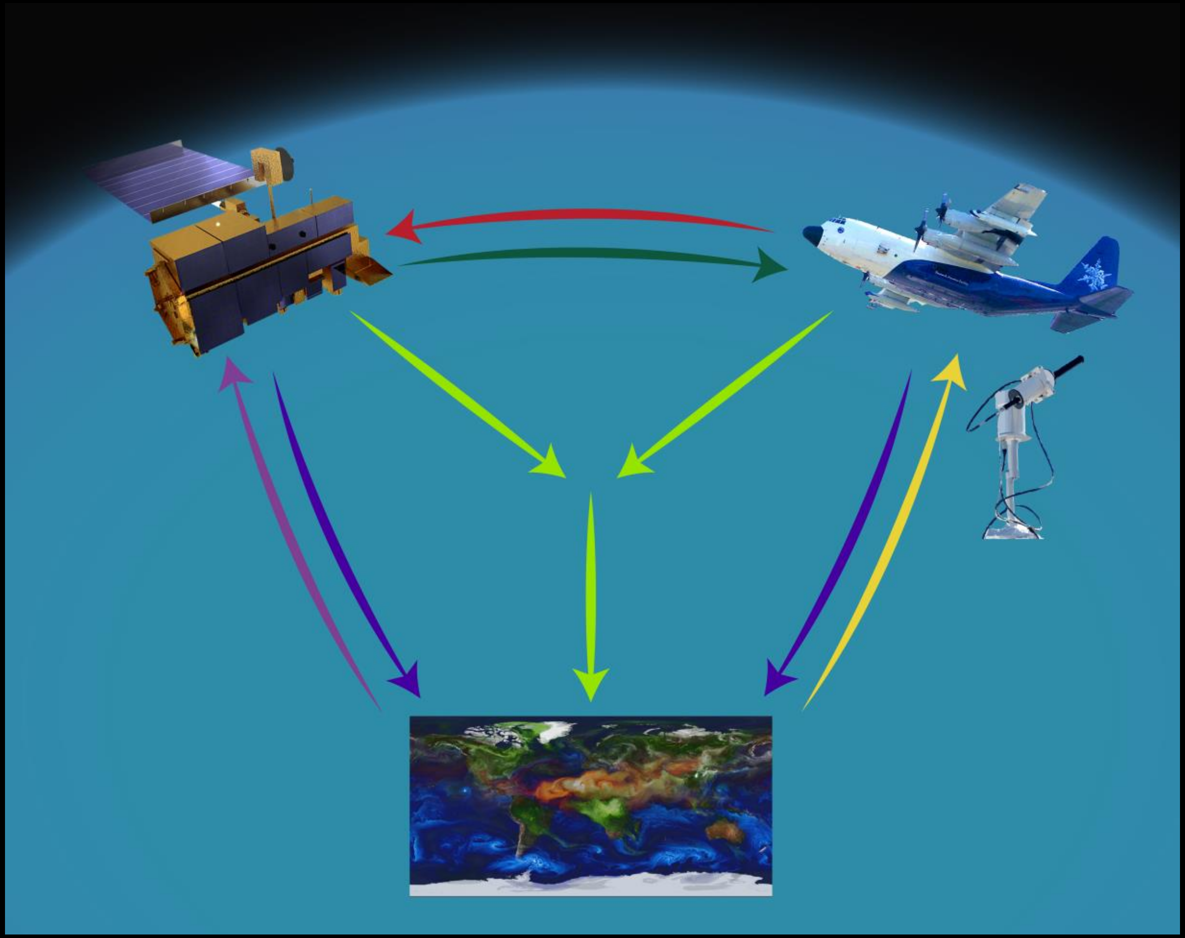
Reducing the Uncertainty in Climate Predictions:

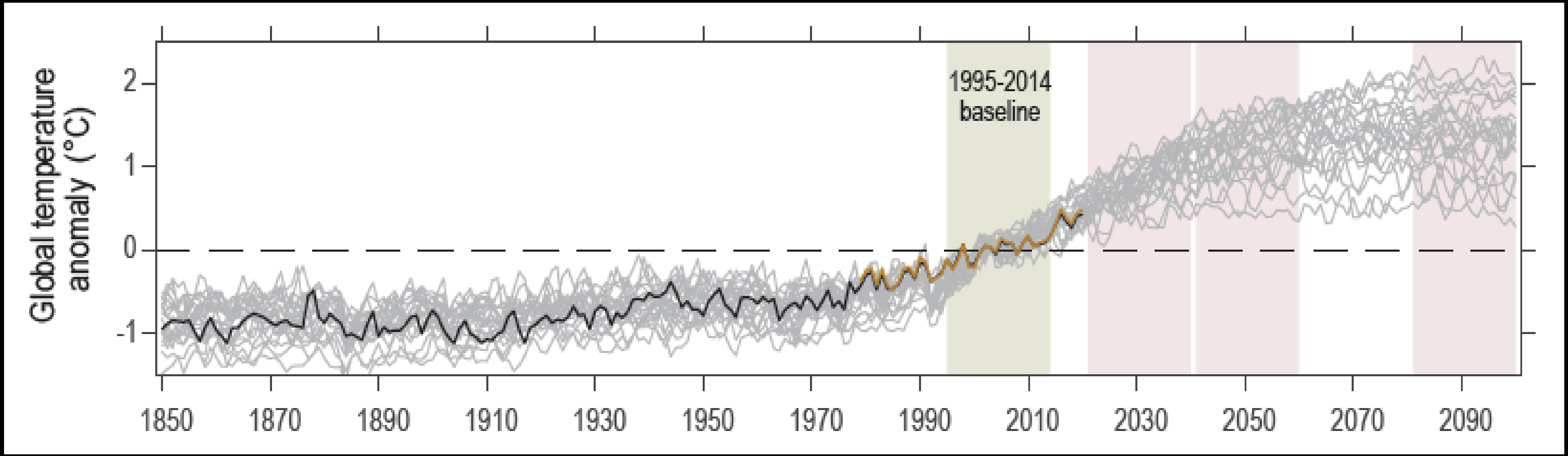
Steps Toward Realizing the Potential of NASA's Earth Observing System, and Reducing Aerosol-Related Climate-Forcing Uncertainty

Ralph Kahn

NASA Goddard Space Flight Center



Multi-model Simulations of Global Mean Surface Temperature Timeline



From IPCC AR-6

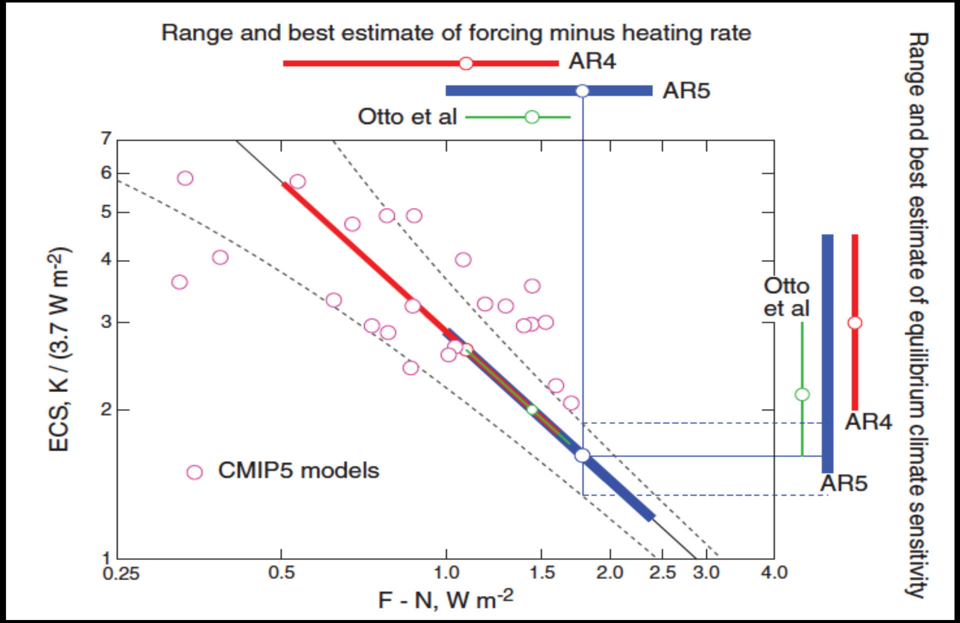
Temperature anomaly simulations for 1850-2014 +
forecasts using a moderate assumed future scenario (SSP1-2.6) for 2015-2100, for 25 models (gray lines)
+
Measurement – where available (black lines)

Aerosol Climate Forcing – The contributions aerosols make toward heating & cooling the Earth System

→ *Particle Microphysical Property Assumption & Cloud Process Uncertainties Dominate; Trace-gas Distributions also matter*

Forcing uncertainty translates into prediction uncertainty

Equilibrium Climate Sensitivity

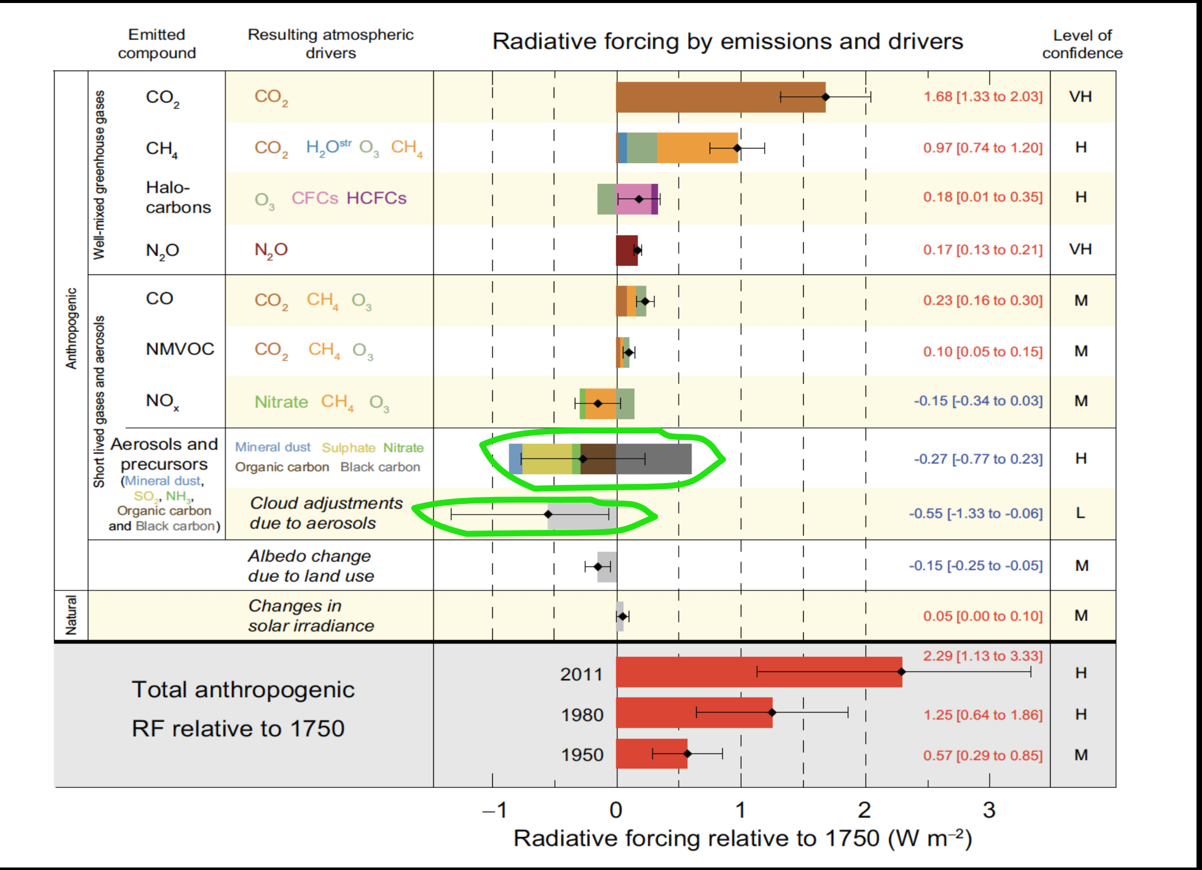


Schwartz et al., Earth's Future 2014

$$(F - N) \times S = \Delta T$$

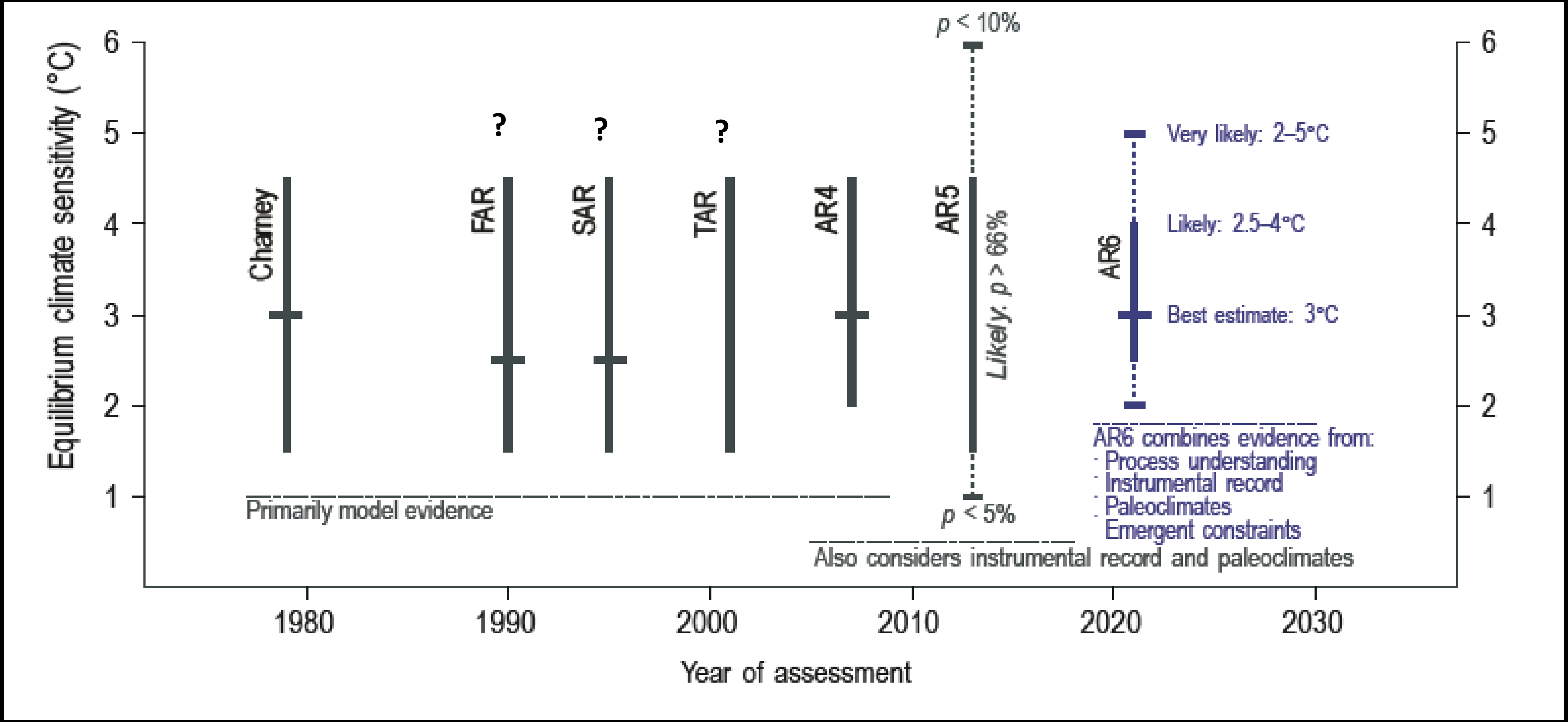
Effective Forcing | Ocean Heat Content | Climate Sensitivity | Response

Aerosol-related forcing uncertainty represents *the largest uncertainty overall* for making climate predictions



IPCC AR5, 2013

IPCC Equilibrium Climate Sensitivity Estimates & Estimated Uncertainties



From IPCC AR-6 Technical Summary

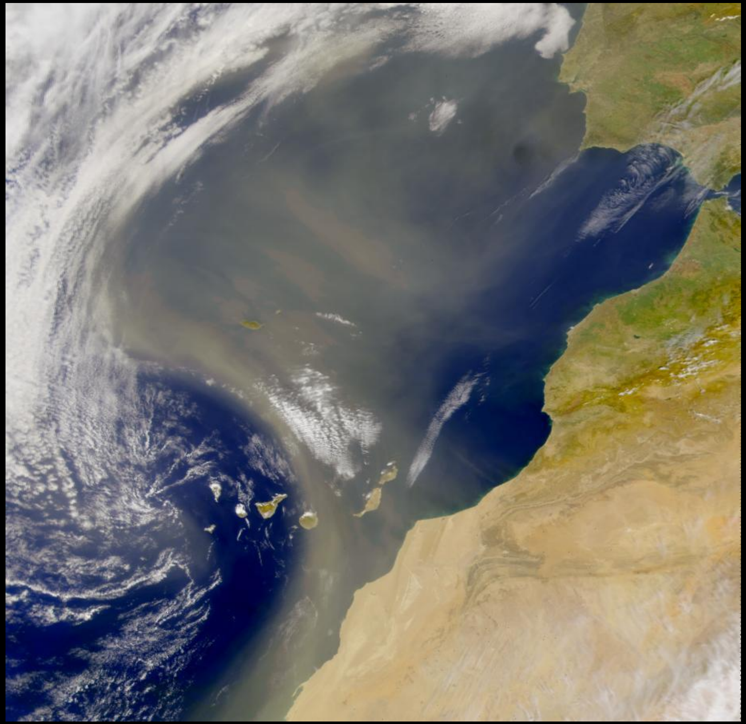
Ground-Based Views

Phoenix Dust Storm 05 July 2011 Phoenix New Times

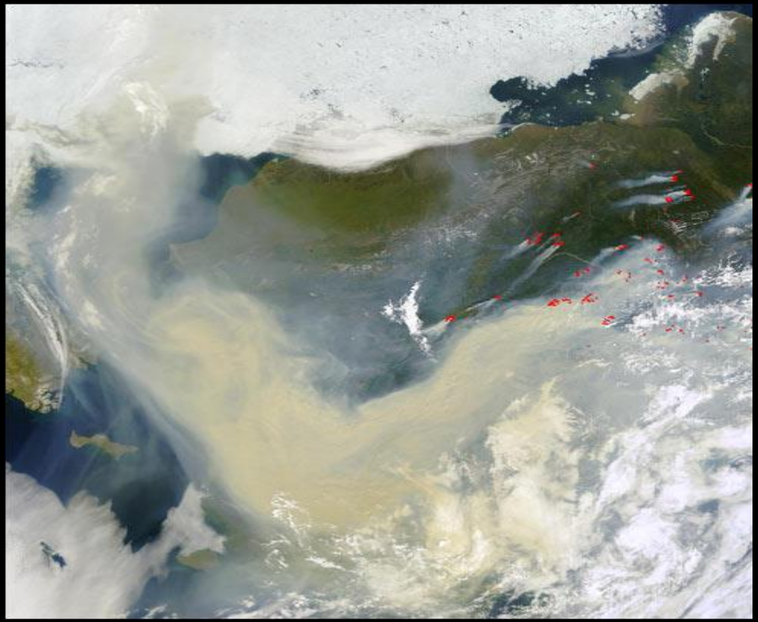
https://www.noaa.gov/stories/where-there-s-wildfire-there-s-forecast

Hunga-Tonga eruption 15 January 2022 – CBS News

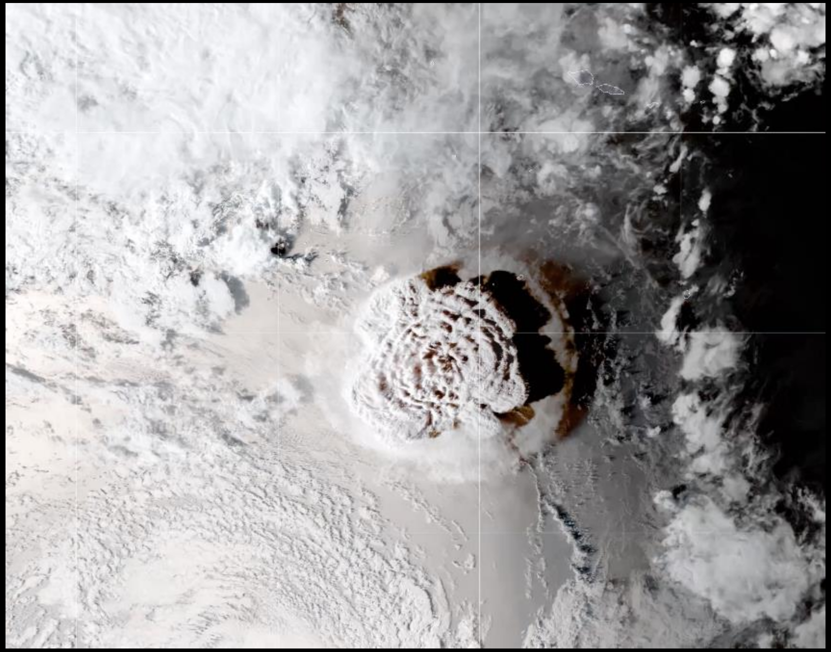
What Satellites Offer



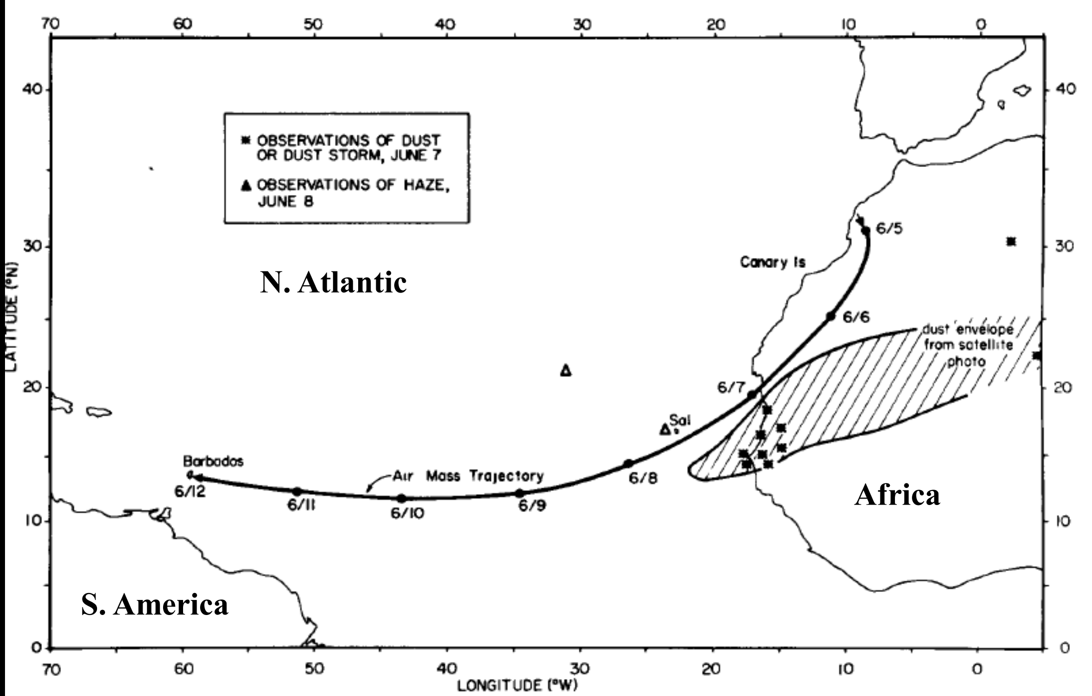
SeaWiFS - Sahara Dust over Canary Islands March 1998

