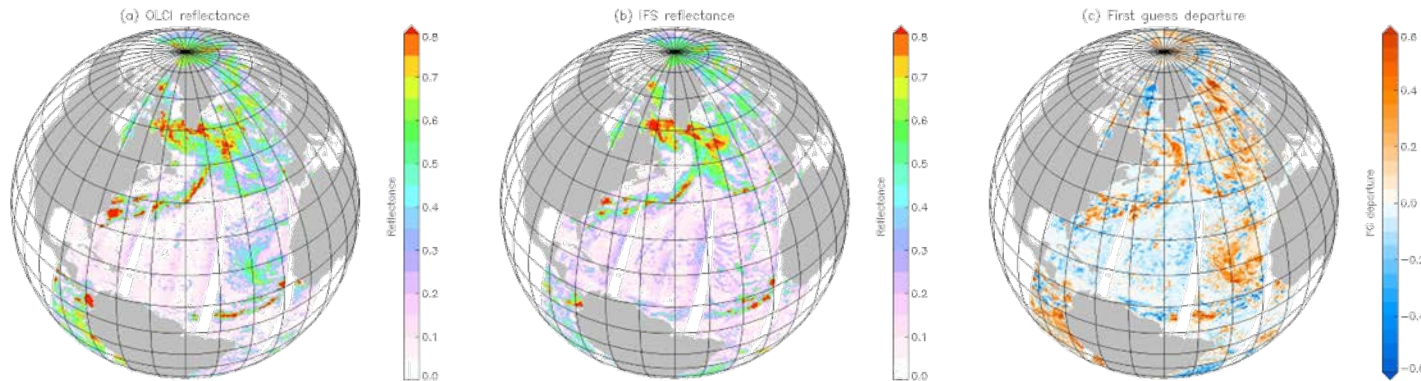
- Aerosol and cloud signals from Lidar ATLID will often be hard to distinguish; cloud screening will mean some aerosol information is lost.
- For optimum use of lidar signal, cloud and aerosol signals should be considered simultaneously.
- Accurate colocations of clouds and aerosols within Earth system models will help improve the representation of cloud-aerosol-radiation interactions.



Courtesy: Angela Benedetti

Cloud Radiation Measurement Monitoring

- Monitoring of radiation measurements would provide a useful tool for independent validation of CPR and ATLID cloud assimilation.
- Operational monitoring of solar radiances could be a precursor to assimilation of such observations in the future.



Successful inclusion of OCLI reflectances and their simulation in IFS during CLOVIS project, courtesy of Liam Steele

