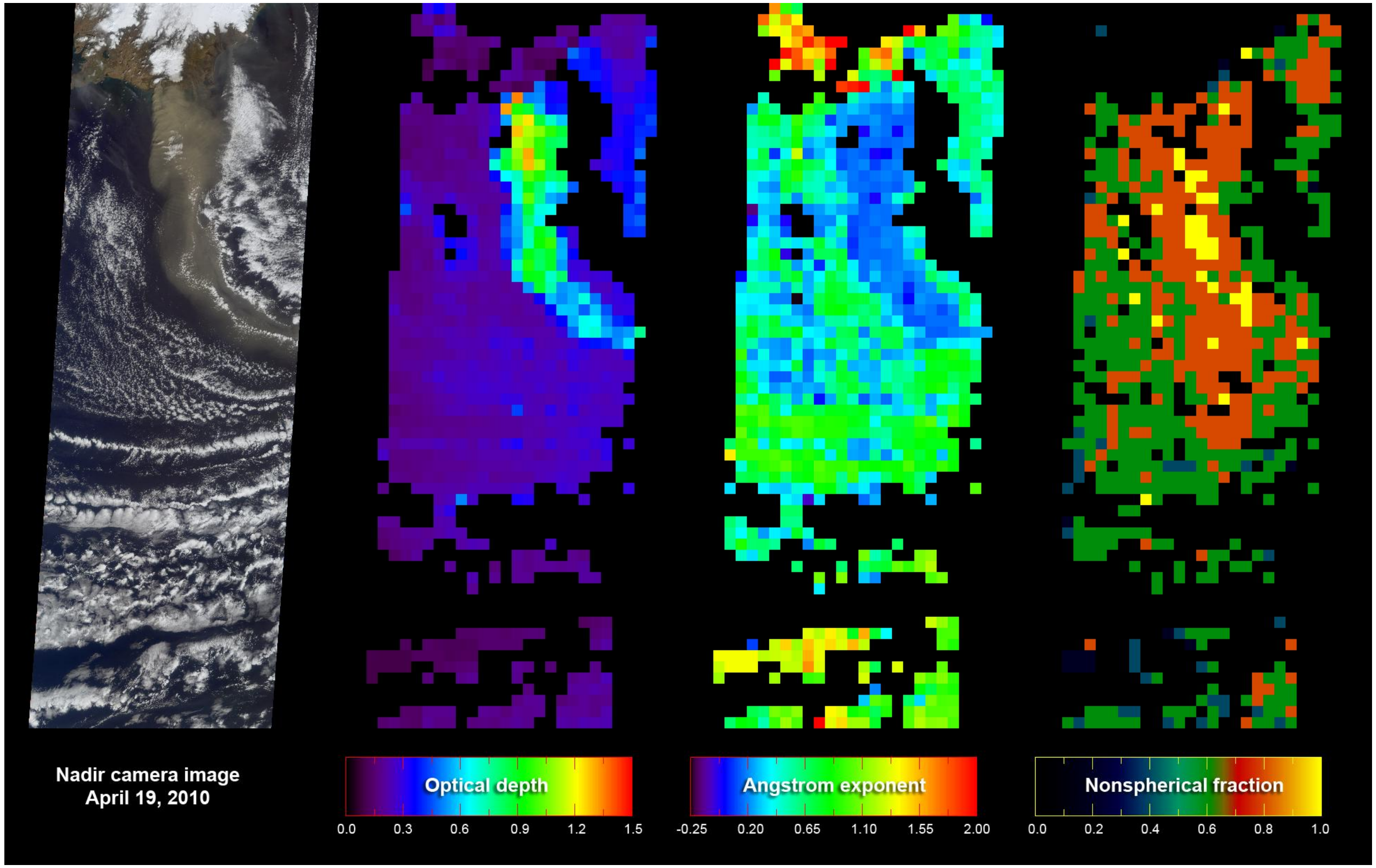
From Measurements to Models: What Satellite and Sub-Orbital Instruments Can and Must Contribute

Ralph Kahn *NASA Goddard Space Flight Center*

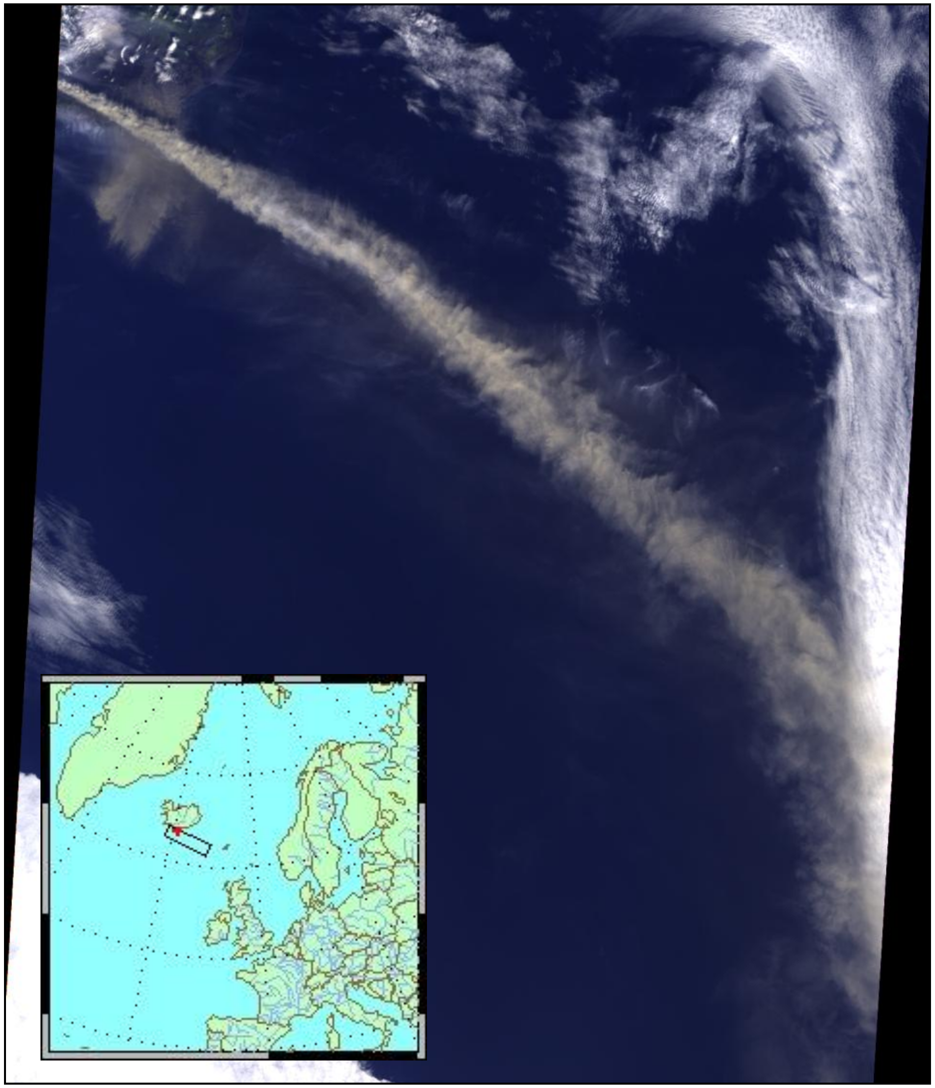


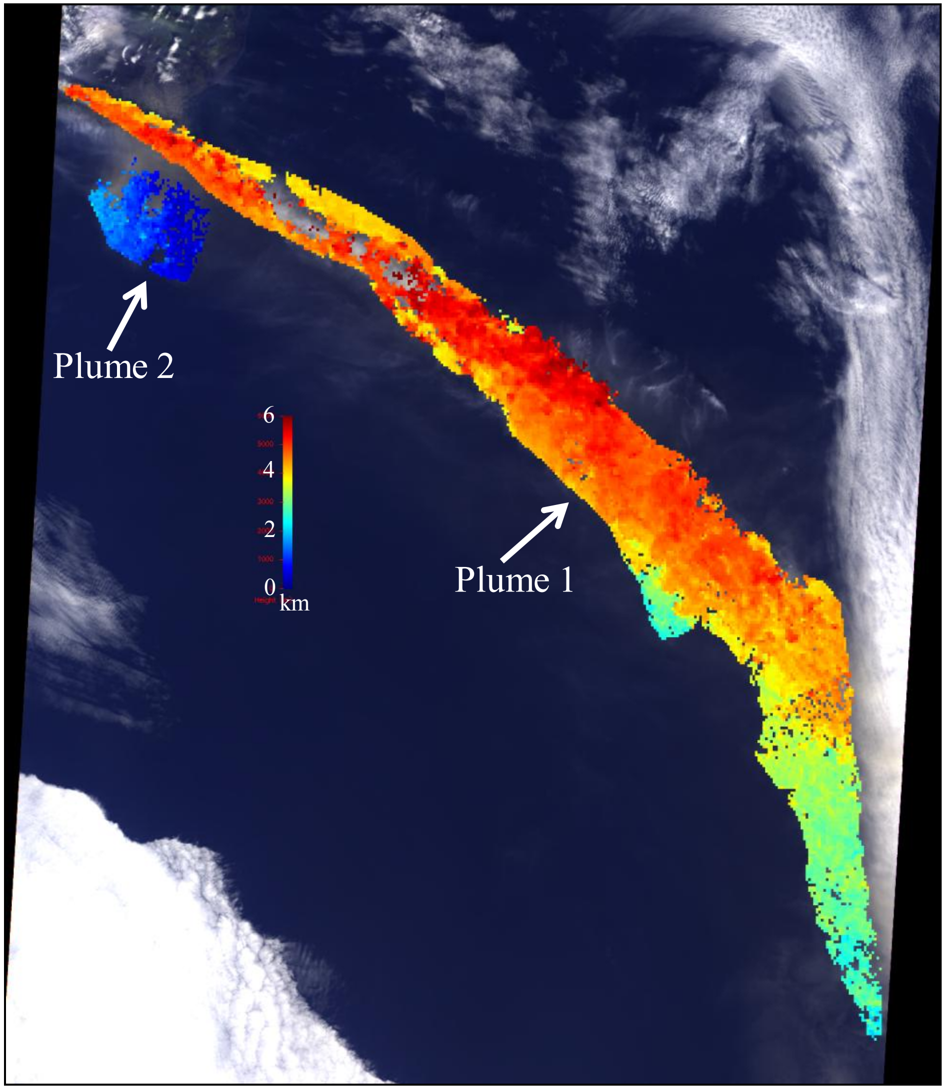
Eyjafjallјökull Volcano Ash Plume – MISR Aerosol Retrieval – April 19, 2010