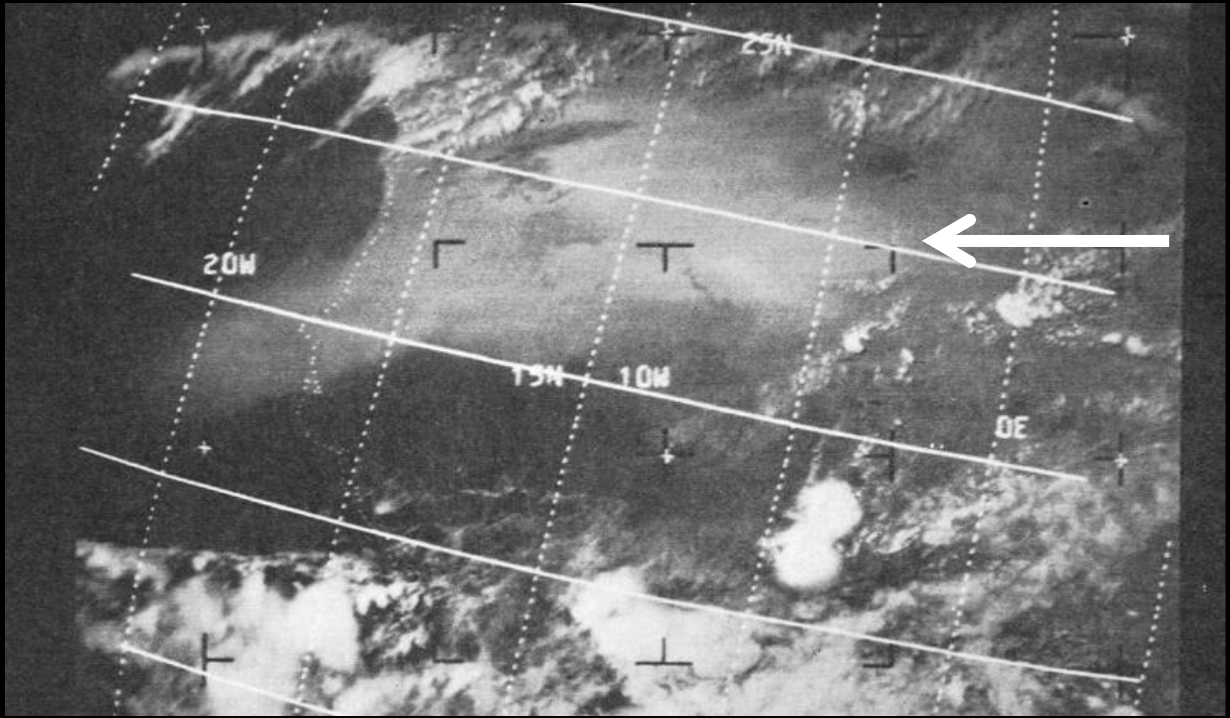


MODIS - Smoke from Alaska fires July 1, 2004



GOES/ABI – Hunga-Tonga eruption 15 January 2022





Saharan Dust Storm

8-day Trajectory

Beginning 07 June 1967

ESSA 5 Satellite

Prospero et al., Earth & Planet. Sci. Let. 1970

Aerosol – Related Climate Effects

Mt. Sinabung, Indonesia, March 2021 From *The Atlantic*

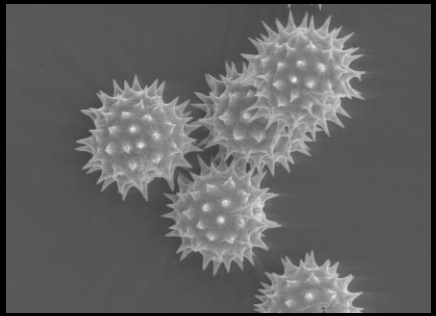
Aerosol Direct Radiative Forcing –

- Surface Cooling by Reflecting Sunlight (most particles)
- Atmospheric Warming by Absorbing Sunlight (dark particles)

Aerosol Indirect Effects on Clouds –

- Cloud Brightening (CCN in aerosol-poor region make more, smaller droplets – but changes in total liquid water also occur)
- Increase in Cloud Lifetime
- Cloud Dissipation (dark-particle "semi-direct" effect)
- Cloud Invigoration (smaller droplets rise to freezing elevation)

From *https://aviation.stackexchange.com*



Helianthus annuus pollen From *en.wikipedia.org*

Other Aerosol Effects –

- Ocean Fertilization (desert dust to iron-poor waters)
- Land Fertilization (e.g., phosphorous to Amazon)
- Transport of Pollen, Disease Vectors, etc.
- Atmospheric Circulation, Water Cycle changes

Climate – Related Changes in Aerosols

Phoenix Dust Storm 05 July 2011 Phoenix New Times

***Increasing Airborne Dust** – Due to:*

- Desertification (Deforestation, Drying Water Resources, Over-grazing, Other Farming Practices)
- Changing Wind & Precipitation Patterns

***Increasing Wildfire Smoke** – Due to:*

- Increasing Temperature
- Decreasing Relative Humidity (Drought + Higher Temp.)
- Ecosystem Collapse (Environmental Stress + Vulnerability to Pests, Disease)

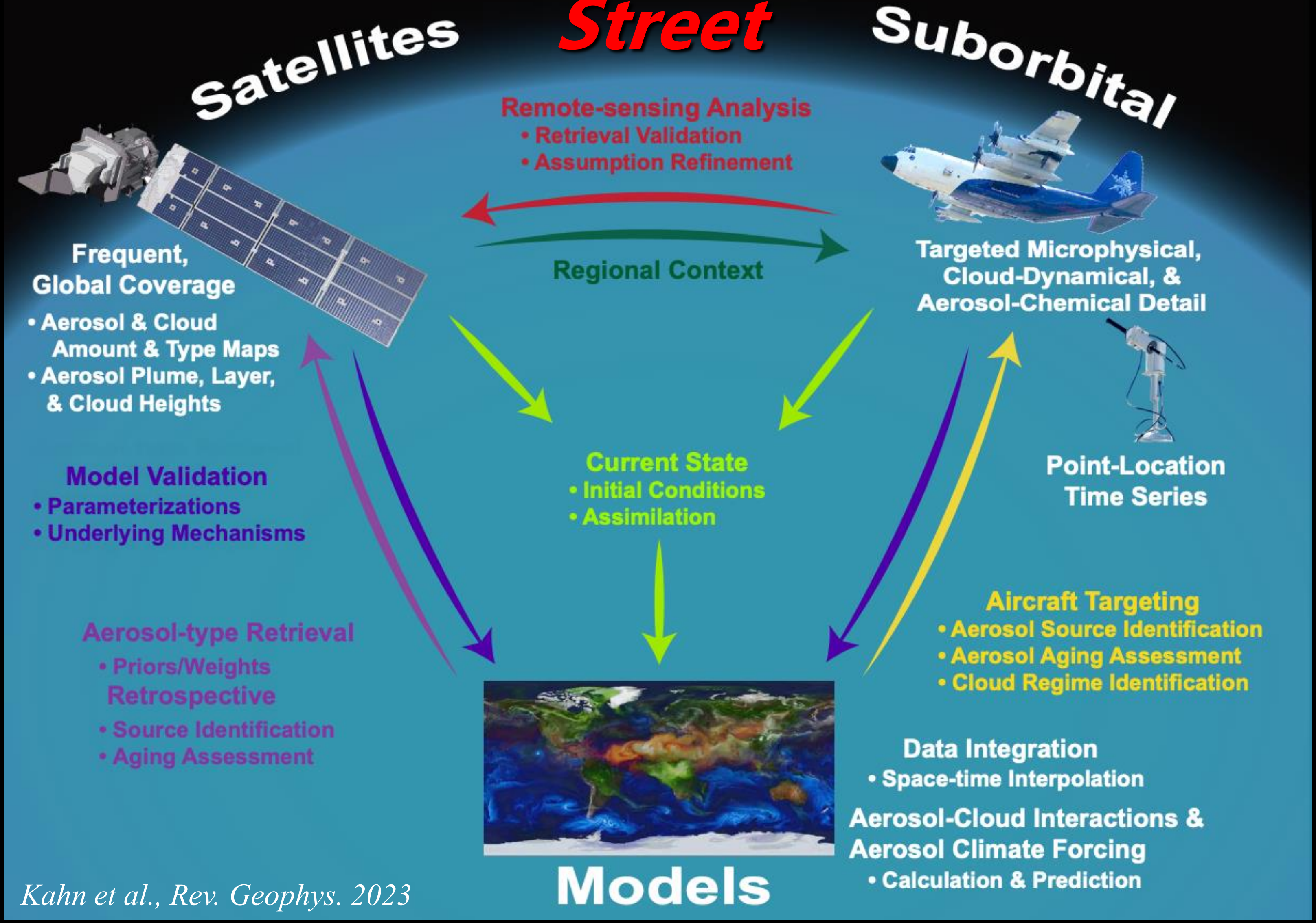
Also Increasing PyroCumulonimbus-formation conditions

Northern California Camp Fire June 2019 Wired

Changes in Biogenic & Photochemical Particle Formation – with changing Temp., Humidity, Land Cover, etc.

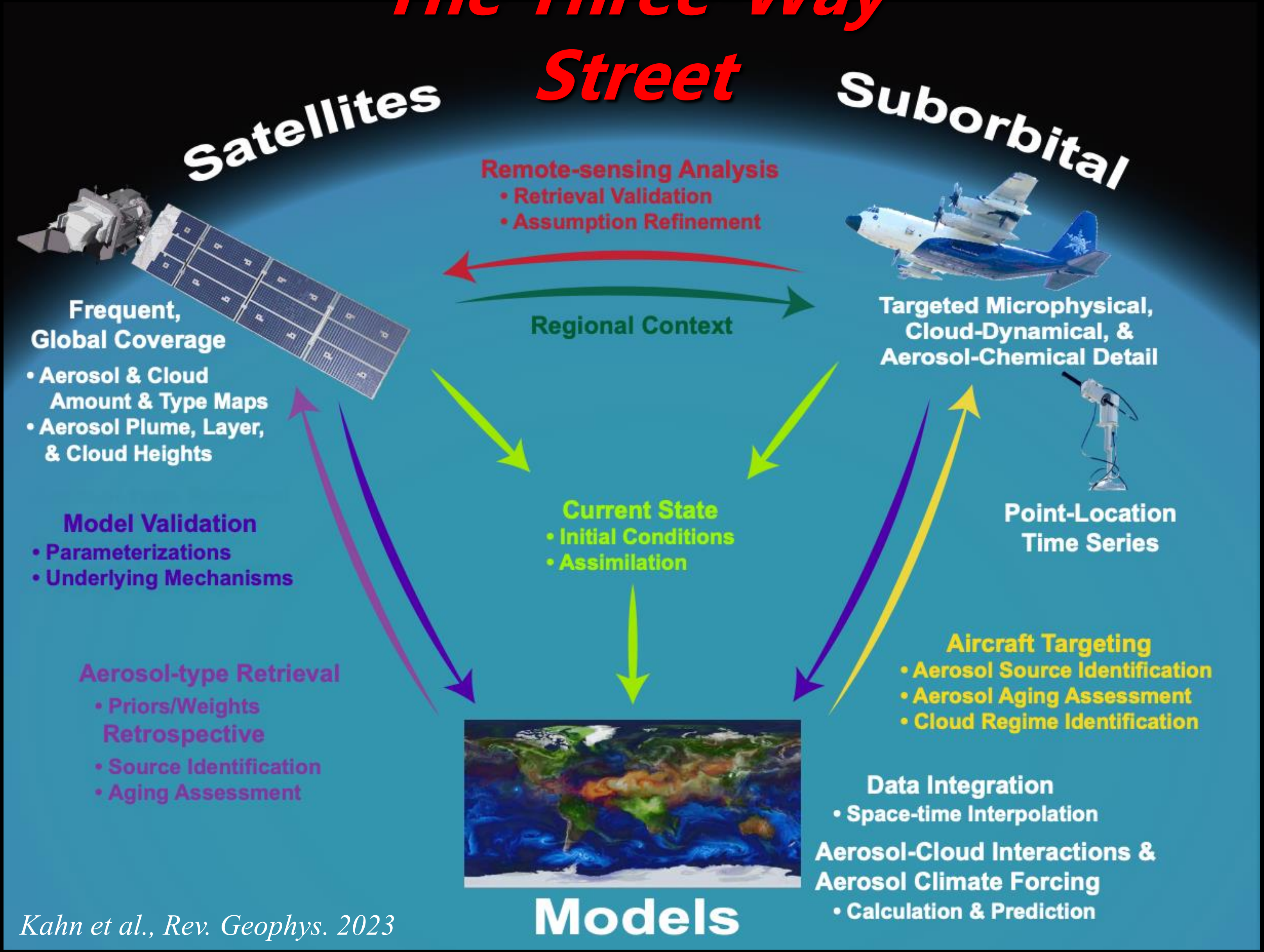
The Distinction between "Natural" and "Anthropogenic" Aerosol Has Become Ambiguous…

The Three-Way Street



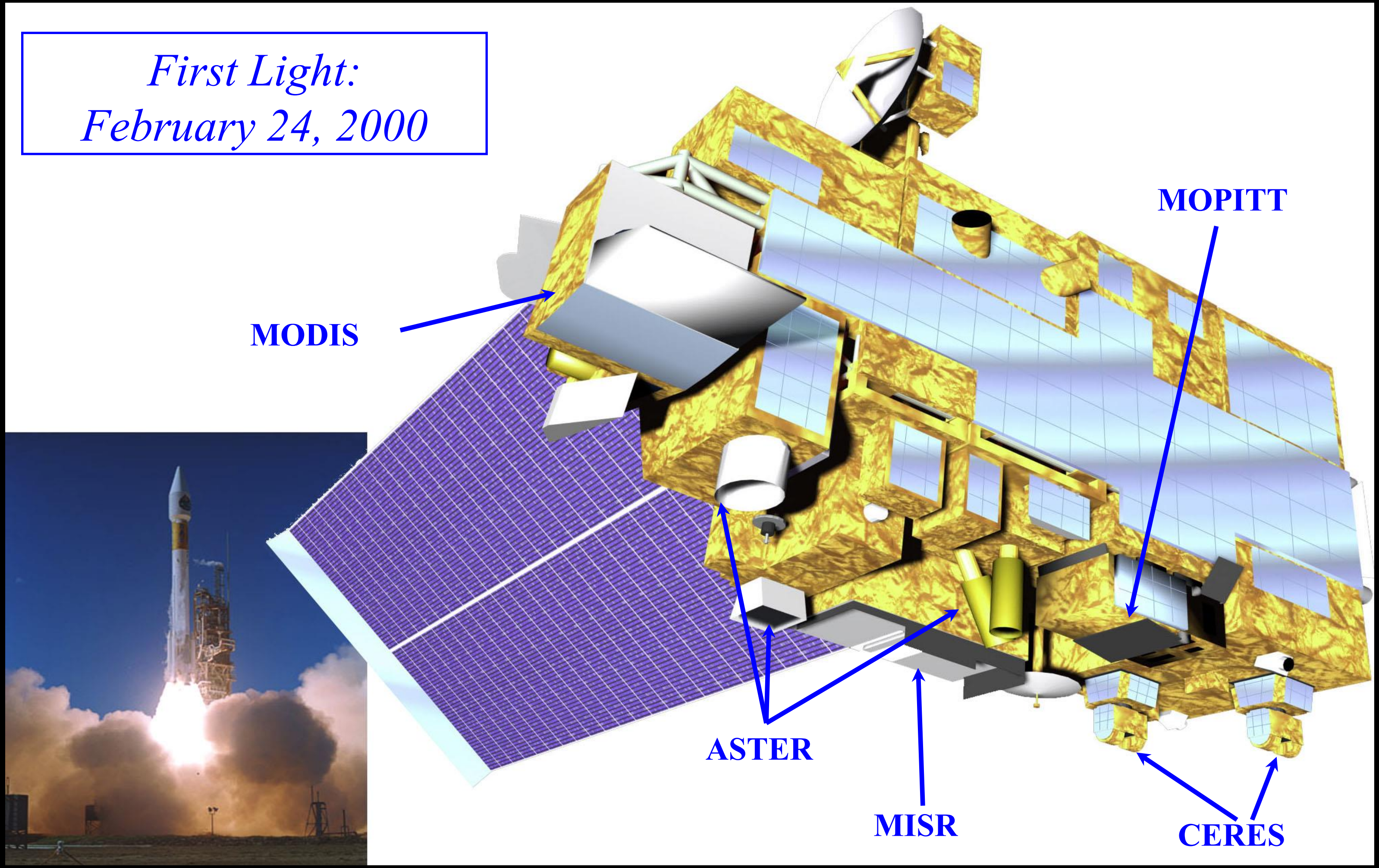
Highlights the essential & unique role of each community in completing the aerosol forcing picture…

The Three-Way Street



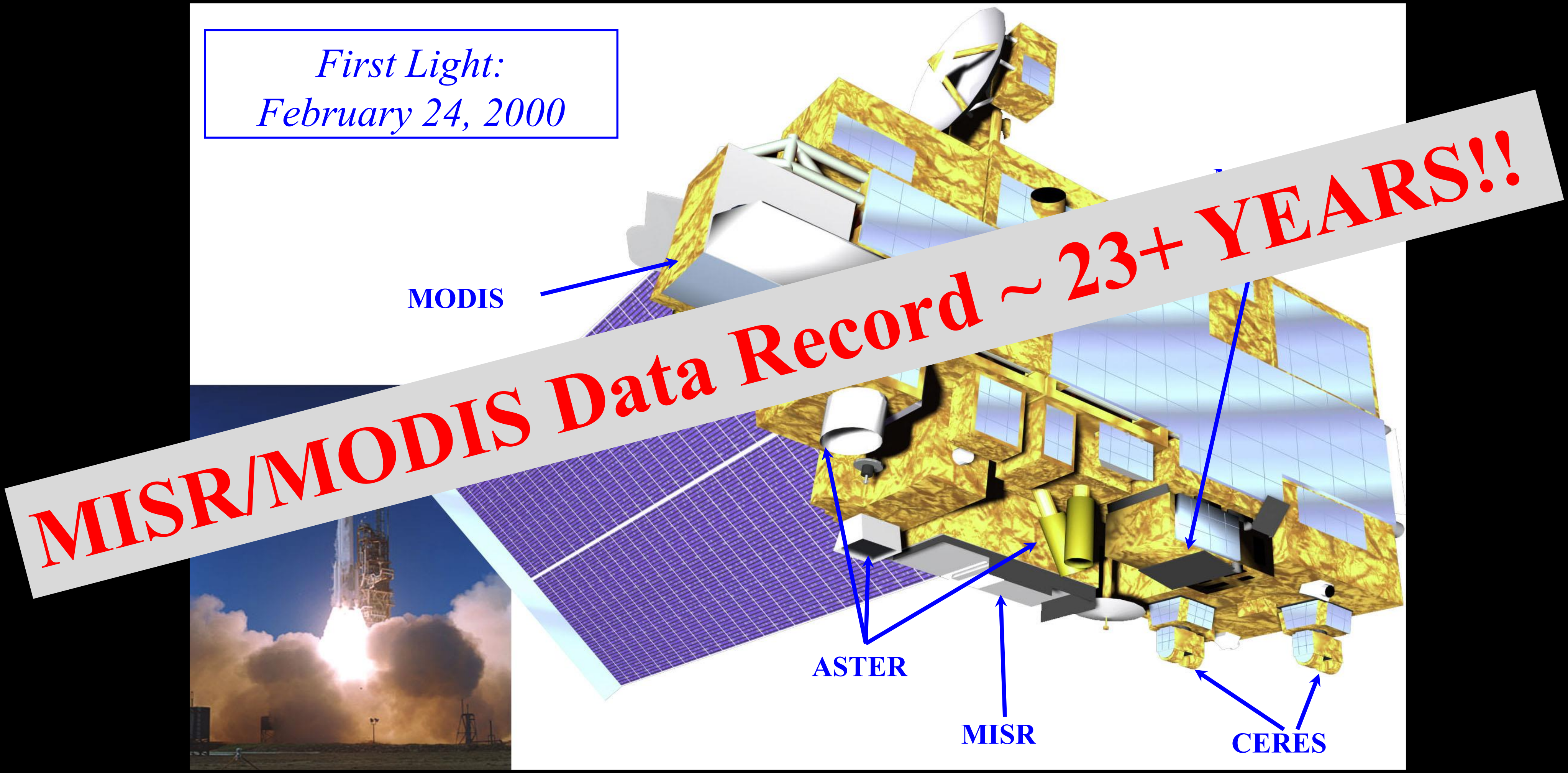
Ralph Kahn
Elisabeth Andrews
Charles Brock
Mian Chin
Graham Feingold
Anderw Gettelman
Robert Levy
Daniel Murphy
Astanasios Nenes
Jeffrey Pierce
Thomas Popp
Jens Redemann
Anderw Sayer
Arlindo da Silva
Larisa Sogacheva
Philip Stier

The NASA Earth Observing System's Terra Satellite



Terra Project Office / NASA Goddard Space Flight Center

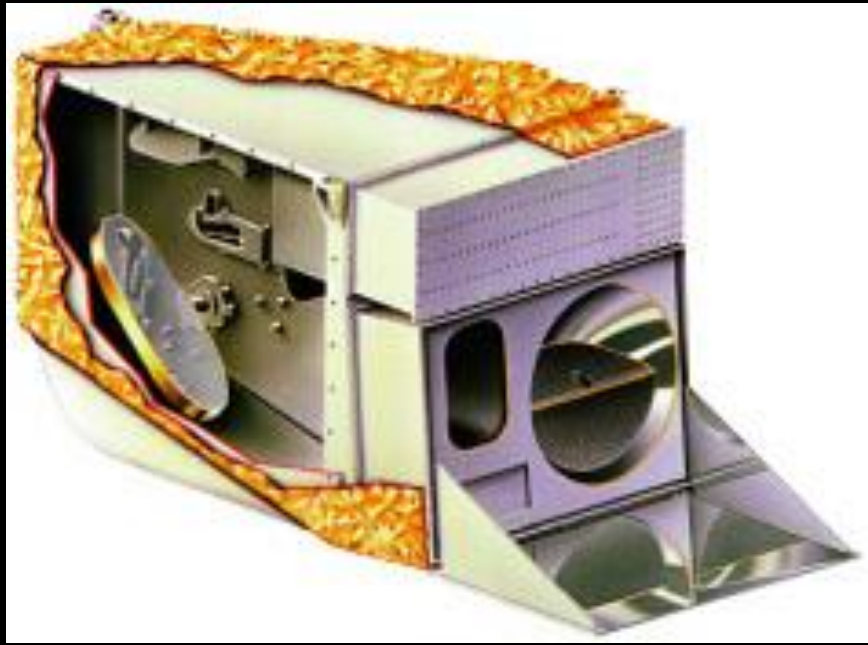
The NASA Earth Observing System's Terra Satellite



Terra Project Office / NASA Goddard Space Flight Center

MODerate-resolution Imaging Spectroradiometer [MODIS]

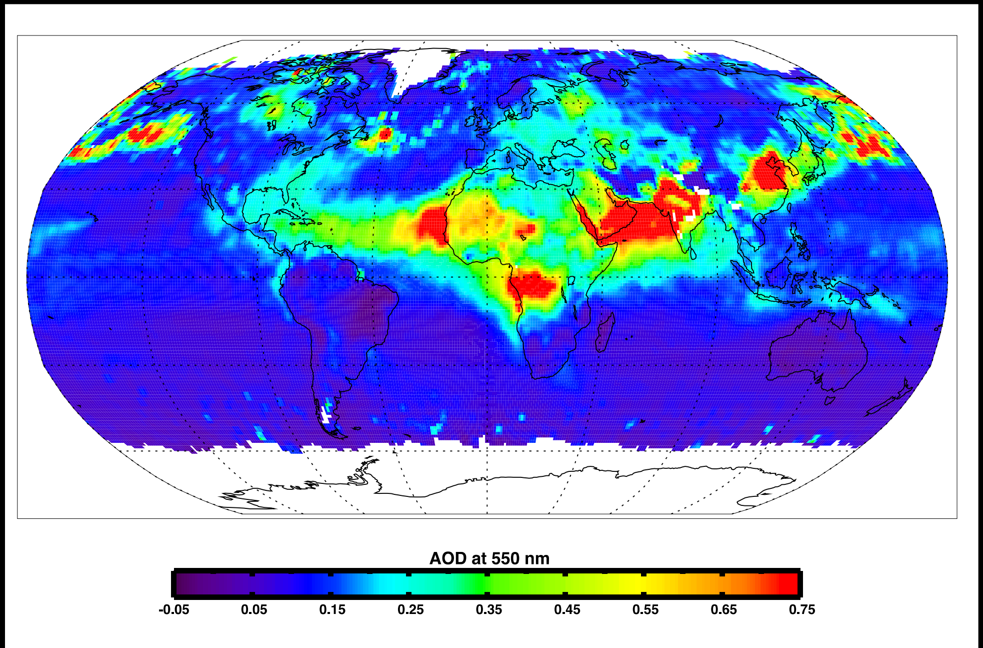
- NASA, Terra & Aqua
  - Launches: 1999, 2001
  - 704 km polar orbits, descending (10:30 a.m.) & ascending (1:30 p.m.)
- Sensor Characteristics
  - 36 spectral bands ranging from 0.41 to 14.385 µm
  - cross-track scan mirror with 2330 km swath width
  - Spatial resolutions:
    - 250 m (bands 1 - 2)
    - 500 m (bands 3 - 7)
    - 1000 m (bands 8 - 36)
  - 2% reflectance calibration accuracy
  - onboard solar diffuser & solar diffuser stability monitor