Courtesy: Angela Benedetti

Credits: Mark Fielding and Liam Steele

EARTH SYSTEM OBSERVATORY

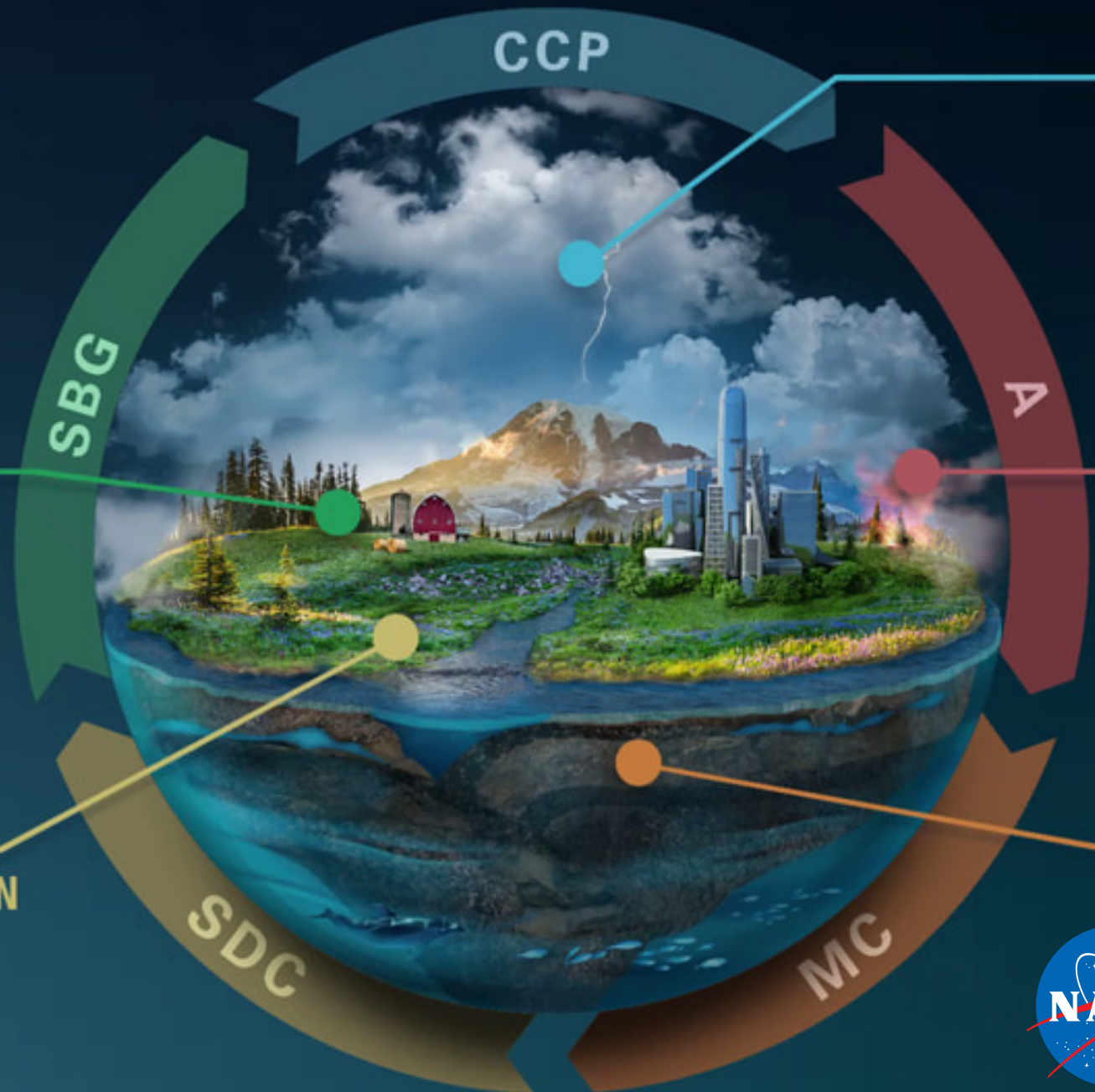
INTERCONNECTED
CORE MISSIONS

SURFACE BIOLOGY AND GEOLOGY

Earth Surface and
Ecosystems

SURFACE DEFORMATION AND CHANGE

Earth Surface Dynamics



CLOUDS, CONVECTION AND PRECIPITATION

Water and Energy in
the Atmosphere

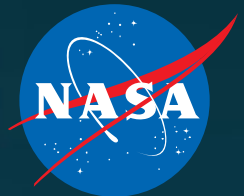
AEROSOLS

Particles in the
Atmosphere

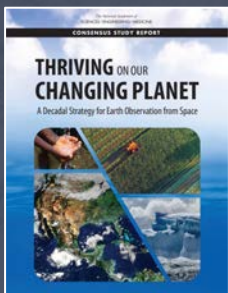
MASS CHANGE

Large-scale Mass
Redistribution

Atmosphere (AOS)



Scientific and Programmatic Basis



- ❖ The 2017 Decadal Survey recommended a new program element called *Designated Observables* with cost-capped missions to provide measurements essential to a comprehensive collection of Earth Science questions.
- ❖ AOS (formerly ACCP) combines 2 Designated Observables

Observable Priorities

Desired Observables

Aerosols

Aerosol properties, aerosol vertical profiles, and cloud properties to understand their effects on climate and air quality

Backscatter lidar and multi-channel, multi-angle imaging polarimeter

Clouds, Convection, and Precipitation

Coupled cloud-precipitation state and dynamics for monitoring global hydrological cycle and understanding contributing processes including cloud feedback

Radar(s), with Doppler, with multi-frequency passive microwave and sub-mm radiometer

• Key AOS INSTRUMENTS

ACCP Aerosols, Clouds, Convection, and Precipitation Study

RADAR

Multi-wavelength (W, Ku)
Doppler
Ku radar may have swath

LIDAR

Multi-wavelength (532 and 1064 nm)
Backscatter and/or HSRL (532 nm)