MISR Team, JPL and GSFC

*MISR Stereo-Derived **Plume Heights***

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

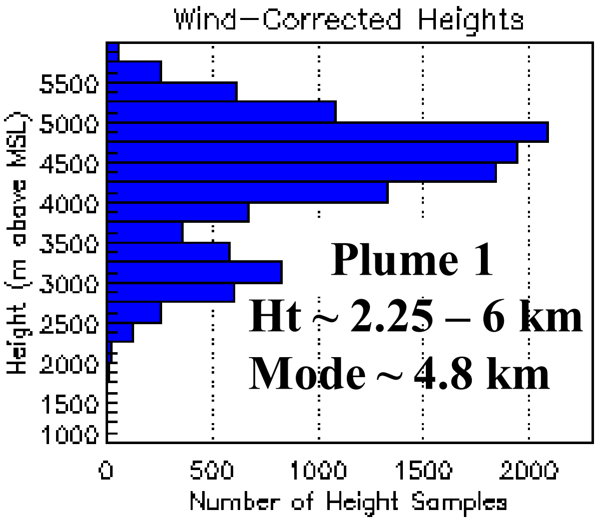




D. Nelson and the MISR Team, JPL and GSFC

*MISR Stereo-Derived **Plume Heights***

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

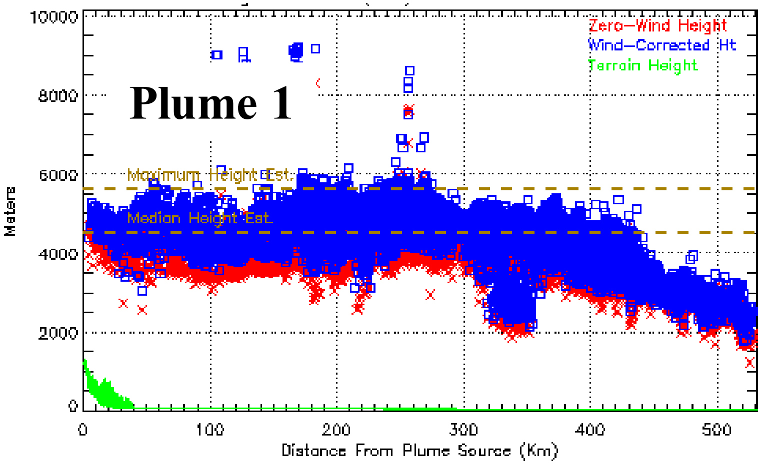


Plume 1

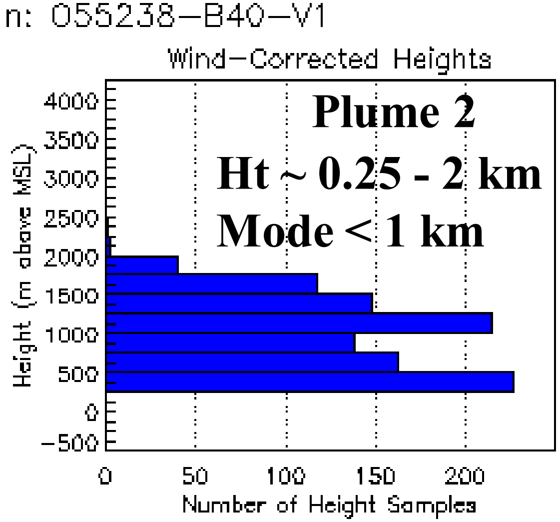
Ht ~ 2.25 – 6 km

Mode ~ 4.8 km

Height: Blue = Wind-corrected



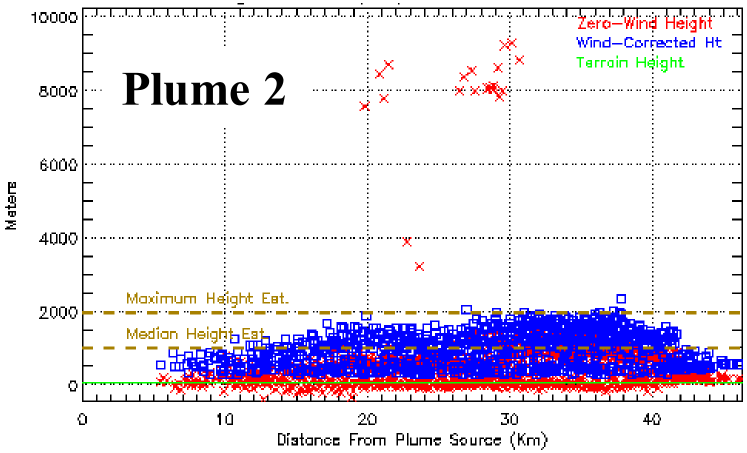
Plume 1



Plume 2

Ht ~ 0.25 - 2 km

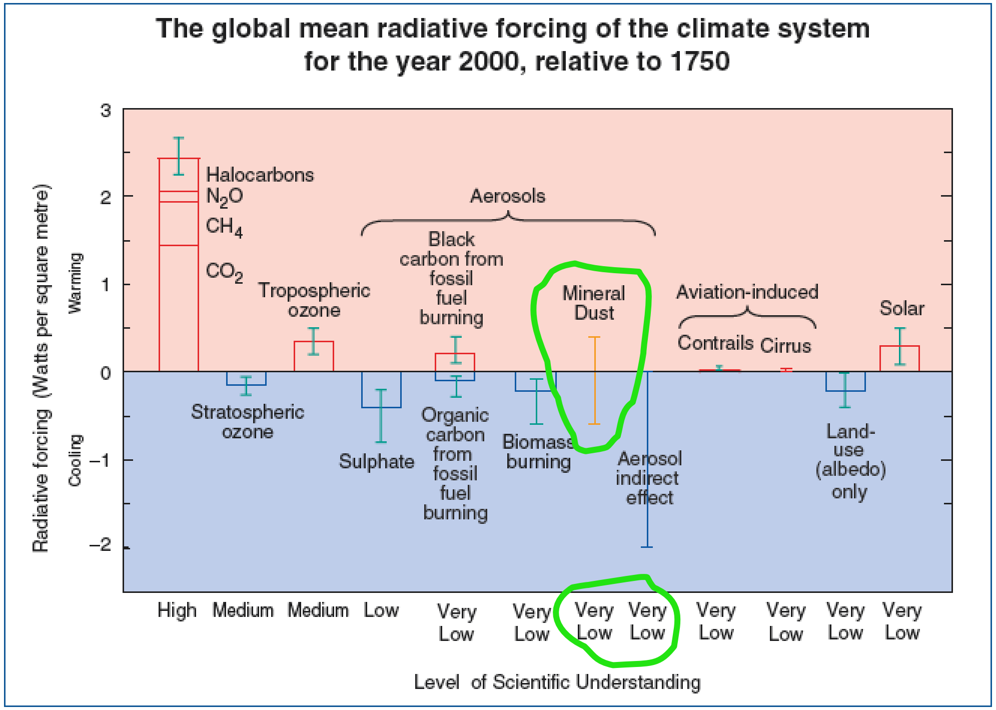
Mode < 1 km



Plume 2

D. Nelson and the MISR Team

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



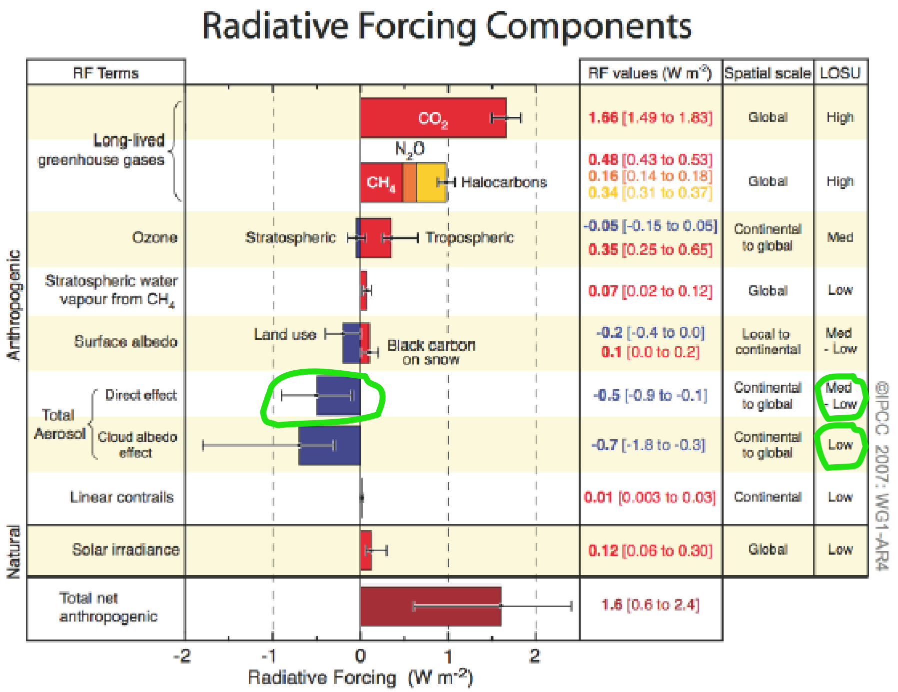


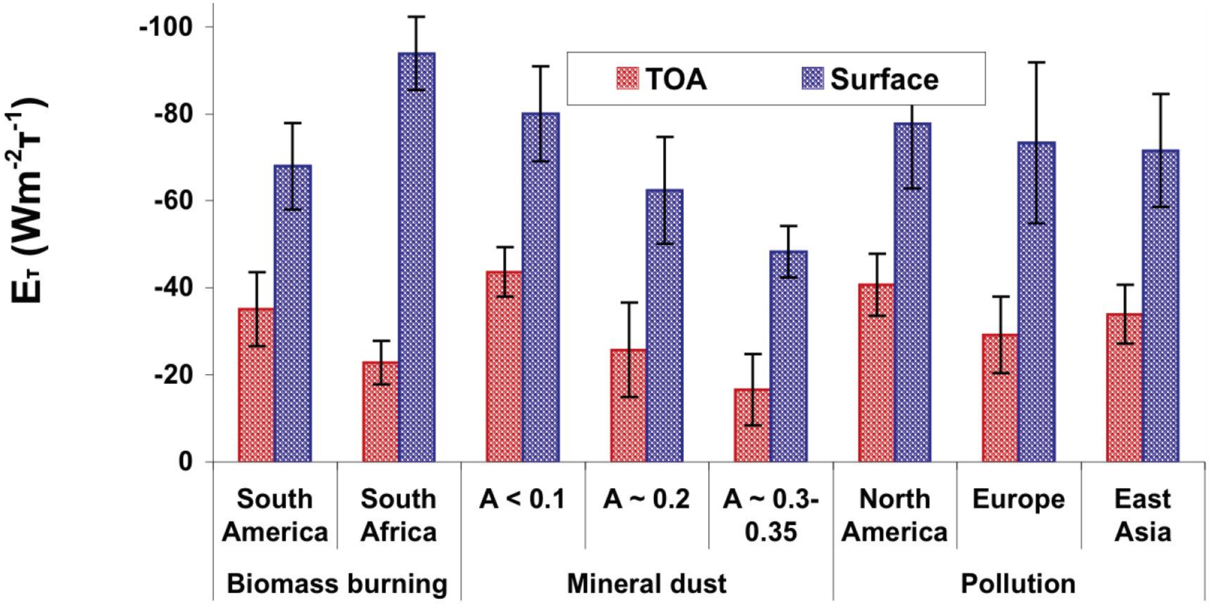
FIGURE SPM-2. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level 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)

