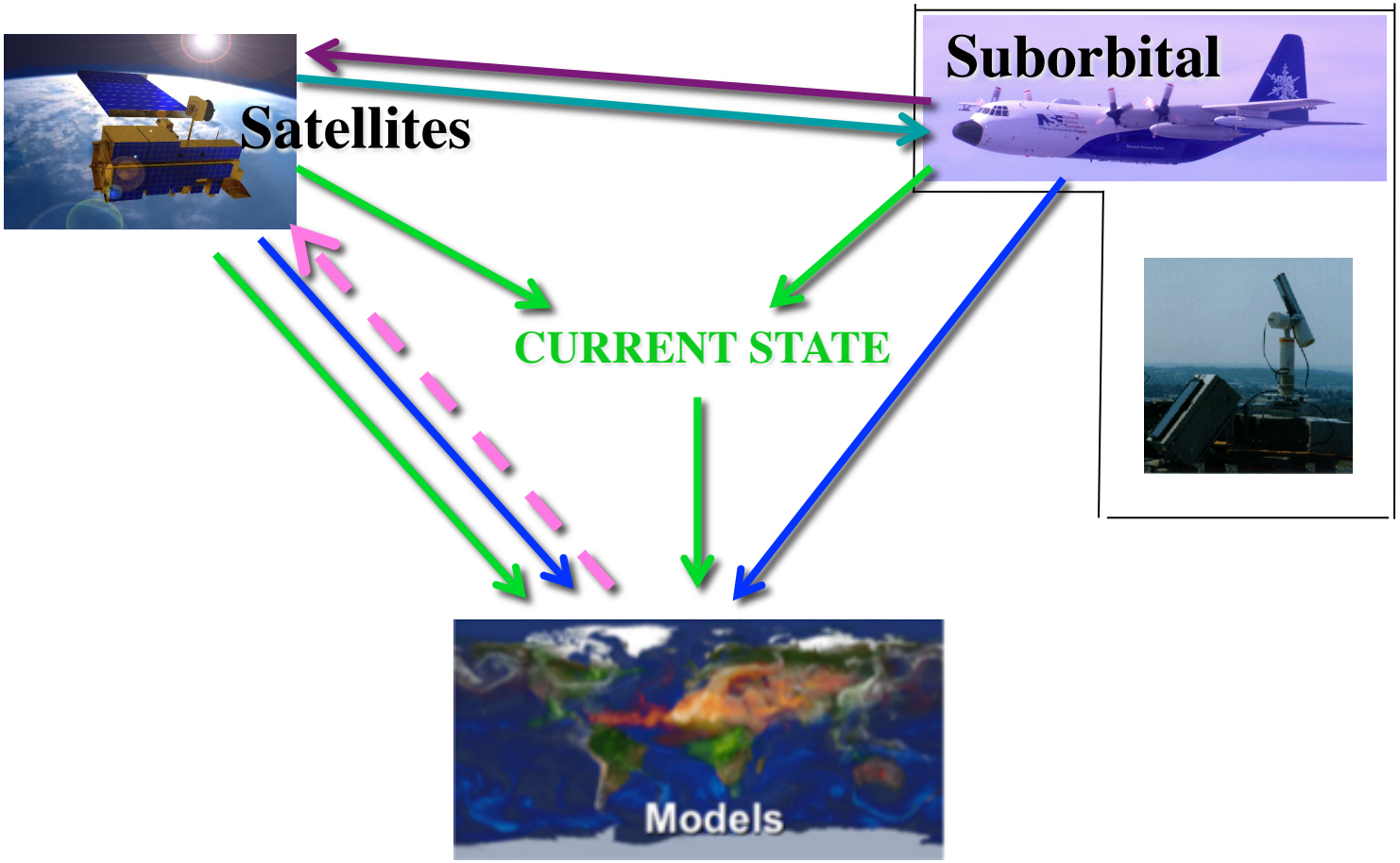
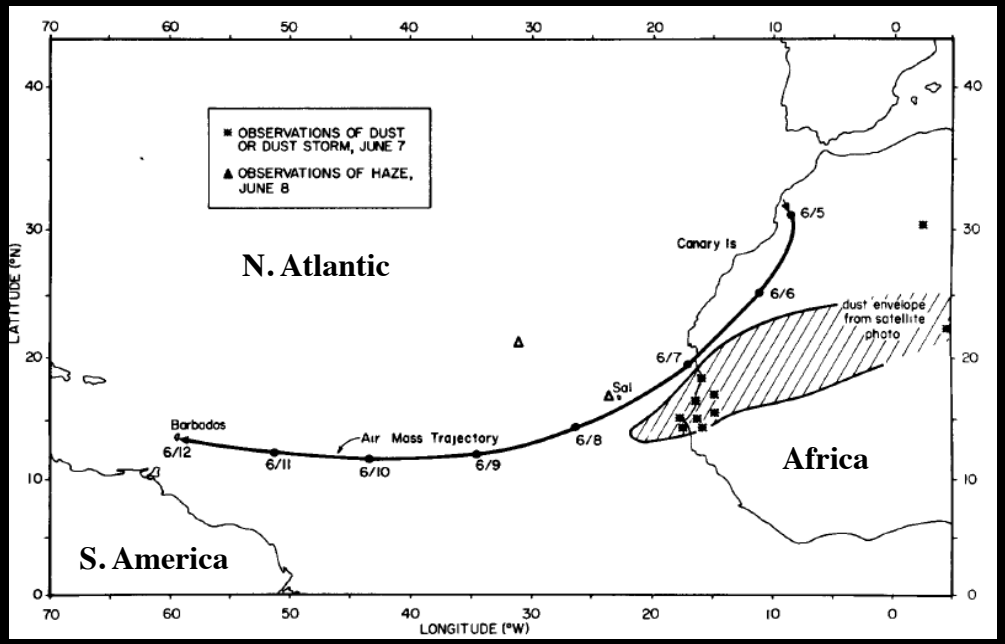
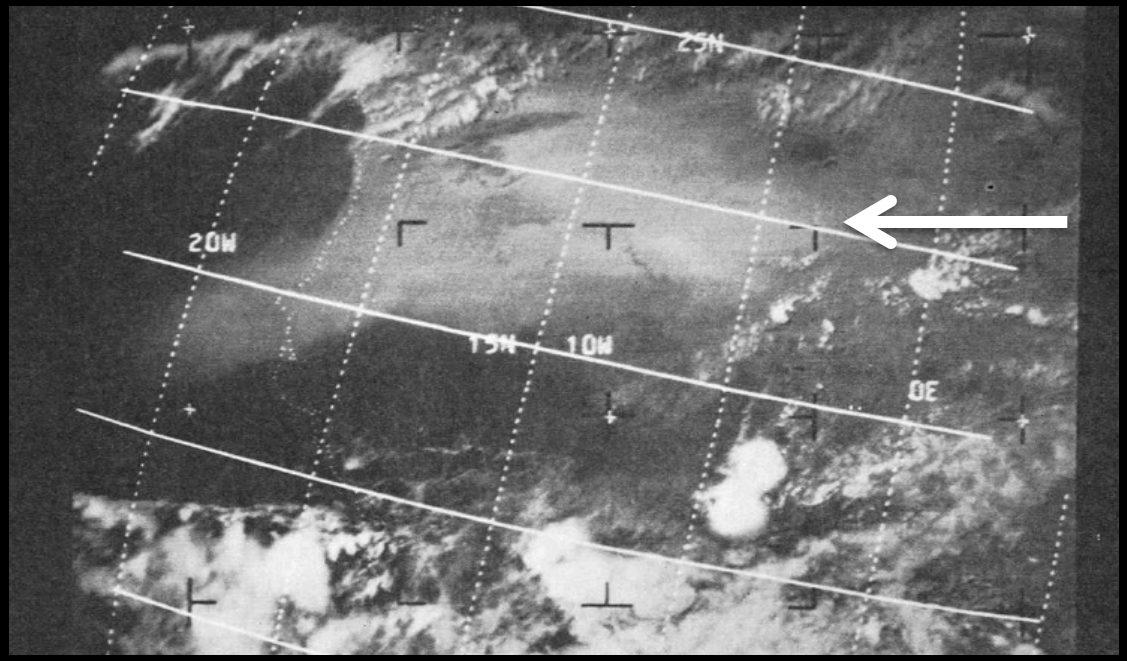
Constraining the components of aerosol forcing:
How well can measurements keep climate models on track?

Ralph Kahn *NASA Goddard Space Flight Center*
And the ***MISR Team****, JPL & GSFC*



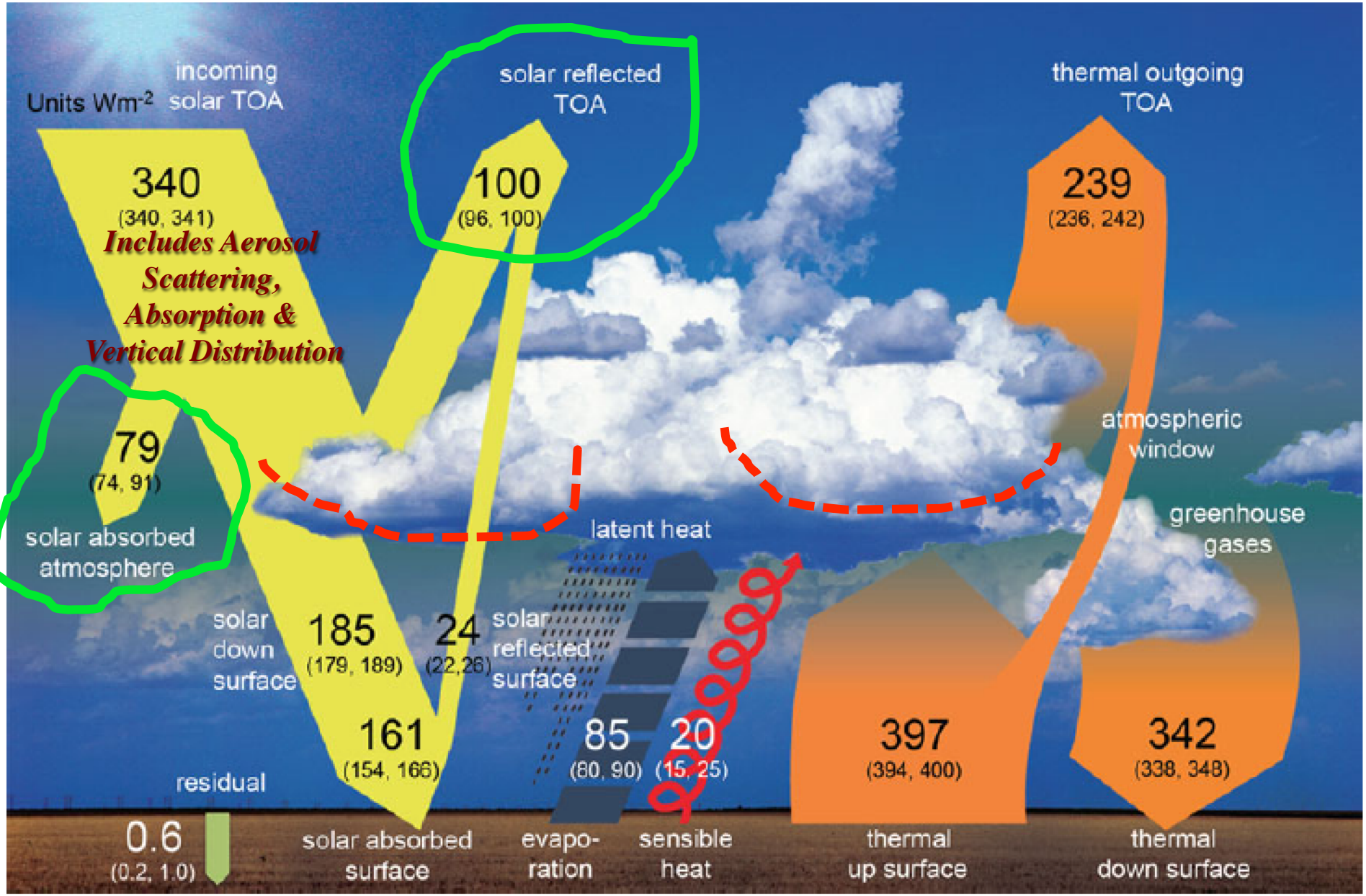


Saharan Dust Storm
8-day trajectory
Beginning 07 June 1967
ESSA 5 Satellite



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

Global Energy Flows (W/m²)



Wild et al., BAMS 2012

What We Need, Globally

- Aerosol ***AMOUNT*** (AOD – 2D)
- Aerosol ***VERTICAL DISTRIBUTION***
- Aerosol "***TYPE***"

  -- ***Light Absorption*** *(direct forcing)*

  -- ***Hygroscopicity*** *(interpreting AOD; indirect forcing)*

  -- ***Composition***

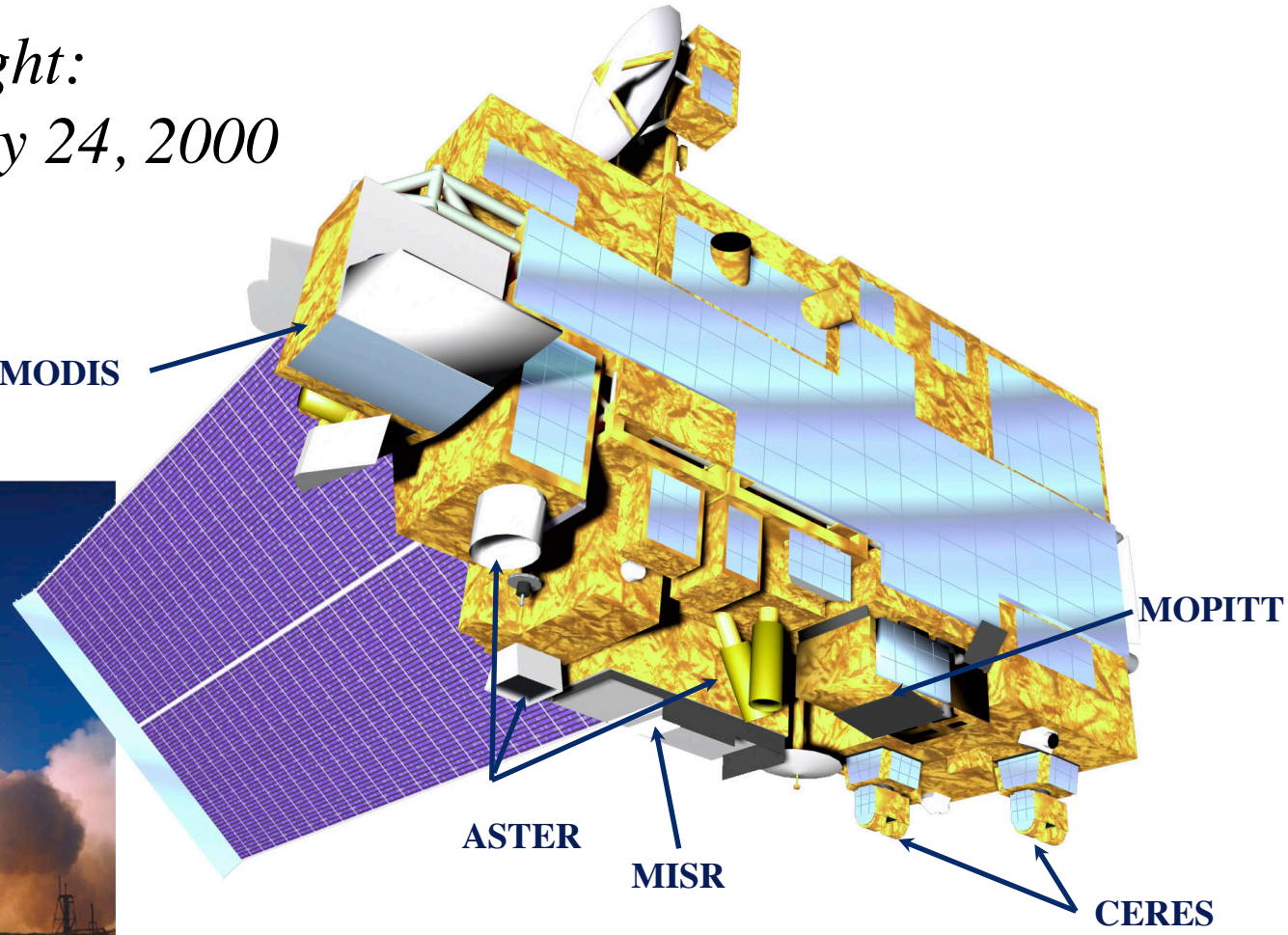
  (source attribution; μ-physical properties; mass flux)

  -- ***Mass Extinction Efficiency (MEE)***

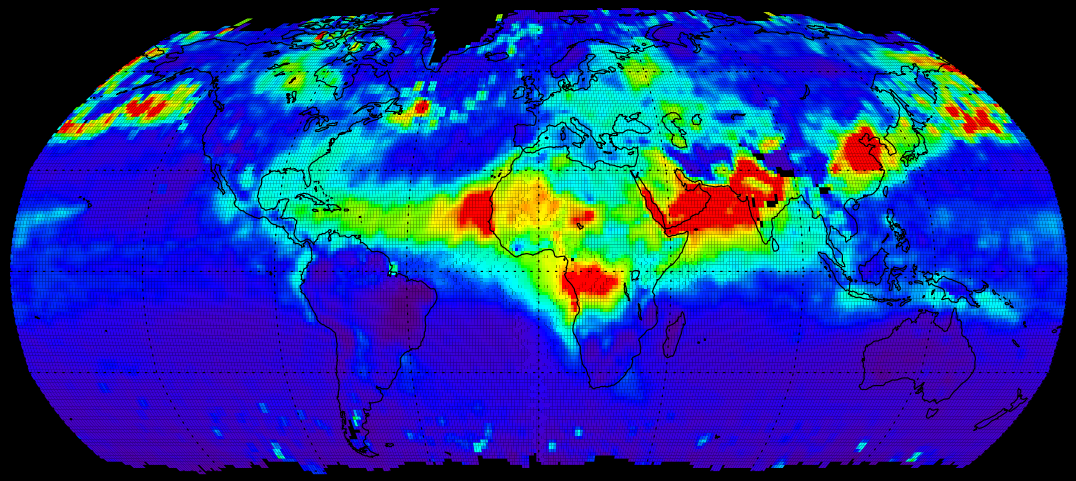
  (measurement ←→ model translation)

The NASA Earth Observing System's Terra Satellite

First Light:
February 24, 2000



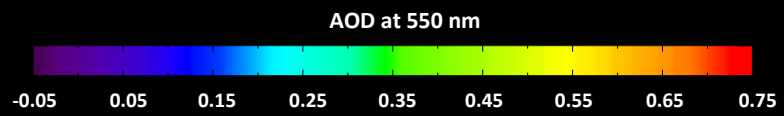
Source: Terra Project Office / NASA Goddard Space Flight Center



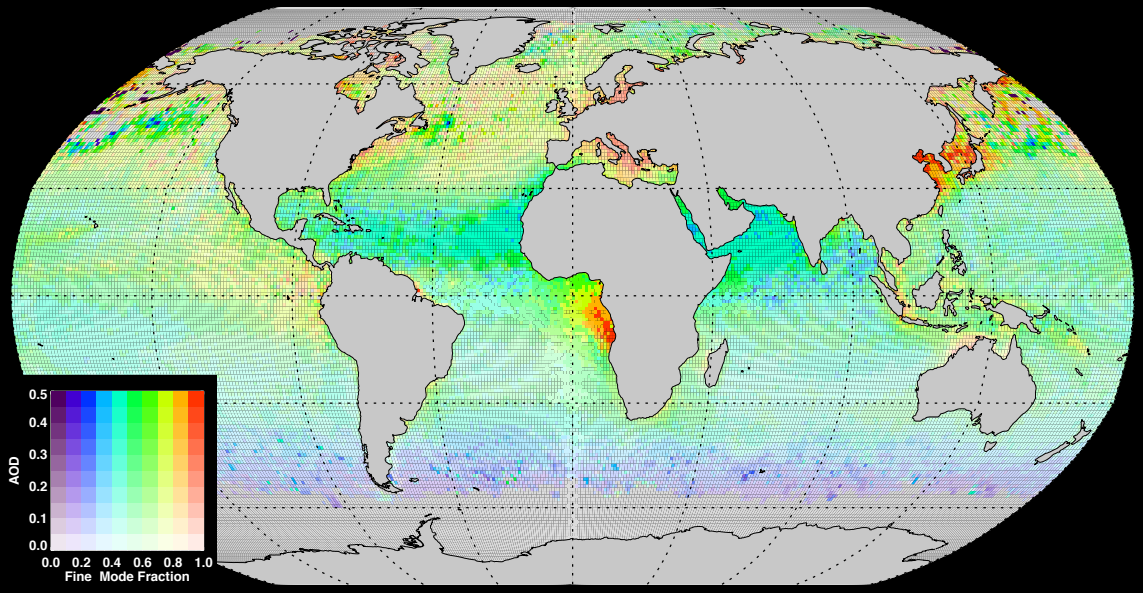
Mid-Visible
AOD
"Dark Target" + "Deep Blue"