Improved over AVHRR:
- Calibration
- Spatial Resolution
- Spectral Range & # Bands

Source: MODIS Team, NASA/GSFC

Satellites Do a Reasonable Job with Monthly, Mid-visible AOD



Monthly, Global Aerosol Amount

MODIS Mid-visible AOD

(Dark Target + Deep Blue)

July 2010

MODIS Team, NASA/GSFC

Recent Advance:
Pixel-Level AOD Uncertainty Estimates

Importantly, this requirement, especially for AOD assimilation, came from AeroCom/AeroSat discussions

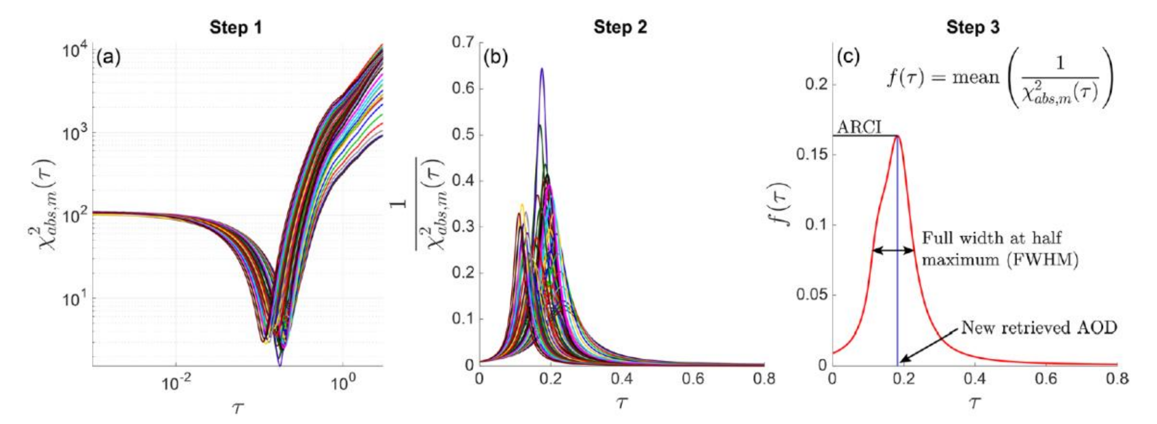


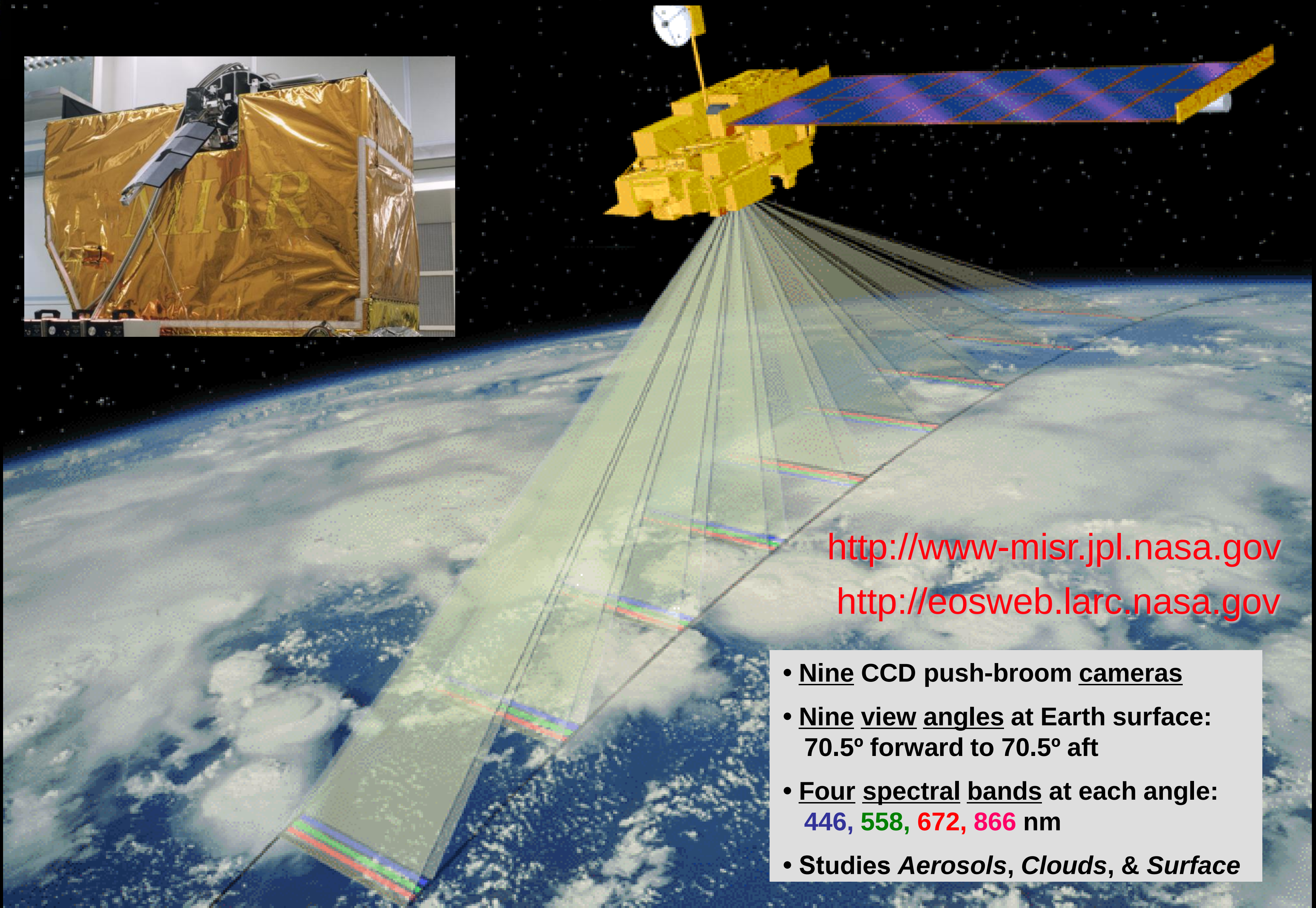
Figure 1. Example of calculation steps performed in the new methodology for determining AOD and its uncertainty. **(a)** χ^2_{abs} values for 74 MISR mixtures as a function of AOD (τ) (Eq. 1); **(b)** inverse (reciprocal) values for the 74 mixtures; and **(c)** inverse residuals averaged over all mixtures (Eq. 2), with the new retrieved AOD, ARCI, and FWHM indicated on the distribution. The x-axis scale is logarithmic in panel **(a)** for a better visualization of the cost function at low τ.

MISR Pixel-Level AOD Uncertainty Estimation Process

Witek et al., AMT 2018

Multi-angle Imaging SpectroRadiometer

MISR



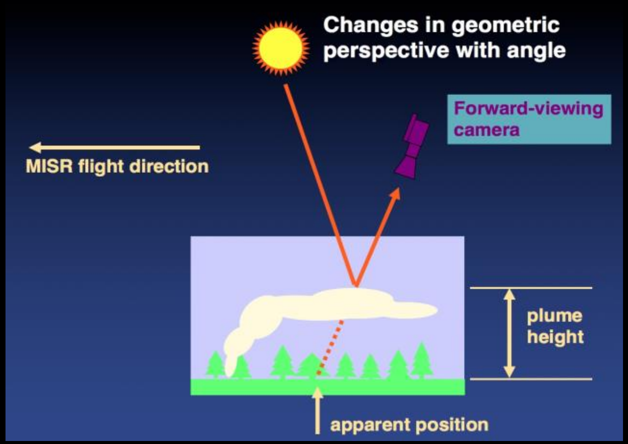
http://www-misr.jpl.nasa.gov

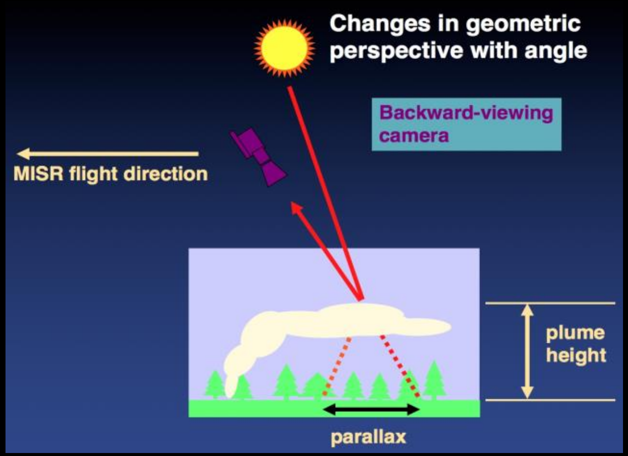
http://eosweb.larc.nasa.gov

- Nine CCD push-broom cameras
- Nine view angles at Earth surface: 70.5º forward to 70.5º aft
- Four spectral bands at each angle: 446, 558, 672, 866 nm
- Studies *Aerosols*, *Clouds*, & *Surface*

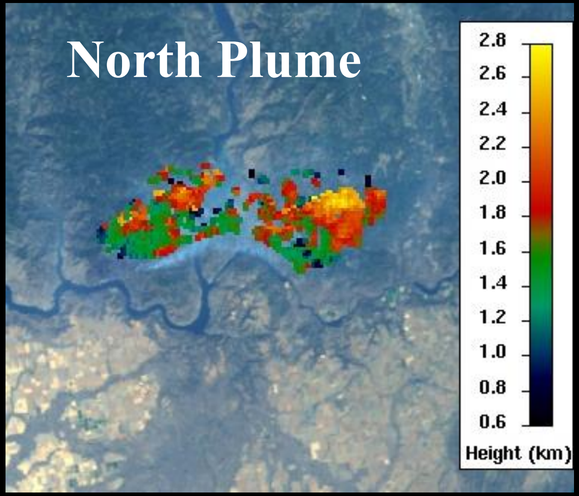
Williams Flats Fire Complex, Washington

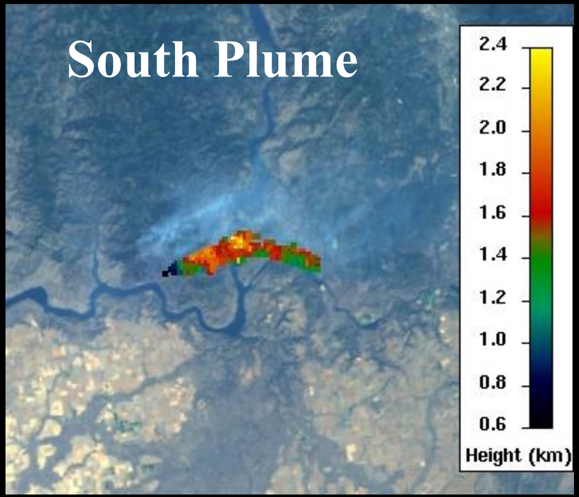
06 August 2019 (FIREX-AQ Campaign)

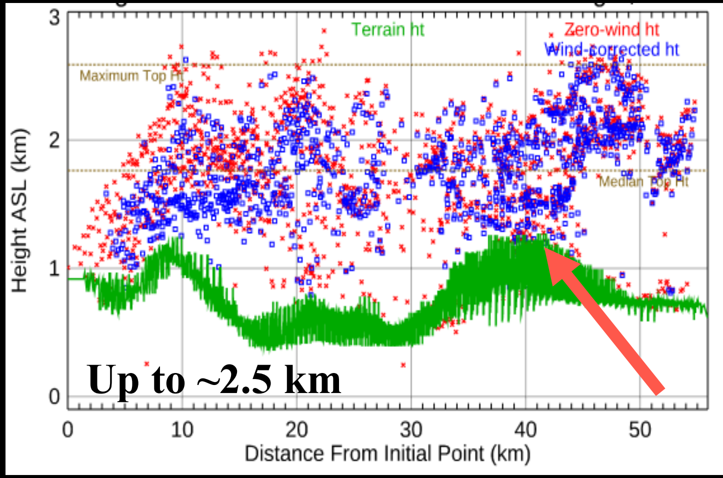


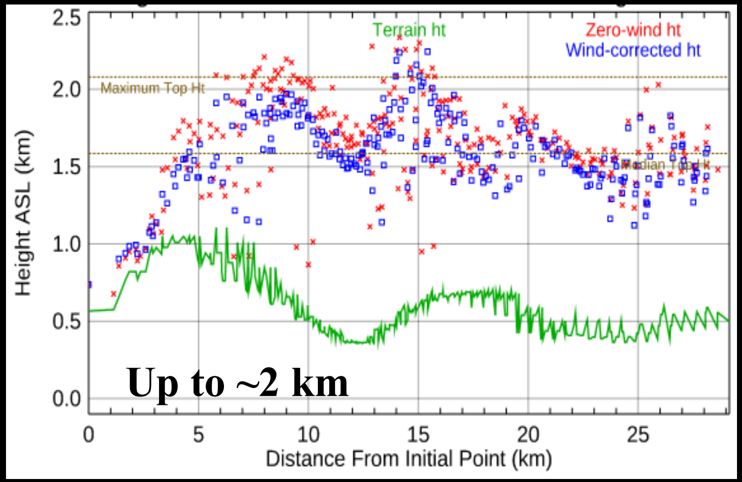


Parallax → Plume Height
Multi-angle (7 min) → Motion Vectors







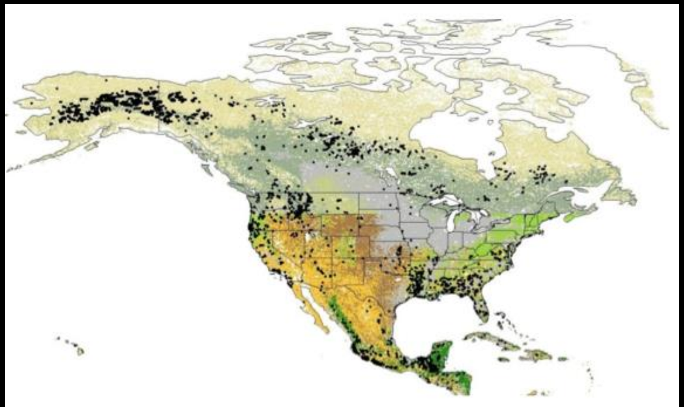


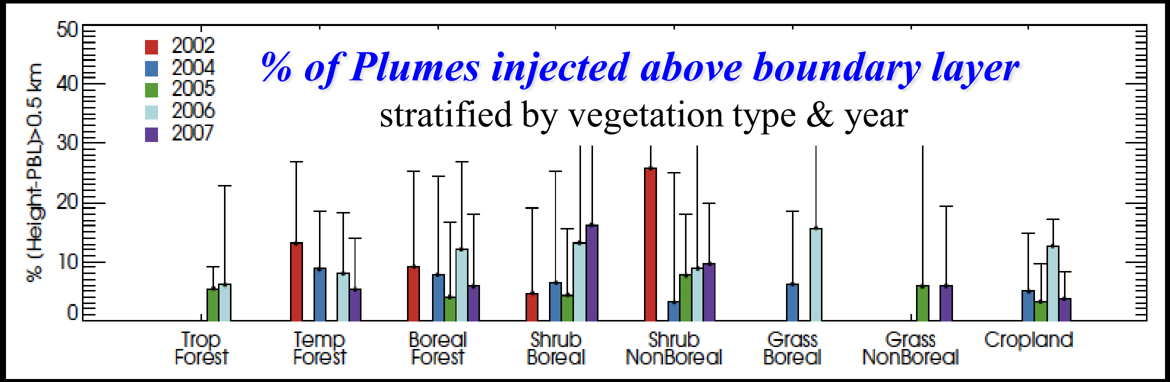
Red = zero-wind height
Blue = wind-corrected height
Green = surface elevation

Junghenn-Noyes, Kahn, et al. 2020

Wildfire Smoke *Injection Heights & Source Strengths*

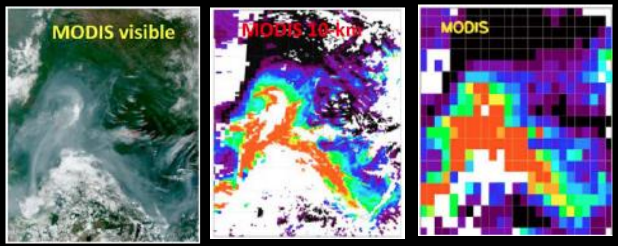
[These are *the two key parameters* representing aerosol sources in climate models]



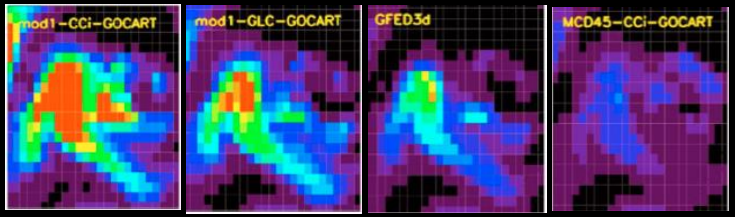


Val Martin et al. ACP 2010; 2012, 2018

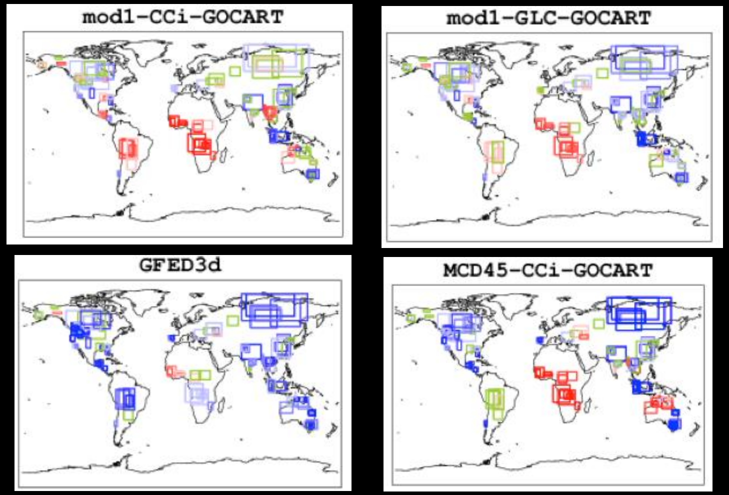
These two projects are the subjects of current AeroCom/AeroSat Experiments



MODIS Smoke Plume Image & Aerosol Amount Snapshots



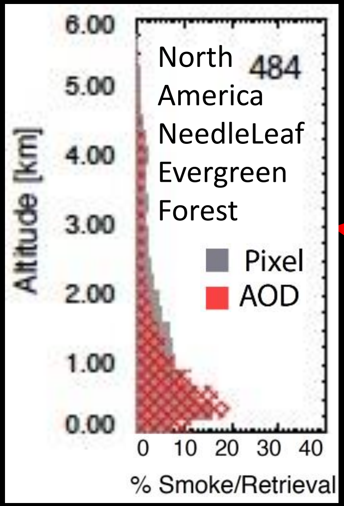
GoCART Model-Simulated Aerosol Amount Snapshots for *Different Assumed Source Strengths*



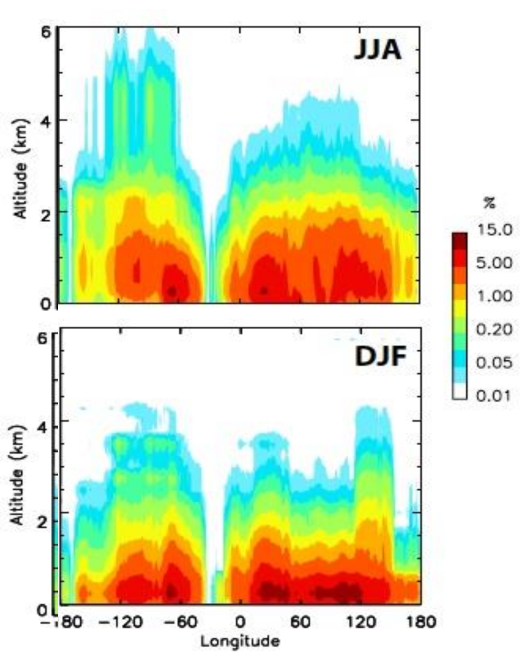
Different Techniques for *Assuming Model Source Strength*
Overestimate or ***Underestimate*** Observation
Systematically in Different Regions

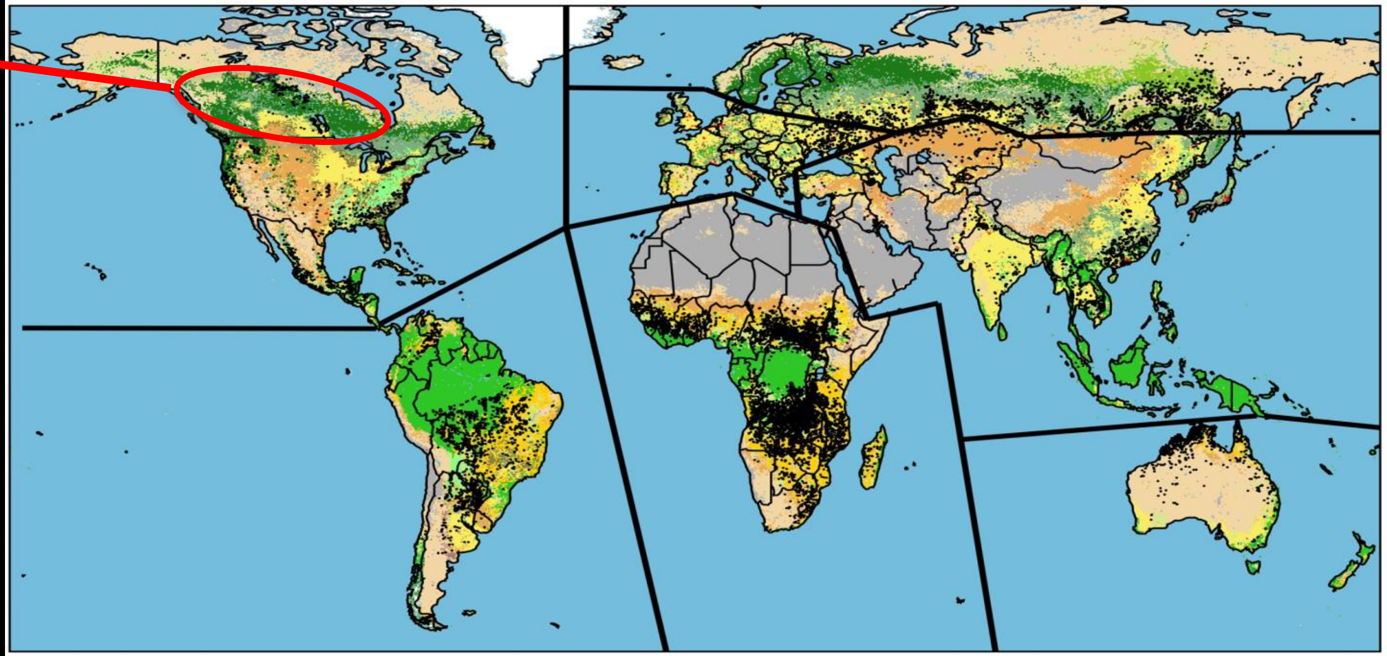
Petrenko, Kahn, et al., JGR 2012; 2017; 2023 in prep.

MISR Wildfire Smoke *Injection Height Climatology*



Global Zonal Ave.