AOD Alone is Not Enough – Even for Direct Aerosol Radiative Forcing

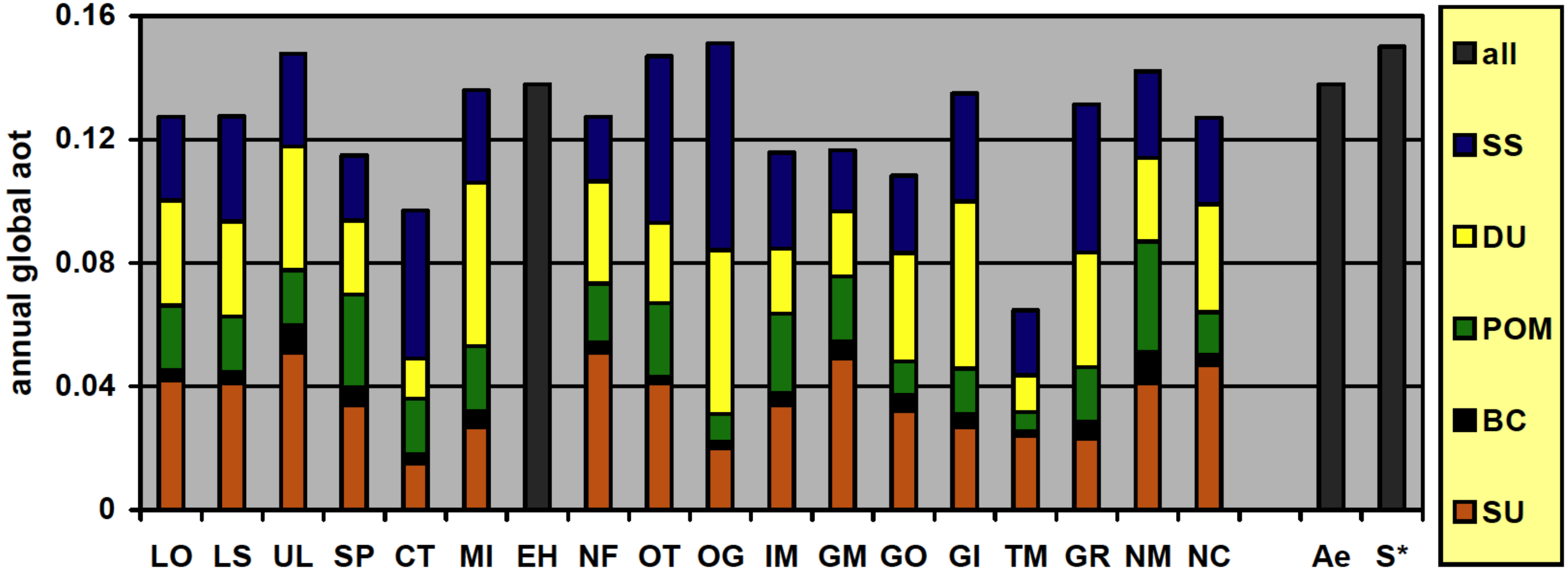
Direct Aerosol Radiative *Forcing Efficiency* per unit AOD



From: Zhao et al., JGR 2005

- ***Aerosol SSA, Vert. Dist.,*** and ***Surface Albedo*** critical, esp. for ***Surface Forcing***
- For ***Semi-direct Forcing***, ***Aerosol SSA*** and ***Vertical Distribution*** are critical

Constraining DARF – The Next Big Challenge



Ae= AERONET; S*= MISR-MODIS composite

Kinne et al., ACP 2006

- Agreement among models is ***increasingly good for AOD***, given the combined ***AERONET***, ***MISR***, and ***MODIS*** constraints

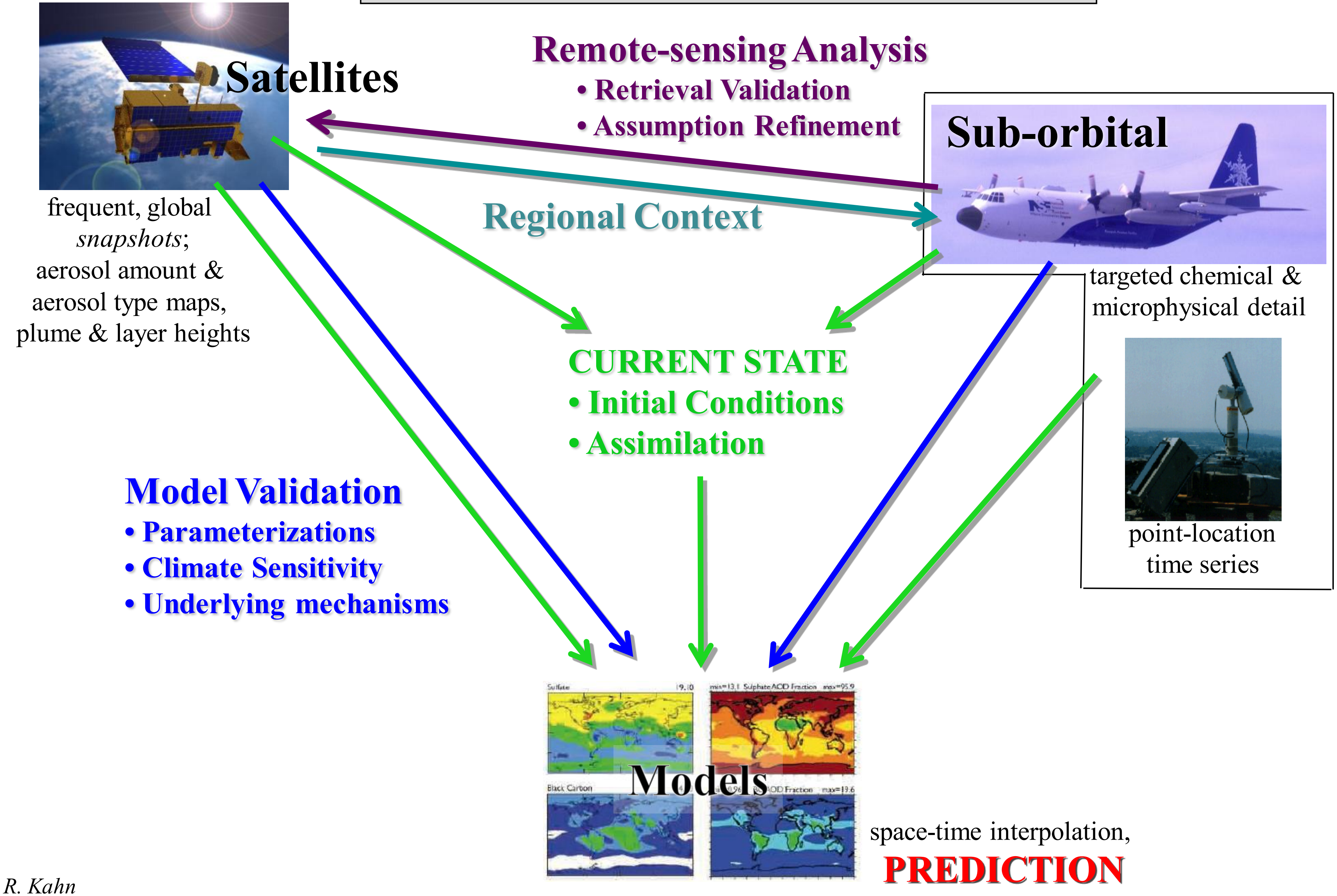
- The next big observational challenge: Producing ***monthly, global maps of Aerosol Type***

How Good is *Good Enough*?

Instantaneous AOD & ***SSA*** uncertainty upper bounds for ~1 W/m^2 TOA DARF accuracy: **~ 0.02**

CCSP - SAP 2.3, 2009

Aerosol-Climate Prediction



Satellites

frequent, global
snapshots;
aerosol amount &
aerosol type maps,
plume & layer heights

Remote-sensing Analysis

- **Retrieval Validation**
- **Assumption Refinement**

Regional Context

Sub-orbital

targeted chemical &
microphysical detail

point-location
time series

CURRENT STATE

- **Initial Conditions**
- **Assimilation**

Model Validation

- **Parameterizations**
- **Climate Sensitivity**
- **Underlying mechanisms**

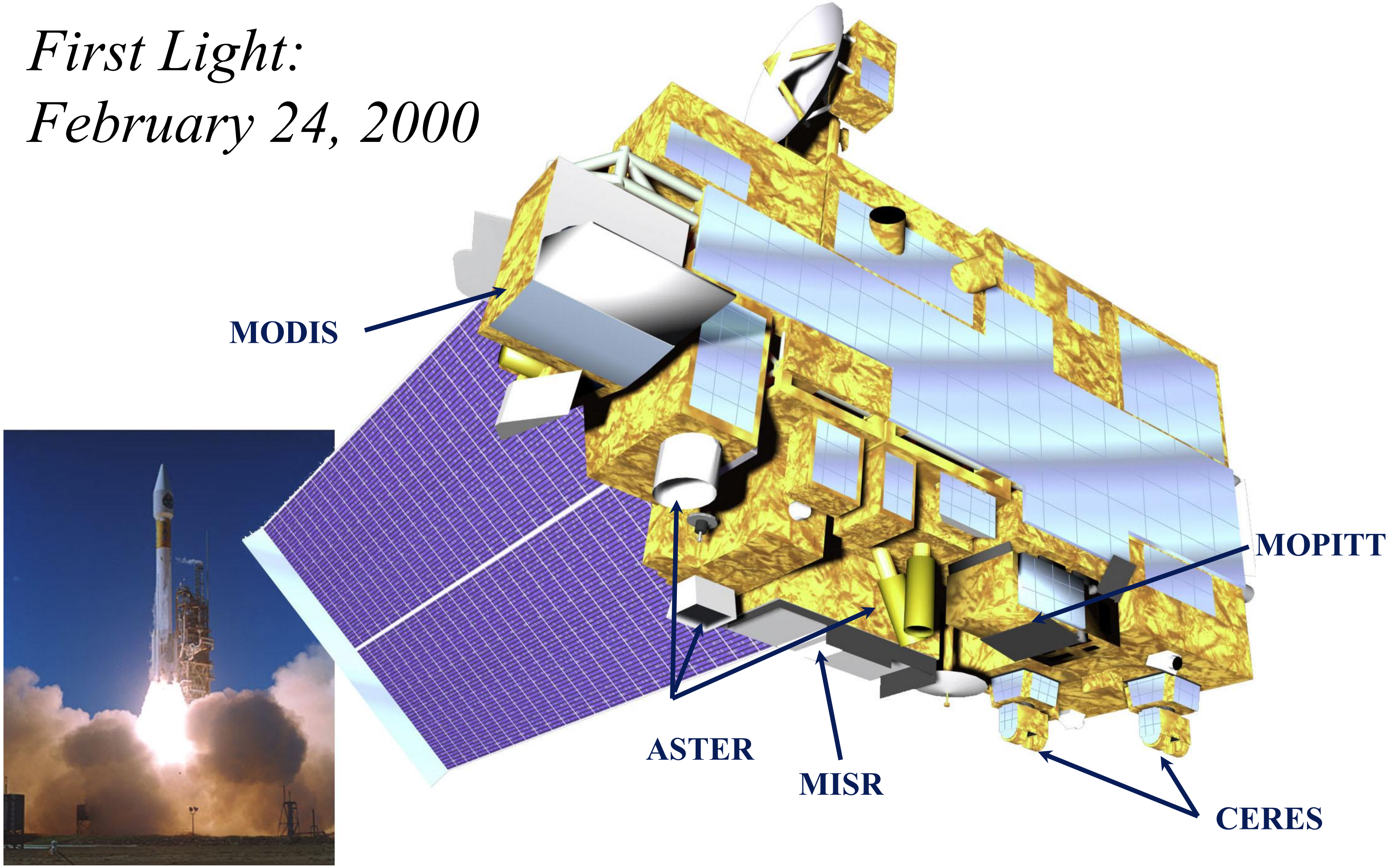
Models

space-time interpolation,
PREDICTION

R. Kahn

The NASA Earth Observing System's Terra Satellite

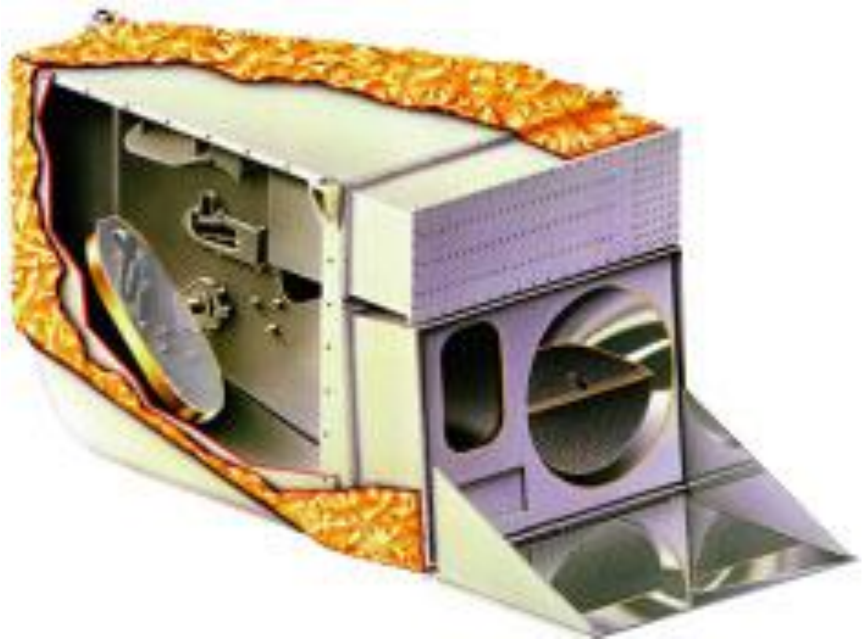
First Light:
February 24, 2000



Terra Project Office / NASA Goddard Space Flight Center

MODerate-resolution Imaging Spectroradiometer [MODIS]