MODIS

July 2010
Monthly Average



- Water & some Land
- Globe ~ Every 2 days
- ~ 10:30 AM & 1:30 PM

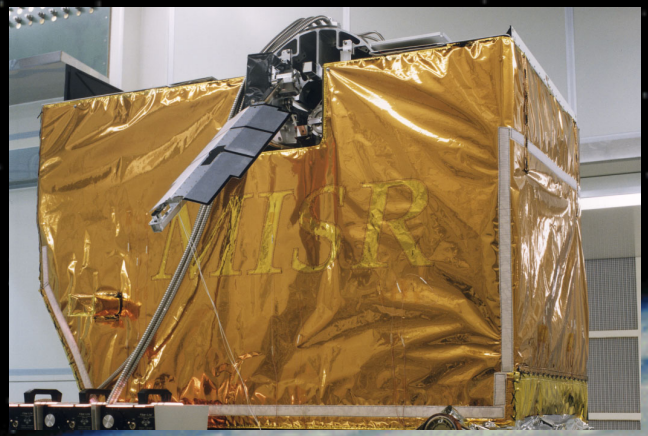


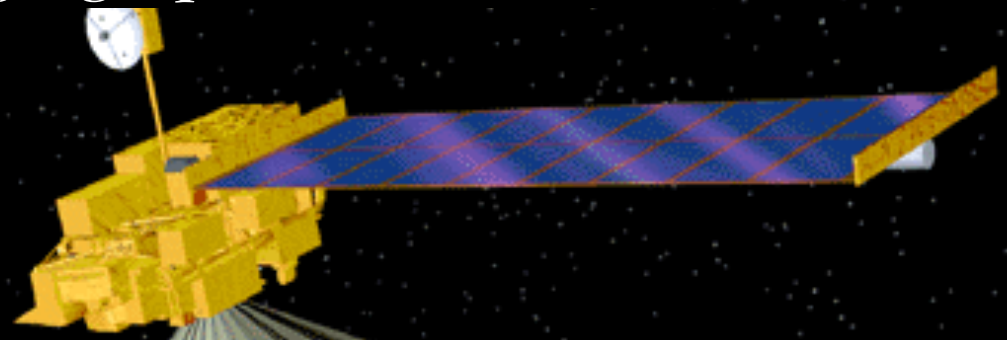
- Fine/Coarse Ratio Over Water + AOD
- Sensitivity to PM10

MODIS Team, NASA Goddard Space Flight Center

Multi-angle Imaging SpectroRadiometer

MISR



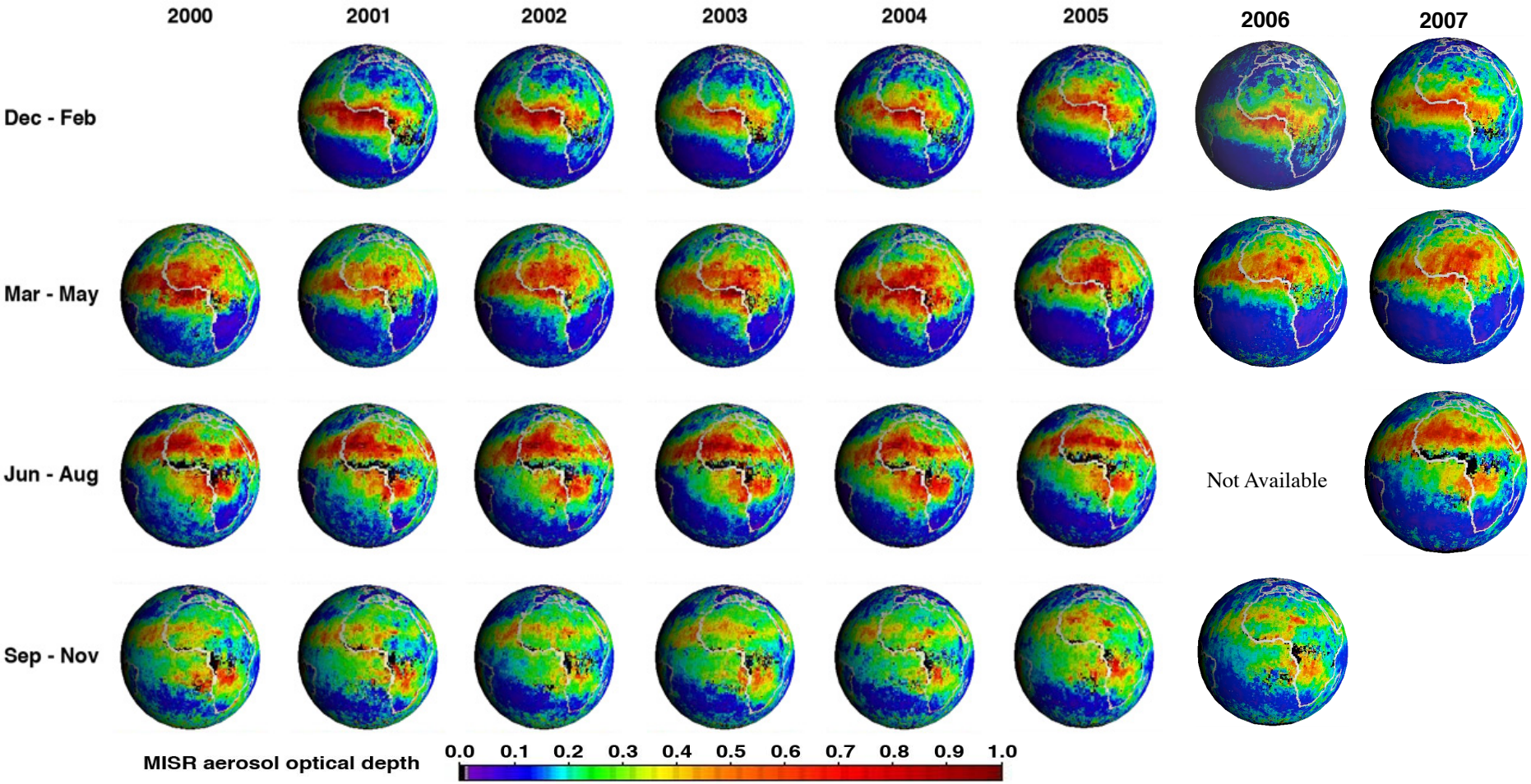


http://www-misr.jpl.nasa.gov

http://eosweb.larc.nasa.gov

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

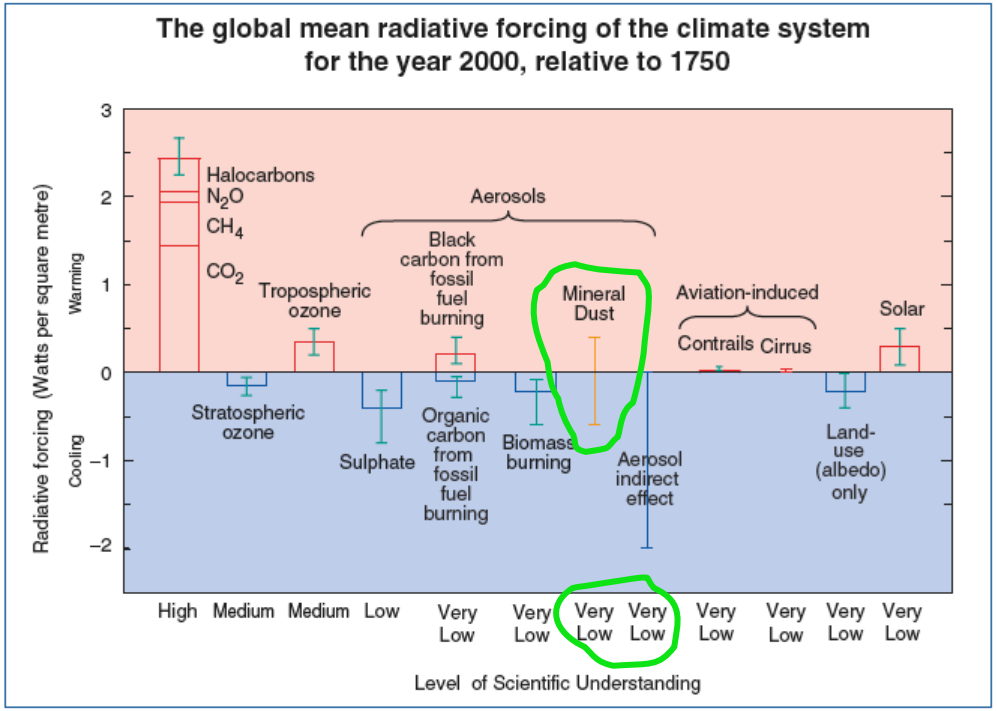
Eight Years of Seasonally Averaged Mid-visible Aerosol Optical Depth from MISR



…includes bright desert dust source regions

MISR Team, JPL and GSFC

Even DARF and Anthropogenic DARF are *NOT* Solved Problems (Yet)



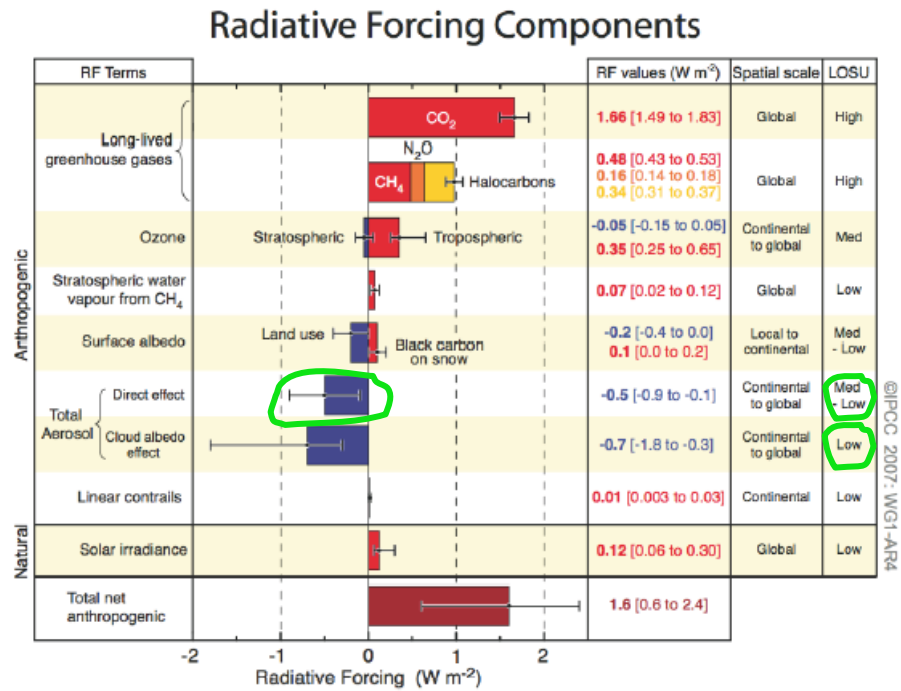
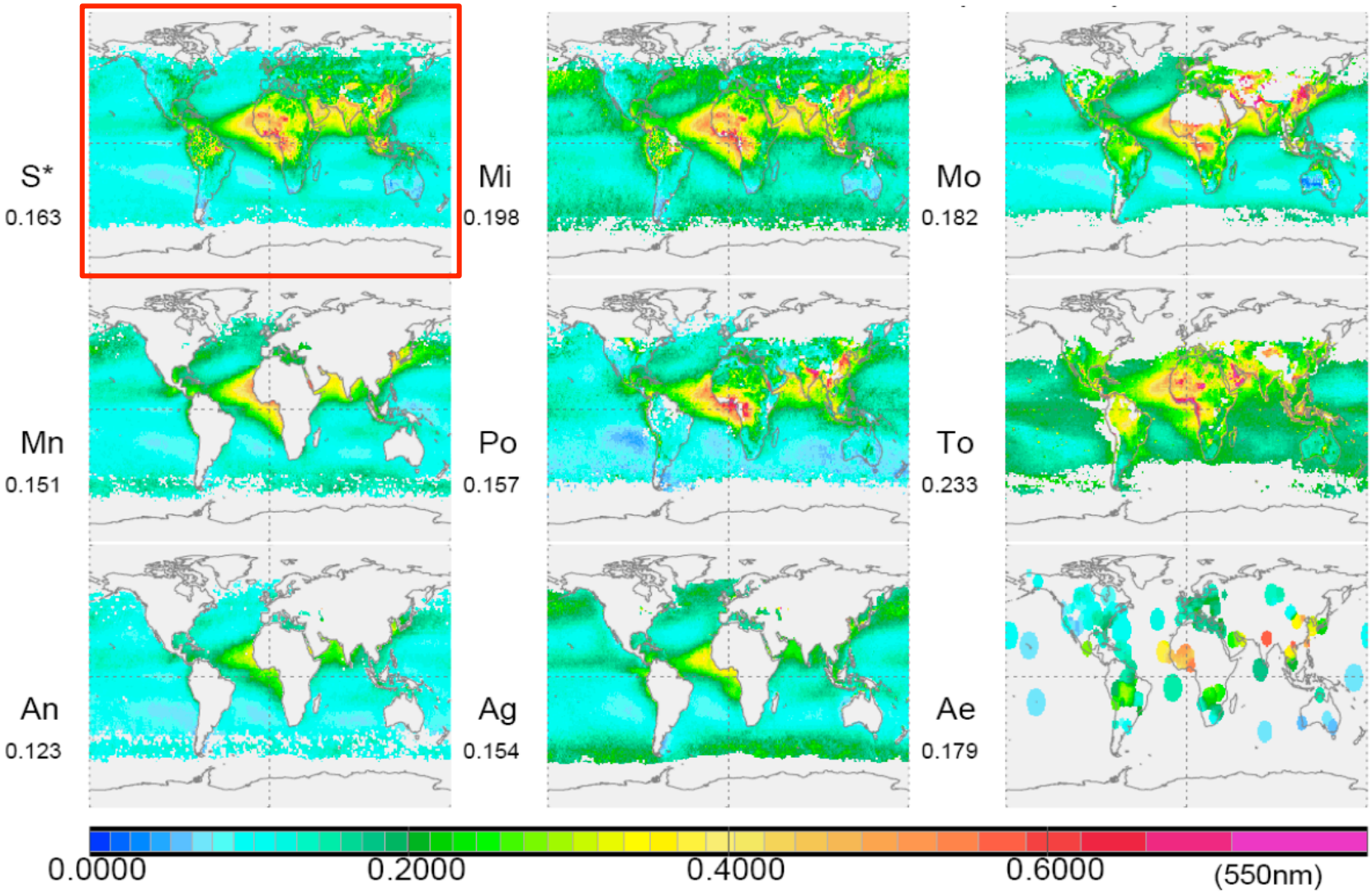


FIGURE SPM-2. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. Range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}

IPCC AR3, 2001
(Pre-EOS)

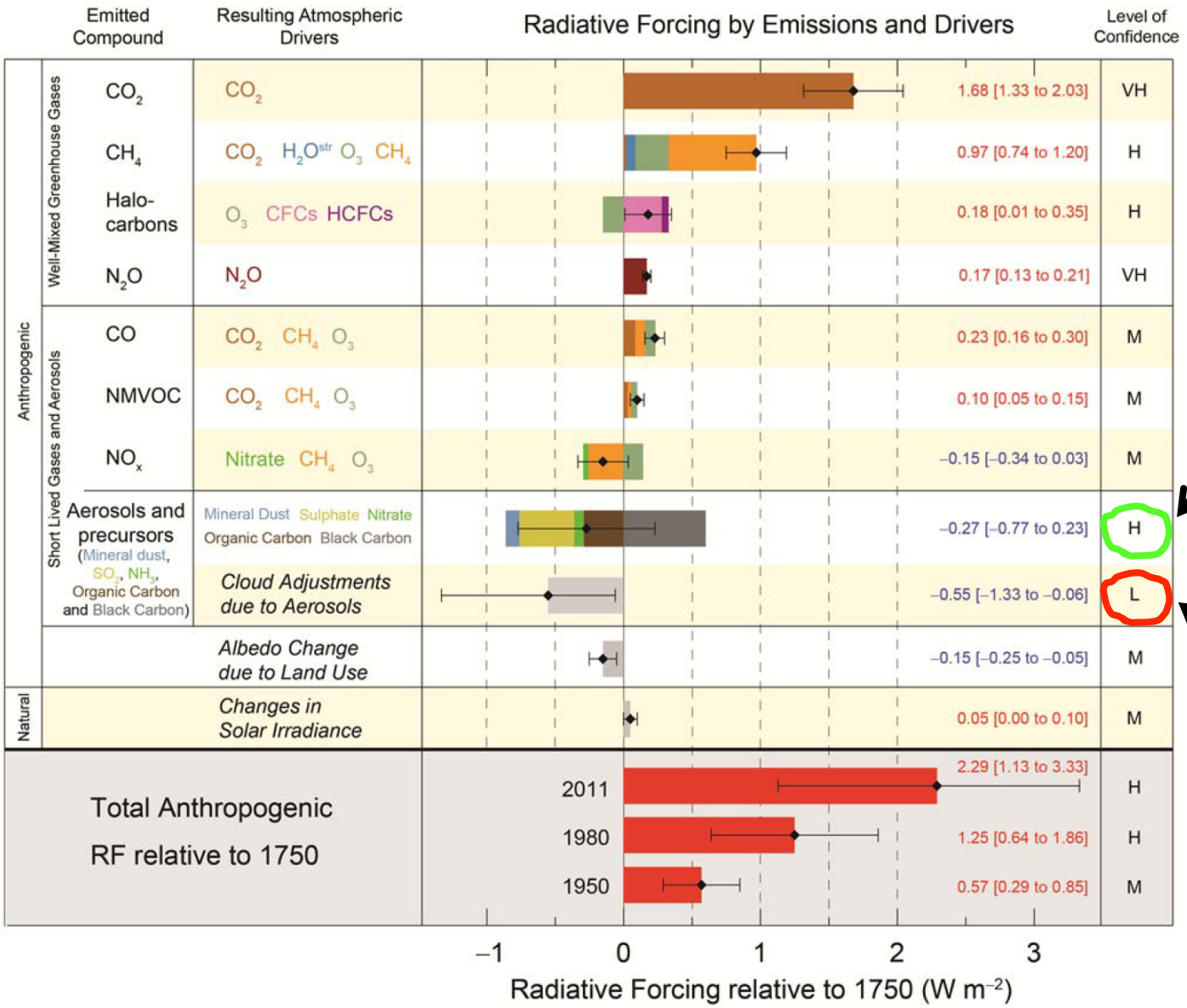
IPCC AR4, 2007
(EOS + ~ 6 years)

Multi-year Annual Average *Aerosol Optical Depth* from Different Measurements + *Synthesis* (S*)