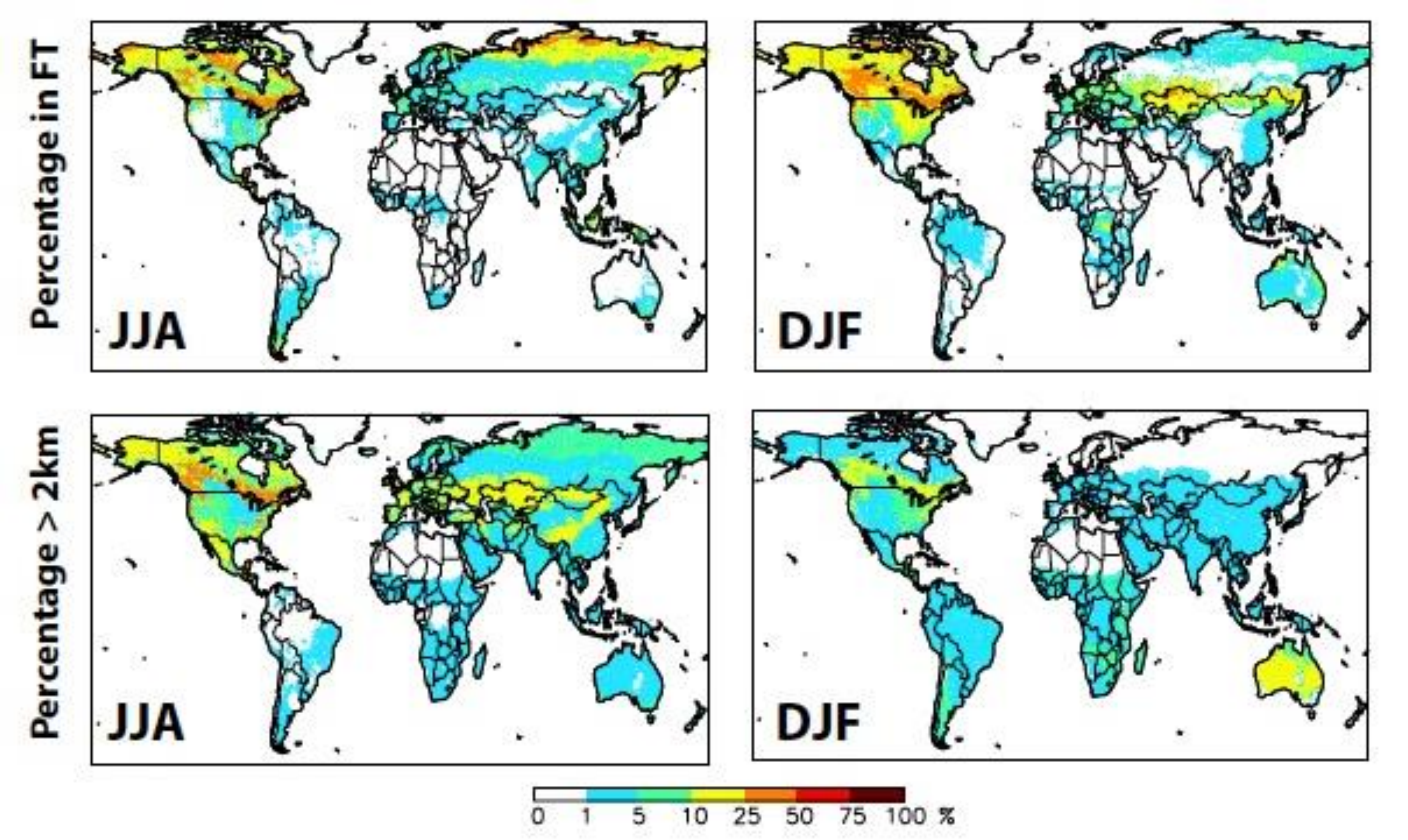
- Individual Heights at ***1.1 km Horizontal*** res., ***~250-500 m Vertical*** res.
- Both ***Pixel-weighted*** and ***AOD-weighted*** profiles derived
- Fire emissions are ***Stratified by Altitude***, ***Region***, ***Ecosystem***, & ***Season***
- The cases in each stratum are ***Averaged*** to produce a statistical summary
- Inter-annual and/or sub-seasonal ***temporal resolution*** might be needed in some cases; requires detailed, regional study (e.g., Amazon)

https://misr.jpl.nasa.gov/getData/accessData/MisrMinxPlumes2/

Val Martin, Kahn & Tosca; Remt. Sens. 2018

Global Distribution of Percent Injected Within/Above the PBL

Based on MERRA-2 Hourly PBL 10:00-13:00 LT



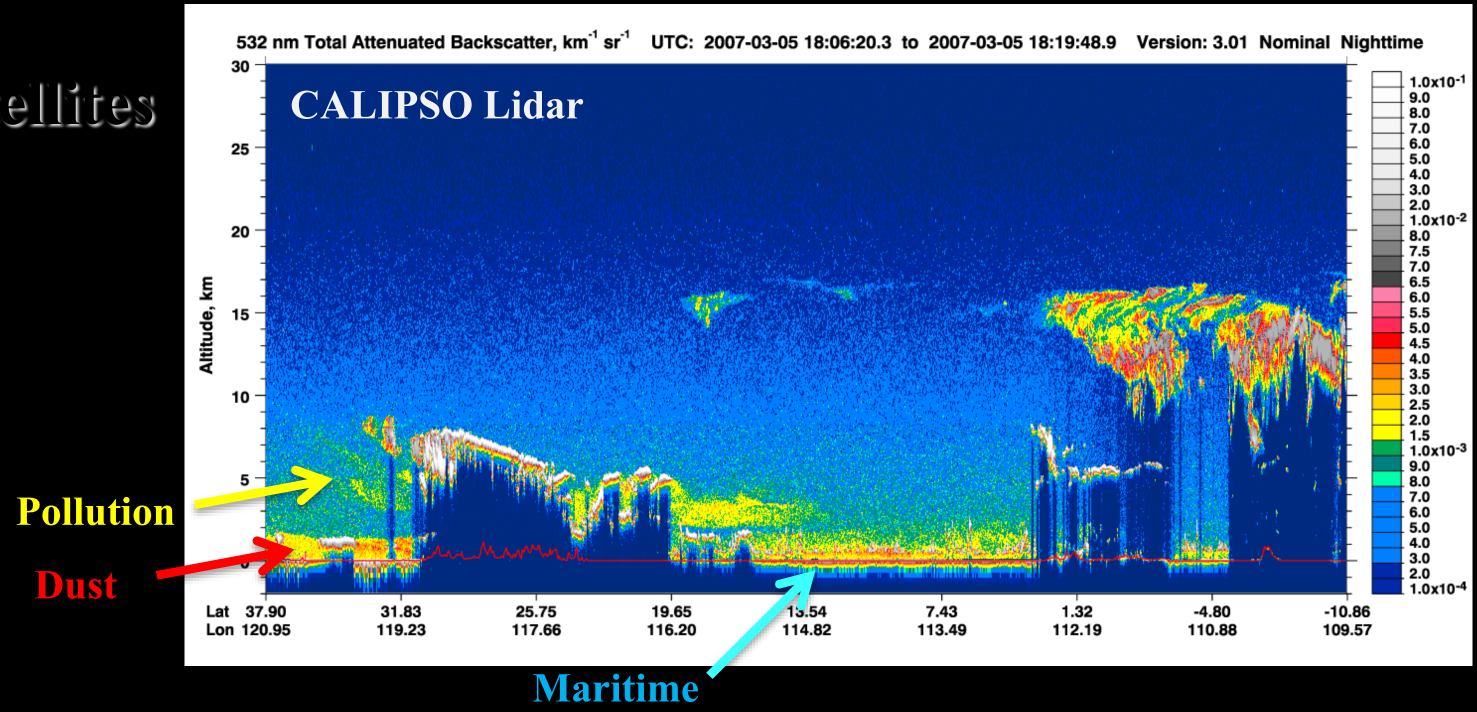
Accounting for uncertainty
FT = PBL + 500 m

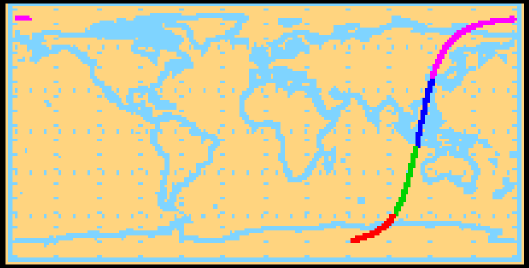
[PBL from MERRA-2]

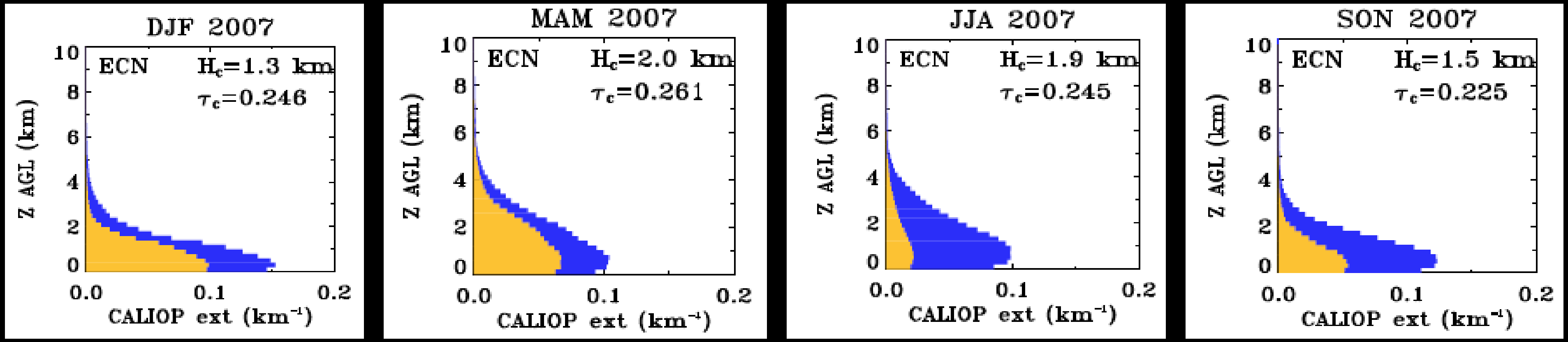
2 km threshold avoids dependence on PBL height estimate

Val Martin, Kahn & Tosca; Remt. Sens. 2018

Satellites Also Constrain Aerosol Layer Height



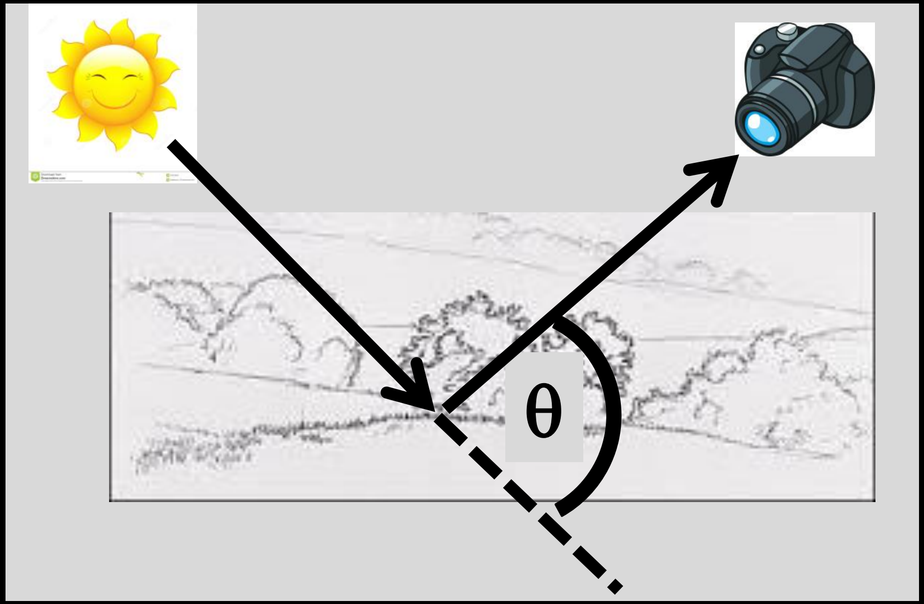


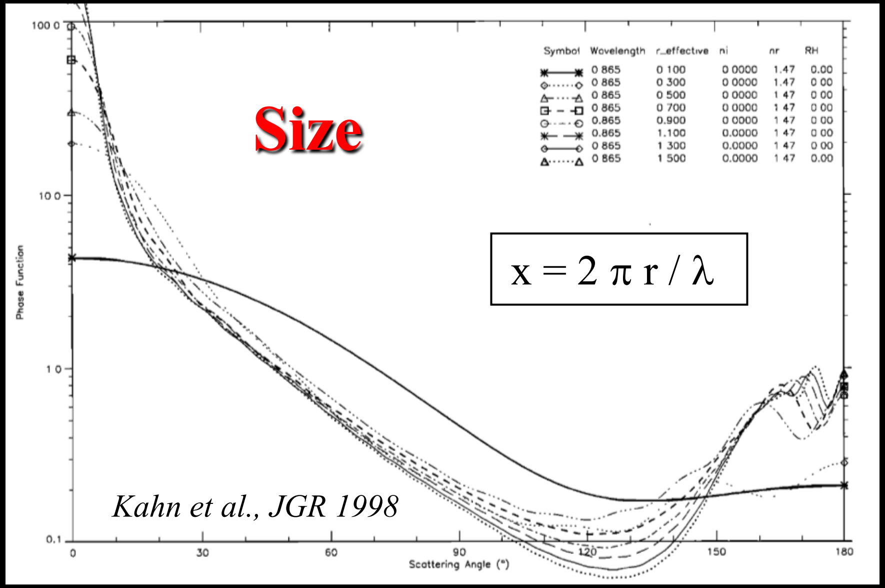


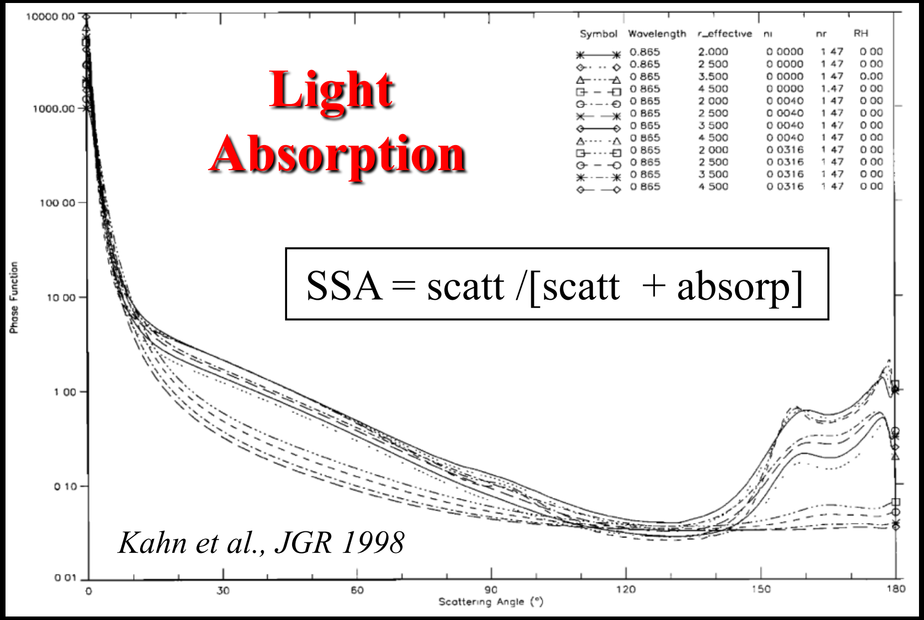
Seasonal dust (orange) and non-dust (blue) aerosol vertical distributions, Eastern China

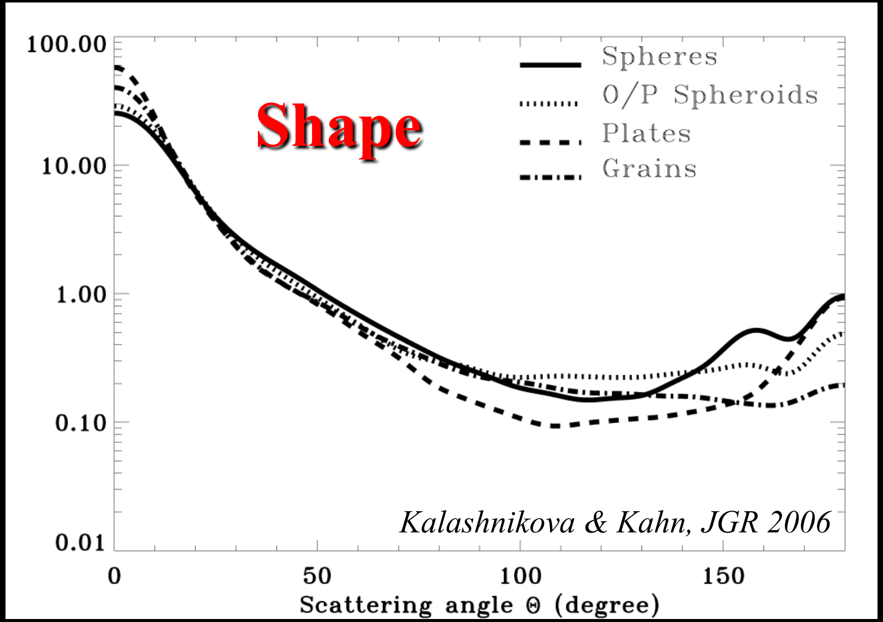
Yu et al., JGR 2010

Single-scattering Phase Functions for *Different Particle Properties*





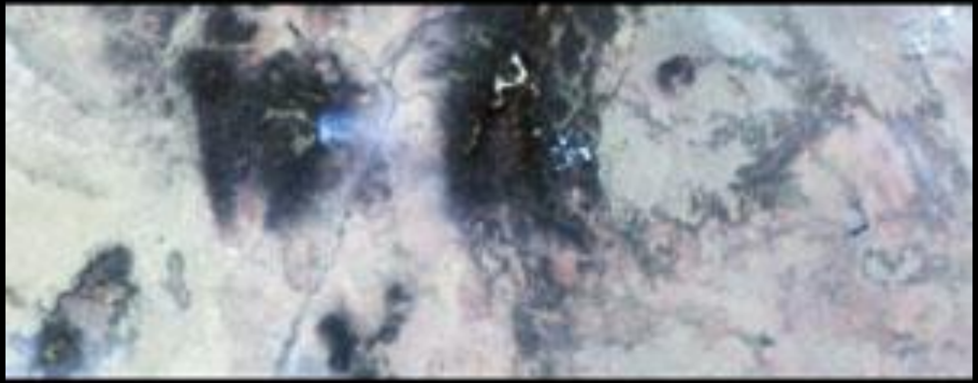




Los Alamos Fire, New Mexico May 9, 2000

MISR 60˚ Forward

MISR Nadir

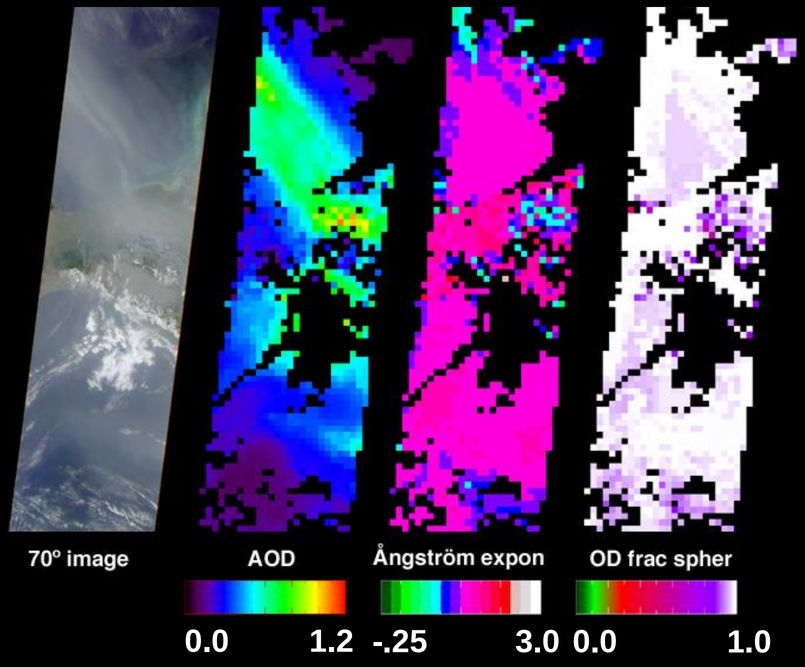


MISR 60˚ Aft

MISR Aerosol Type:

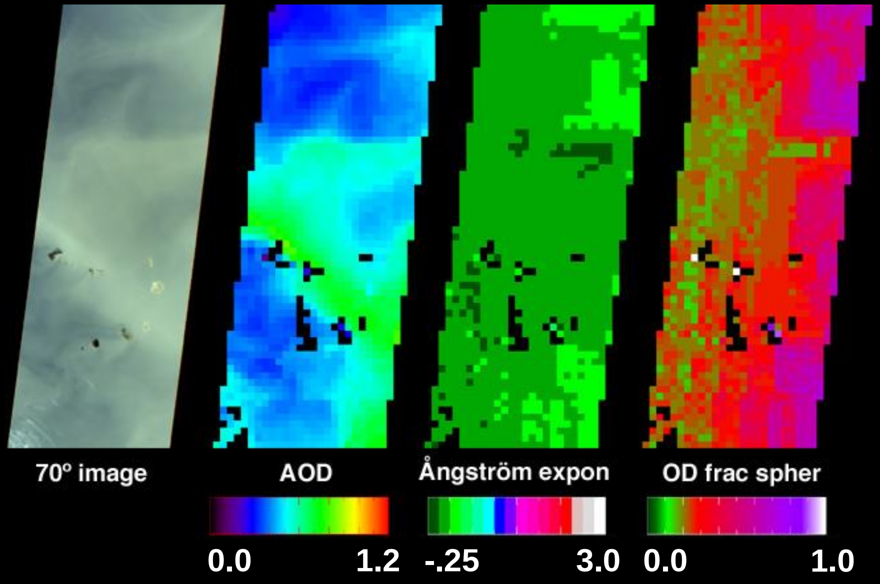
- Size
- Shape
- Brightness

Smoke from Mexico -- 02 May 2002



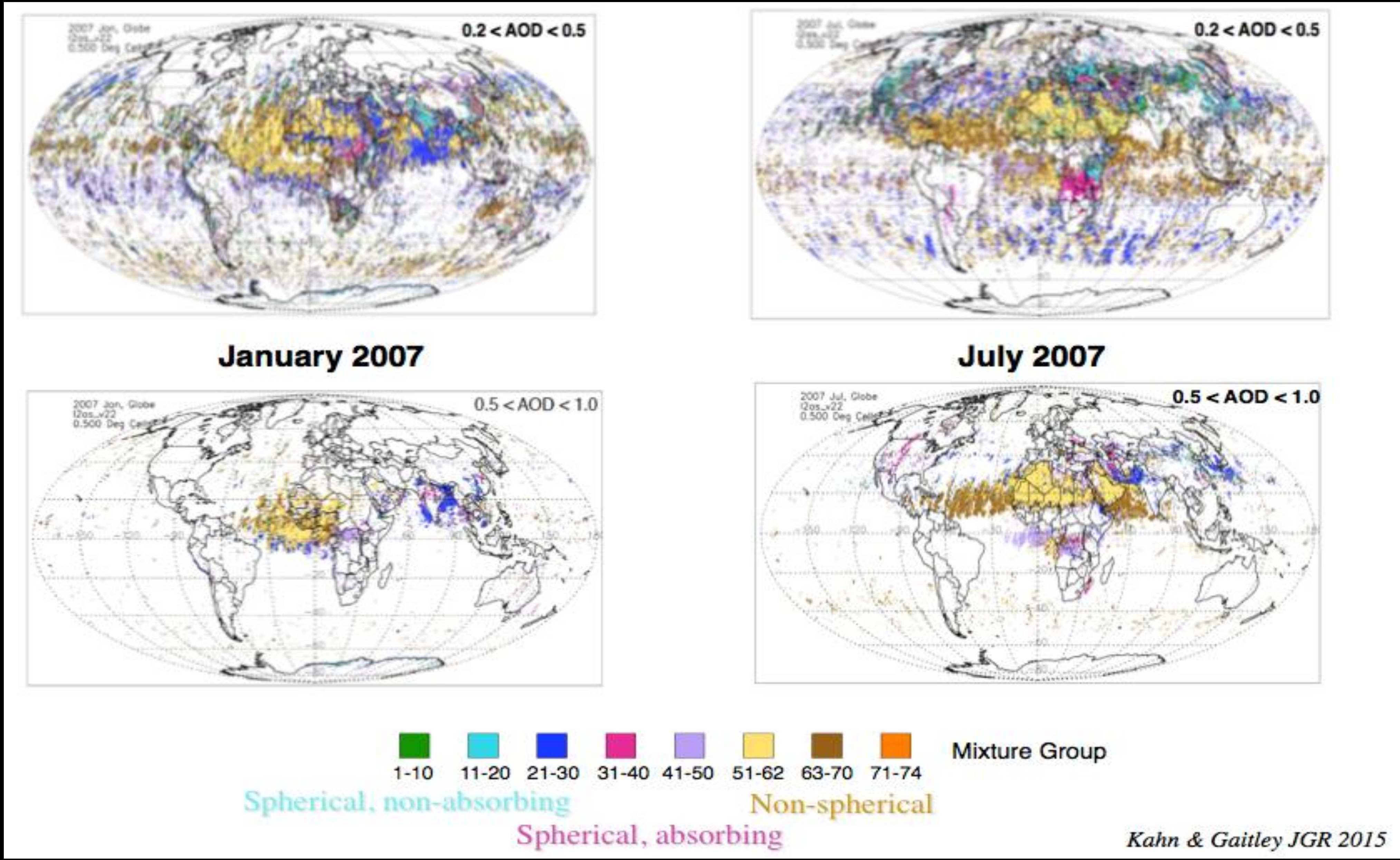
Medium Spherical Smoke Particles

Dust blowing off the Sahara Desert -- 6 February 2004

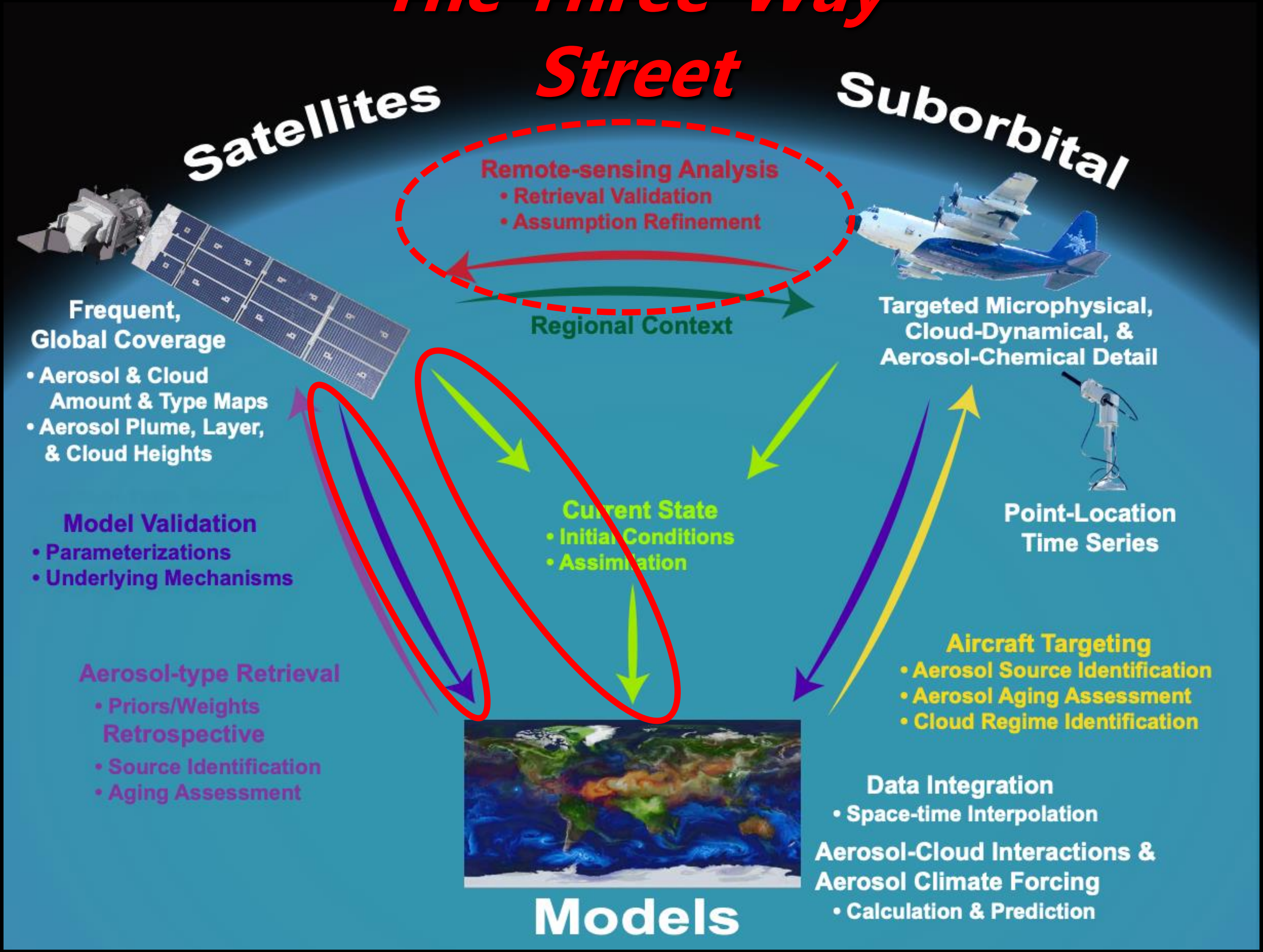


Large Non-Spherical Dust Particles

MISR Aerosol Type Discrimination



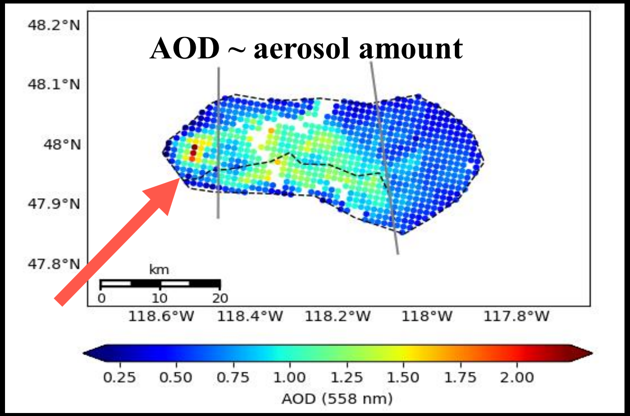
The Three-Way Street

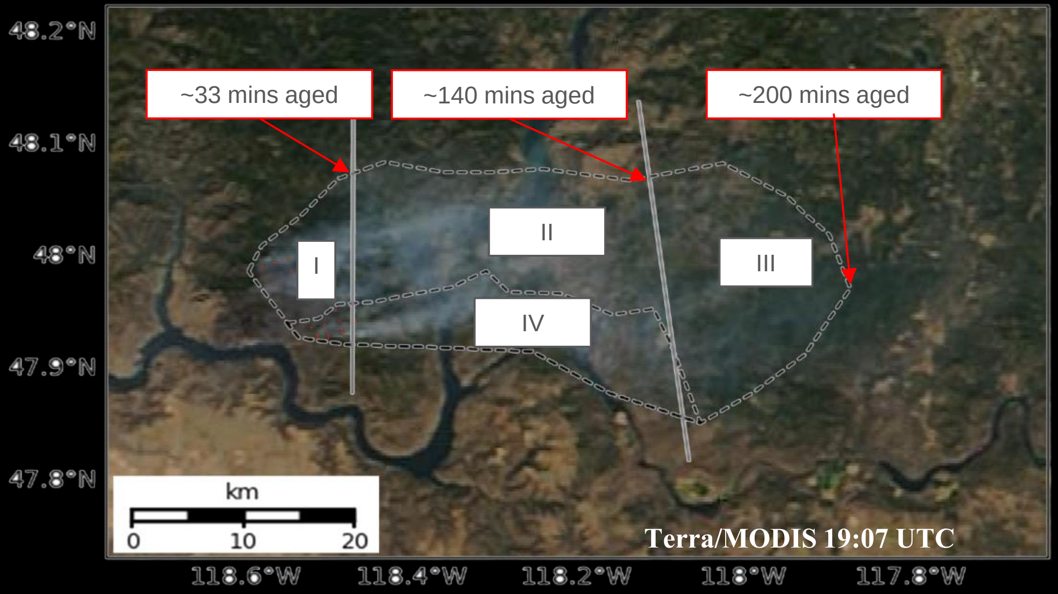


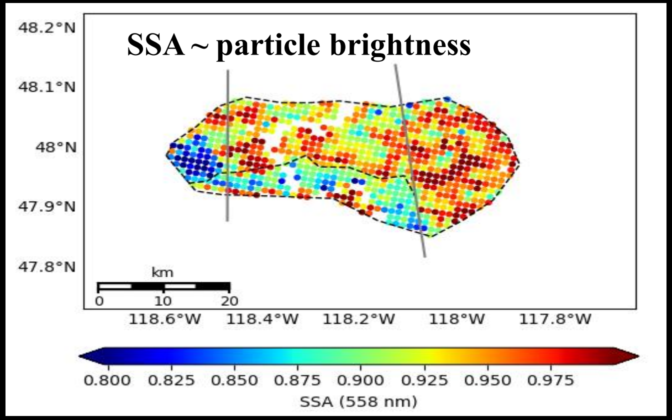
Kahn et al., Rev. Geophys. 2023

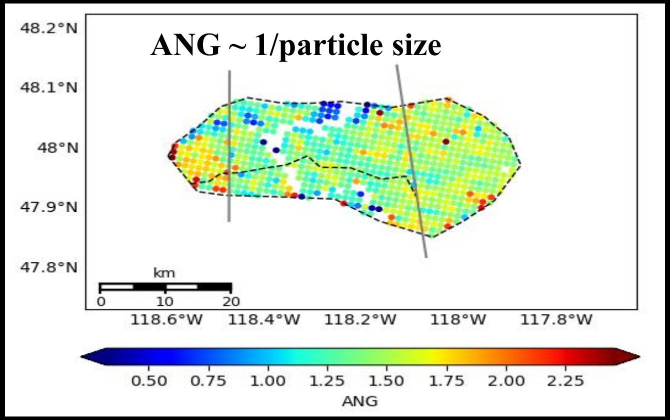
Williams Flats Fire Complex, Washington

06 August 2019 (FIREX-AQ Campaign)







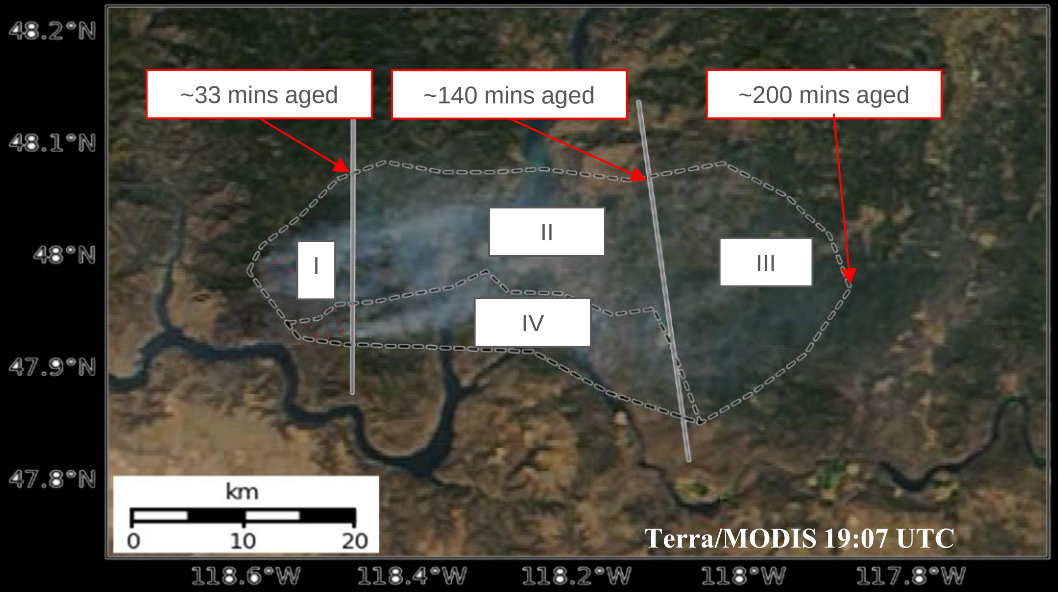


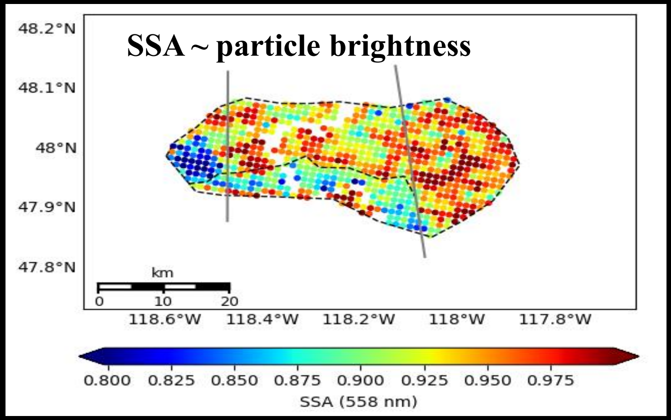
Junghenn-Noyes, Kahn, et al. 2020

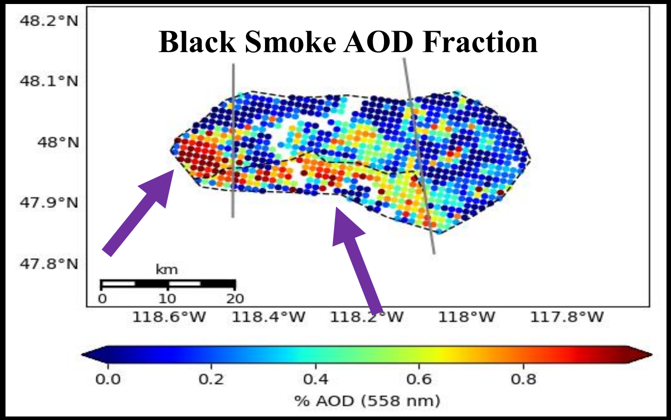
Williams Flats Fire Complex, Washington
06 August 2019 (FIREX-AQ Campaign)

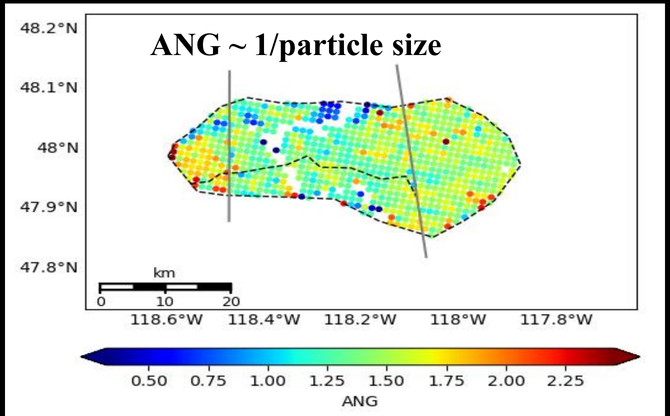
From ***Particle Type***, can infer:
Processes & ***Timescales***

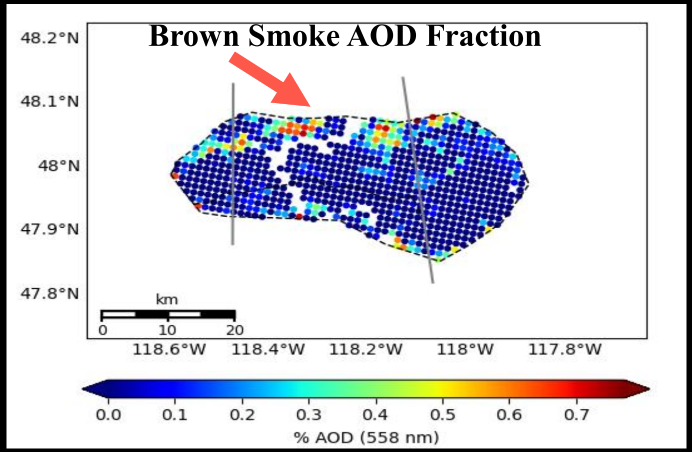
- Oxidation progressively along plume
- Region II: Coagulation or hydration
- Region III: Gravitational settling
- Region IV: More BC from SW fire
- Validated w/FIREX *in situ* data
- Can now use MISR data globally, where field data are lacking



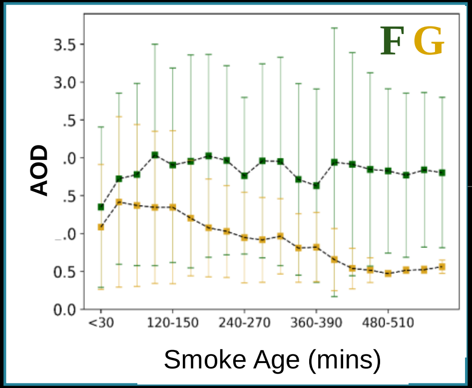






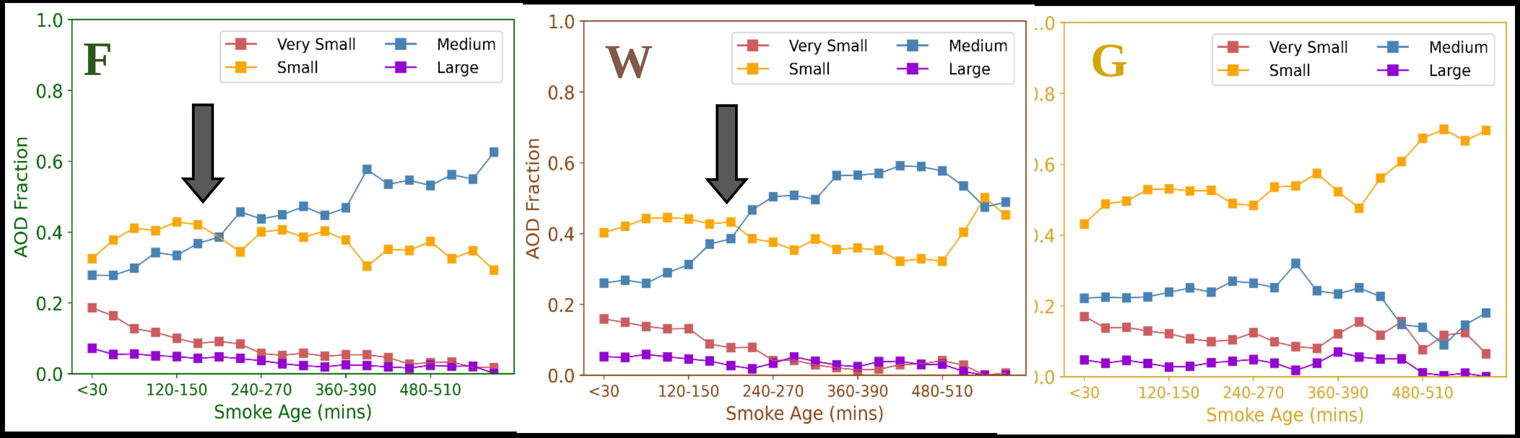


Junghenn-Noyes, Kahn, et al. 2020



Canada-Alaska Smoke Plume Property Trends

(663 plumes; 2016-2019)



Particle Size – *Very Small* *Small* *Medium* *Large*

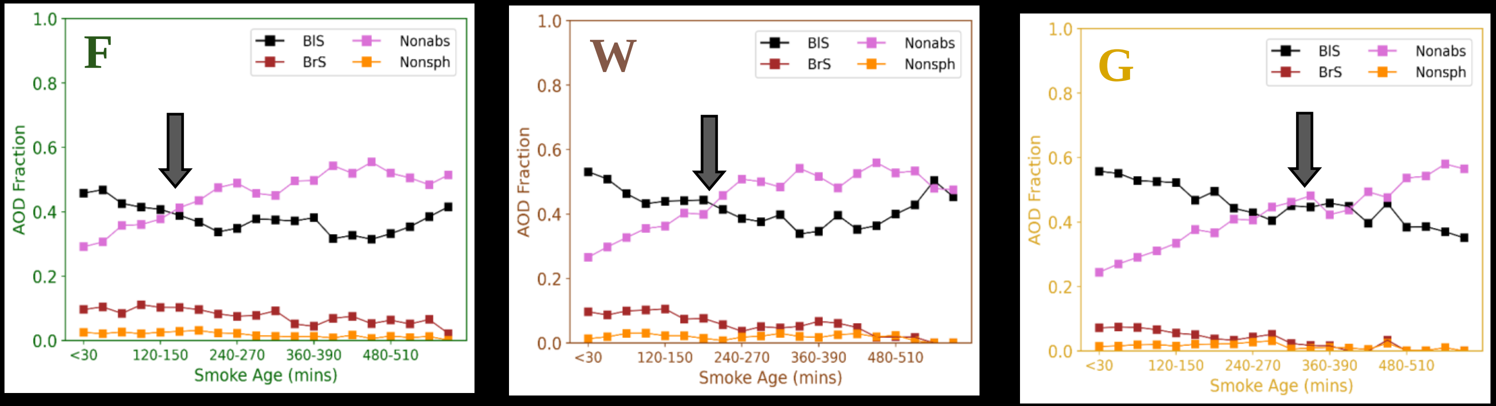
The ***timescales*** over which ***particle-type transitions*** occur differ between plume types

- ***Nonabsorbing*** components begin to dominate over ***absorbing*** components
- ***Medium*** size components begin to dominate over ***small*** size components

Forest plumes ~ 2.5 - 3 hours; Larger, brighter particles; higher AOD & BrS

Woody plumes ~ 3 - 3.5 hours

Grassy plumes ~ 4 - 7 hours for type NO increase in size; Smaller, darker particles; Lower AOD, highest BlS



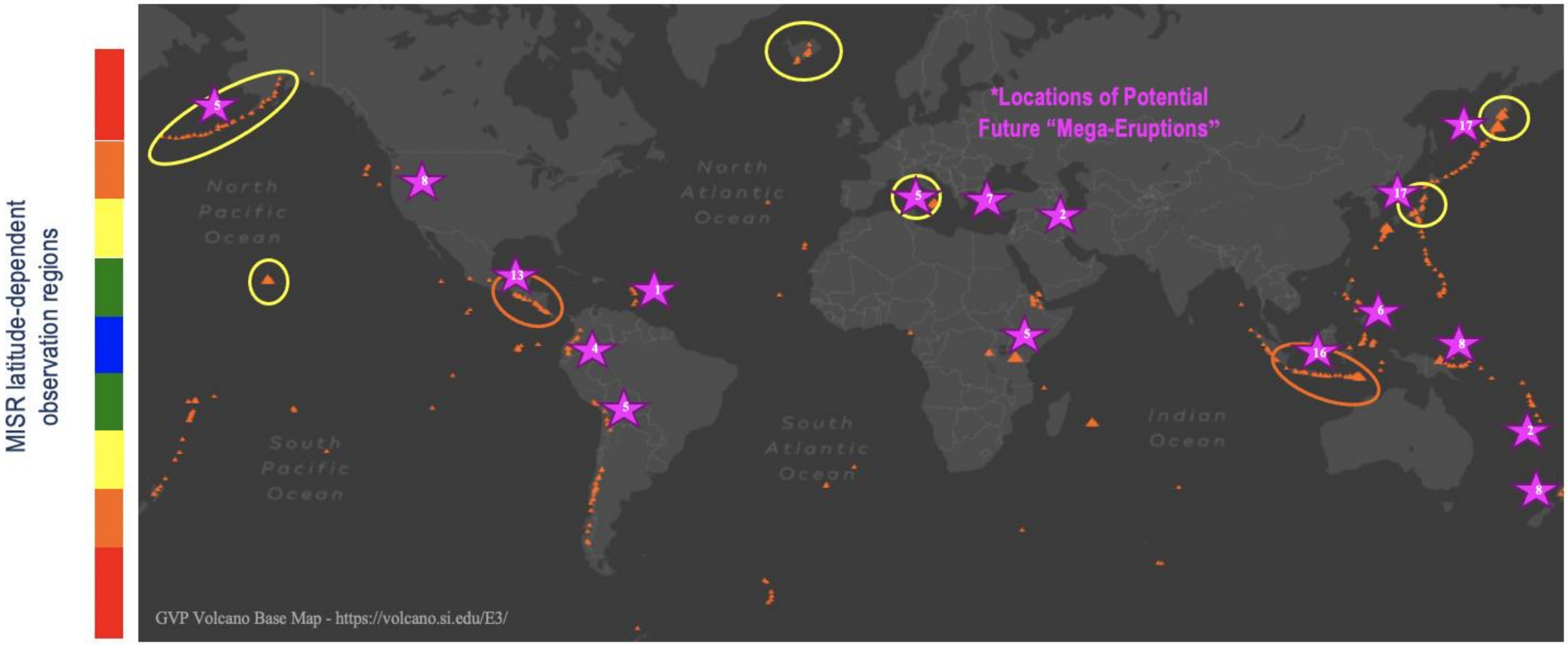
Particle Type – *Black Smoke* *Brown Smoke* *Non-absorbing*