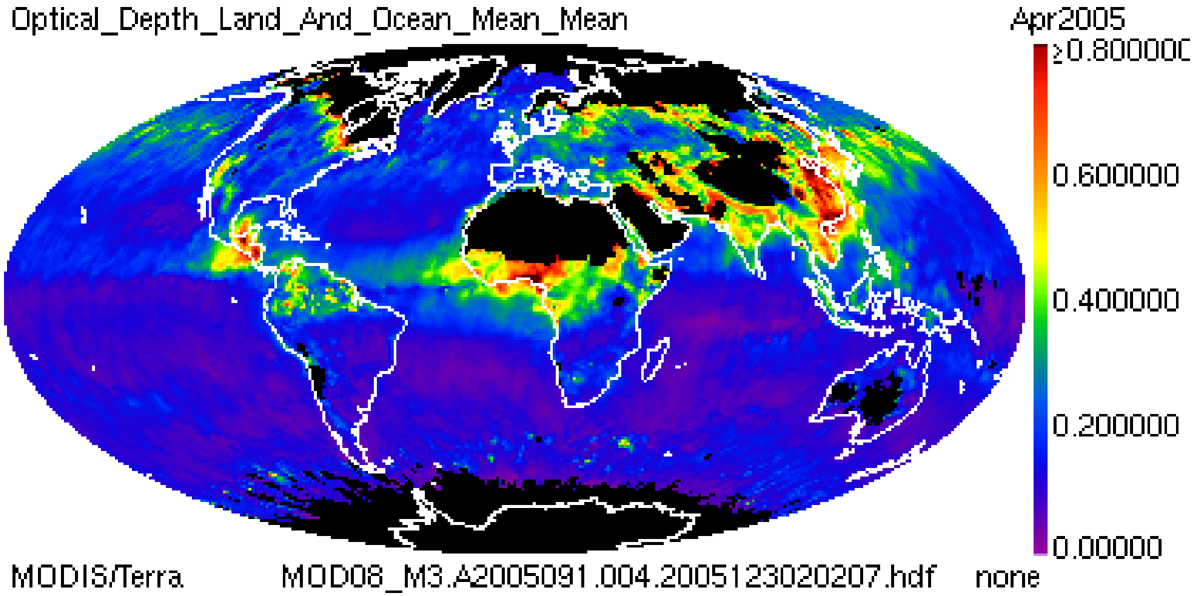
- NASA, Terra & Aqua
  - launches 1999, 2001
  - 705 km polar orbits, descending (10:30 a.m.) & ascending (1:30 p.m.)
- Sensor Characteristics
  - 36 spectral bands ranging from 0.41 to 14.385 µm
  - cross-track scan mirror with 2330 km swath width
  - Spatial resolutions:
    - 250 m (bands 1 - 2)
    - 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

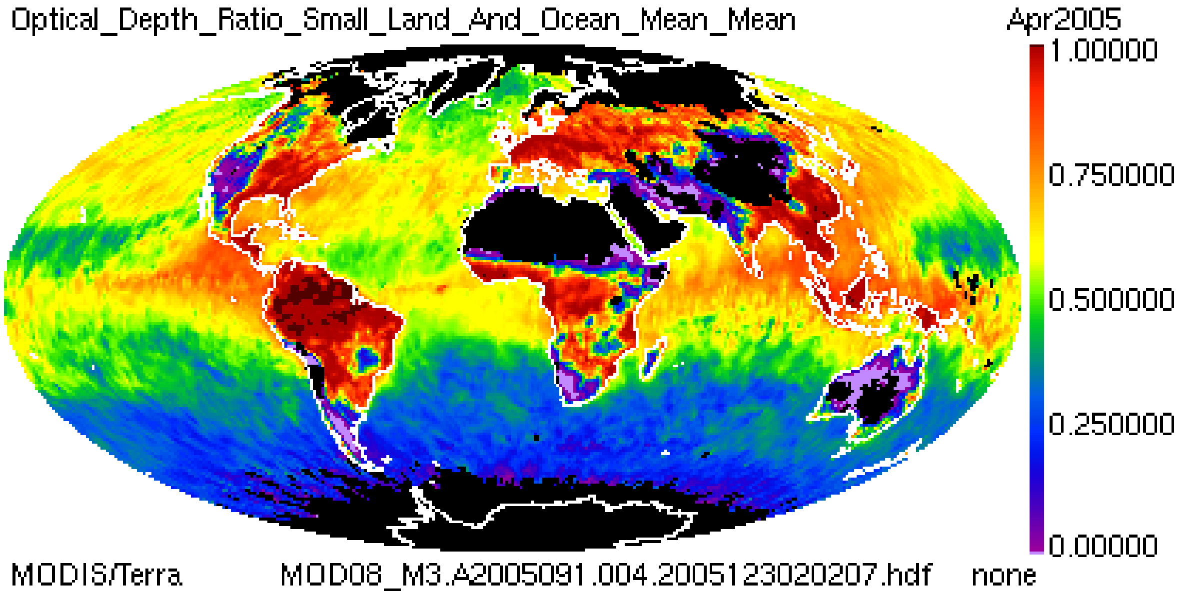
MODIS Team, NASA/GSFC

MODIS Monthly Global Aerosol Products



Mid-vis AOT

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



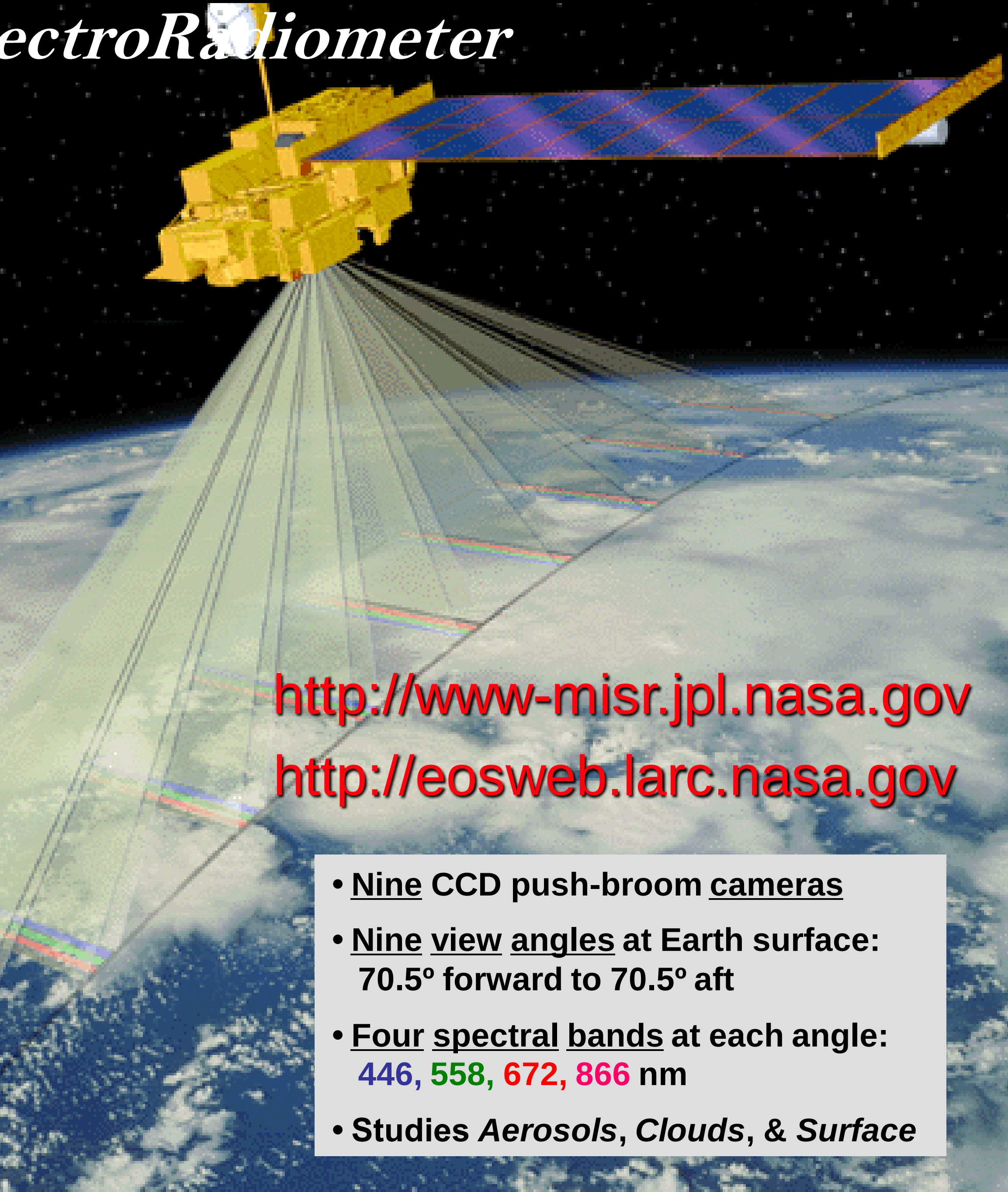
- **Fine/Coarse Ratio**
- **Sensitivity to PM$_{10}$**