From: *Kinne et al. ACP 2006*

The *Current* Assessment of Climate Forcing Factors



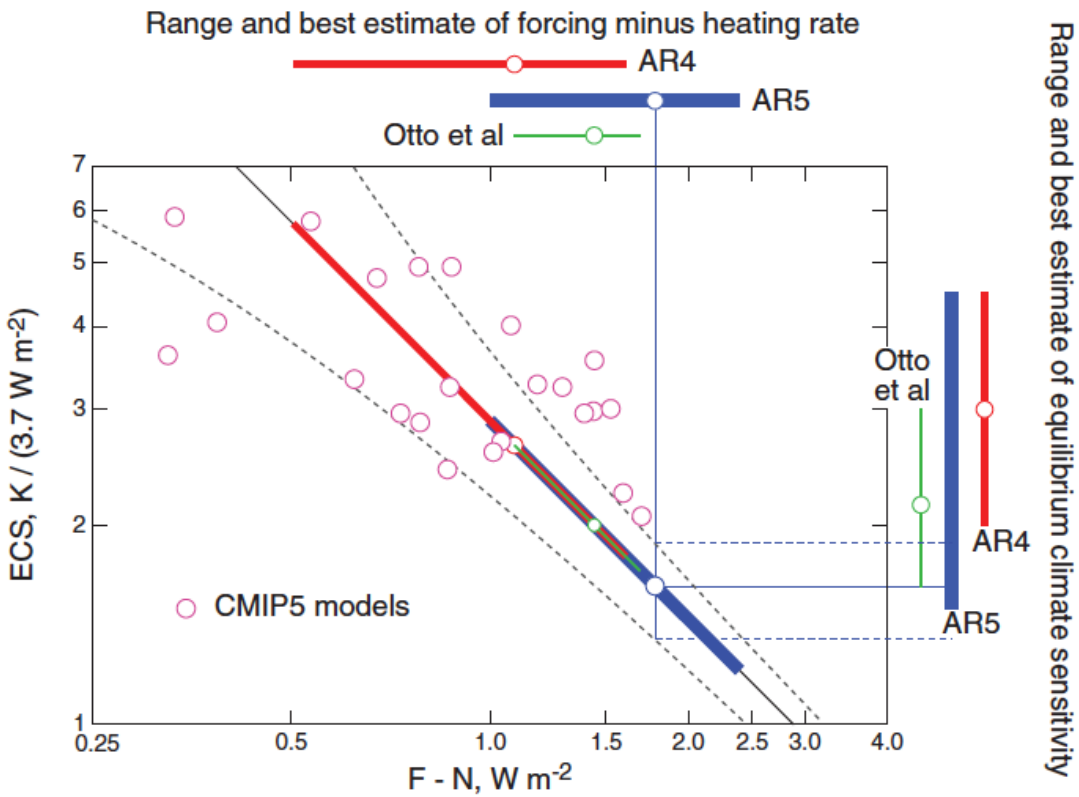
Global average, & compared to other uncertainties in the models – ***What about aerosol type?!***

The next big area to address

*IPCC **AR5** 2013*

The *AR5* Assessment of Climate Forcing Factors

Equilibrium Climate Sensitivity



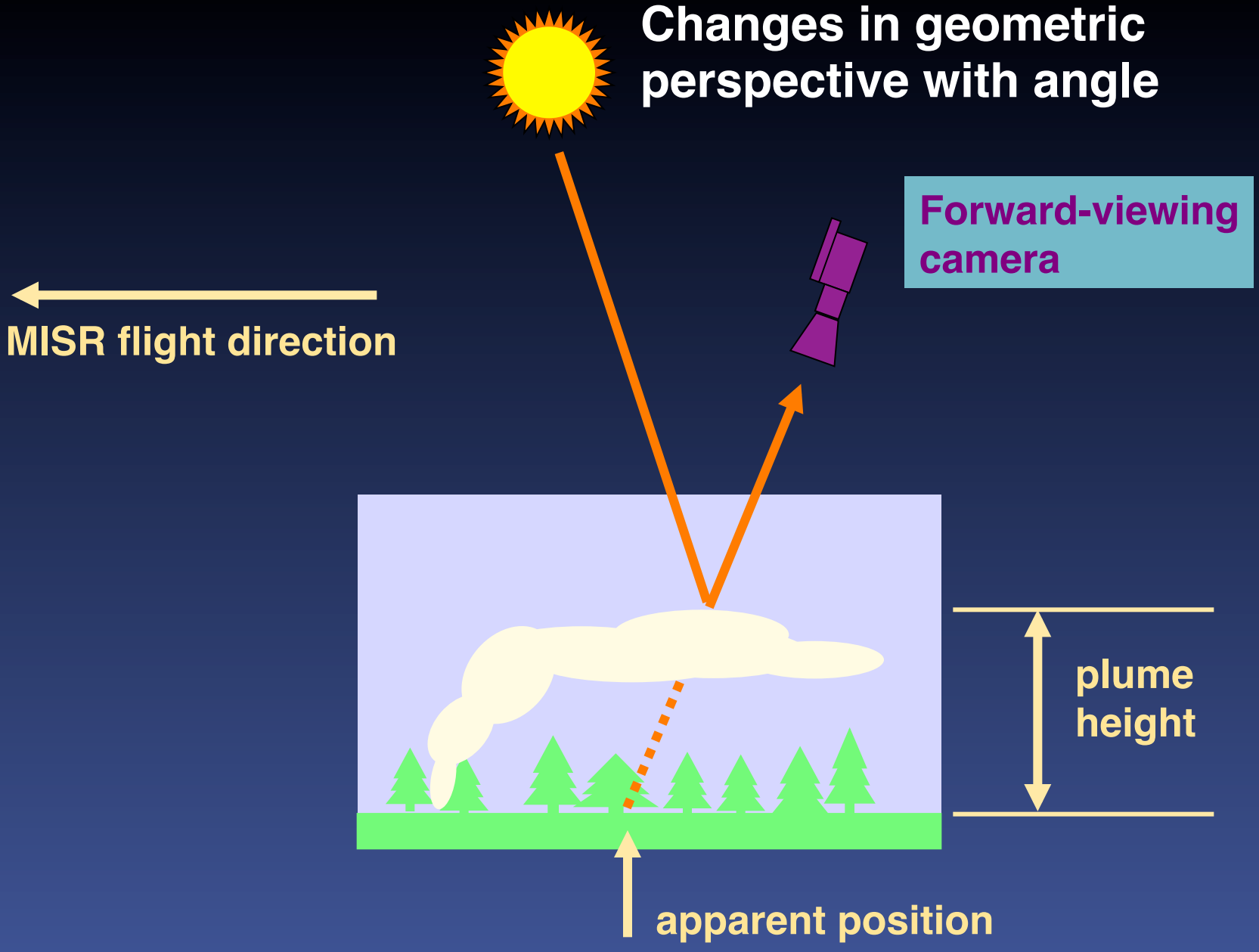
$$(F - N) \times S = \Delta T$$

Effective Forcing — Δ Heat Content — Climate Sensitivity — Response

- For AR5, aerosol forcing was reduced (so F increased overall). *Why*?
- Yet, the range of ECS was only slightly reduced compared to AR4.

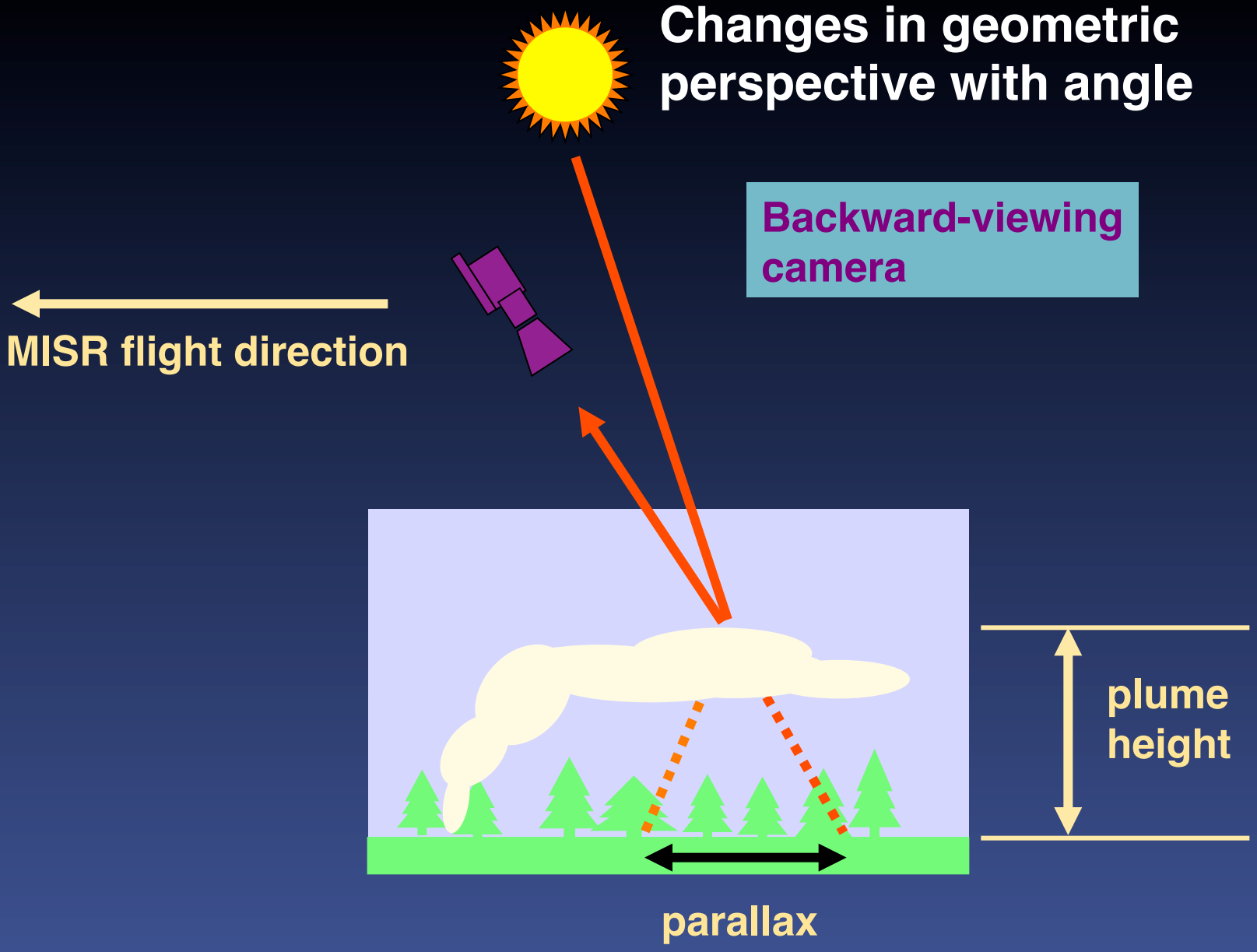
Schwartz et al., Earth's Future 2014

Changes in geometric perspective with angle



Diner 2003

Changes in geometric perspective with angle

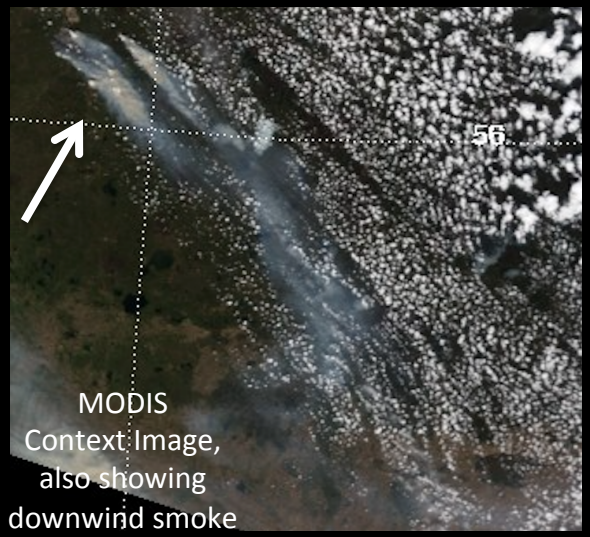


Diner 2003

Ft. McMurray Wildfire Smoke Plume Heights

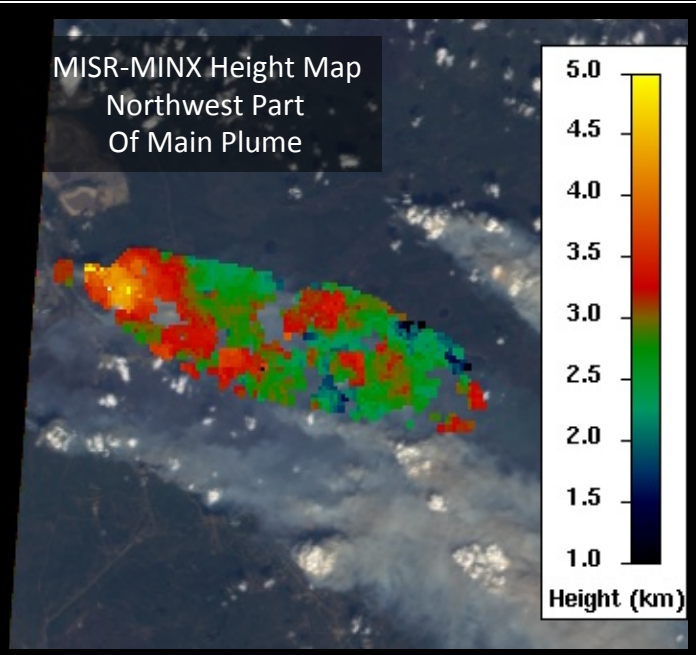
MISR Active Aerosol Plume-Height (AAP) Project 06 May 2016

The ***height*** at which smoke is lofted into the atmosphere affects ***how long*** it will stay aloft, ***how far*** it will travel, and ***how much of an impact*** it will have on air quality downwind, and regional climate.

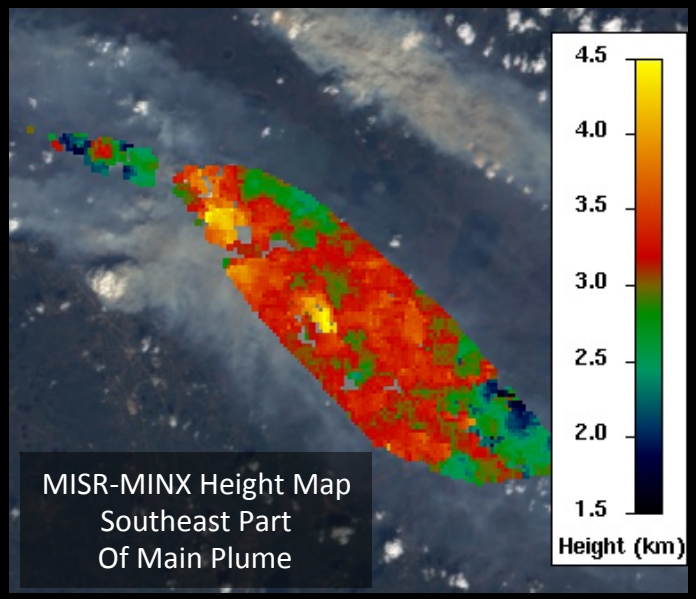


MODIS Context Image, also showing downwind smoke

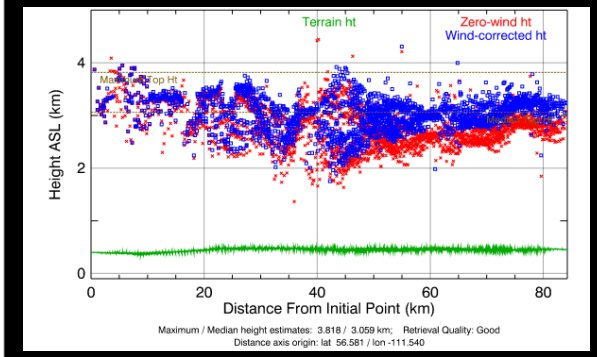
Parallax, the change in apparent plume position relative to the surface, as observed from the NASA Earth Observing System's Multi-angle Imaging Spectroradiometer (***MISR***) instrument, makes it possible to map the height of ***smoke***, ***dust***, and ***volcanic plumes*** near-source, where plume features are visible in the multi-angle views.



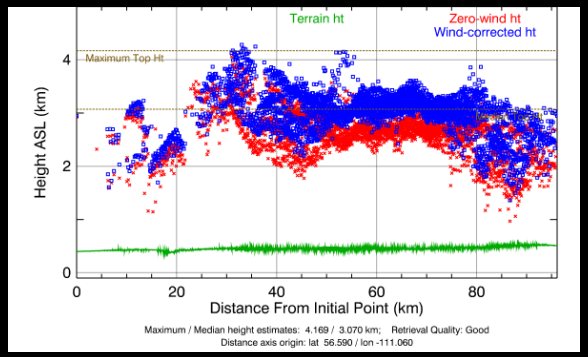
MISR-MINX Height Map
Northwest Part
Of Main Plume