Condensation/hydration probably dominate for F and W plumes, but dilution probably affects G plumes more

[Current study: ***Siberia***]

Junghenn-Noyes, Kahn, et al. ACP 2022

Volcanology from Space



MISR latitude-dependent observations/month

- ~15
- ~11
- ~9
- ~6
- ~4

Suborbital Monitoring Networks

- Well-monitored
- Partially-monitored

Global Active Volcanism (1960-2017)

- VEI 0
- VEI 1
- VEI 2
- VEI 3
- VEI 4

***VEI – Volcanic Explosivity Index**

Key Information from Global Volcano Monitoring

Aviation and downwind environmental ***hazard response***

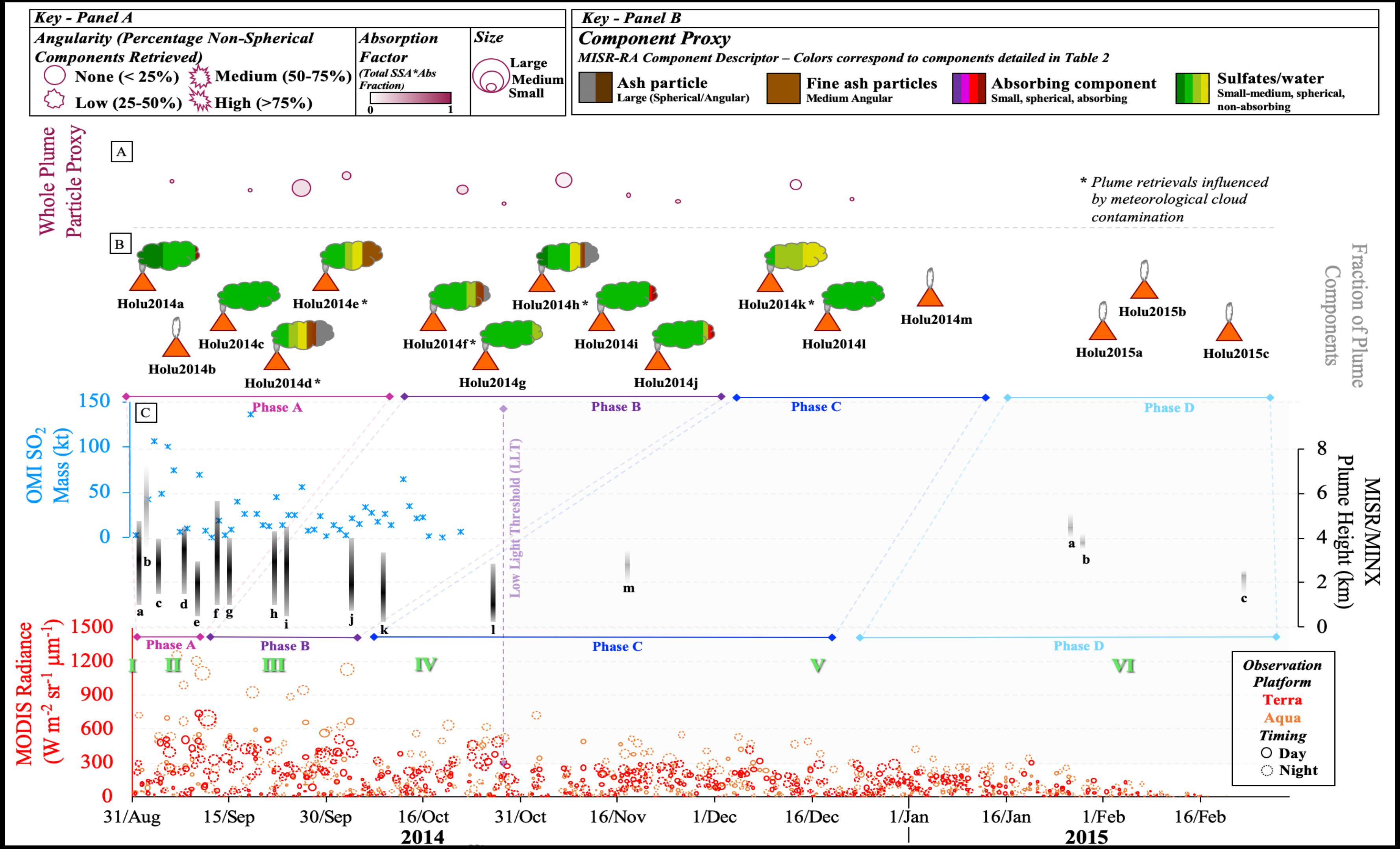
Constraints on ***air quality and climate modeling***

*Surface and subsurface **geology implications***

Flower & Kahn 2017-2019

Timeline of Plume Observations – *Holuhraun*

Aug 2014-Feb 2015



Multi-sensor eruption assessment

Particle properties relatively constant as the eruption progressed (minor variations due to cloud contamination)

- Retrievals dominated by ***small, spherical, non-absorbing*** components

As the eruption progressed there were ***decreases*** in:

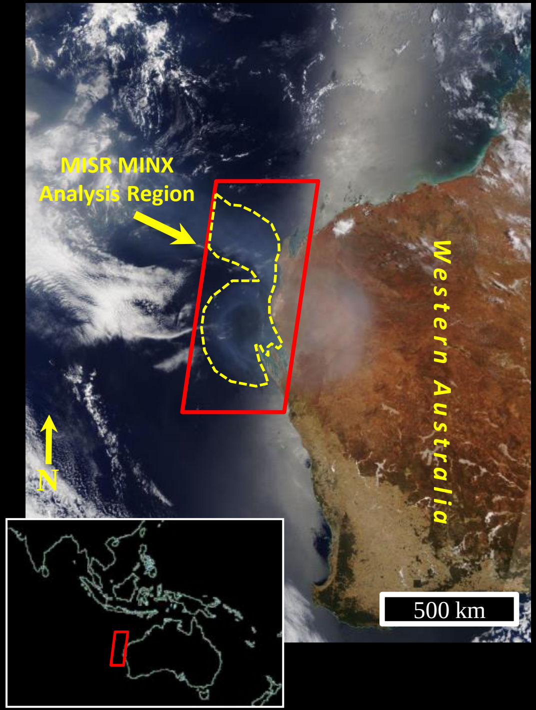
- plume detection and height
- SO_2 emission
- lava flow detection

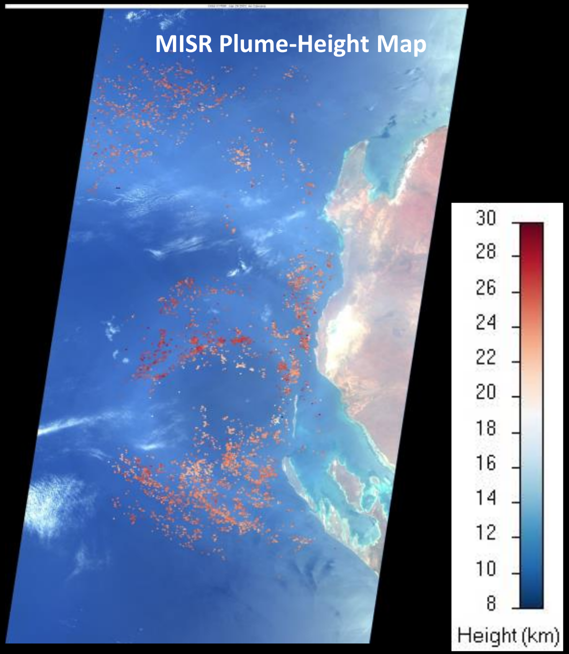
Overall ***higher thermal radiance*** and ***large flow area*** than observed at Eyjafjallajökull

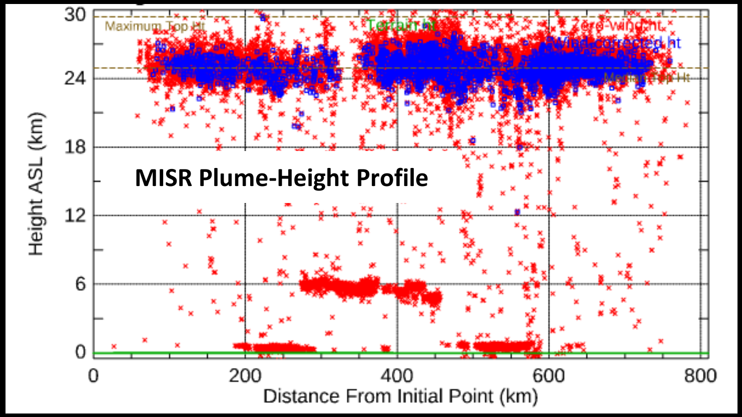
Flower & Kahn JGR., 2020

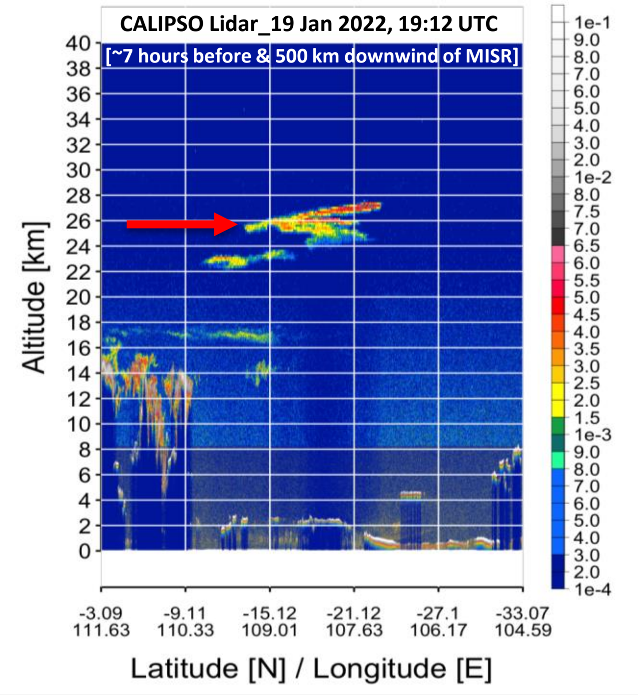
Plume from the *Hunga-Tonga Hunga-Ha'apai Volcano Eruption*

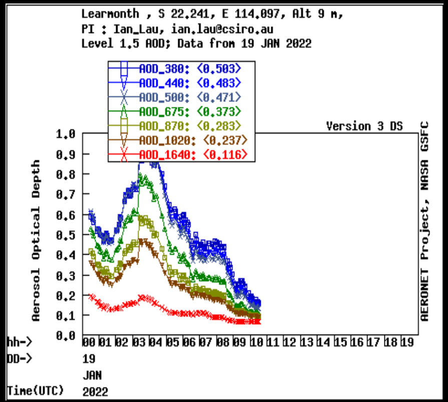
***MISR** Active Aerosol Plume-Height (AAP) Project 20 January 2022, ~02:38 UTC*



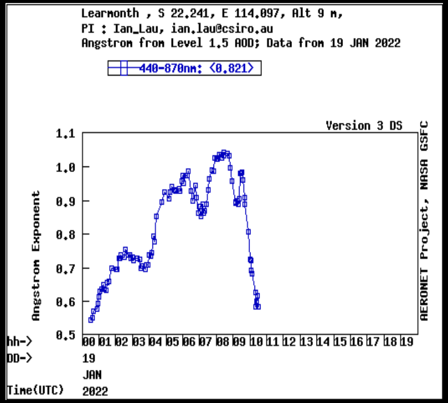








Larmonth AERONET Aerosol Amount



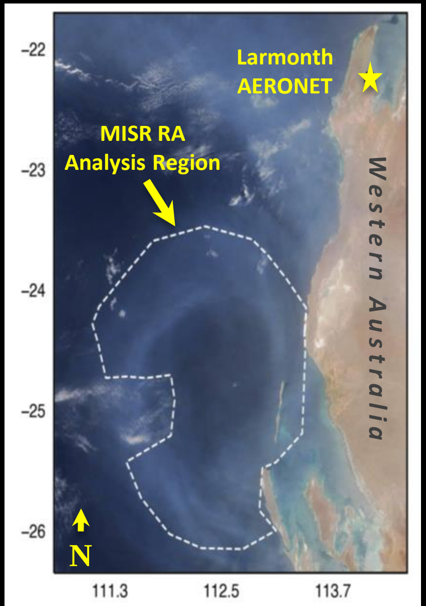
AERONET ANG ~ 1/particle size

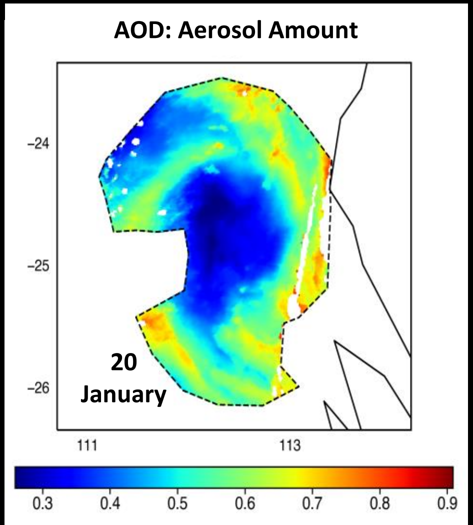
MISR Plume Height 24- 29; **AERONET AOD** ~0.9; **ANG** ~1.05

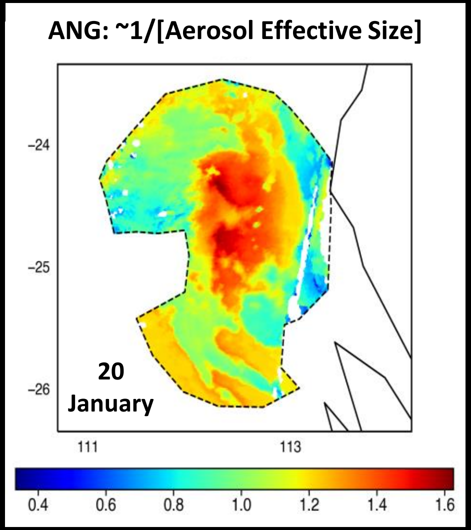
Kahn, et al. 2023, in preparation

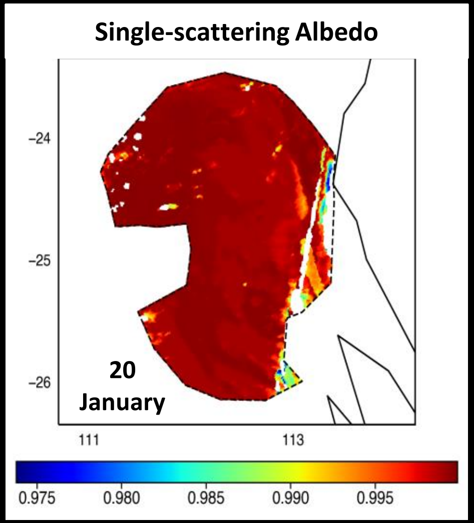
Plume from the *Hunga-Tonga Hunga-Ha'apai Volcano Eruption*

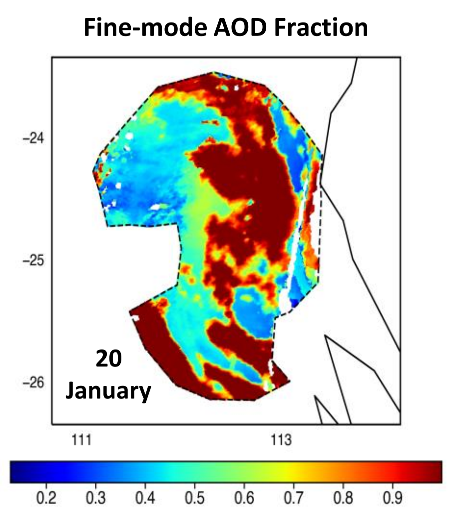
***MISR** Active Aerosol Plume-Height (AAP) Project 20 January 2022*

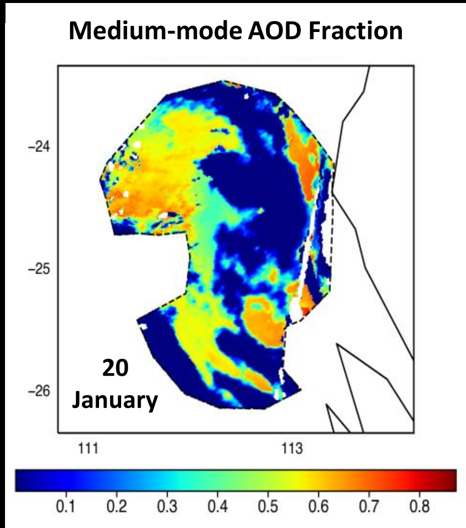


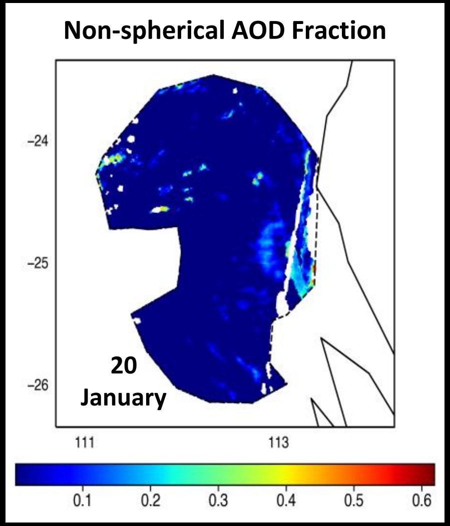








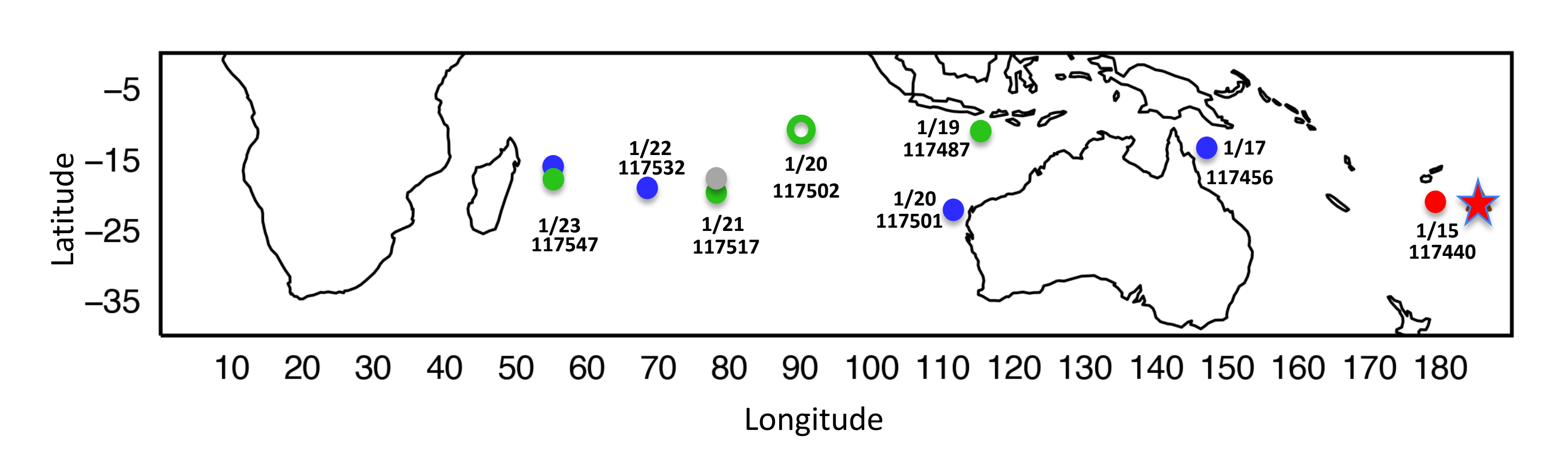




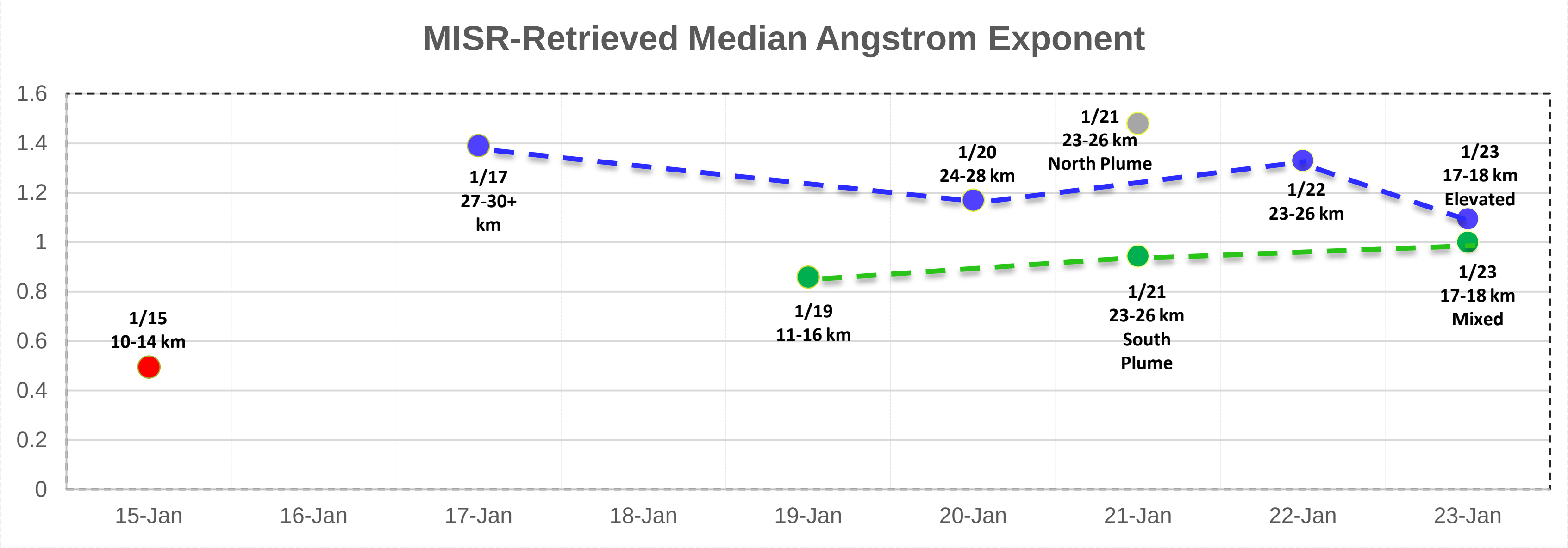
AOD ~ 0.4-0.6; **ANG** ~1.2; **SSA** ~1.0; **Fine-mode** ~0.9%, **Medium-mode** ~0.1%, **NSph** < 5%