Direct Downlink

MODIS Atmospheres Web Site

Multi-angle Imaging SpectroRadiometer

MISR



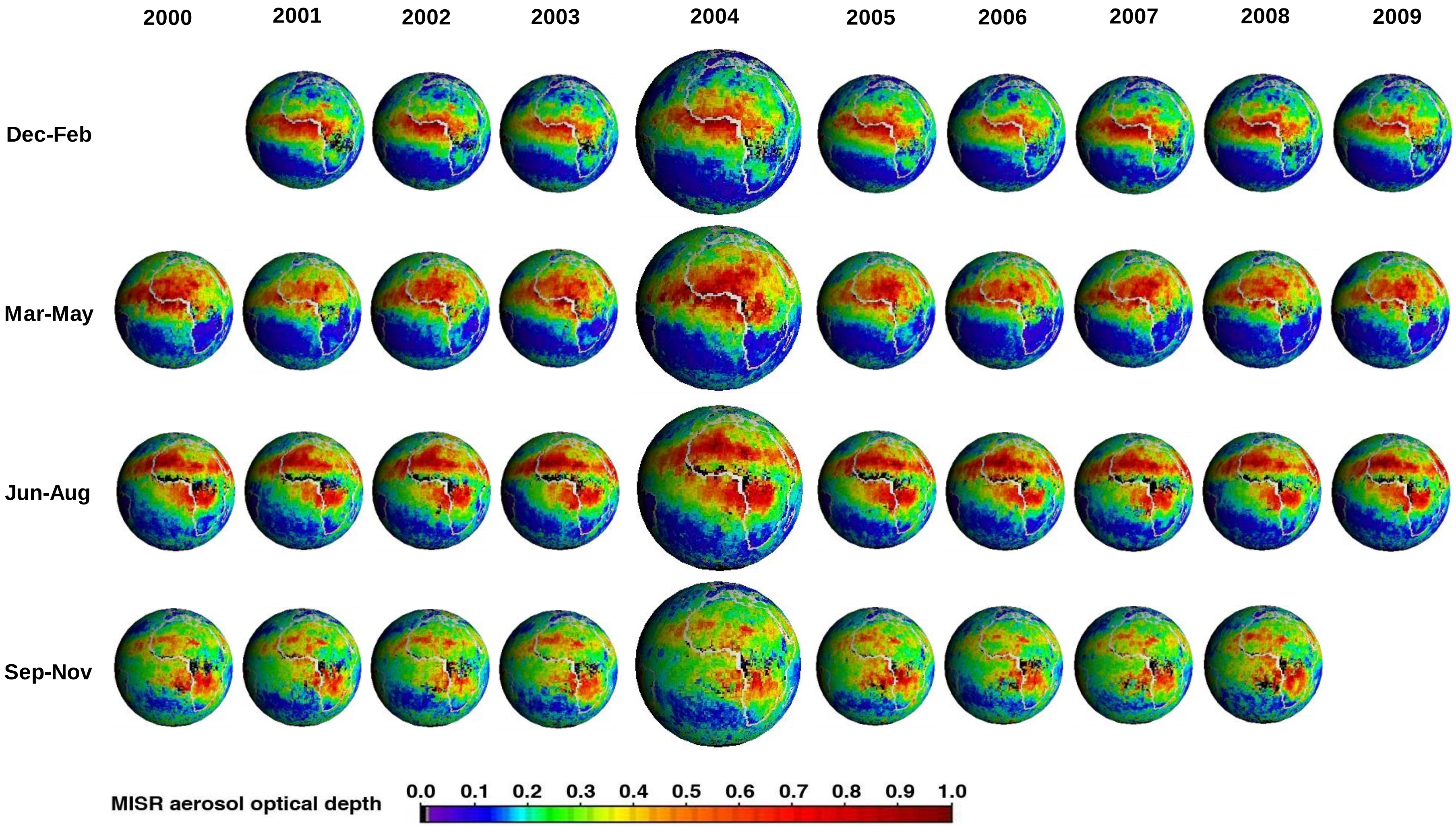
http://www-misr.jpl.nasa.gov

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*

Aerosol Retrievals –
Aerosol Optical Depth

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

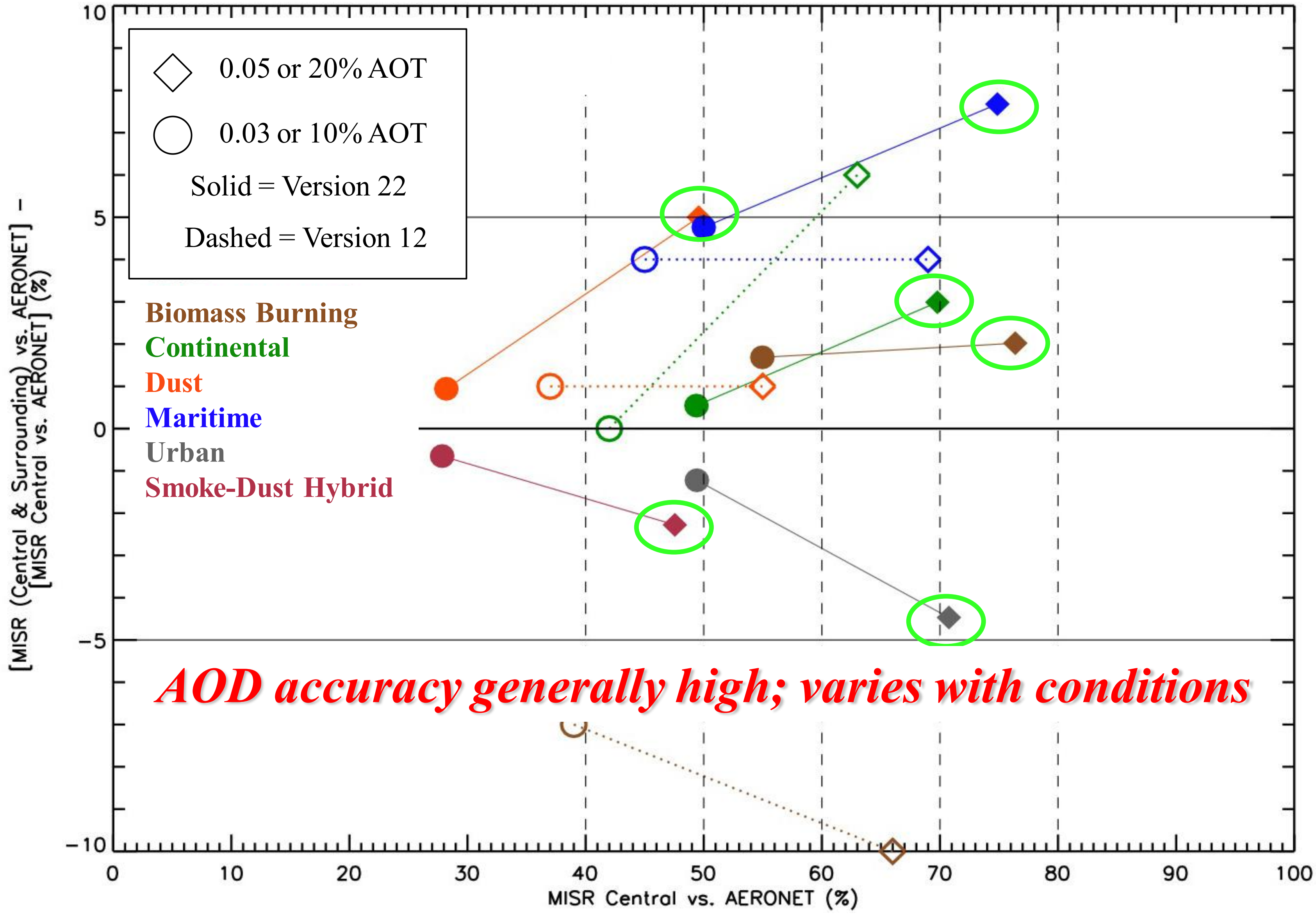


…includes bright desert dust source regions

MISR Team, JPL and GSFC

MISR-AERONET AOD Comparison for 5,156 Coincidences

MISR Version 22 – Stratified by expected aerosol air mass type

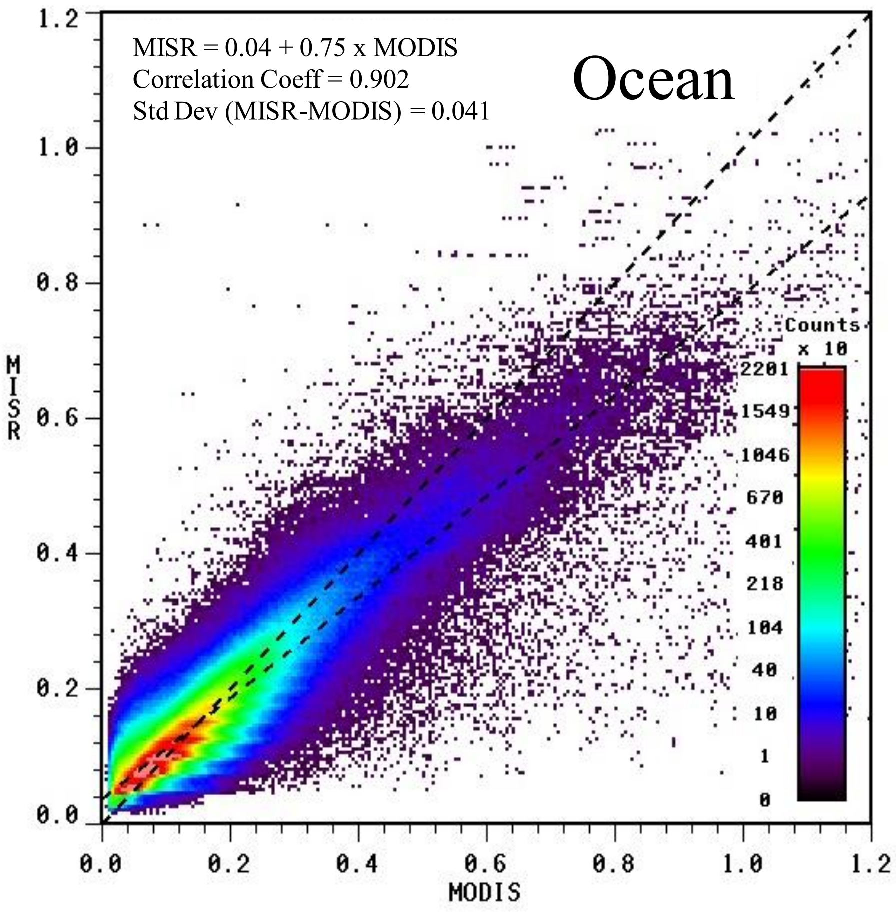


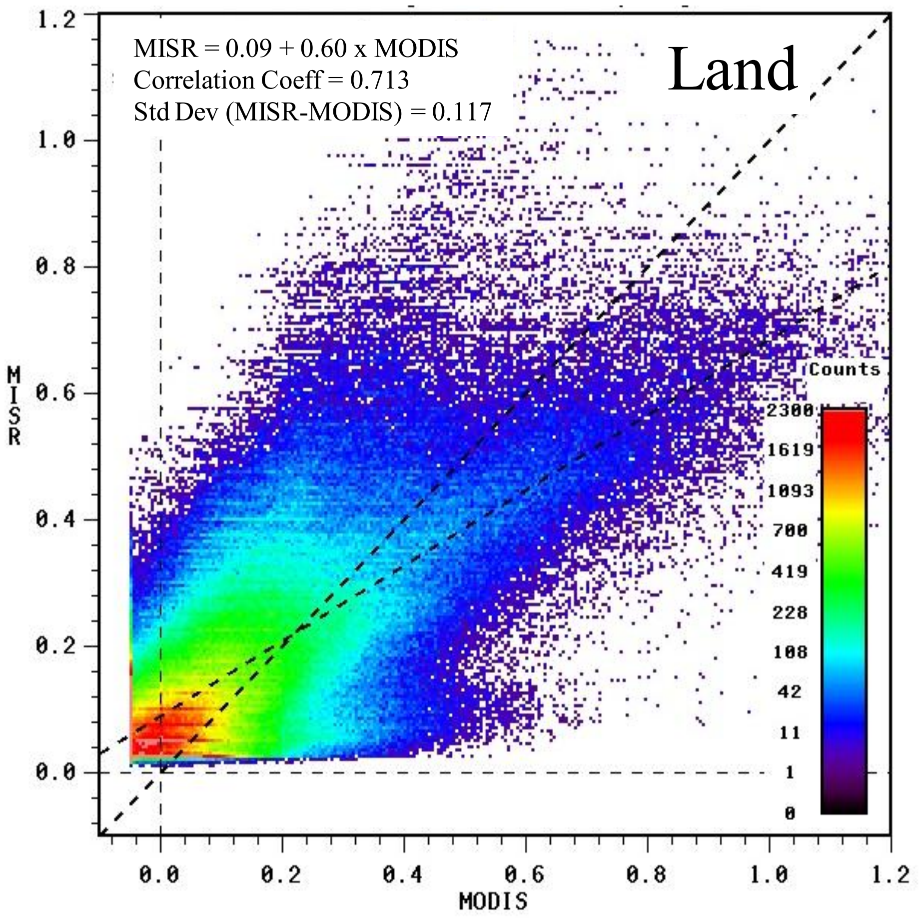
AOD accuracy generally high; varies with conditions