MISR-MINX Height Map
Southeast Part
Of Main Plume

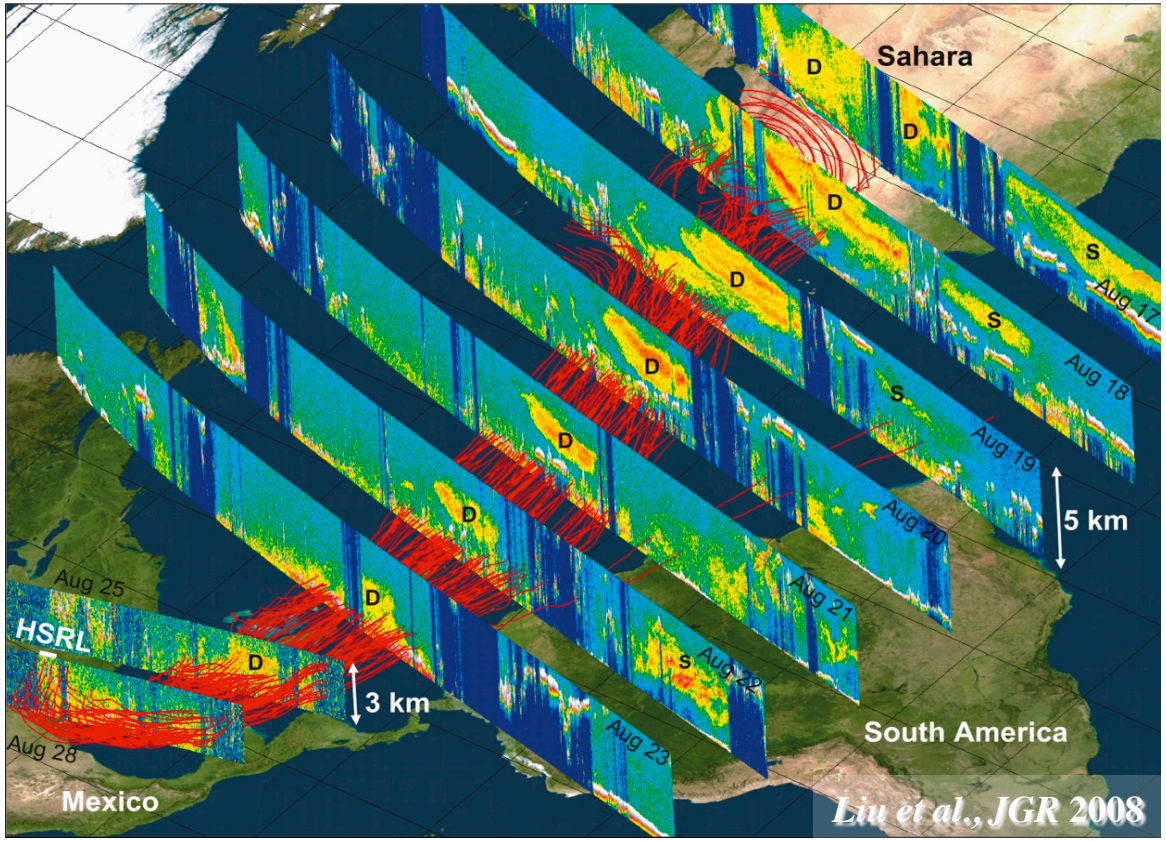


Zero-wind & Wind-Corrected
MISR Height Profiles
Downwind from Near-source



R. Kahn, **T. Kucsera** / NASA GSFC
T. Canty, **R. Bolt**, **CJ Vernon** / U. Maryland

Aerosol Sources, Processing, Transports, Sinks: Lidar + Model



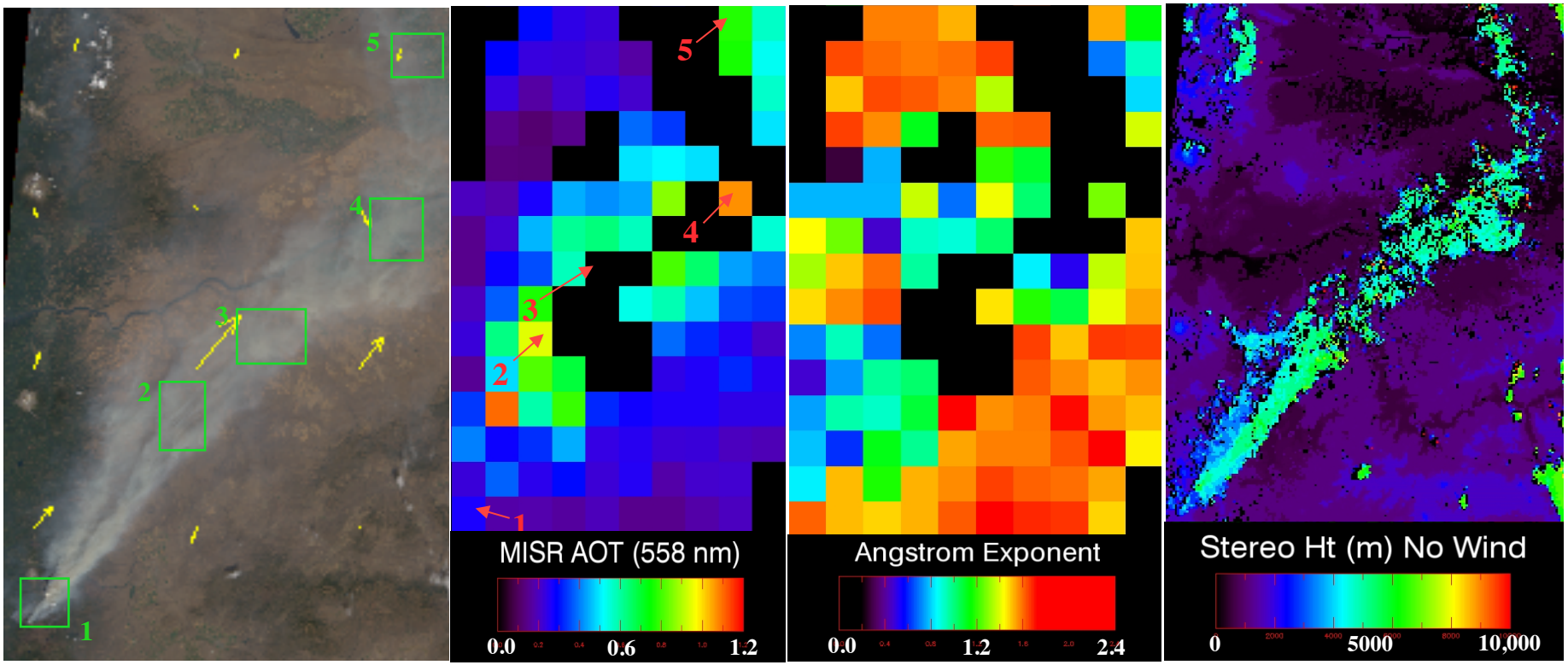
August 2007 Saharan dust "D" and smoke "S" event
mapped by CALIPSO 532 nm backscatter, with superposed model back trajectories and airborne HSRL observations

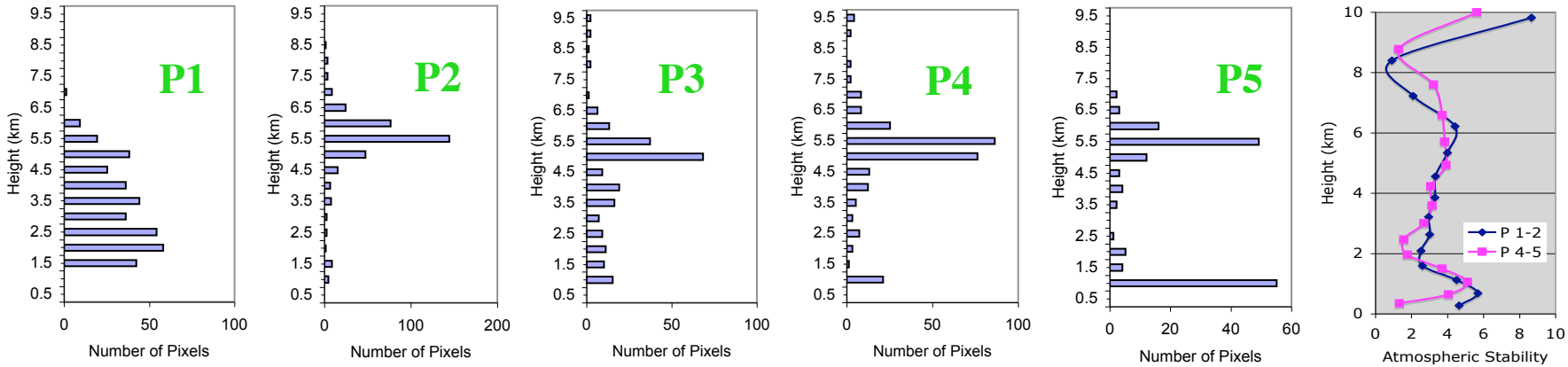
Piecing together the bigger picture. Consistency requires –

- An understanding of the ***mechanisms*** governing aerosol evolution
- Adequately constrained ***initial & boundary*** conditions

Oregon Fire Sept 04 2003

Orbit 19753 Blks 53-55 MISR Aerosols V17, Heights V13 (no winds)





Kahn, et al., JGR 2007

Why We Care About *Aerosol Air Mass Type*

Some applications of satellite-mapped aerosol type, especially when ***combined with*** otherwise-constrained, detailed particle properties:

- ***Source Attribution***
- Mapping 3-D ***Aerosol Absorption*** that mediates impacts on ***atmospheric stability structure*** and can affect ***convection***, ***cloud evolution***, and ***larger-scale atmospheric circulation***
- Mapping ***Particle Hygroscopicity*** required to account for humidity-dependent ***particle optical property changes*** as well as ***particle activation conditions*** that initiate cloud formation
- Deducing ***Mass Extinction Efficiency*** (MEE) distributions, required to ***constrain & validate air quality***, ***aerosol-transport***, and ***climate model*** aerosol mass with remote-sensing-derived particle ***optical*** properties.

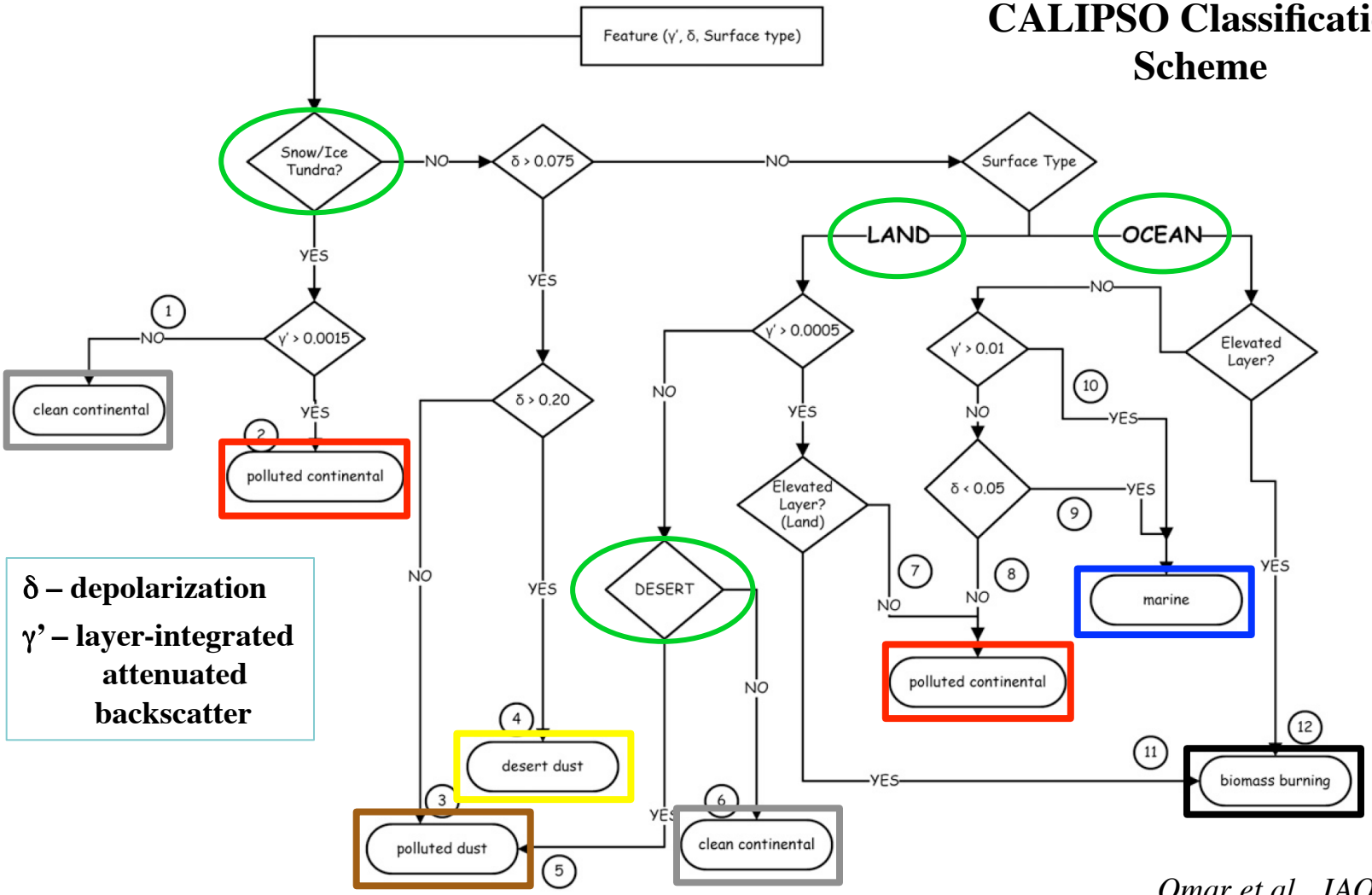
Aerosol Air Mass Type derived from remote sensing can provide ***2-D and 3-D mapping required*** for many of these applications.

Progress Toward a Global Aerosol Type Climatology

Ralph Kahn

NASA/Goddard Space Flight Center

CALIPSO Classification Scheme

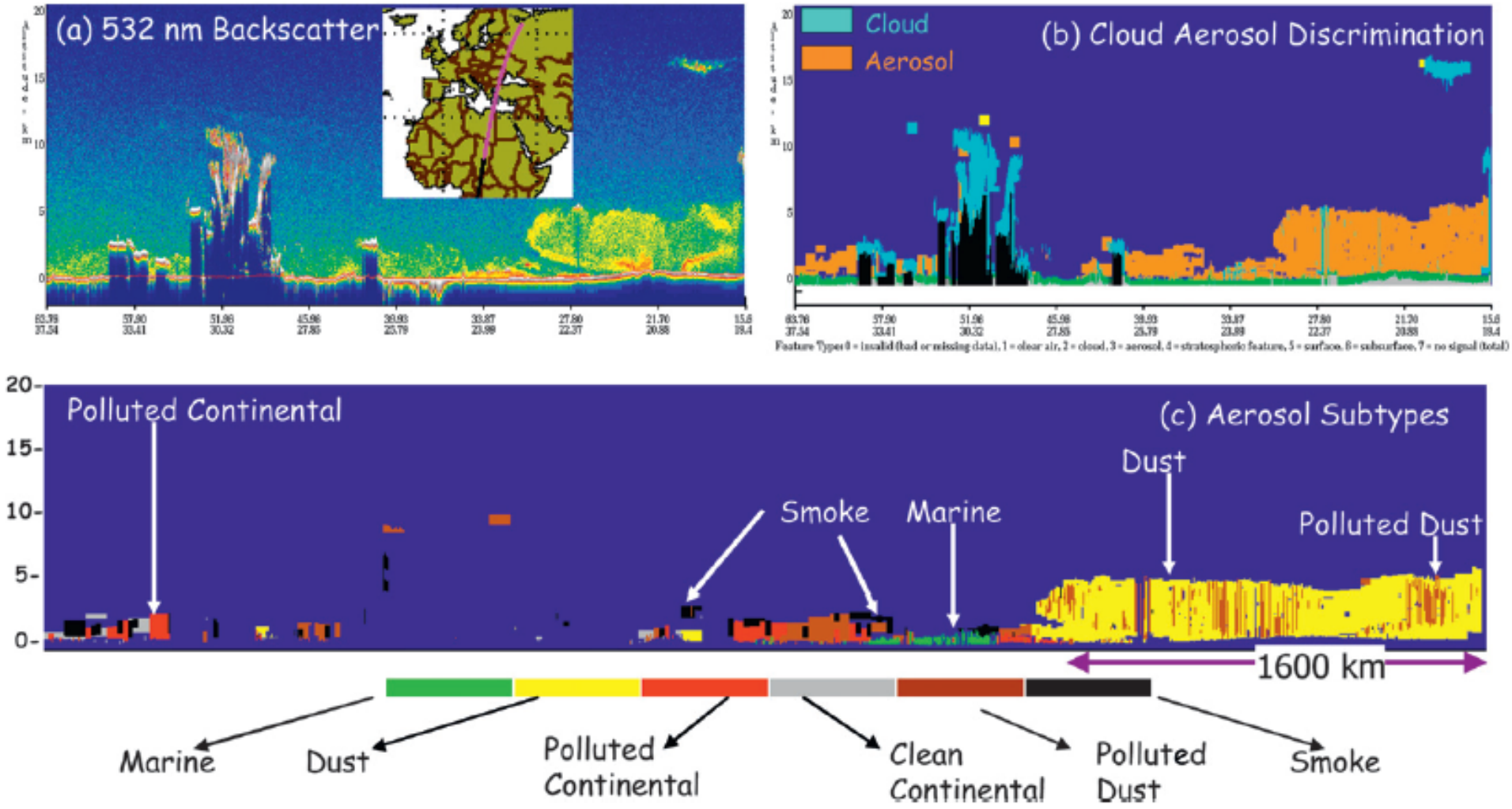


δ – depolarization

γ' – layer-integrated attenuated backscatter

Omar et al., JAOT 2009

CALIPSO 6-Grouping Aerosol Type Classification

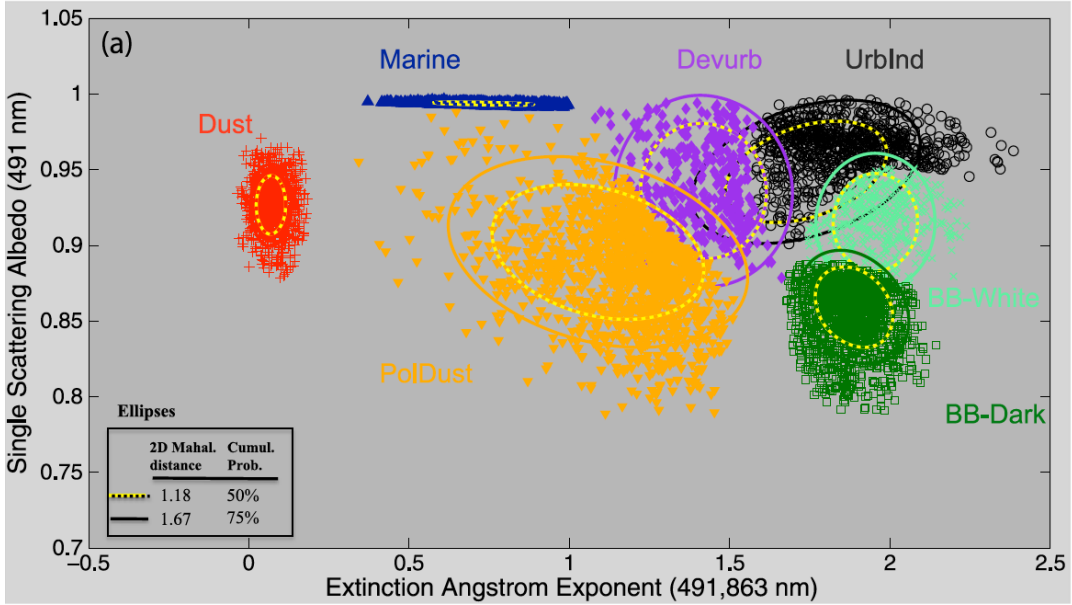


Omar et al., JAOT 2009

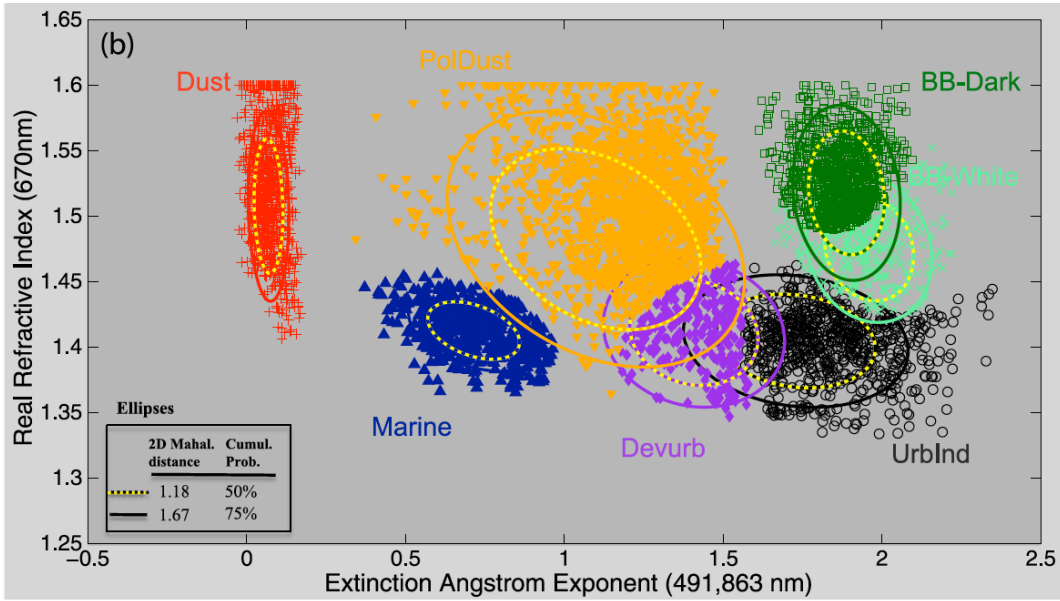
AERONET Aerosol Type 7-Grouping Classification

Four-parameter AERONET-derived classification:

- $EAE_{491,863}$
- SSA_{491}
- RRI_{670}
- $dSSA_{863\text{-}491}$



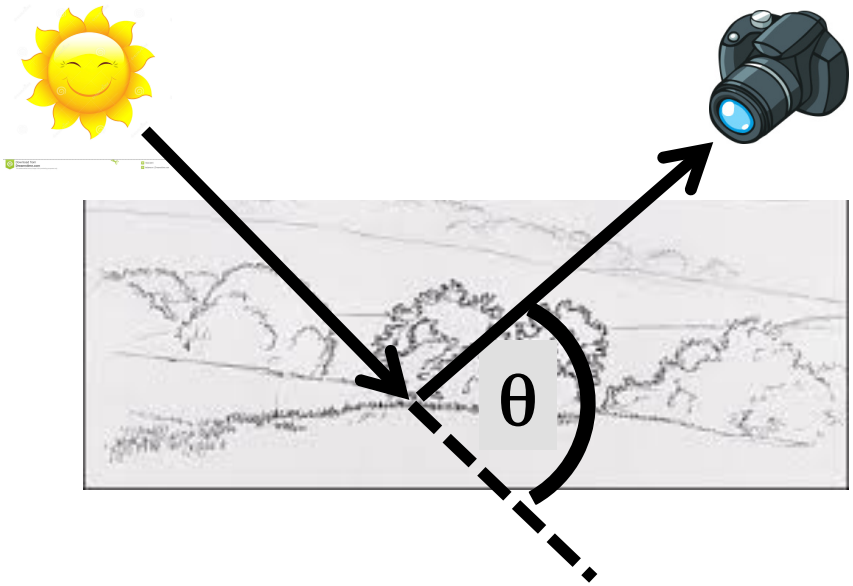
7 Groupings SSA_{491} vs. Extinction ANG