Kahn, et al. 2023, in preparation

Hunga Plume Evolution



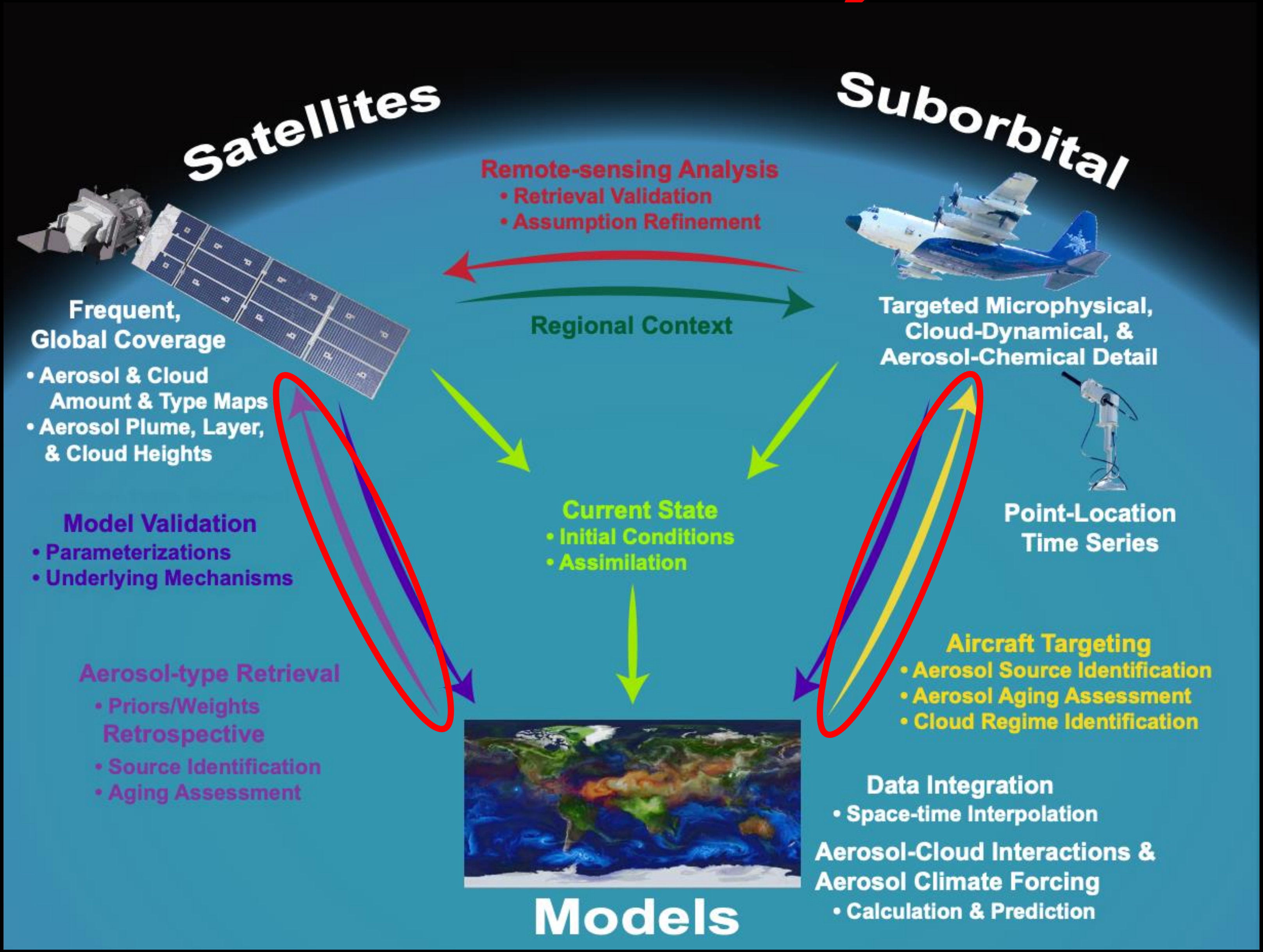
MISR Observations: Dates & Orbit #s. Blue = mid-stratosphere; Green = near-tropopause; Red = Day-1, near-source



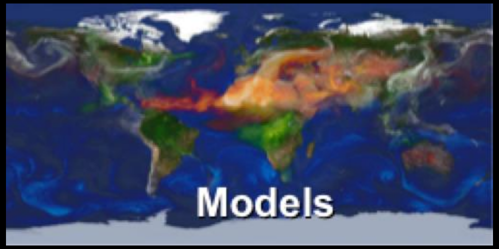
- For the mid-stratospheric plume (~30 km ASL), we see small-medium, spherical, non-light-absorbing particles dominating in the MISR retrievals, and they grow between 17 and 20 January, and then a reduction in retrieved effective particle size between 20 and 22 (blue dots).
- The mid-stratosphere plume AOD decreases systematically over these days, so new particle formation between 1/20 and 1/22 is less likely.
- For the near-tropopause plume (<~20 km ASL), the particles are predominantly medium, spherical non-light-absorbing, and do not change appreciably in size between 19 and 23 January (green dots).
- An unprecedented amount of water was injected into the mid-stratosphere by the eruption. This was expected to produce OH that would oxidize SO_2 rapidly, creating a great deal more sulfate than would otherwise occur.
- The MISR-observed growth in sulfate particles in the mid-stratosphere layer is at least consistent, and possibly supports, the model expectation.

Kahn et al., 2023 (submitted)

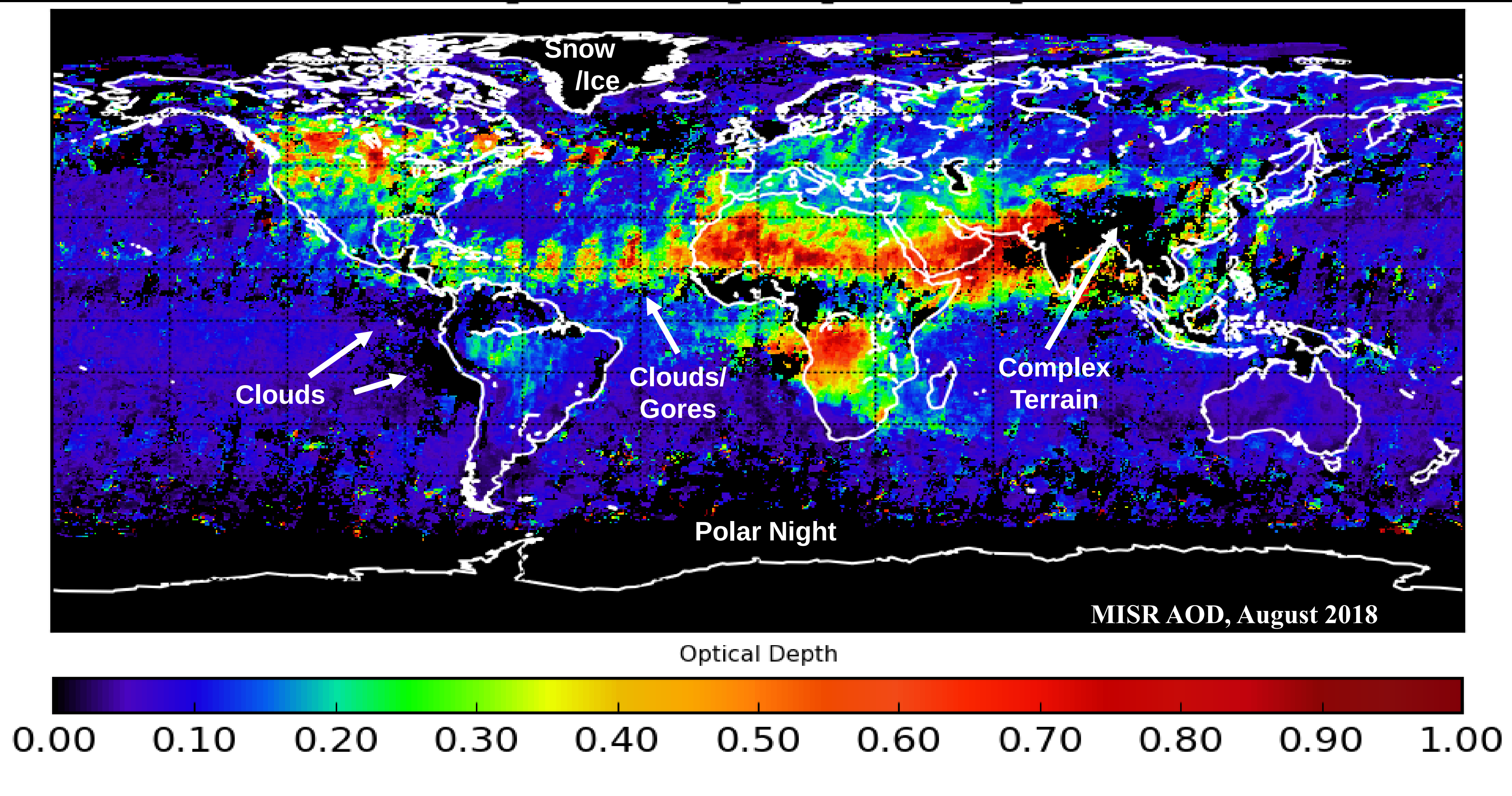
The Three-Way



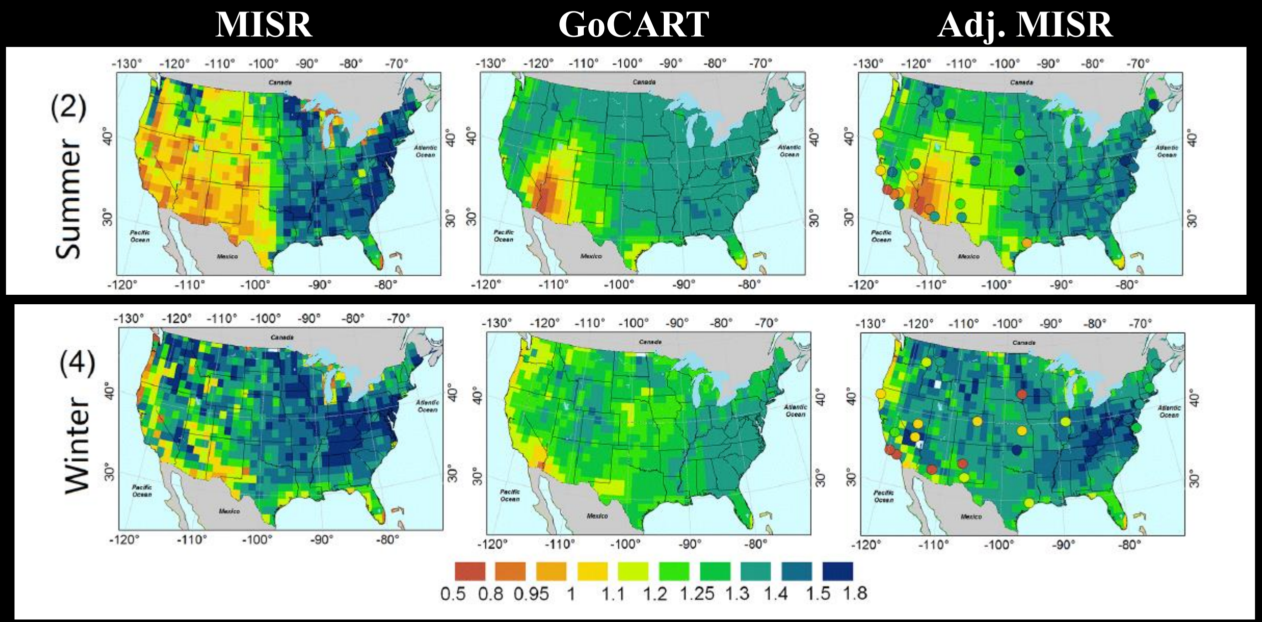
Kahn et al., Rev. Geophys. 2023

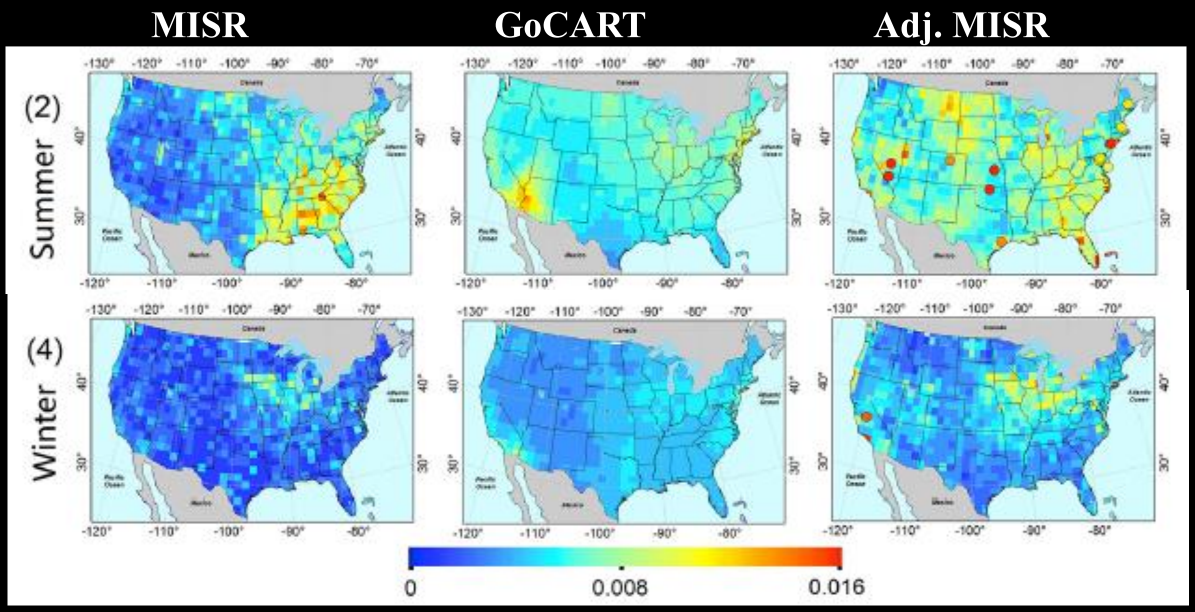


Models are Required to *Fill Gaps, Assess Forcing* and *Make Predictions*



MISR *ANG*, *AAOD* Results ***Constrained by GoCART Model***





Shenshen Li, R. Kahn, et al. AMT 2015

ANG

Four years of data (2006-2009)
Seasonally averaged

AAOD

$$\mathrm{Diff}_{\mathrm{ANG}} = |\alpha_{\mathrm{MISR}} - \alpha_{\mathrm{GOCART}}| \leq \varepsilon_{\mathrm{ANG}}$$

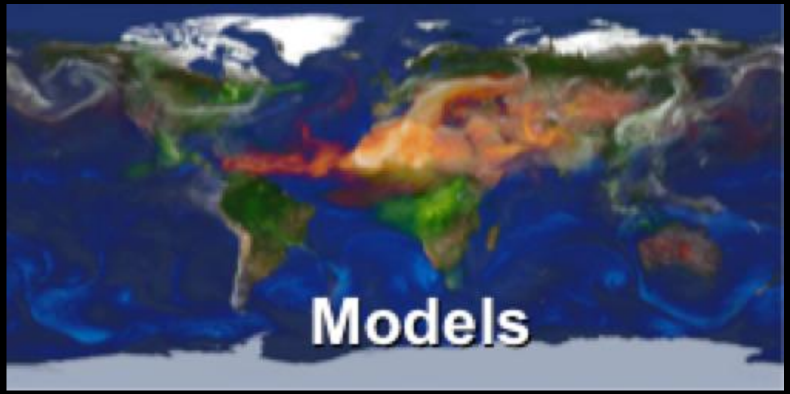
We rank the ε_{ANG}, ε_{AAOD} and select the common or the lowest mixtures

$$\mathrm{Diff}_{\mathrm{AAOD}} = \left|\mathrm{Fraction}_{\mathrm{MISR\_AAOD}} - \mathrm{Fraction}_{\mathrm{GOCART\_AAOD}}\right| \leq \varepsilon_{\mathrm{AAOD}}$$

$\mathrm{Fraction}_{\mathrm{MISR\_AAOD}}$ is the absorbing fraction of total AOD

Where remote-sensing data are ambiguous, can ***use a model to weight the options***

Understanding changes in the radiative forcing of climate is critical for any effort to attribute, mitigate, or predict climate change



However, models must adopt particle microphysical properties from ***somewhere***.

Statistically representative particle microphysical property distributions are lacking for most aerosol air masses

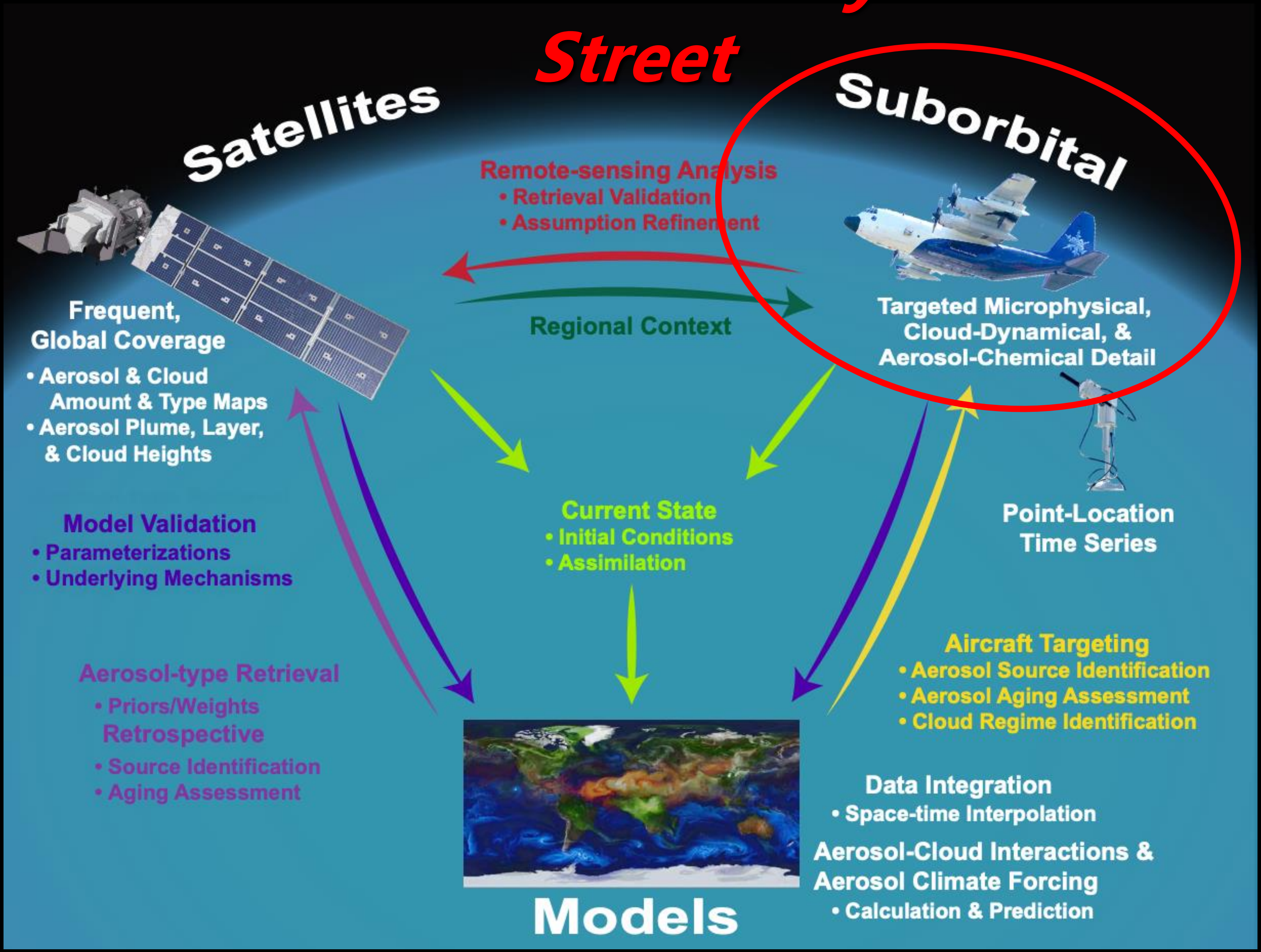
And also:

- ***Models*** are required for ***deployment-site selection*** and for ***flight planning***

  -- To determine the climatologically likely locations of aerosol ***sources***
  -- To determine the aerosol air mass ***downwind trajectories*** that the aircraft must sample

- ***After*** the actual aircraft measurements have been acquired, ***Models*** are also needed to help assess the ***sources***, as well as the ***ages*** and likely ***aging mechanisms*** sampled

The Three-Way Street



Kahn et al., Rev. Geophys. 2023

SAM-CAAM *Concept*

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

Primary Goal*:** [This is currently a ***concept-development effort, not yet a project]

- ***Characterize statistically particle properties*** **for major aerosol types globally, to provide detail unobtainable from space, adding value to models & satellite aerosol data, offering *improved aerosol property assumptions for:***
  - -- ***Modeling*** **aerosol direct forcing and aerosol-cloud interactions**
  - -- ***Satellite retrieval algorithm*** **climatology options or priors**

Plus: More robust *translation between satellite-retrieved aerosol optical properties and* species-specific aerosol mass and size tracked in *aerosol transport, climate, & air quality models*

Substantially reduce model uncertainty & enhance the value of 23+ years of satellite aerosol retrieval products

Kahn et al., BAMS 2017

Suborbital *In Situ* Required for PDFs of Particle Microphysical Properties

Aerosol intensive properties required for key aerosol science objectives, but ***cannot be retrieved adequately*** or are ***entirely unobtainable from remote sensing***

- ***Hygroscopicity**** – Ambient ***particle hydration***, ***aerosol-cloud interactions***
- ***Mass Extinction Efficiency*** – Translate between retrieved ***optical properties*** from remote sensing ***& aerosol mass*** book-kept in models
- ***Spectral Light-Absorption*** – Aerosol ***direct & semi-direct forcing***, atmospheric stability structure & circulation
- ***CCN Properties**** – At least part of the CCN size spectrum is ***too small to be retrieved*** by remote-sensing

Acquiring such data is feasible because:
Unlike aerosol amount, ***aerosol microphysical properties tend to be repeatable*** from year to year, for a given source in a given season

Kahn et al., BAMS 2017

*Under special conditions, hygroscopicity (*Dawson et al. 2020*) and CCN # (*Rosenfeld et al. 2016*) can be derived from remote sensing; however: (*Stier*, ACP 2016)

Current GSFC **MISR** Team Activities*

Climate

AeroCom/AeroSat
model
assessment

Plume/layer height
MISR Stereo-

Aeros

studies
•Noyes/Kahn
•Kahn/Cant
•Pan/Kahn/
•Petrenk

lity
Obs.
eS *ver*/Kahn

Volca
McKee/*Va*
Flower

gorithm
on,
A/Kahn
Code
/NOAA/Kahn
A

d
s

-C Team

l activities
AeroCom
PAR
U. of Maryland
PUMAS
ACPC – iLEAPS/GEWEX
NOAA CalFiDE Campaign
NASA ARCSIX Campaign