POLARIMETER

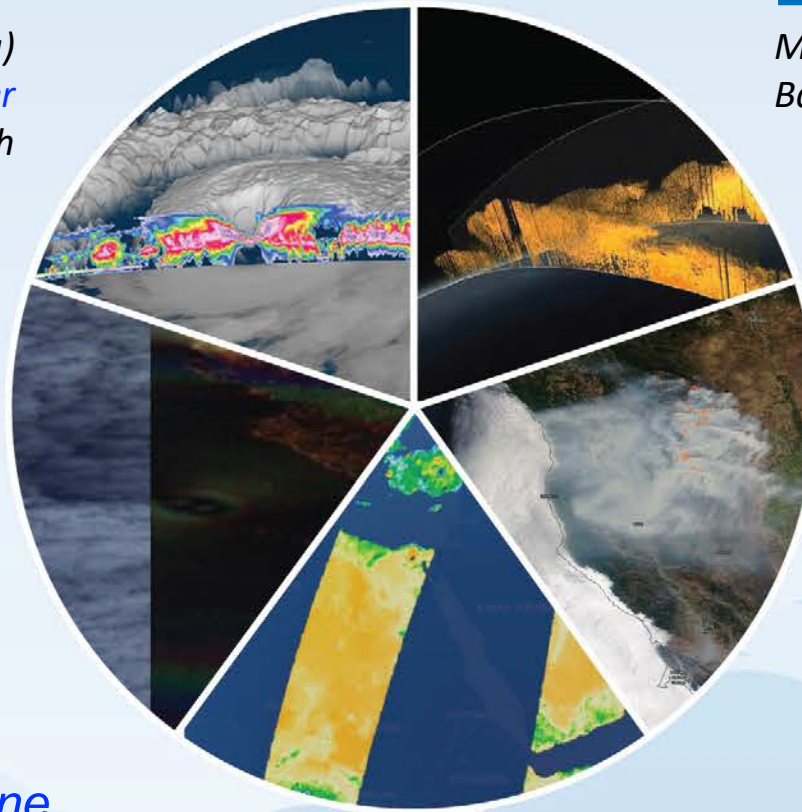
Multi-wavelength (UV-VNIR-SWIR)
Multi-angle, 500m or 1 km footprint
Swath: 600 km or 1,100 km

SPECTROMETER

Multi-wavelength (UV-VIS-
NIR-SWIR-LWIR-FIR)
reflectances and brightness
temperatures

RADIOMETER

Multi-wavelength Microwave
(~100-900 GHz)



AOS requires a suite of spaceborne instruments to measure and characterize the complexity of hydrometeors and aerosols.*

**To also include as, or more capable, airborne in-situ and remote sensing instruments, deployed in synergistic/complementary suborbital campaigns.*



<https://aos.gsfc.nasa.gov>

**EARTH
SYSTEM**
OBSERVATORY

The AOS Constellation

- Science objectives addressed by the *constellation*
- *Polar orbit* essential for meeting almost all objectives
- *Inclined orbit* targets important processes tied to sub-daily variability
- *Suborbital* component addresses science not achievable from space
- AOS explores how interconnections between aerosols, clouds and precipitation impact public health, weather and climate



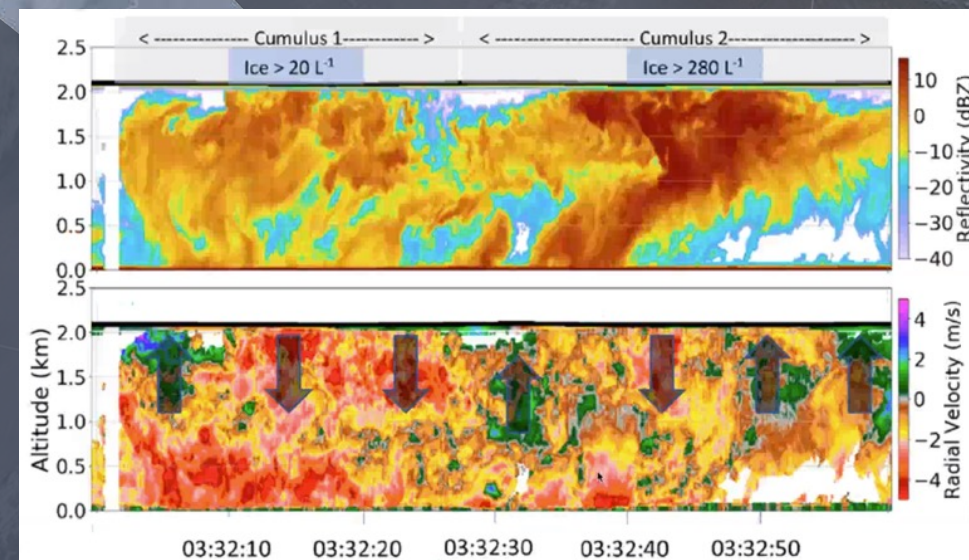
KDP-A planned for June 2022
Launches NET: 2028 (AOS-I), 2030 (AOS-P)