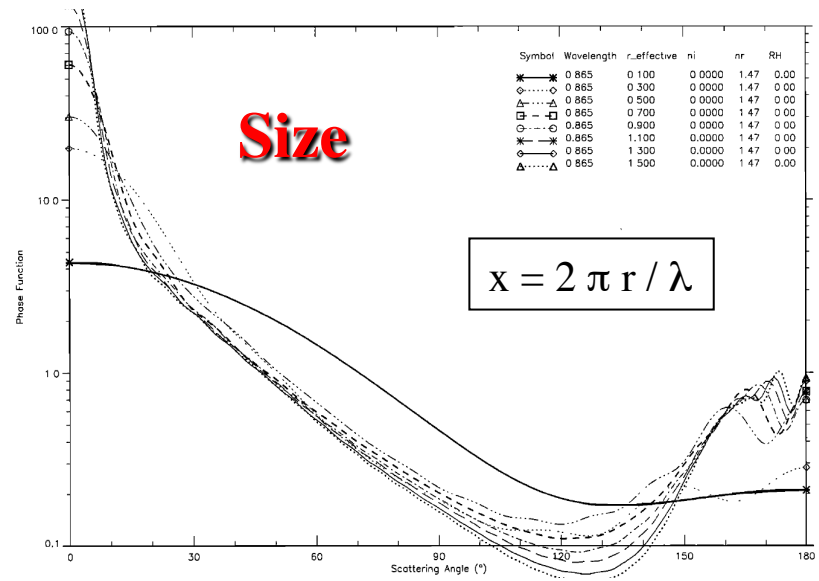


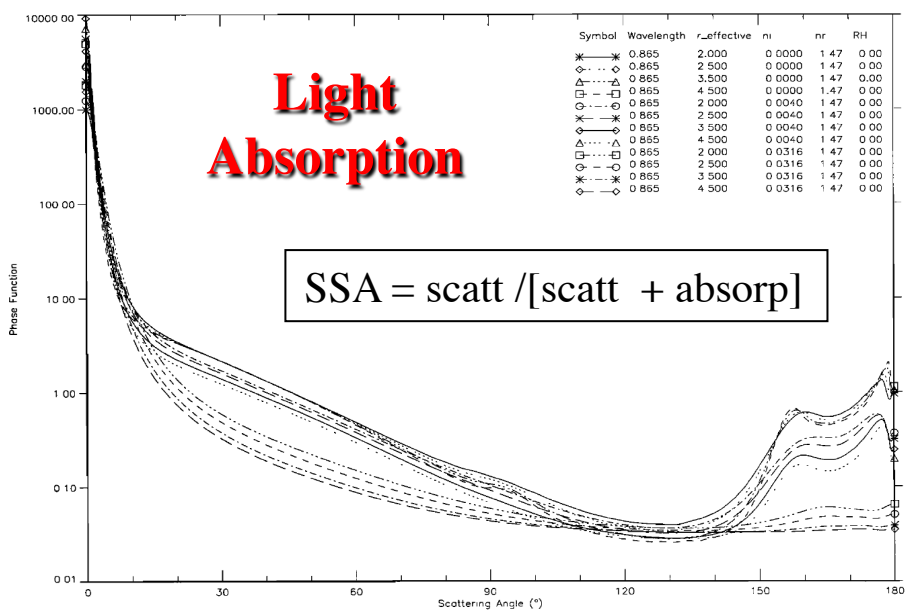
7 Groupings Real RI_{670} vs. Extinction ANG

Russell et al. JGR 2014

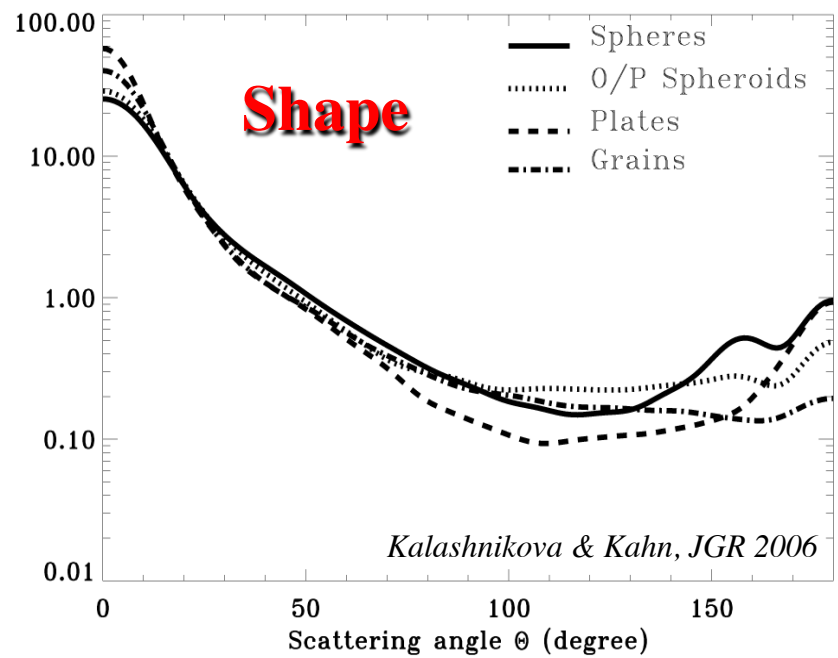
Single-scattering Phase Functions for **Different Particle Properties**





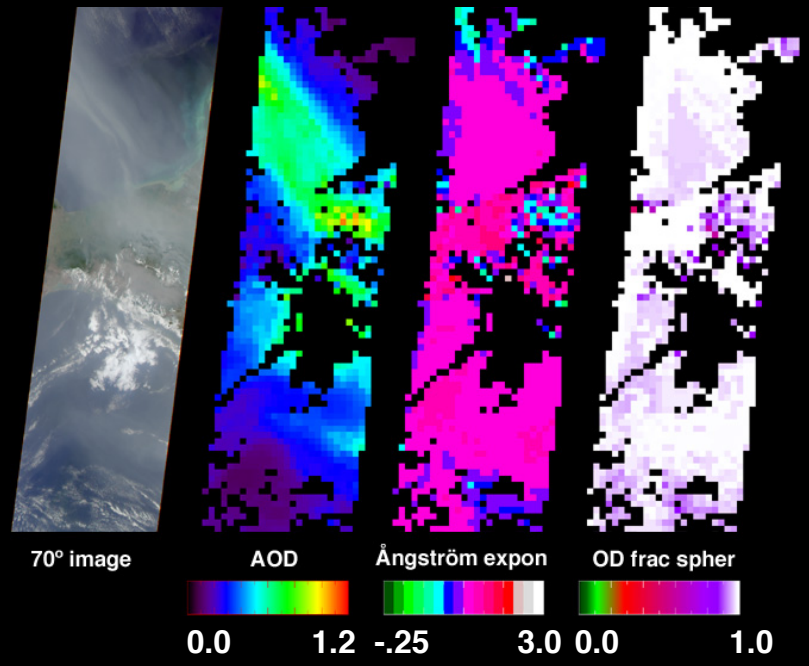


Kahn et al., JGR 1998



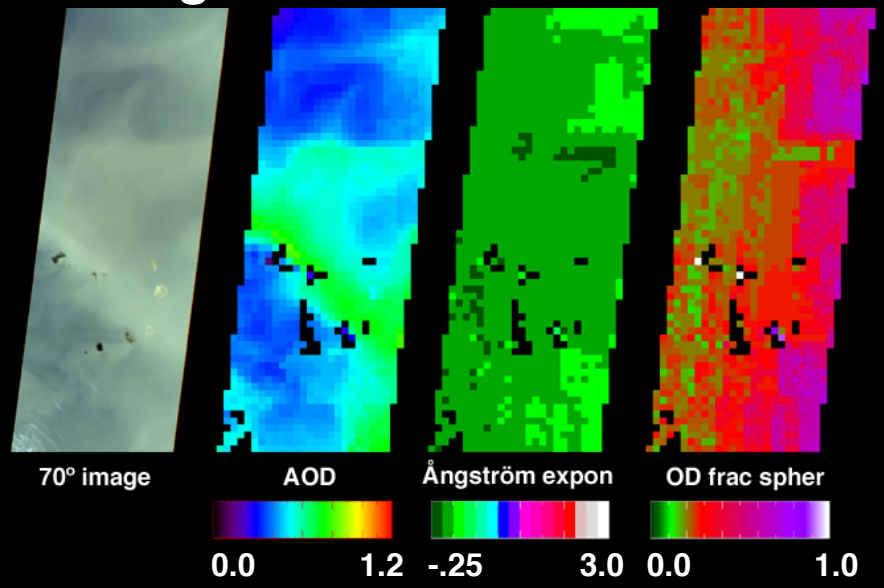
Smoke from Mexico -- 02 May 2002

Aerosol:
Amount
Size
Shape



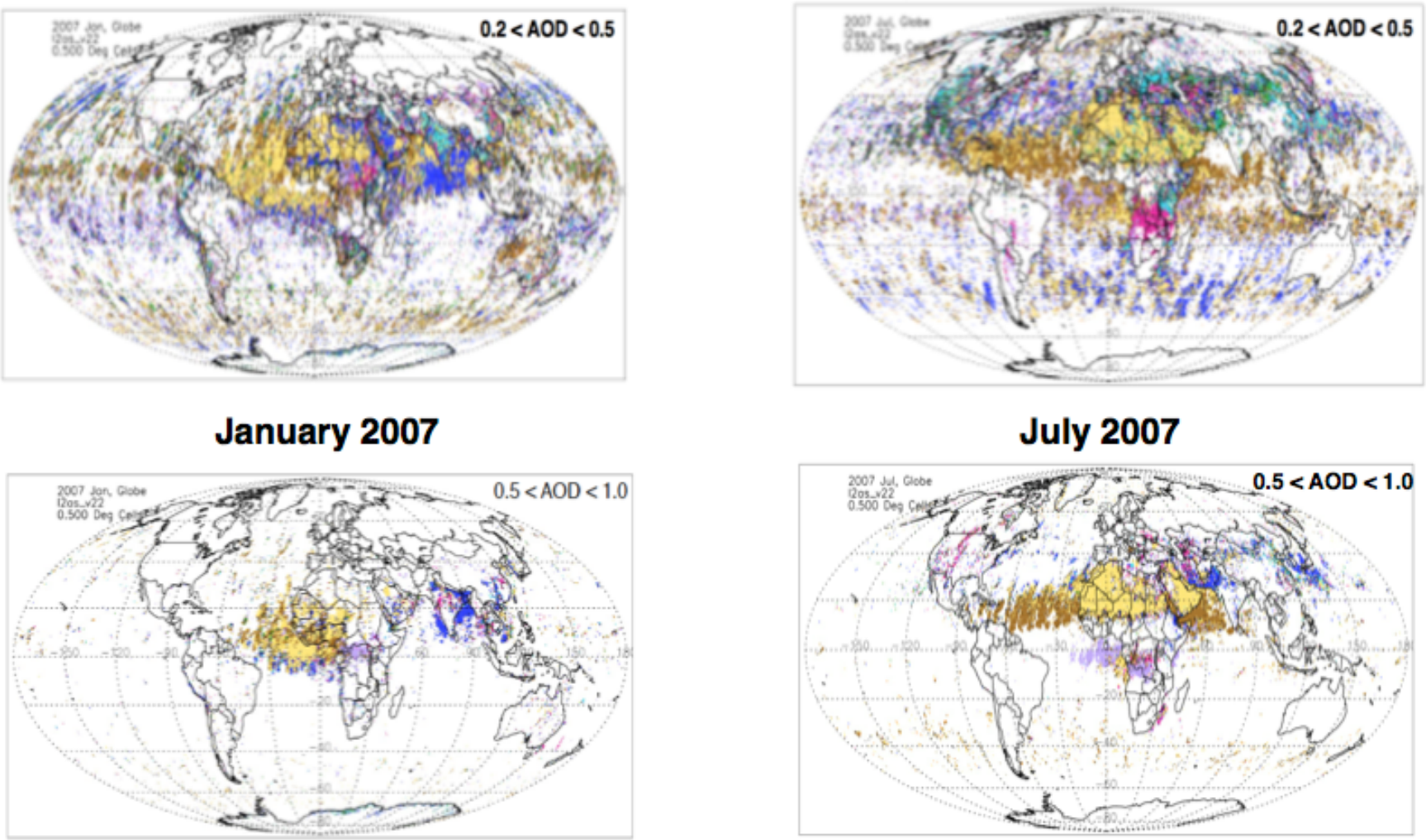
Medium
Spherical
Smoke
Particles

Dust blowing off the Sahara Desert -- 6 February 2004



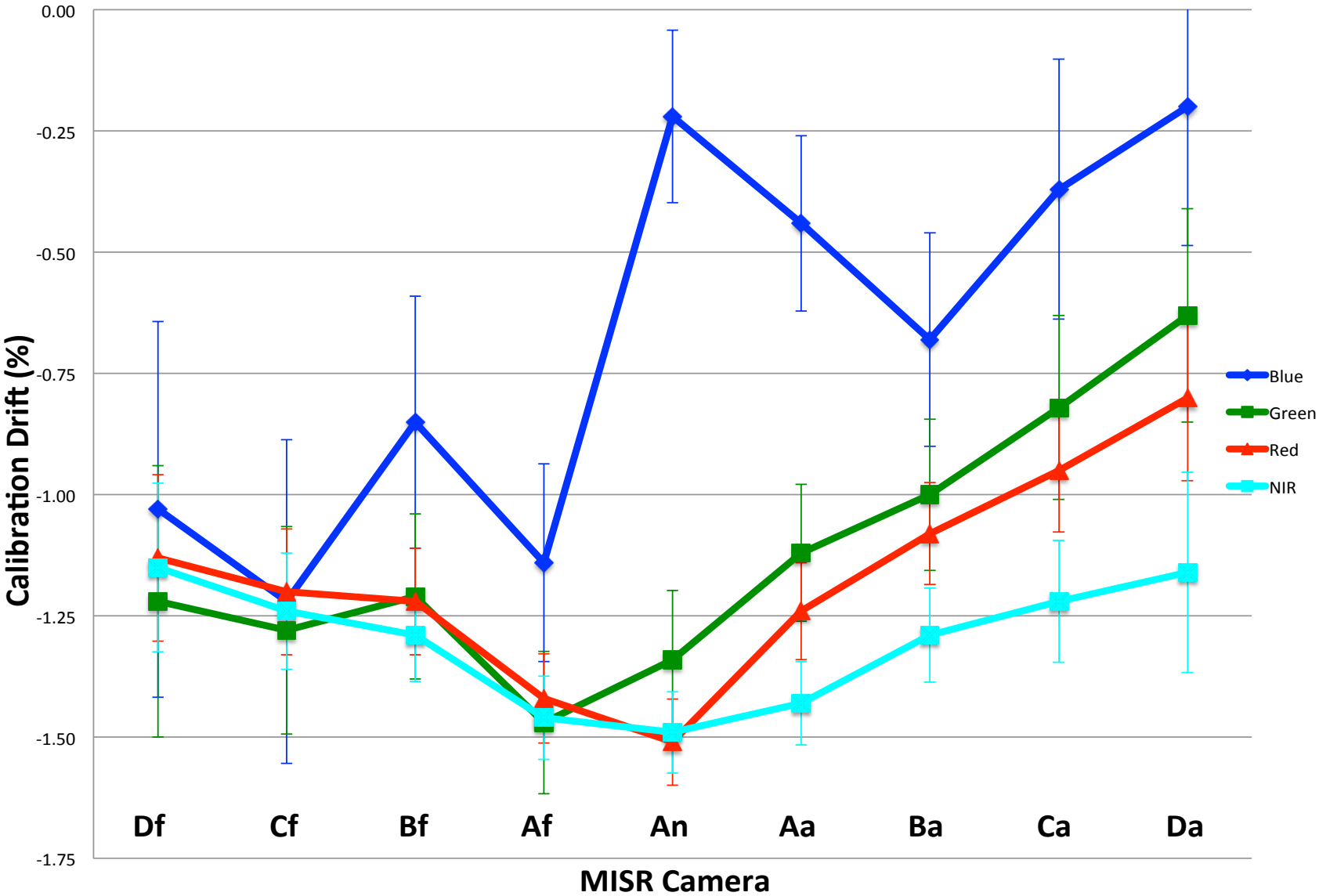
Large
Non-Spherical
Dust
Particles

MISR Aerosol Type Discrimination



Kahn & Gaitley JGR 2015

MISR Radiometric Calibration Drift / Decade

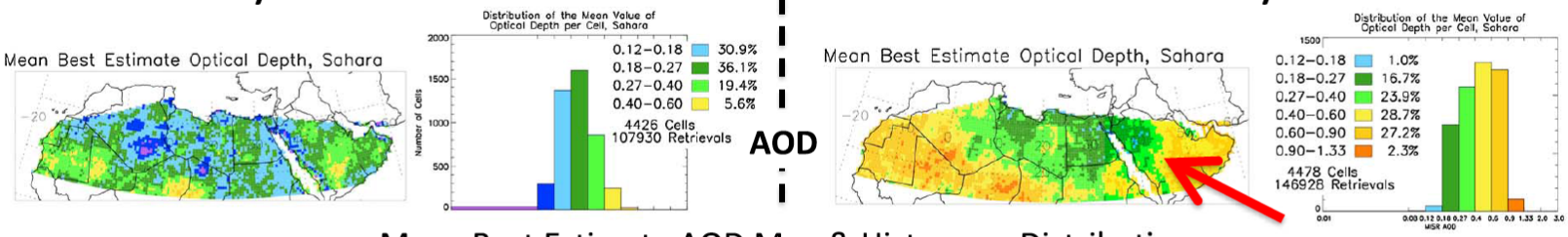


Limbacher & Kahn AMT **2017**

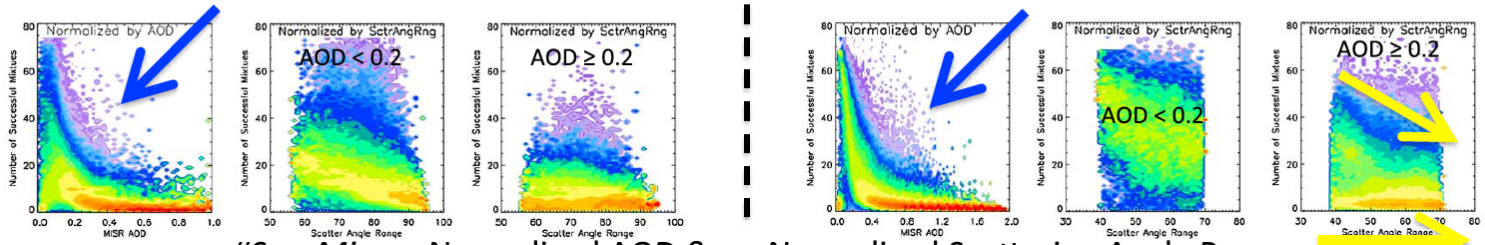
MISR Aerosol Type Discrimination

Sahara Desert (Arid Region)