Kahn, Gaitley et al., JGR 2010

MISR-MODIS *Aerosol Optical Depth* Comparison

[MISR V22 vs. MODIS/Terra Collection 5; January 2006 Coincident Data]



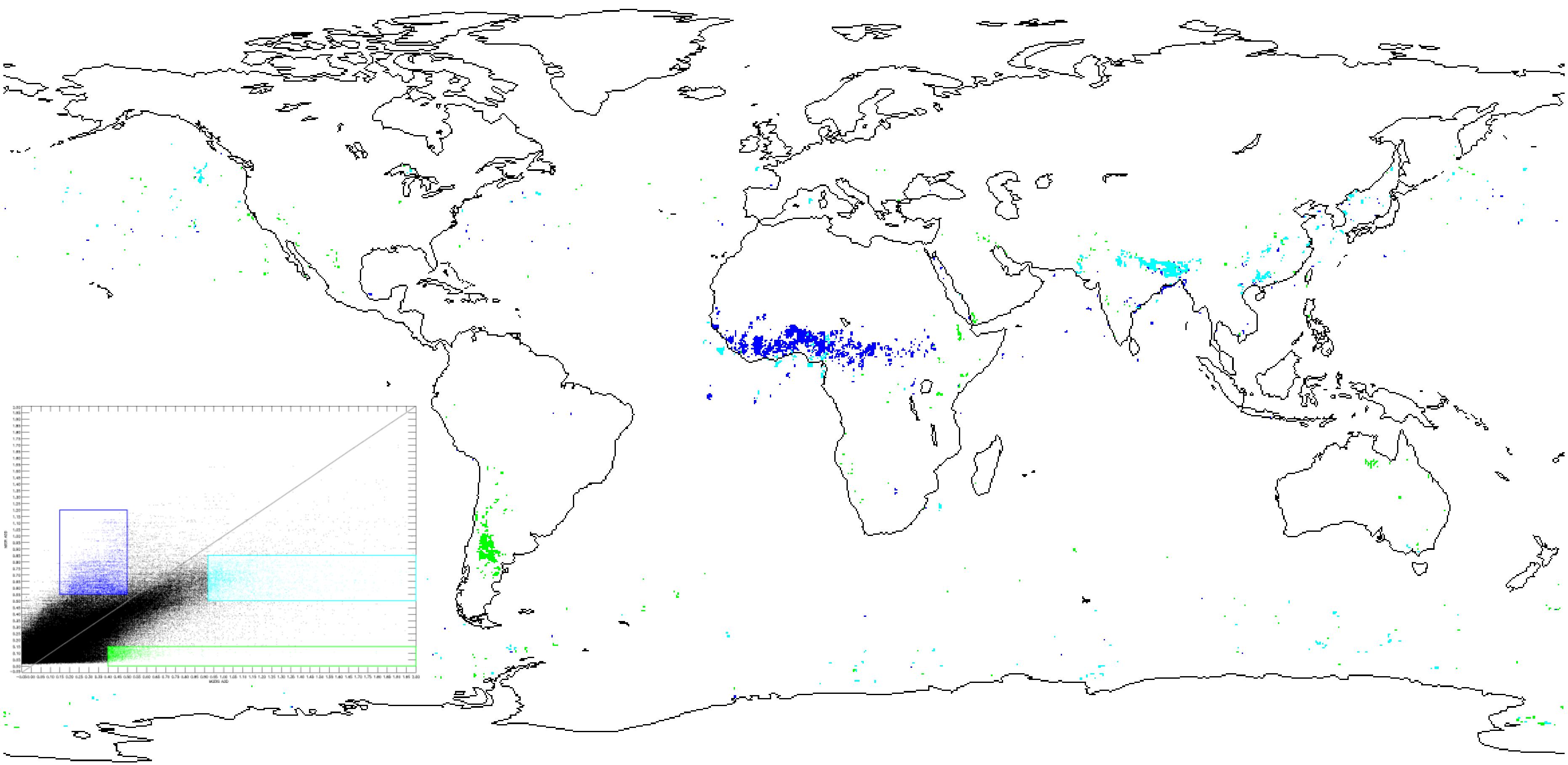


Over-ocean regression coefficient **0.90**
Regression line slope 0.75
MODIS QC ≥ 1

Over-land regression coefficient **0.71**
Regression line slope 0.60
MODIS QC = 3

Kahn, Nelson, Garay et al., TGARS 2009

MISR-MODIS Coincident AOD ***Outlier Clusters***



Dark Blue [MISR > MODIS] – N. Africa ***Mixed Dust & Smoke***

Cyan [MODIS > MISR, AOD large] – Indo-Gangetic Plain ***Dark Pollution Aerosol***

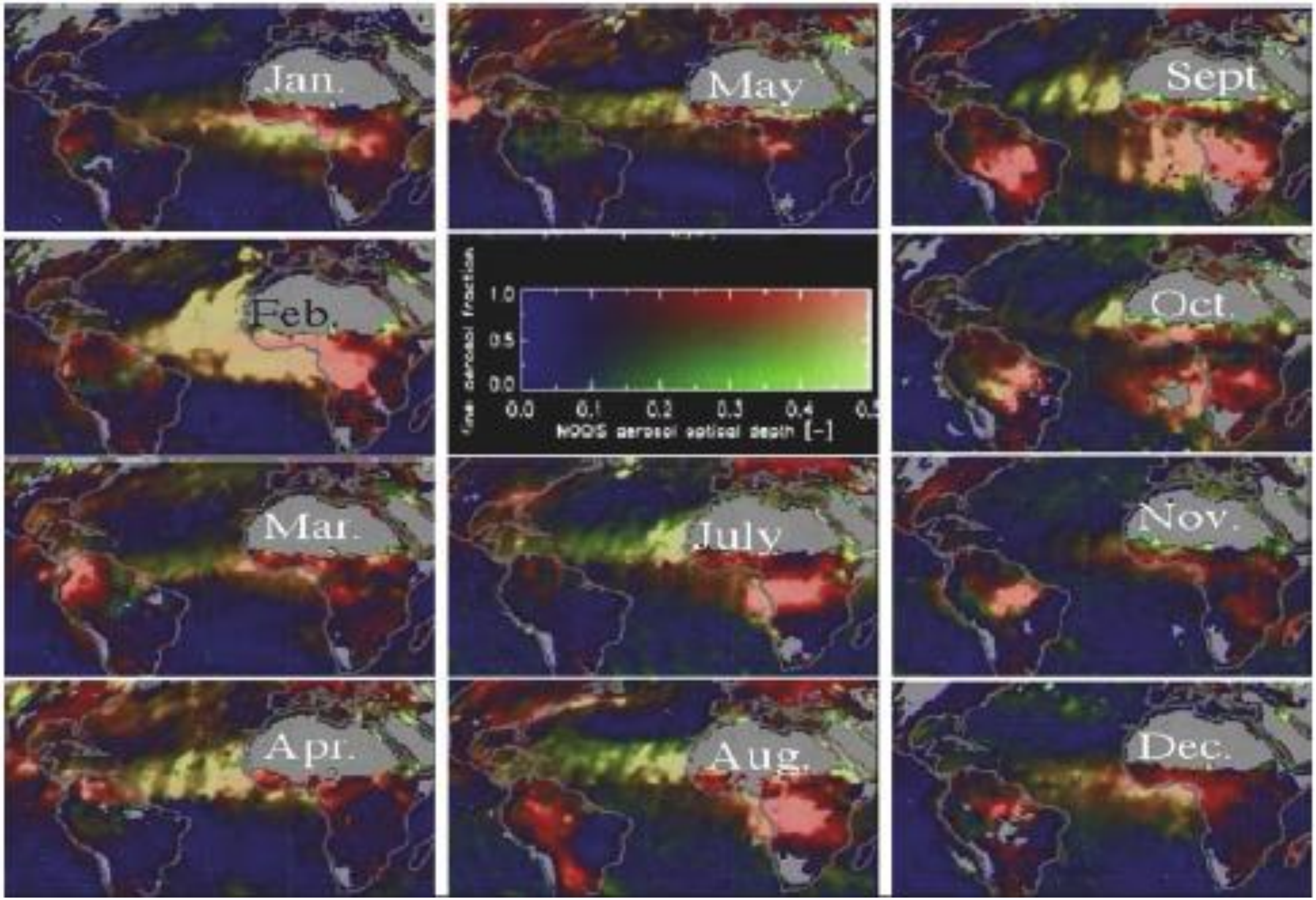
Green [MODIS >> MISR] – Patagonia and N. Australia ***MODIS Unscreened Bright Surface***

Kahn et al., TGARS 2009

Aerosol Retrievals –
Aerosol Microphysical Properties

One MODIS *Aerosol Type* Classification:

Low AOT (blue), **High AOT+Coarse** (green), **High AOT+Fine** (red)



Kaufman et al., *JGR*, 2005

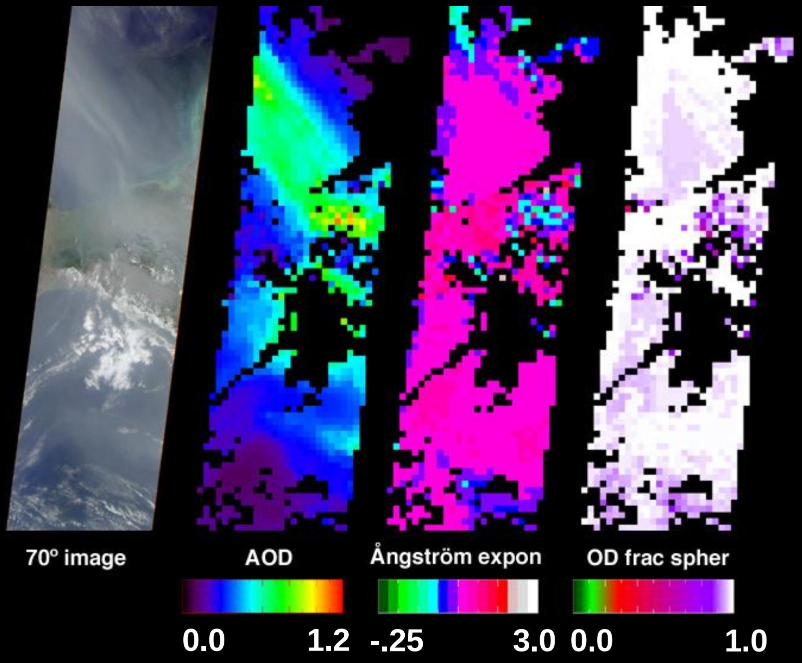
Smoke from Mexico -- 02 May 2002

Aerosol:

Amount

Size

Shape



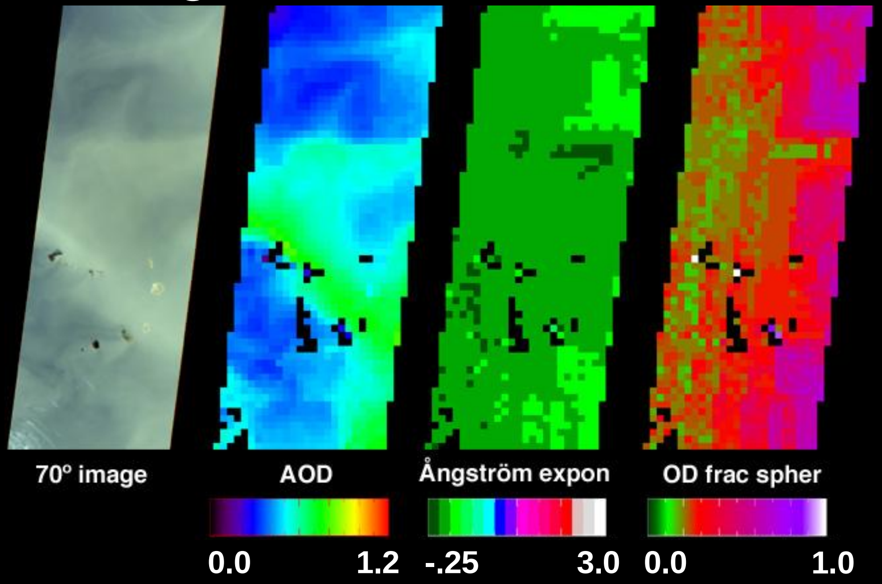
Medium

Spherical

Smoke

Particles

Dust blowing off the Sahara Desert -- 6 February 2004



Large

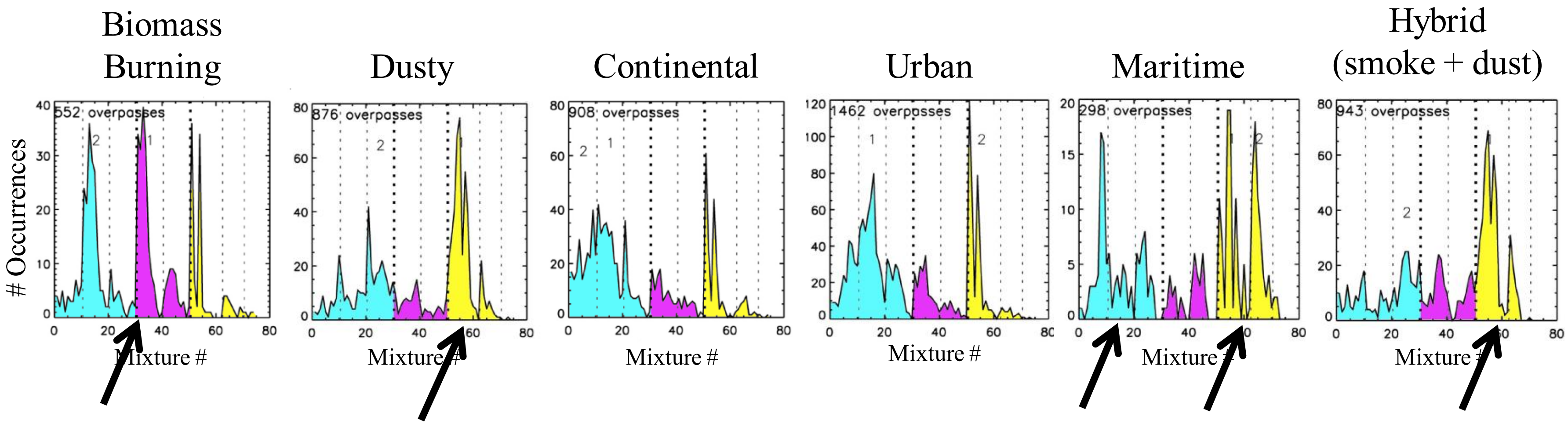
Non-Spherical

Dust

Particles

MISR ***Aerosol Type*** Distribution

MISR Version 22, July 2007

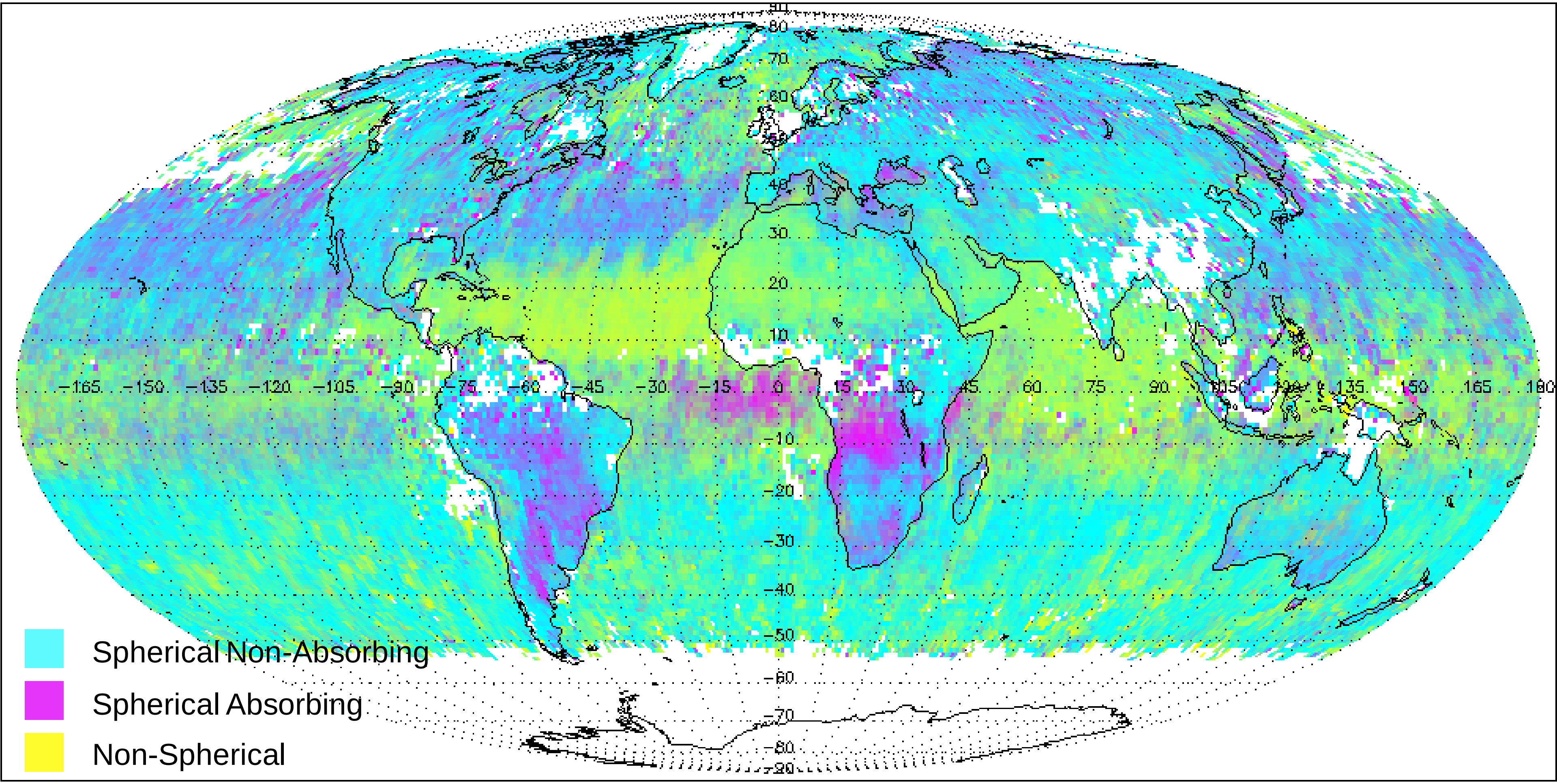


🟦 Spherical Non-Absorbing 🟪 Spherical Absorbing 🟨 Non-Spherical

Kahn, Gaitley, Garay, et al., JGR 2010

MISR ***Aerosol Type*** Distribution

MISR Version 22, July 2007

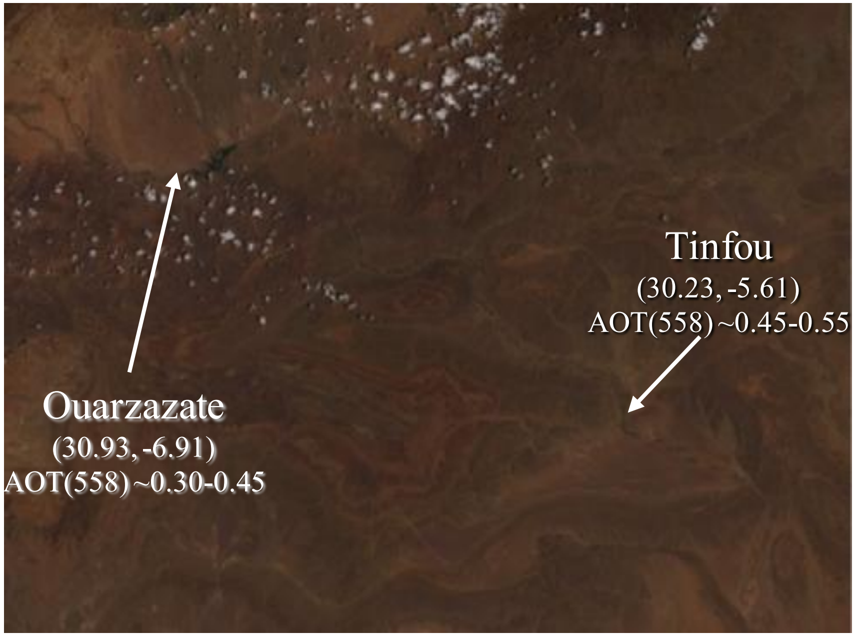


Sensitivity to particle properties varies enormously with conditions –

Low sensitivity for AOD <~ 0.15 or 0.2

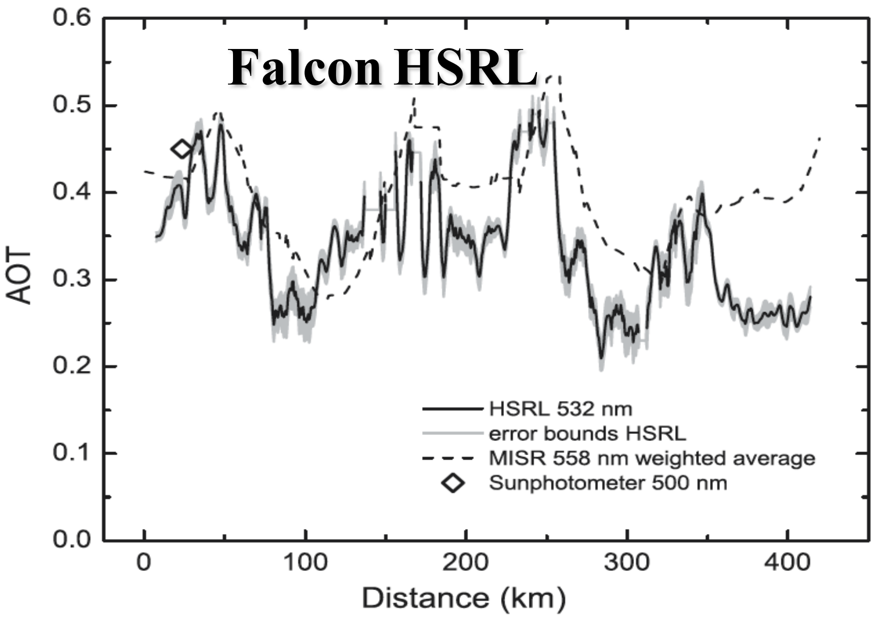
Kahn, Gaitley, Garay, et al., JGR 2010

SAMUM Campaign Morocco – June 04, 2006

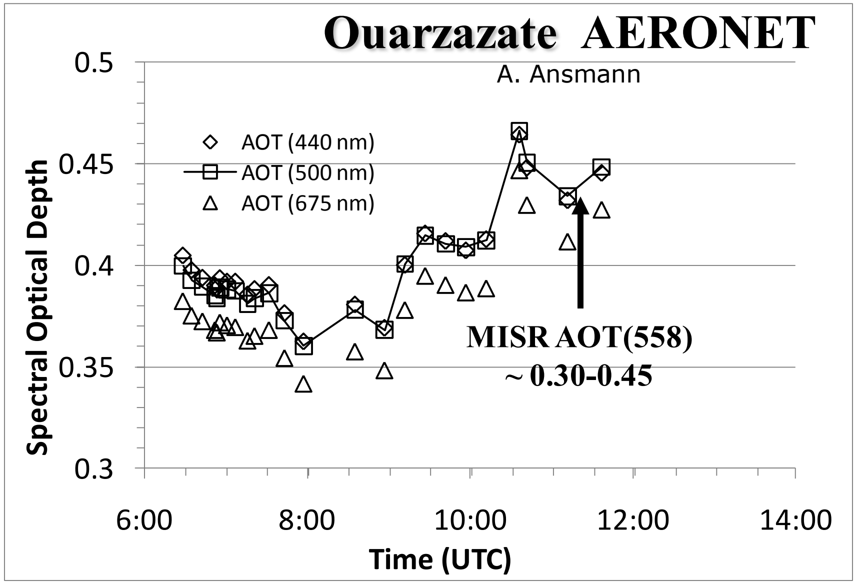


Ouarzazate