The 5 First-Evers of AOS

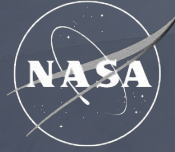
1. Global Observations of Vertical Motion
2. Co-located Dynamics, Cloud AND Precipitation Microphysics with Aerosol Characteristics
3. Global Profiles of Aerosol Properties (absorption, type, size, number)
4. Evolution of Cloud and Aerosol Processes
5. Diurnal Variability of Clouds and Aerosols

McFauhar et al. 2020



Cloud dynamics influences cloud microphysics and aerosol activation

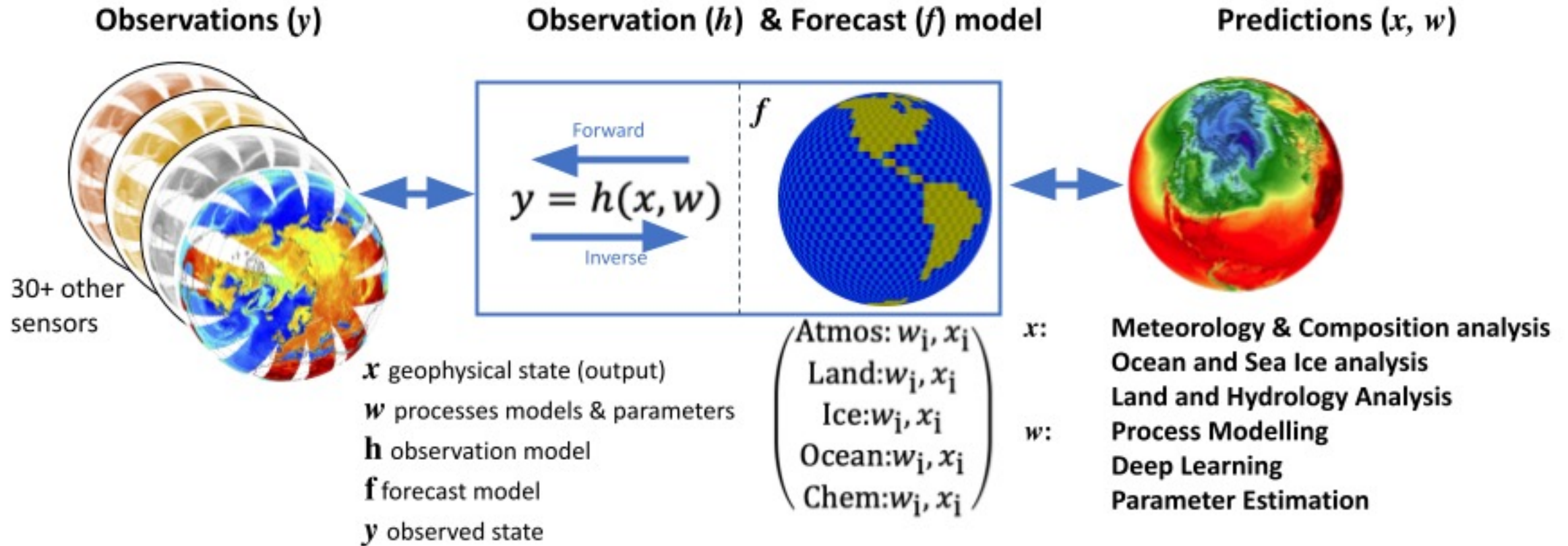




AOS Modeling & DA Priorities

- Support and accelerate critical development activities
 - Nature Runs and generation of instrument observables for algorithm development and evaluation
 - Suborbital campaign planning
- Develop Modeling & DA capabilities for AOS
 - Enable infrastructure for assimilation AOS data in NWP and atmospheric composition models (via JEDI)
 - Plan and Develop key Level 4 products for AOS
 - Develop COSP-like simulators for instrumenting climate models