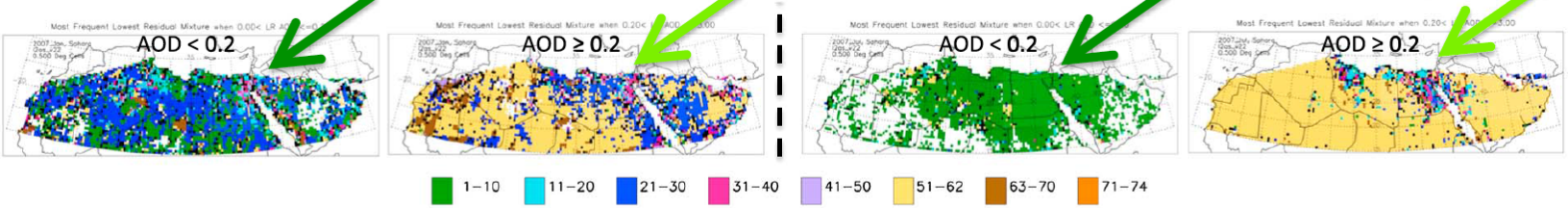
January 2007 | July 2007



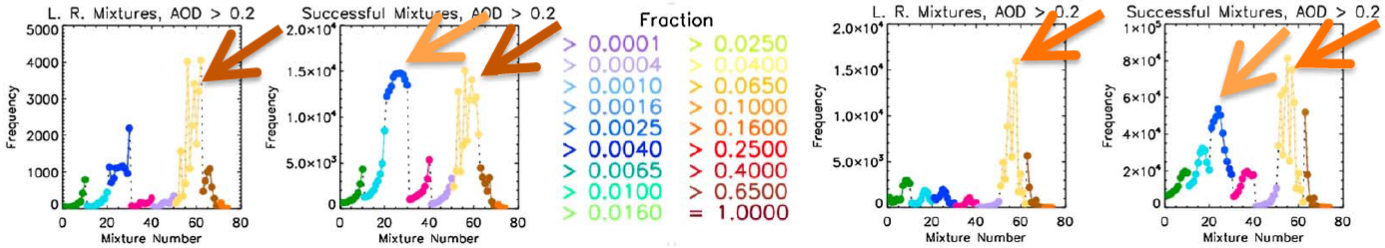
Mean Best Estimate AOD Map & Histogram Distribution



#SuccMix vs. Normalized AOD & vs. Normalized Scattering Angle Range



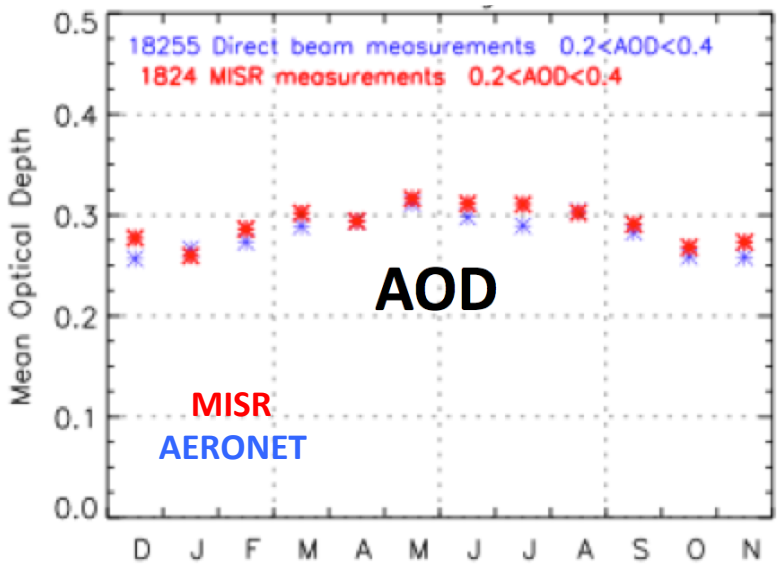
Most Frequent Lowest Residual Aerosol Type Mixture Group, Stratified by AOD

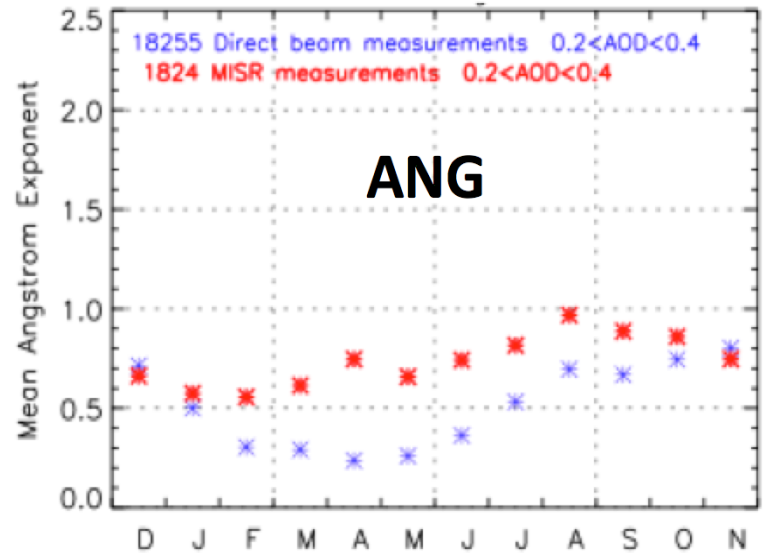


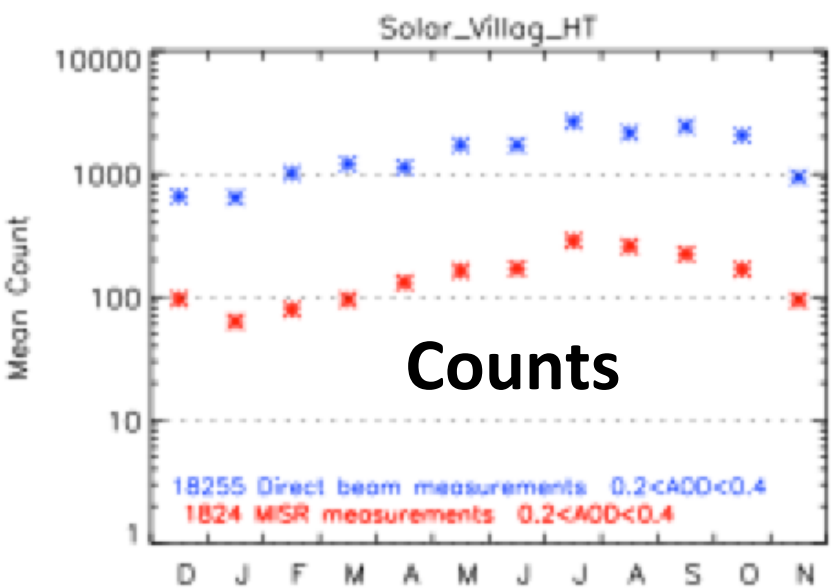
Histograms of Lowest Residual & All Successful Aerosol Type Mixture Groups vs. AOD

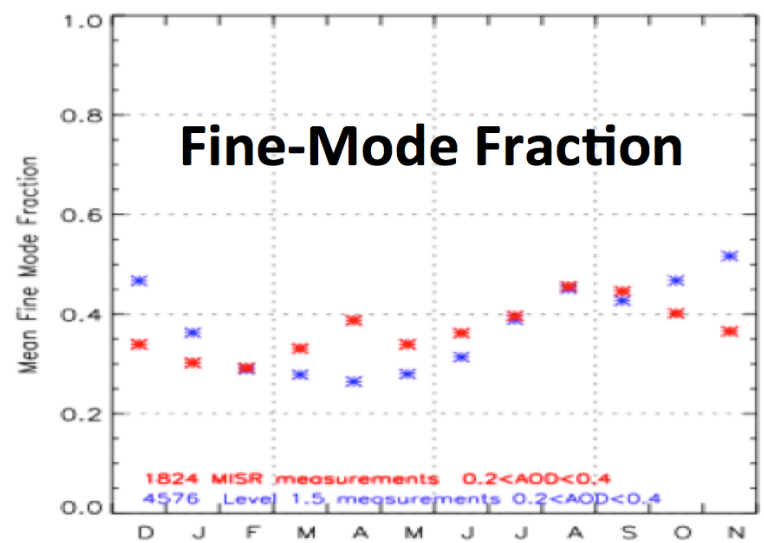
Kahn & Gaitley JGR 2015

Statistical *Comparisons* with AERONET – *Solar Village*



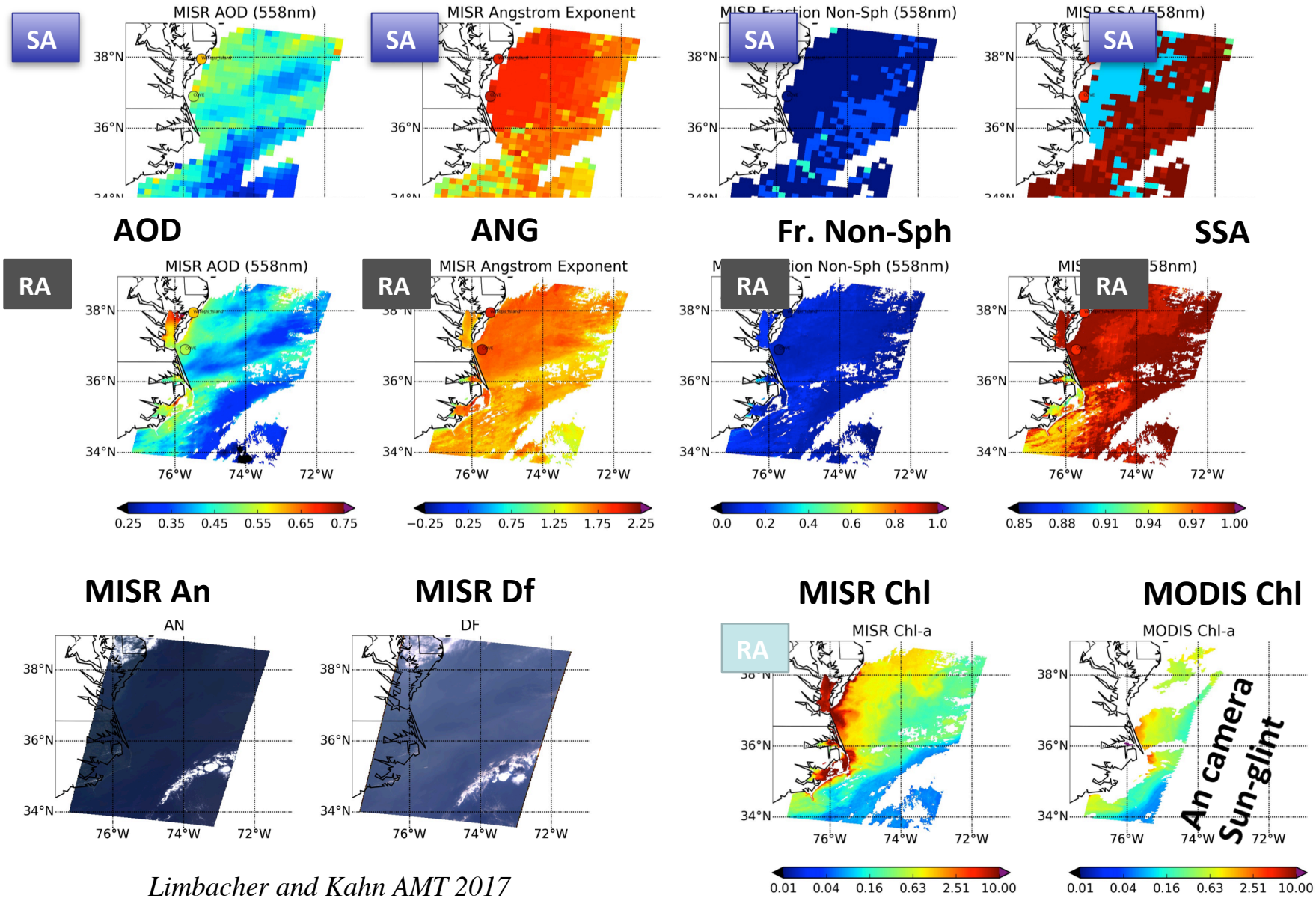






Kahn & Gaitley JGR 2015

MISR *Research Algorithm* With Self-consistent Ocean Surface Retrieval



Limbacher and Kahn AMT 2017

Satellite *Aerosol Type* Summary

- Remote-sensing can provide optical constraints interpreted as particle ***Size, Shape, and Indices of Refraction***

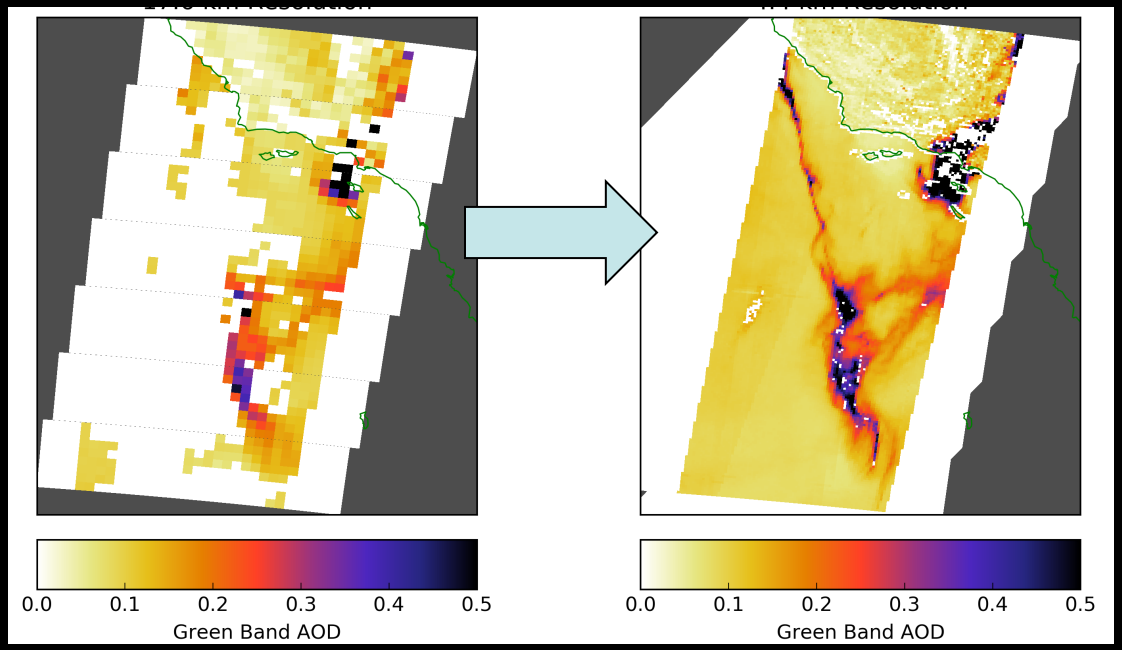
- A ***further*** interpretative step, entailing additional assumptions, reports particle ***Chemical Composition***

- Remote-sensing ***sensitivity to particle properties is much more dependent than AOD on retrieval conditions***
  (***Not*** straightforward to provide quantitative uncertainty estimates)

- ***Validation Data*** for aerosol type are ***very limited***

  -- ***Model simulations*** and ***In Situ measurements*** can help

New MISR Standard Aerosol Algorithm



Orbit 88284, 2016-07-23 View of Smoke from Soberanes Fire (Left) and Sand Fire (Right) off Southern California

Old (V22)

- 17.6 km
- No uncertainty estimates
- Nav & time info. in spearate files
- Complicated field names
- Good performance relative to AERONET
- Particle property information

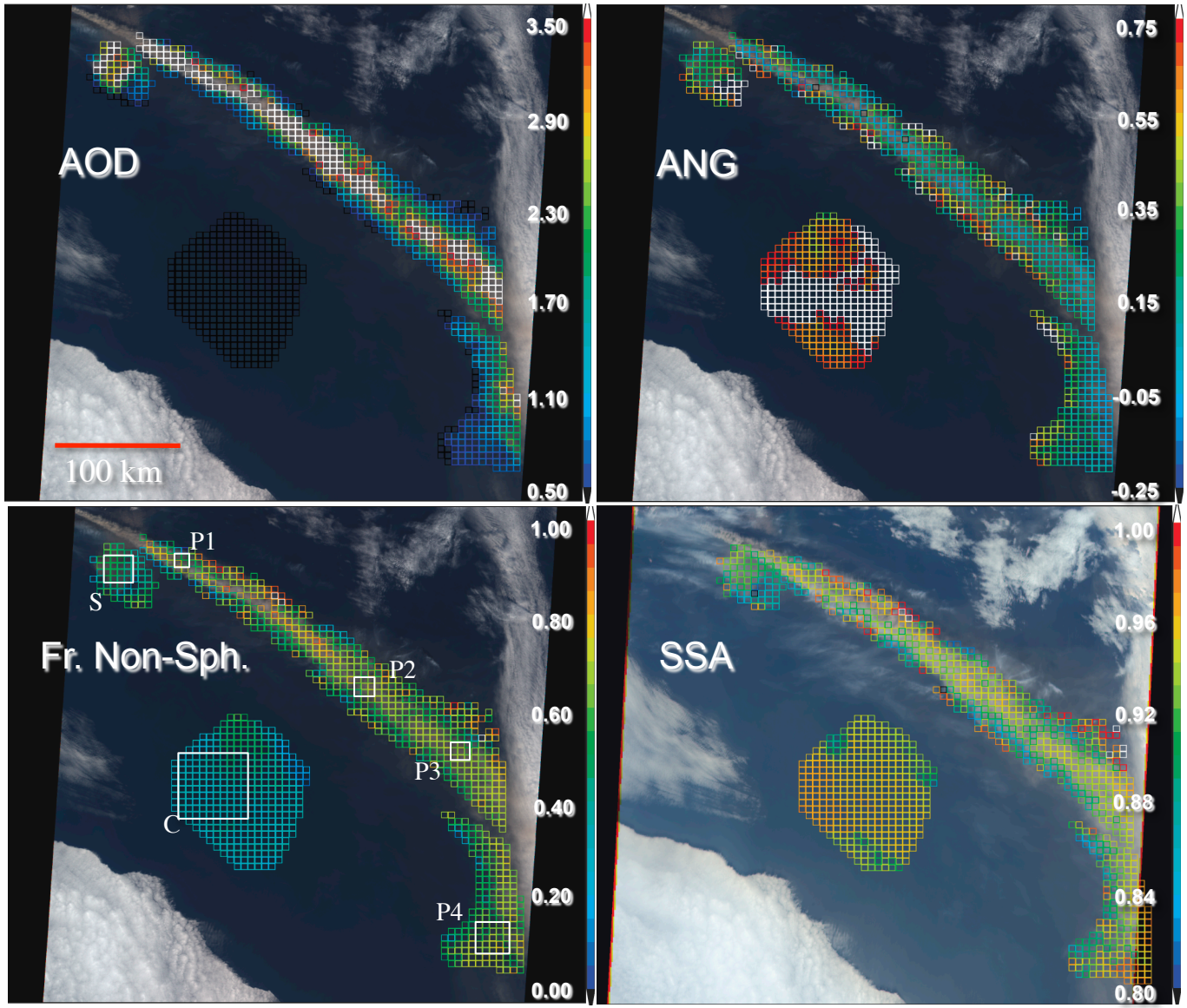
New (V23)

- 4.4 km
- Per retrieval uncertainty
- Easy to use (can be read with std. tools)
- Simplified content and field names
- Improved performance relative to AERONET (DRAGON)
- Particle property information

M. Garay, *M. Bull, M. Witek, F. Seidel, D. Diner, E. Hansen, O. Kalashnikova, F. Xu, K. Lee, A. Nastan* /**JPL**
R. Kahn, J. Limbacher / ***GSFC***