Aerosol amount
MODIS/MISR/AERONET

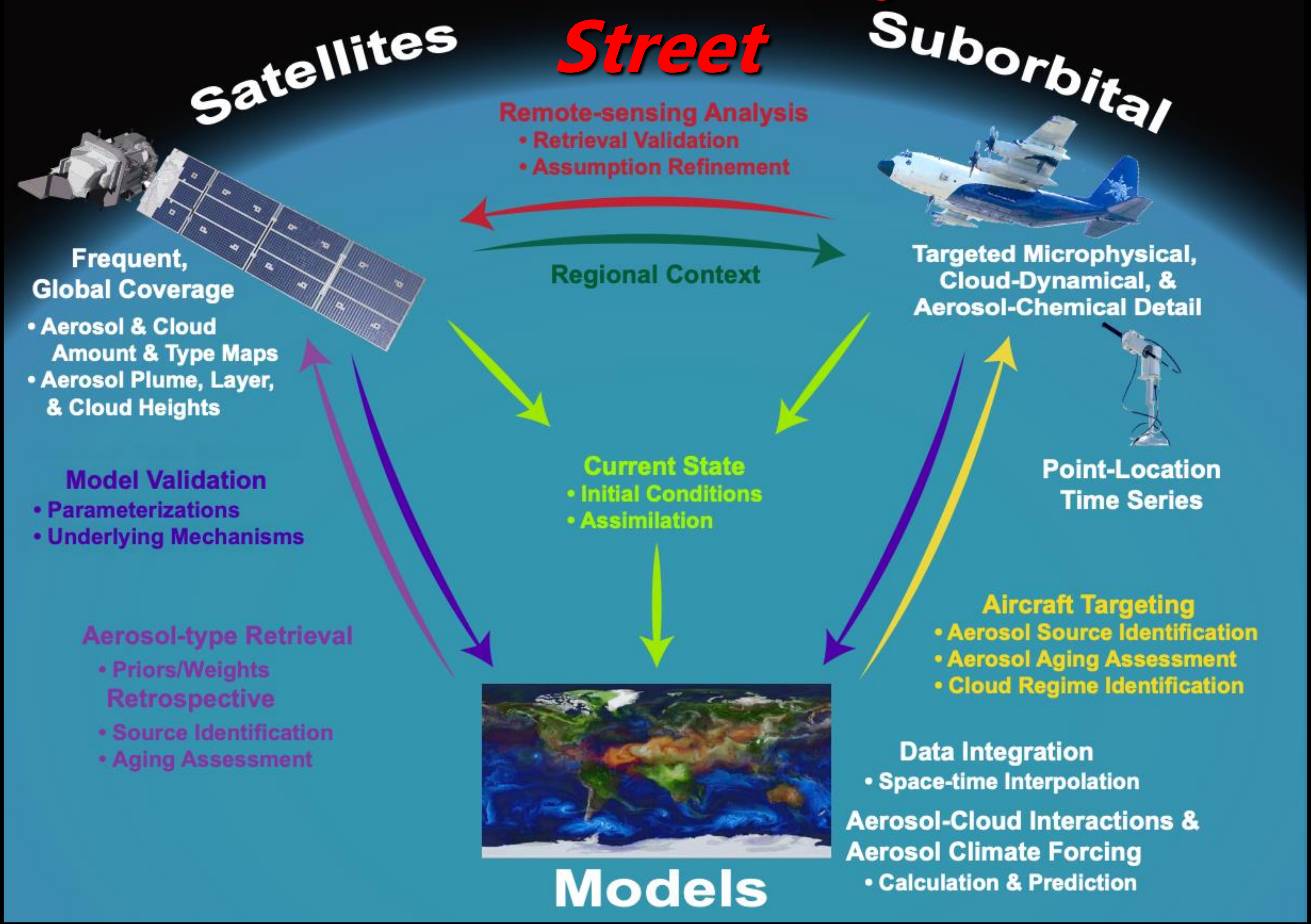







April 2023

The Three-Way Street

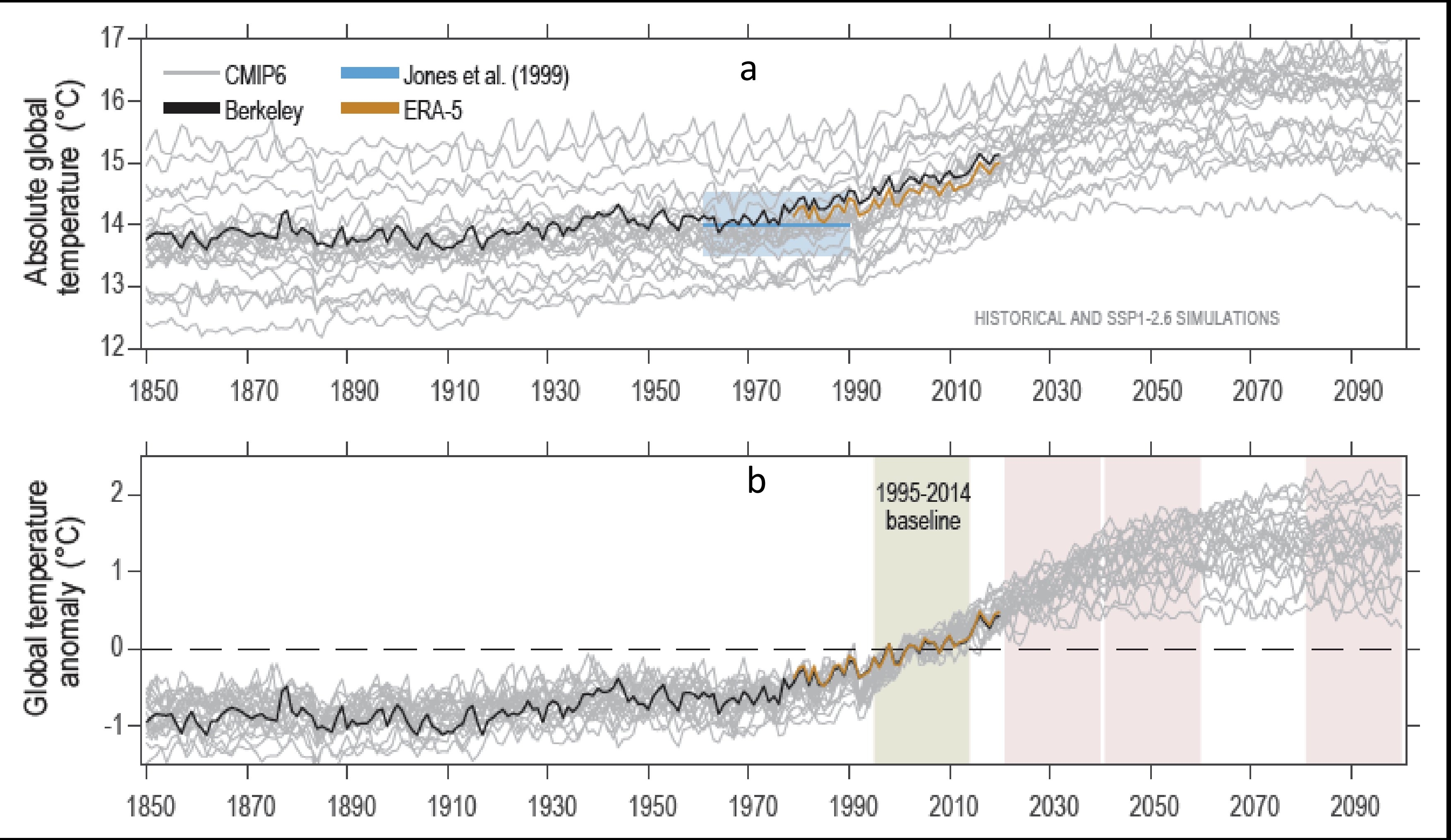


Kahn et al., Rev. Geophys. 2023

Highlights the essential & unique role of each community in completing the aerosol forcing picture…

Backup Slides

Multi-model Simulations of Global Mean Surface Temperature Timeline



(a) Absolute temperature simulations for 1850-2014

+

forecasts using a moderate assumed future scenario (SSP1-2.6) for 2015-2100, for 25 models (gray lines)

+

Measurement – where available (black lines)

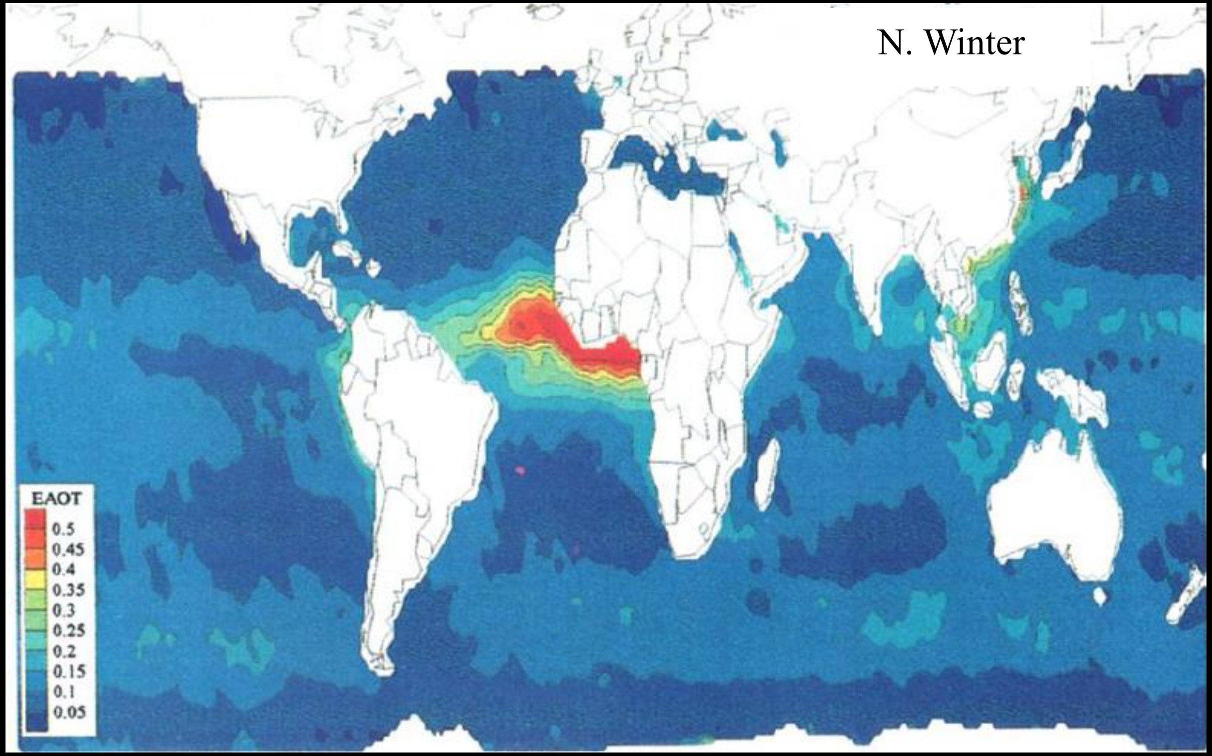
(b) Temperature anomalies

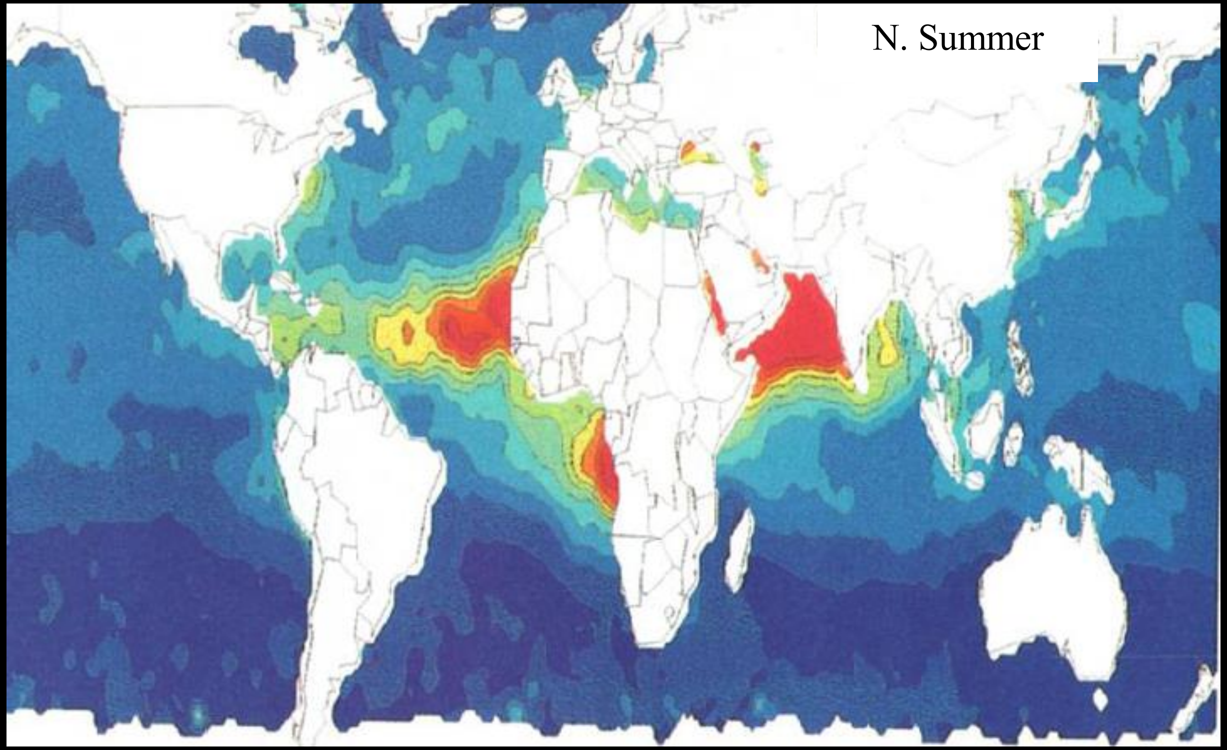
From IPCC AR-6

AVHRR (Advanced, Very High-Resolution Radiometer)

Aerosol Optical Depth (*Aerosol Column Amount*)

July 1989-June 1991

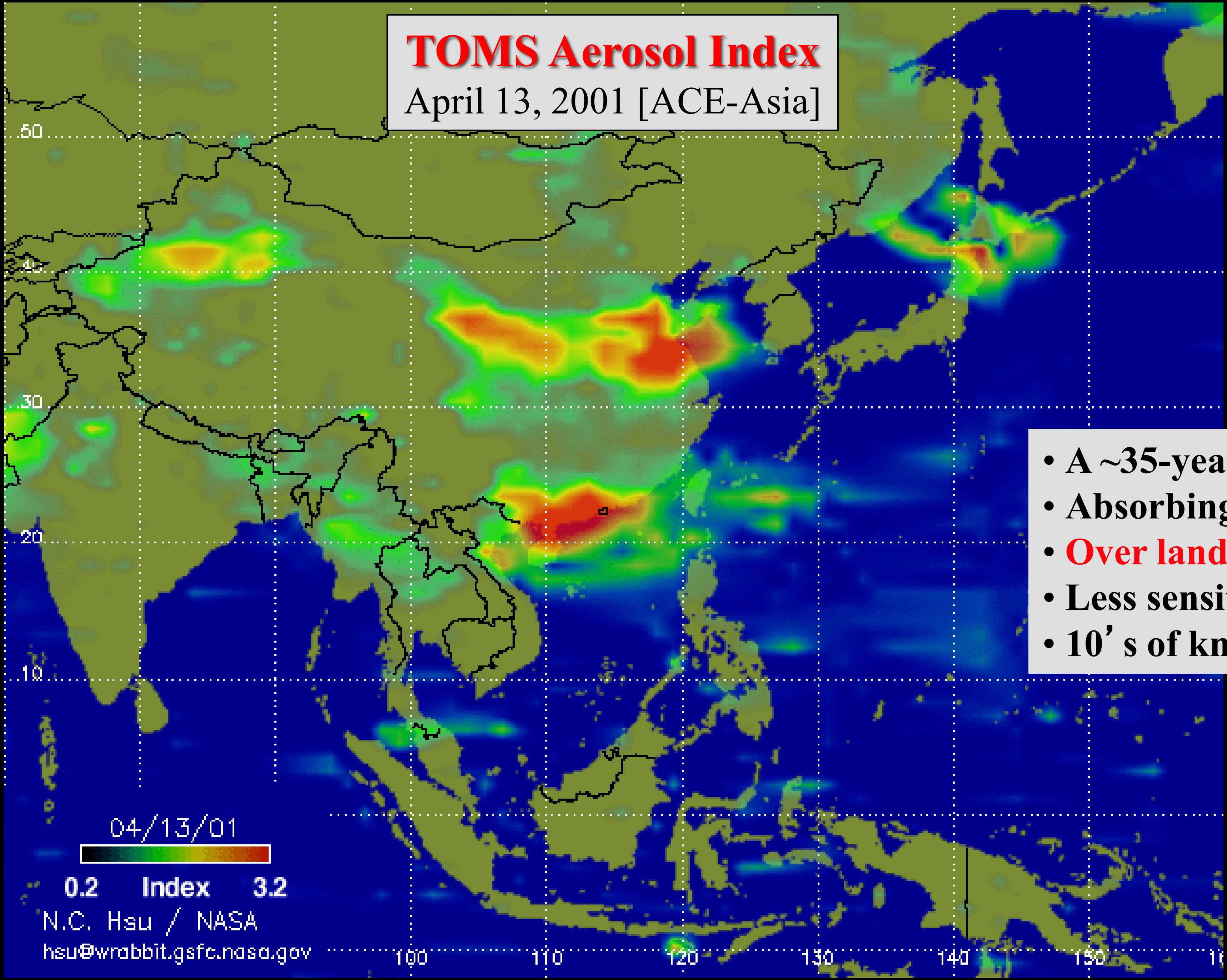




Husar, Prospero, & Stowe JGR 1997

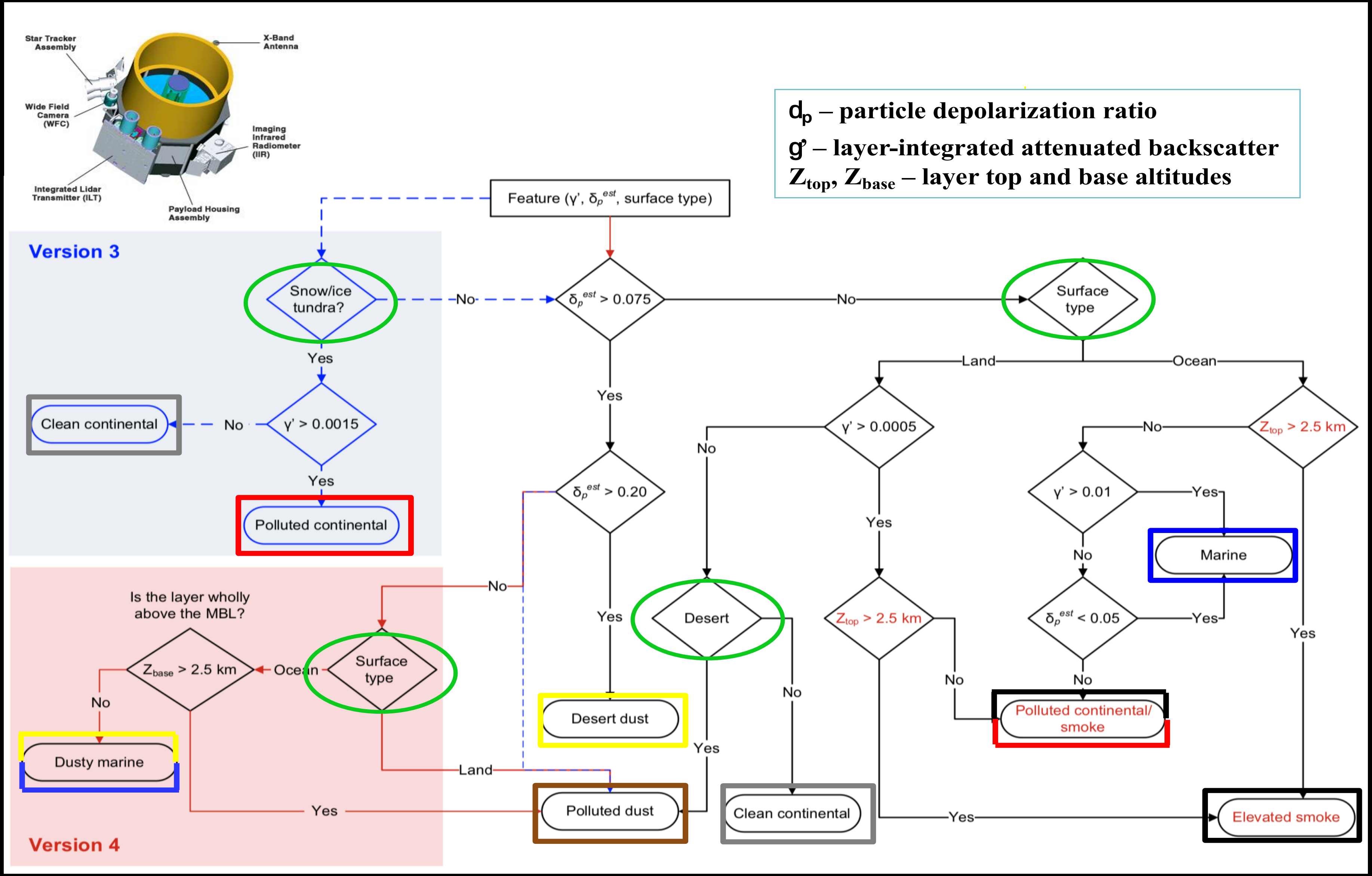
TOMS Aerosol Index

April 13, 2001 [ACE-Asia]



- A ~35-year record
- Absorbing aerosols
- Over land & water
- Less sensitive to BL
- 10’ s of km resolution

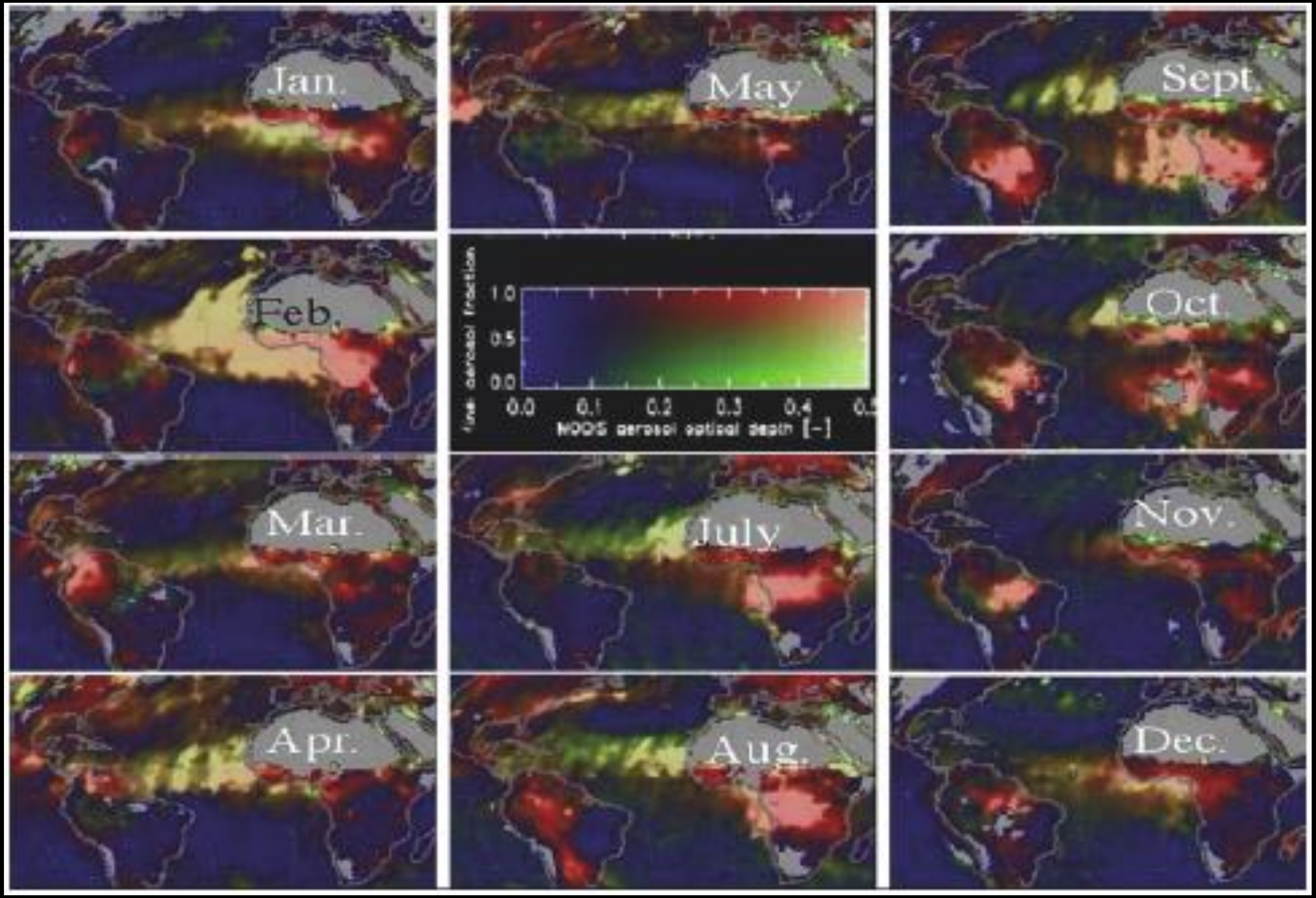
CALIPSO 6-Type Interpretive Aerosol Classification Scheme



Kim et al., 2018

One MODIS Aerosol Type Classification

Low AOD High AOD+Coarse High AOD+Fine



Kaufman et al., JGR, 2005