Earth System Data Assimilation



Courtesy: Andrew Gettelman

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:

$$\tau = \beta \cdot M$$

Aerosol Observing System

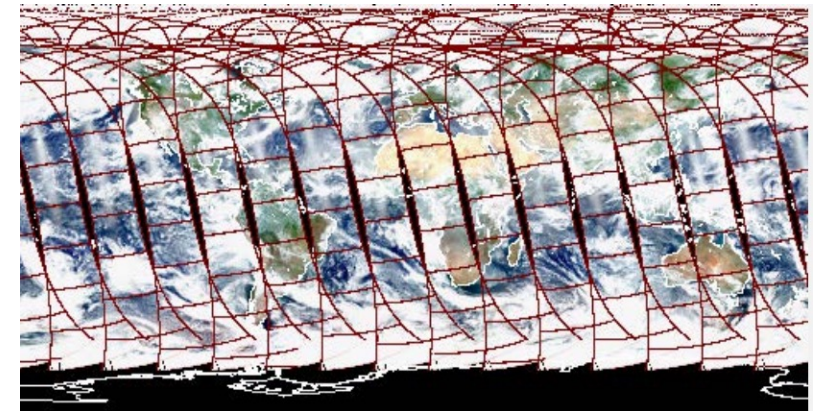
- **Aerosol Optical Depth (AOD)** is the most commonly available observable
 - Vertically integrated mass weighted by extinction coefficient, summed over multiple species: *low observability*
 - multi-spectral AOD measurements
- **Radiance assimilation:**
 - Vector scattering calculations needed for UV-VIS measurements are not cheap
 - Surface BRDF characterization is a challenge
- **Surface PM 2.5**
 - Single level
 - Often plagued by representativeness
- **Lidar measurements** provide vertical info
 - Spatially coverage is poor (pencil thin)
 - Attenuated backscatter again requires optical assumptions which are not directly measured
 - New HSRL concept provides (calibrated) particulate backscatter

Aerosol Observing System in MERRA-2

- **AVHRR for pre-EOS era**
- **MISR: bright surfaces**
- **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
- **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
 - Retrieves on NxN boxes of native-resolution pixels
 - > product is ~10 km resolution:
 - ✓ Cloud-cleared Reflectances at 7 wavelengths
 - ✓ AOD at 550 nm and spectral AOD