MISR Research ***Aerosol Retrievals***

07 May 2010 *Orbit 55238 Path 216 Blk 40 UT 12:39*



Plume Particles

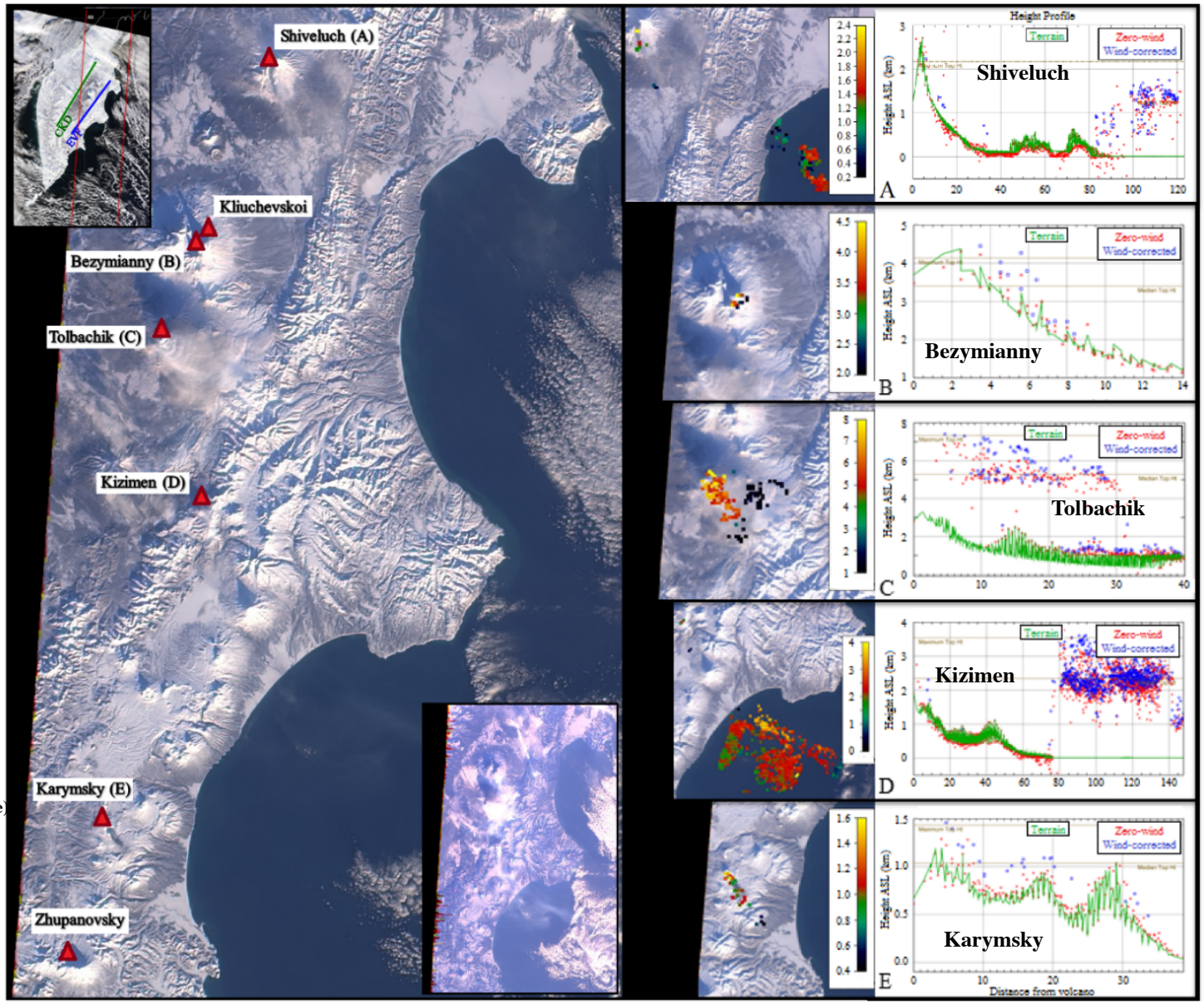
- Distinct from background
  - -- ***larger***, ***darker***
  - -- ***much higher AOD***
- ***Non-spherical*** dominated
- Brighten downwind
- Tend to decrease in size downwind

Kahn & Limbacher, ACP 2012

Seven Kamchatka Volcanoes *06 January 2013*

CKD: Central Kamchatka Depression
(Higher volitiles: subducting Emperor Sea Mount)

EVF: Eastern Volcanic Front
(Lower volitiles: subducting Pacific Plate)

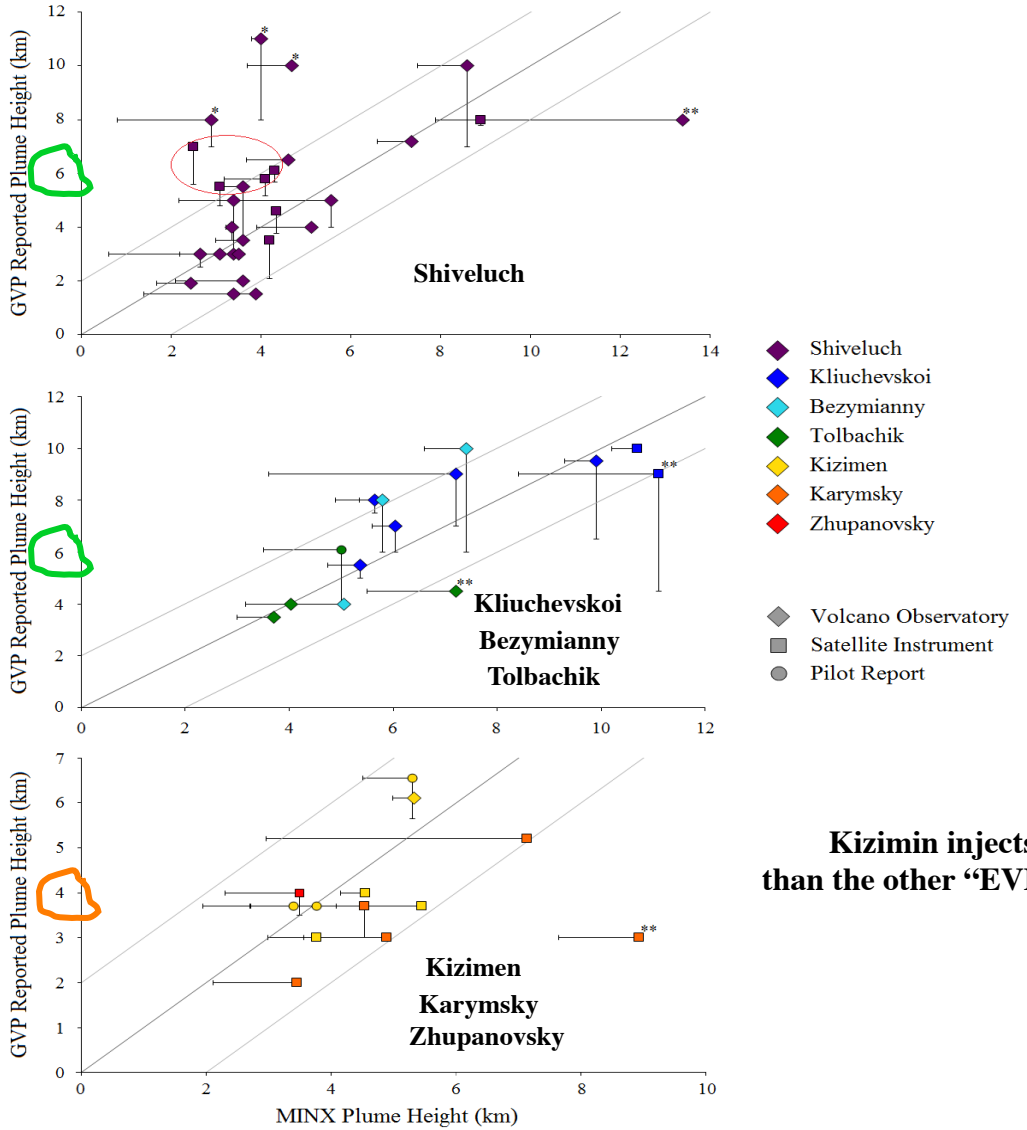


Flower & Kahn J. Volc., 2017

Kamchatka Volcano Heights by Region

CKD: Central Kamchatka Depression
(Higher volitiles: subducting Emperor Sea Mount)

EVF: Eastern Volcanic Front
(Lower volitiles: subducting Pacific Plate)

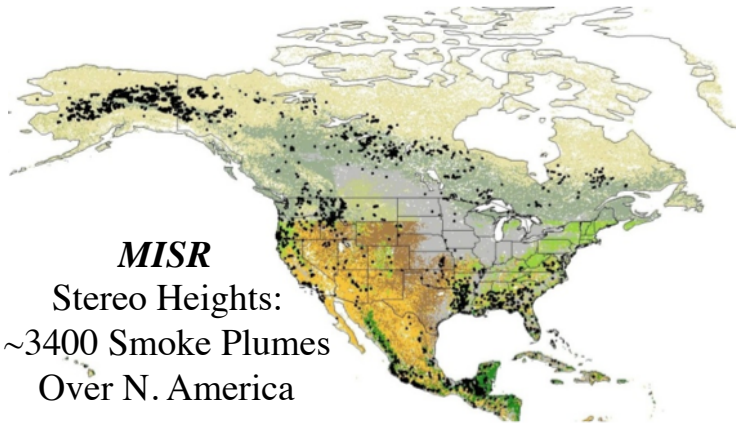


Kizimin injects higher than the other "EVF" volcanoes

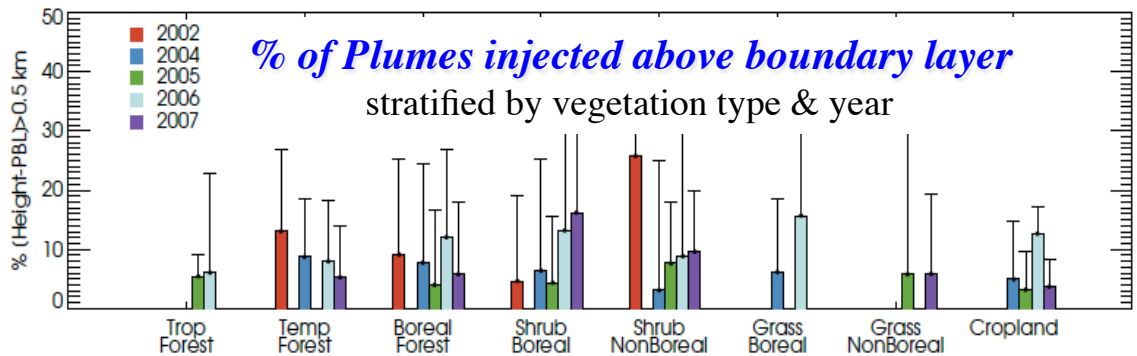
Flower & Kahn J. Volc., 2017

Wildfire Smoke *Injection Heights* & *Source Strengths*

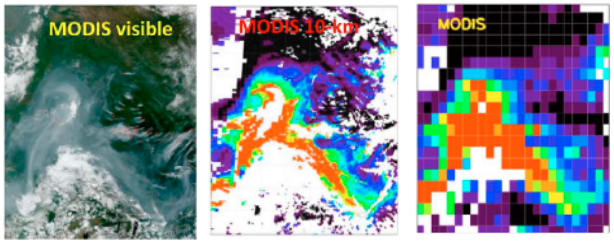
[These are *the two key parameters* representing aerosol sources in climate models]



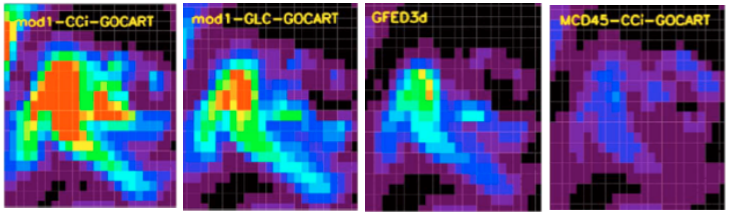
MISR
Stereo Heights:
~3400 Smoke Plumes
Over N. America



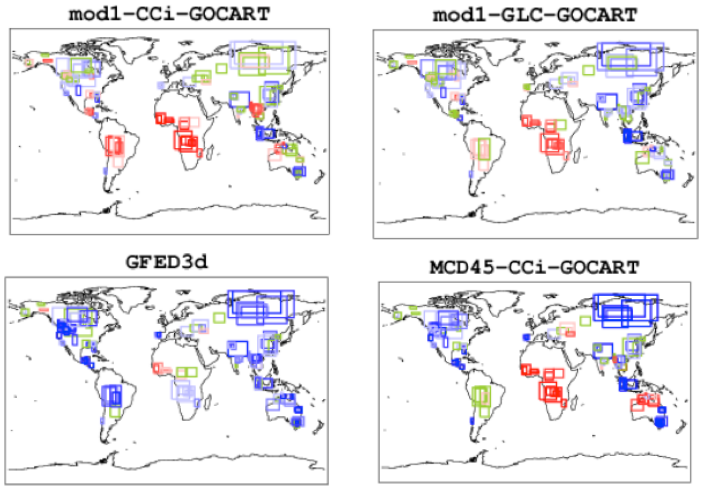
Val Martin et al. ACP 2010



MODIS Smoke Plume Image & Aerosol Amount Snapshots



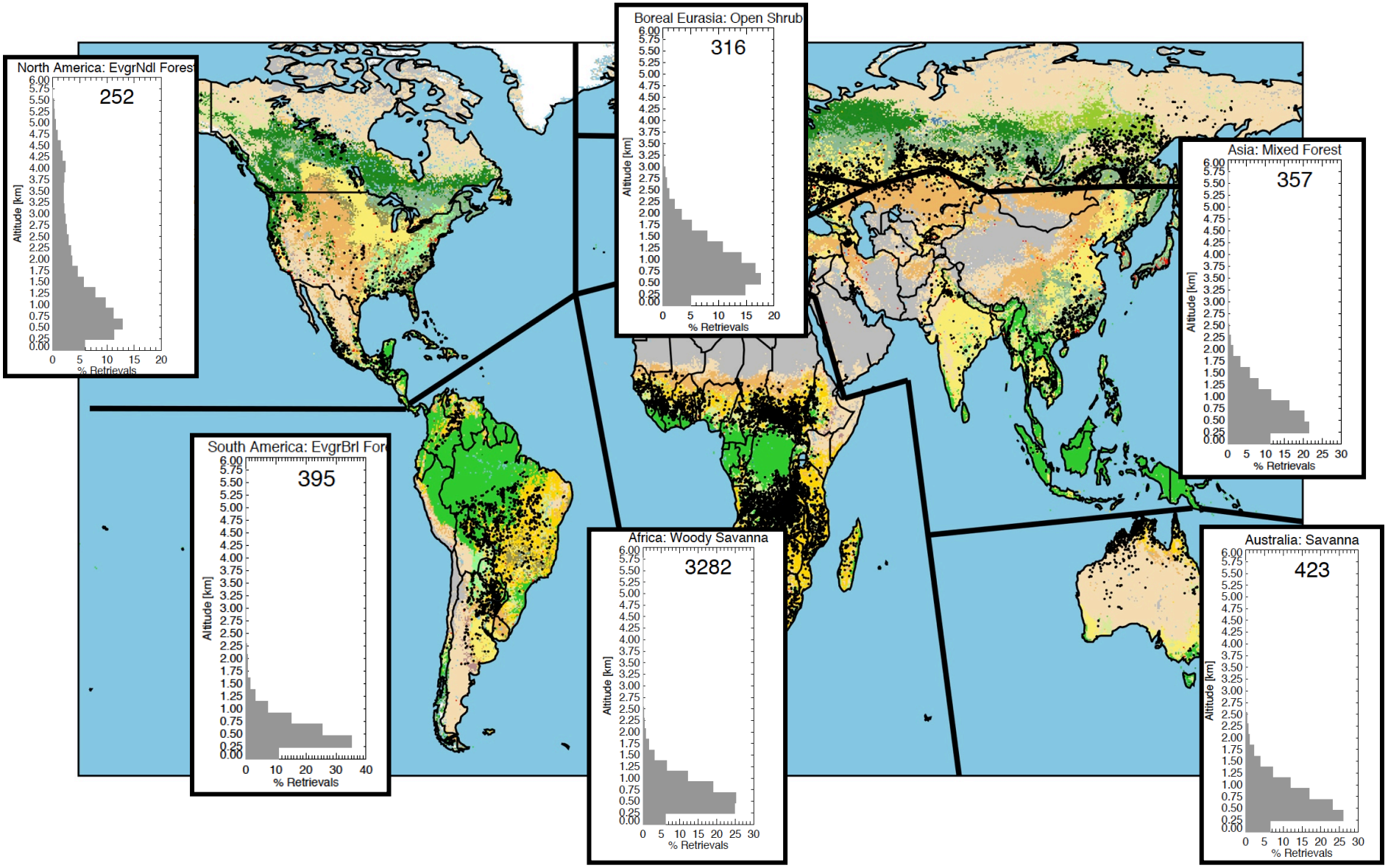
GoCART Model-Simulated Aerosol Amount Snapshots
for *Different Assumed Source Strengths*



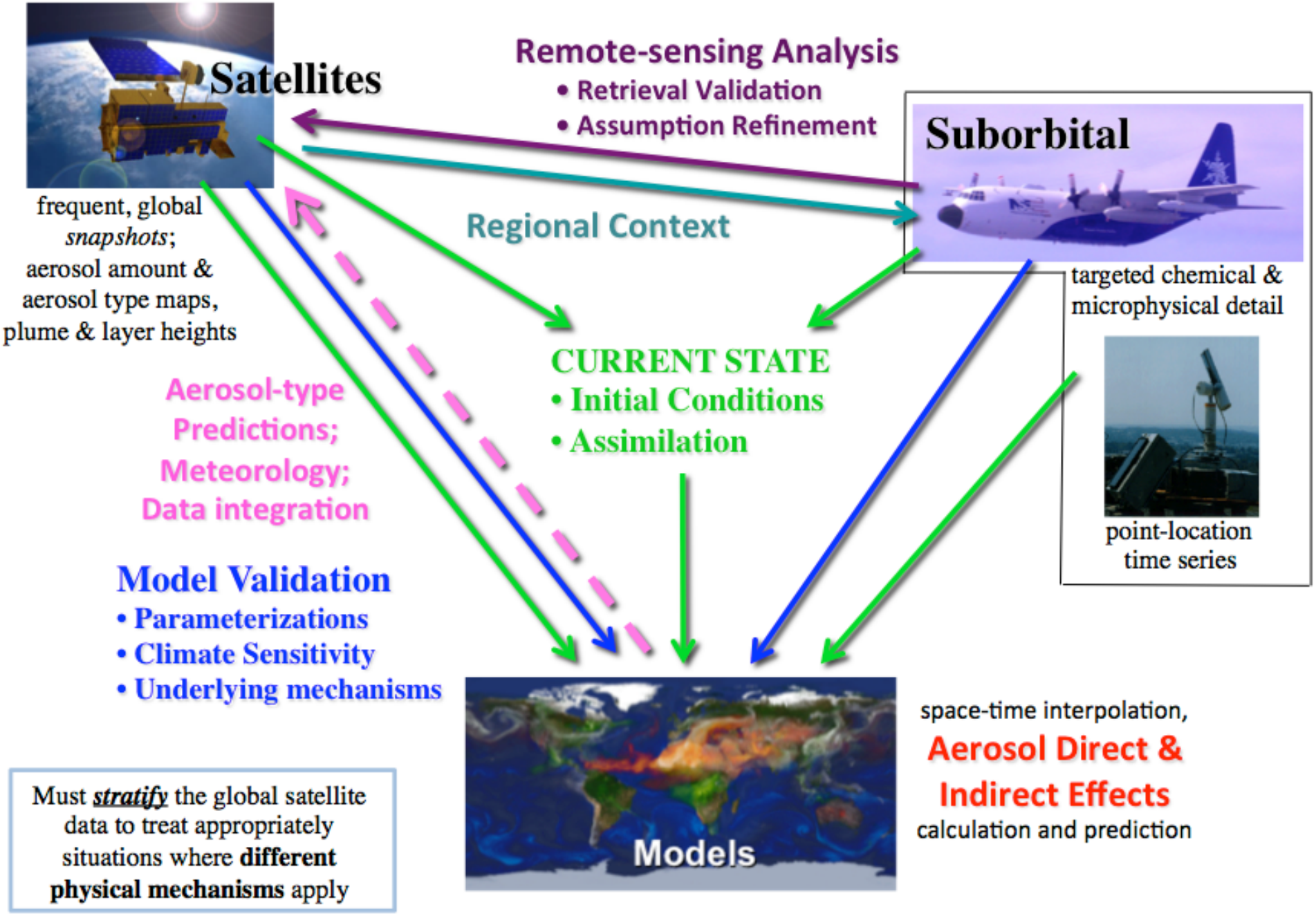
Different Techniques for *Assuming Model Source Strength*
Overestimate or ***Underestimate*** Observation
Systematically in Different Regions

Petrenko et al., JGR 2012

Examples of vertical distribution of injection heights across regions and biomes for 2008