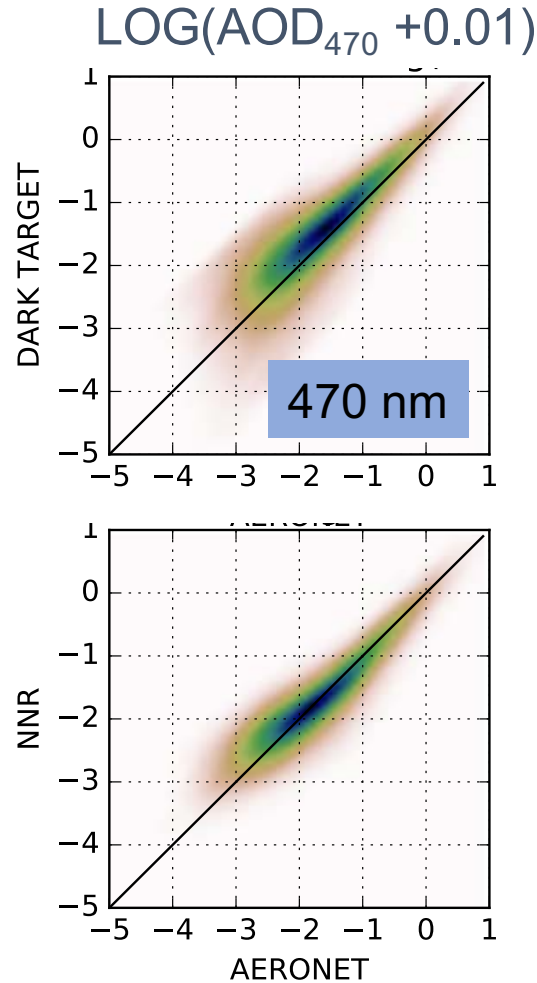
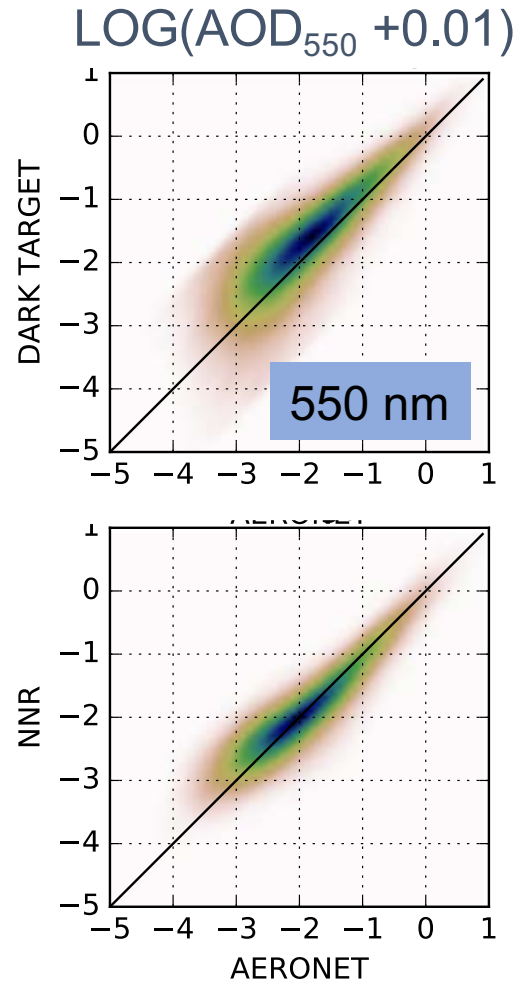


<https://aeronet.gsfc.nasa.gov/>



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

Observing System Homogenization: AERONET Reference



ORIGINAL MODIS AOD

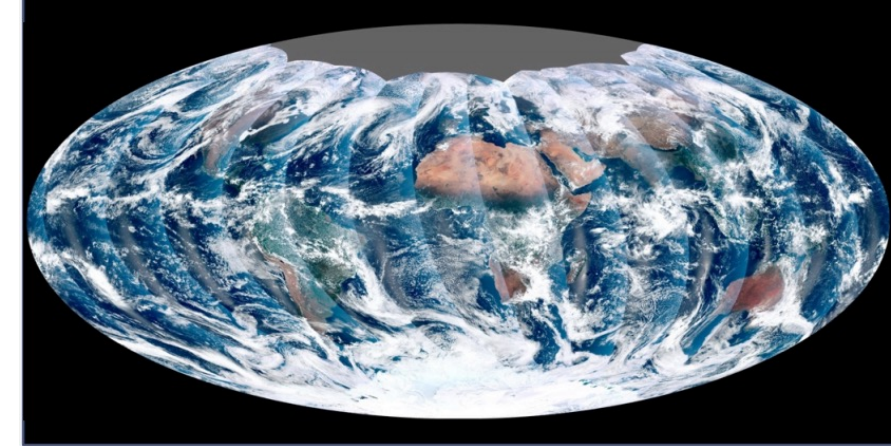
NNR retrievals extended to multiple wavelengths

BIAS CORRECTED AOD
(NNR AOD retrievals)

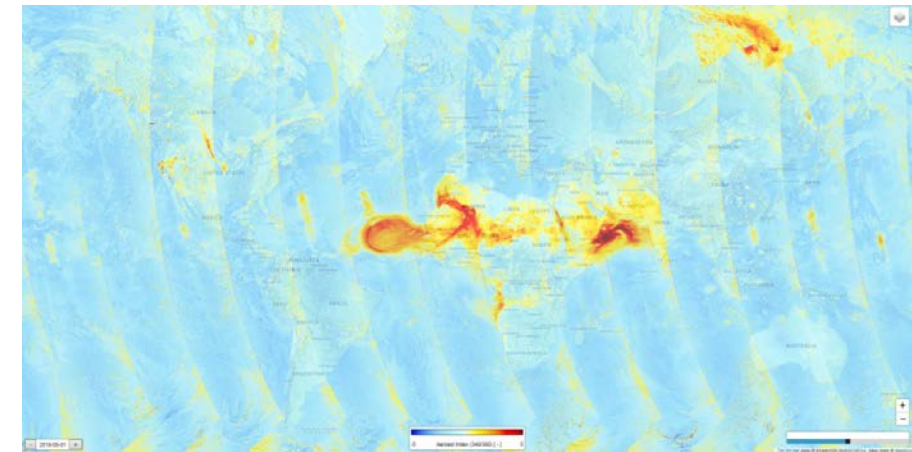
MODIS Neural Net AOD Retrievals trained on AERONET

Aerosol Data Available: LEO satellites

- **VIIRS onboard Suomi-NPP and N20 satellites:**
replacement for Aqua MODIS
 - Available since 2011
 - Temporal resolution: **Daily coverage of the globe**
 - Spatial Resolution: ~750m for aerosol retrieval
 - Same retrievals algorithm as MODIS
 - NASA product “Level 2: cloud-cleared reflectance”
- **TROPOMI onboard SENTINEL-5P**
 - Launched in 2017
 - Temporal resolution: **Daily coverage of the globe**
 - Spatial Resolution: ~7km
 - Spatial resolution is a challenge, peaky about cloud clearing
 - Reflectance measurements over the UV-SWIR spectral range



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



<http://www.tropomi.eu/>

Future Data of Interest

- **The GEO Ring**
- **Ocean Color Instrument and Multi-angle Polarimeters on PACE**
 - Launch planned in Fall 2023
 - 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 2023
 - Lidar and a Multi-Spectral Imager (MSI)
→ Vertical profiles of aerosol extinction
- **AOS**
 - Date planned: 2028
 - Polarimeter and a lidar



Earthcare

Concluding Remarks

Question		Answer
1	What do you see are the most significant advances for the field of reanalysis in 5-10 years?	<i>Within the atmosphere, emergence of concurrent measurements of aerosols, clouds and precipitation and development of corresponding DA capabilities coupled to cloud and precipitation processes.</i>
2	What do you see are the most significant barriers to progress in the field of reanalysis?	<i>As resolution collapses, computational resources for resolving processes needed for assimilating these measurements</i>
3	Which collaborations are currently working and which collaborations need to be fostered?	<i>Partnership between satellite data producers and DA outfits strengthening. Early engagement during mission formulation is a must.</i>
4	What are the critical requirements for consistent Earth system reanalysis?	<i>Within the atmosphere, incorporation of aerosol, cloud convection and precipitation measurements for state and parameter estimation.</i>
5	What observational datasets are required to support these requirements?	<i>Concurrent measurements of aerosols, clouds, convection and precipitation and their radiative effects for closure.</i>
6	What modeling components are mature enough to enable reanalysis for your specific science question or application?	<i>Cloud and aerosol microphysical parameterizations at least at storm resolving scales. Computational resources are a challenge.</i>
7	How is uncertainty quantified for your application? Are there significant barriers for quantifying uncertainty in your field?	<i>Besides detector noise, measurement community being sensitized about need for simulators with proper error characterization and availability of averaging kernels when appropriate.</i>



Extra Slides

Open Source Science

Expanding participation,
improving reproducibility, and
accelerating scientific discovery
for societal benefit.

Open-Source Science

*“We define open-source science as a collaborative culture enabled by technology that empowers the **open sharing of data, information, and knowledge** within the scientific community and the wider public to accelerate scientific research and understanding.”*

Ramachandran, R., Bugbee, K., & Murphy, K. J. Moving from Open Data to Open Science. Earth and Space Science, Wiley Publication <https://doi.org/10.1029/2020EA001562>





Building an Open Source Science Ecosystem

- **Initiate** new missions, research and applied activities as open-source science projects.
- **Implement clear policies** for software, publications and data.
- **Integrate and improve** data management, access, computing, analytics and scientific collaboration.
- **Build the community** through open science team meetings, training, workshops, competitions, awards and prizes.

A CONTINUUM OF OPEN-SOURCE SCIENCE