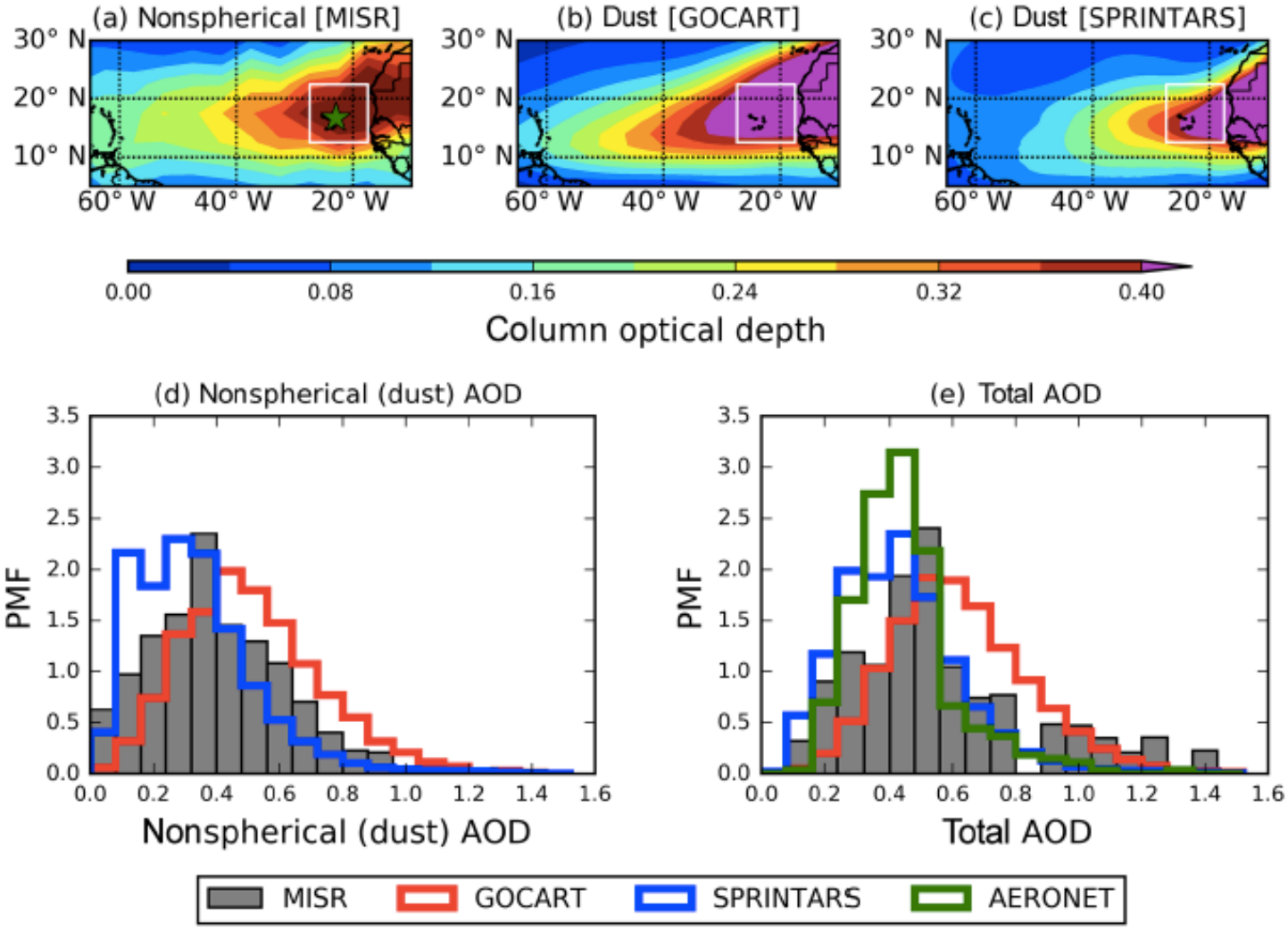


Val Martin et al. JGR 2017 in prep.



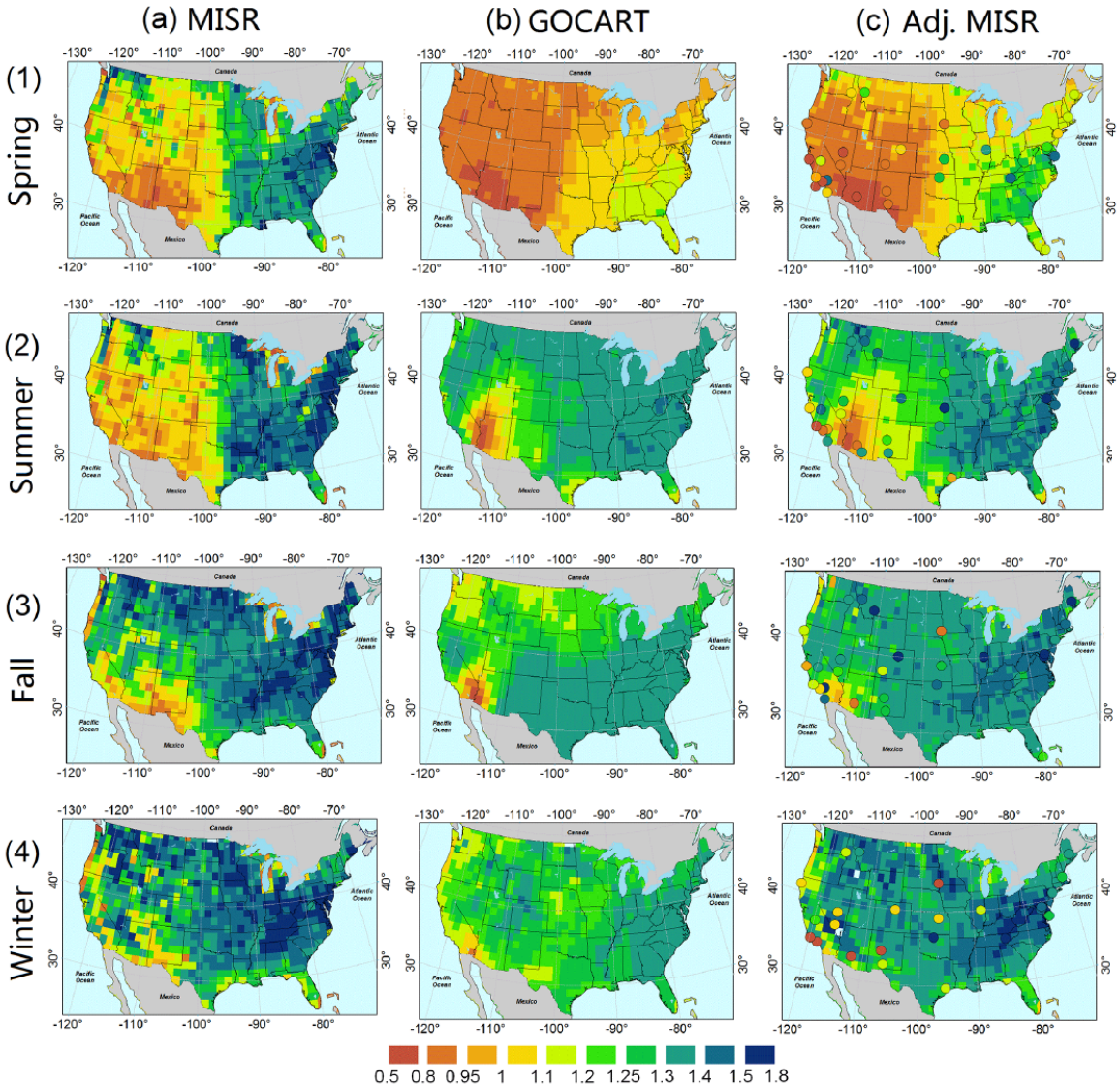
Adapted from: Kahn, Survy. Geophys. 2012

Model Validation using MISR Dust AOD Climatology



Huikyo Lee et al. ACP 2016

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



ANG

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

$$\mathrm{Diff}_{\mathrm{AAOD}} = \left|\mathrm{Fraction}_{\mathrm{MISR_AAOD}} - \mathrm{Fraction}_{\mathrm{GOCART_AAOD}}\right| \leq \varepsilon_{\mathrm{AAOD}}$$

Four years of data (2006-2009)
Seasonally averaged

Shenshen Li et al. AMT 2015

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

SAM-CAAM

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

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

Primary Objectives:

- **Interpret and *enhance ~17 years of satellite aerosol retrieval* products**
- ***Characterize statistically particle properties* for major aerosol types globally, to provide detail unobtainable from space, but needed to *improve*:**

-- Satellite aerosol *retrieval algorithms*

-- The *translation between satellite-retrieved aerosol optical properties and* species-specific aerosol mass and size tracked in *aerosol transport & climate models*

Kahn et al., BAMS submitted

SAM-CAAM *Concept*

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

- ***Dedicated Operational Aircraft*** – routine flights, 2-3 x/week, on a continuing basis

- ***Sample Aerosol Air Masses*** accessible from a given base-of-operations, then move; project science team to determine schedule, possible field campaign participation

- Focus on *in situ* ***measurements required*** to characterize particle ***Optical Properties*** (esp. ***Light Absorption***), ***Composition***, ***Hygroscopicity***, and ***Mass Extinction Efficiency***

- ***Process Data Routinely*** at central site; instrument PIs develop & deliver algorithms, upgrade as needed; data distributed via central web site

- Peer-reviewed paper to identifying ***4 Payload Options***, of varying ambition; subsequent selections based on agency buy-in and available resources

SAM-CAAM 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

SAM-CAAM *Required Variables*

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

1. AEROSOL PROPERTIES FROM *IN SITU* MEASUREMENTS & INTEGRATED ANALYSIS

	Abbrev.	Required Variable
1	EXT	Spectral Extinction
2	ABS	Spectral Absorption
3	GRO	Hygroscopic Growth
4	SIZ	Particle Size
5	CMP	Particle Type (a composition constraint)
6	PHA	Single-scattering Phase Function
7	MEE	Mass Extinction Efficiency
8	RRI	Real Refractive Index

SAM-CAAM *Required Variables*

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

2. METEOROLOGICAL CONTEXT

	Abbrev.	Required Variable
9	CO	Ambient Gases ($CO + O_3 + NO_2$)
10	T; P; RH	Standard Ambient Meteorological Variables
11	LOC	Geographic Location

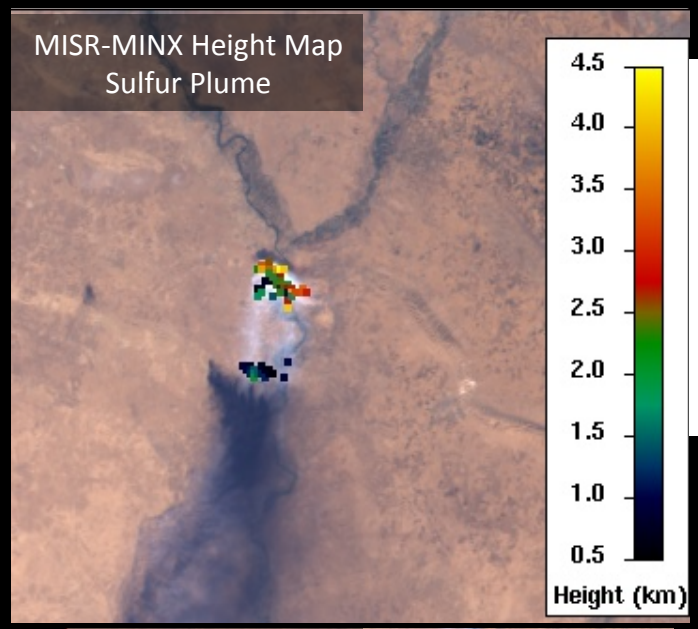
3. AMBIENT REMOTE-SENSING CONTEXT

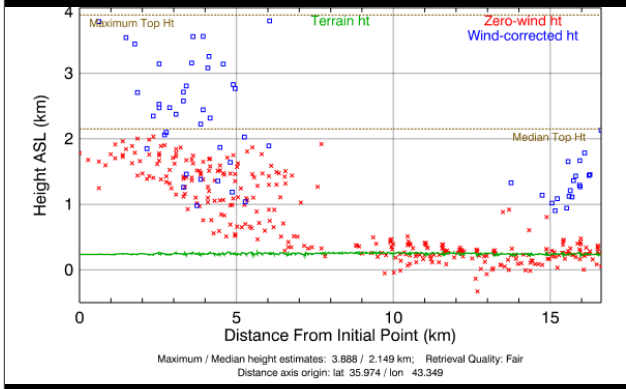
	Abbrev.	Required Variable
12	A-EXT & A-ABS	Ambient Spectral Extinction & Absorption
13	A-PHA	Ambient Particle Phase Function
14	A-CLD	Ambient Cloud & Large-Particle Size/Type
15	HTS	Aerosol Layer Heights

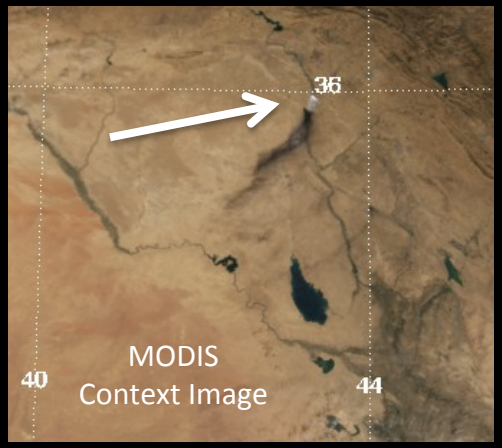
Iraq's Mishraq Sulfur Plant and Oil Well Smoke Plume Heights

MISR Active Aerosol Plume-Height (AAP) Project 21 October 2016

The ***height*** at which smoke is injected into the atmosphere affects ***how long*** it will stay aloft, ***how far*** it will travel, and ***how much of an impact*** it will have on air quality downwind, and regional climate. In ***northern Iraq***, at least two people have lost their lives, up to 1000 hospitalized, and 200 families evacuated from their homes due to sulfur & smoke pollution.

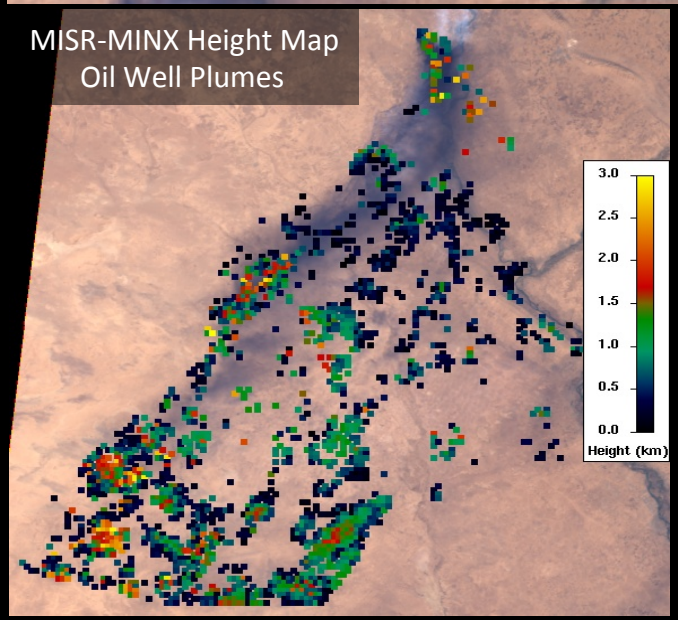


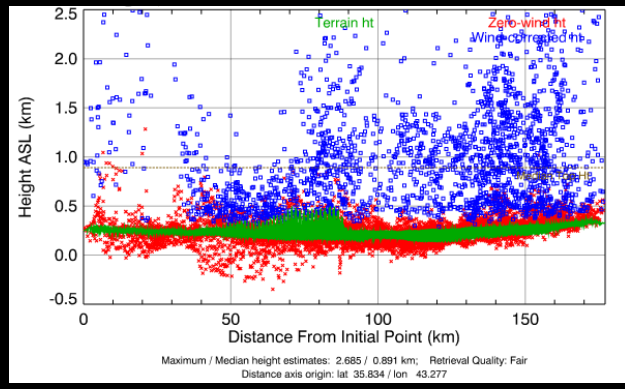




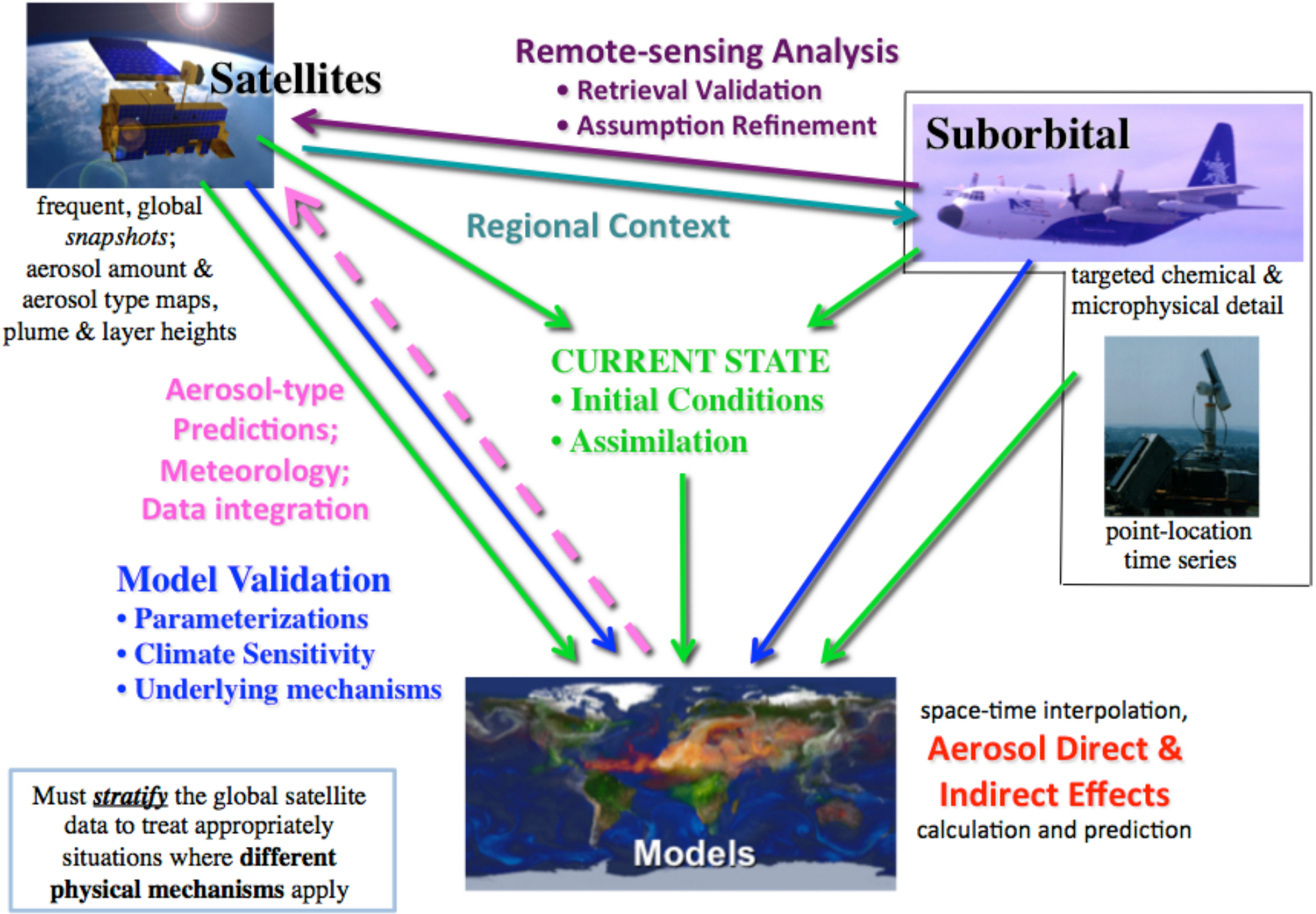
Zero-wind & Wind-Corrected
MISR Height Profiles
Downwind from Near-source

Parallax, the change in apparent plume position relative to the surface, as observed from the NASA Earth Observing System's Multi-angle Imaging Spectroradiometer (***MISR***) instrument, makes it possible to map the height of ***smoke***, ***dust***, and ***volcanic plumes*** near-source, where plume features are visible in the multi-angle views.





R. Kahn, **T. Kucsera** / NASA GSFC
T. Canty, **R. Bolt**, **CJ Vernon** / U. Maryland



Adapted from: Kahn, Survy. Geophys. 2012