(30.93, -6.91)
AOT(558) ~0.30-0.45

Tinfou
(30.23, -5.61)
AOT(558) ~0.45-0.55



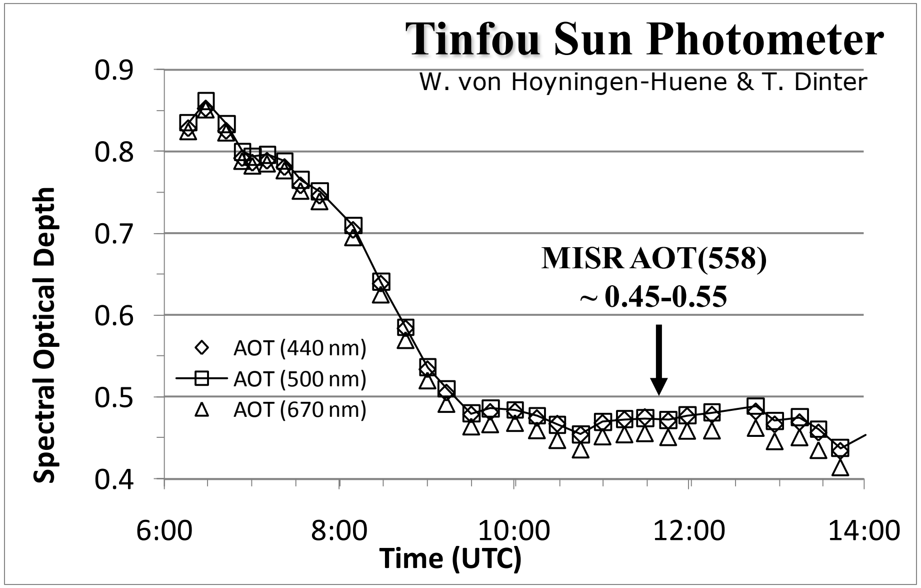
Falcon HSRL



Ouarzazate AERONET

A. Ansmann

MISR AOT(558)
~ 0.30-0.45



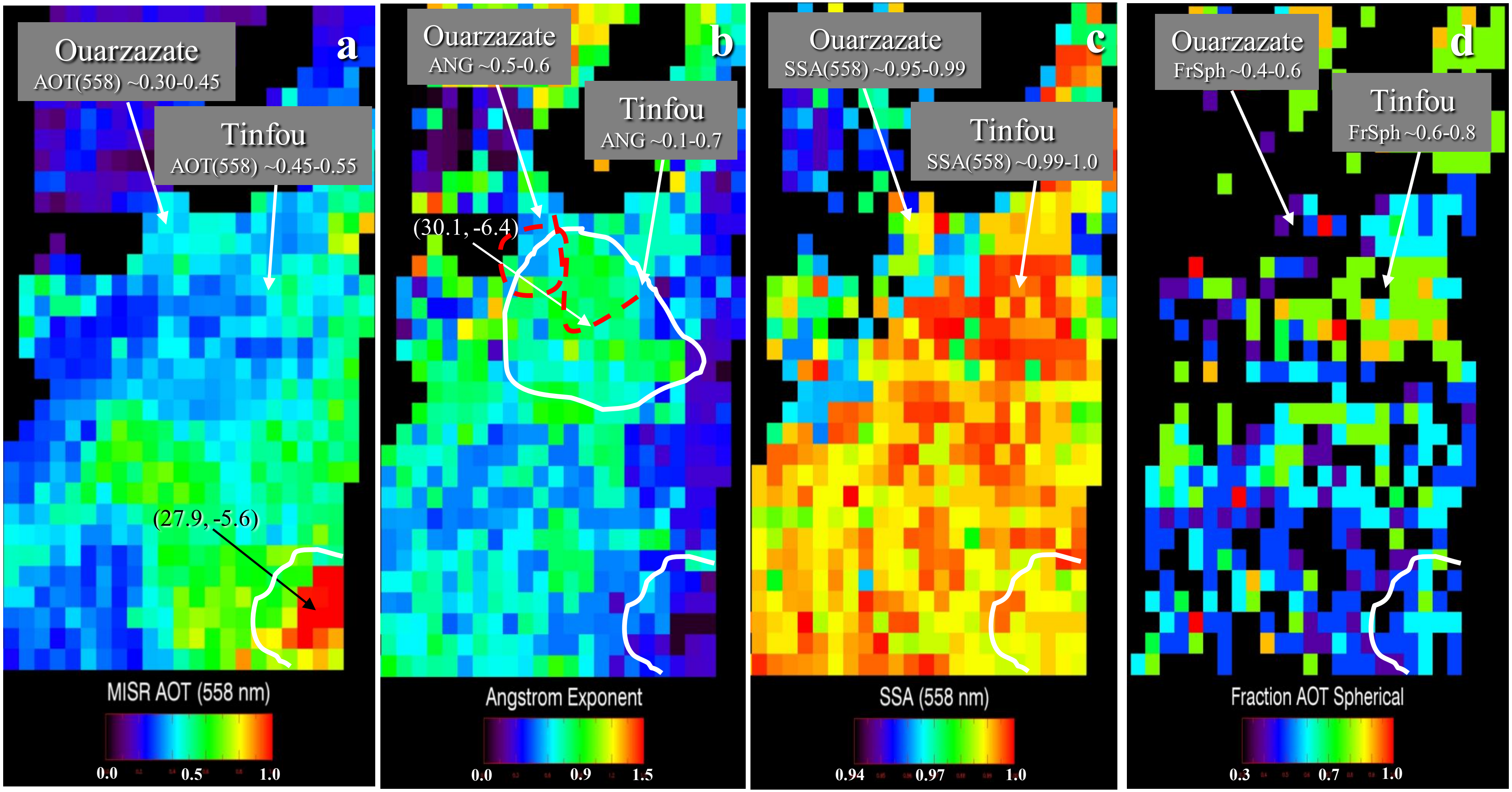
Tinfou Sun Photometer

W. von Hoyningen-Huene & T. Dinter

MISR AOT(558)
~ 0.45-0.55

MISR SAMUM Aerosol Air Masses (V19) - June 04, 2006

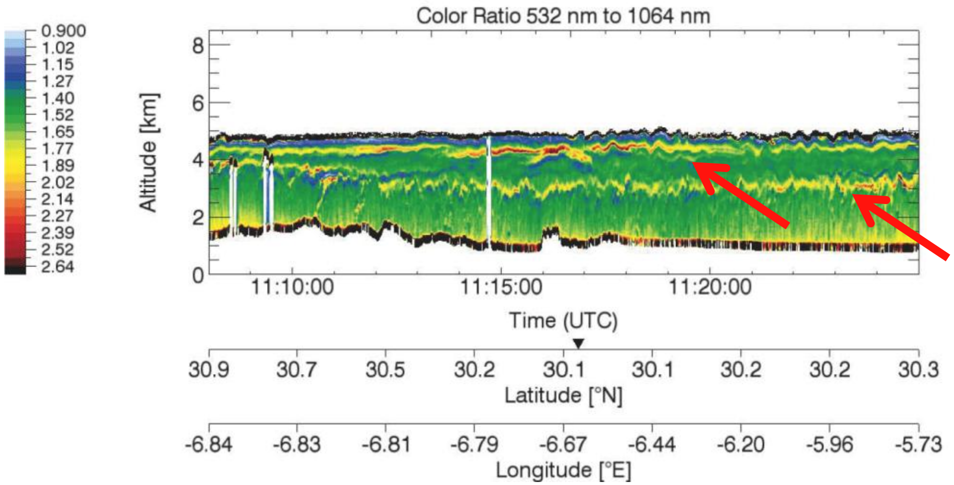
Orbit 34369, Path 201, Blocks 65-68, 11:11 UTC



- A **dust-laden density flow in the SE** corner of the MISR swath
- **High SSA, ANG** & **Fraction Spherical** region SE of Ouarzazate, includes Zagora

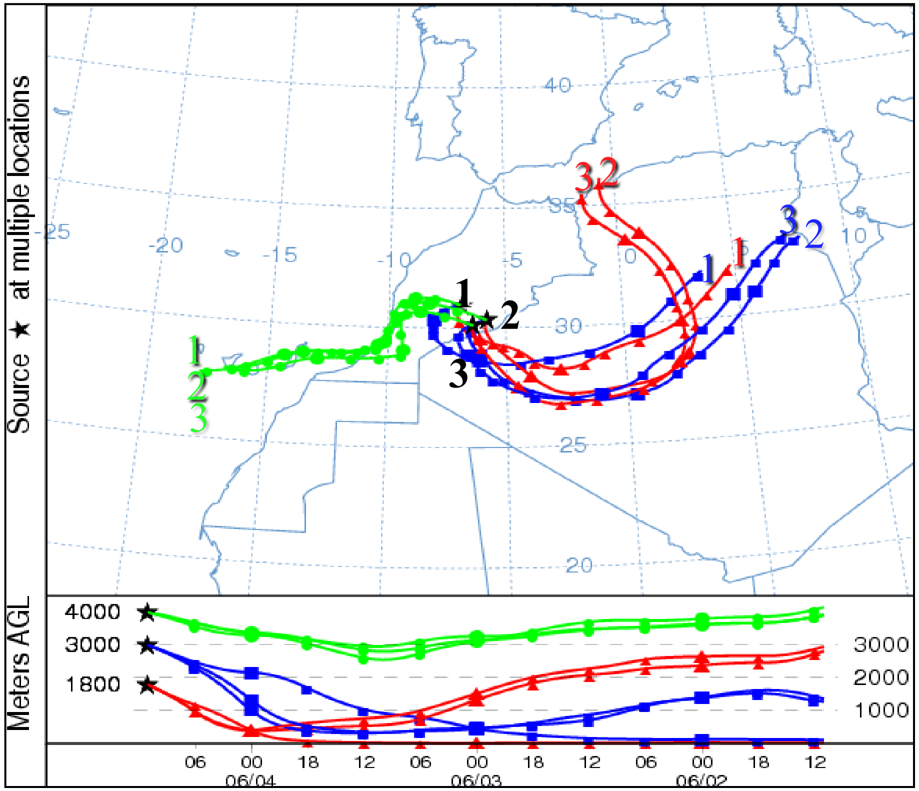
Kahn et al., Tellus 2009

MISR SAMUM Aerosol Air Mass Validation - June 04, 2006



Falcon F-20 HSRL

- Thin layers of small, bright particles



NOAA/HYSPLIT Back Trajectories

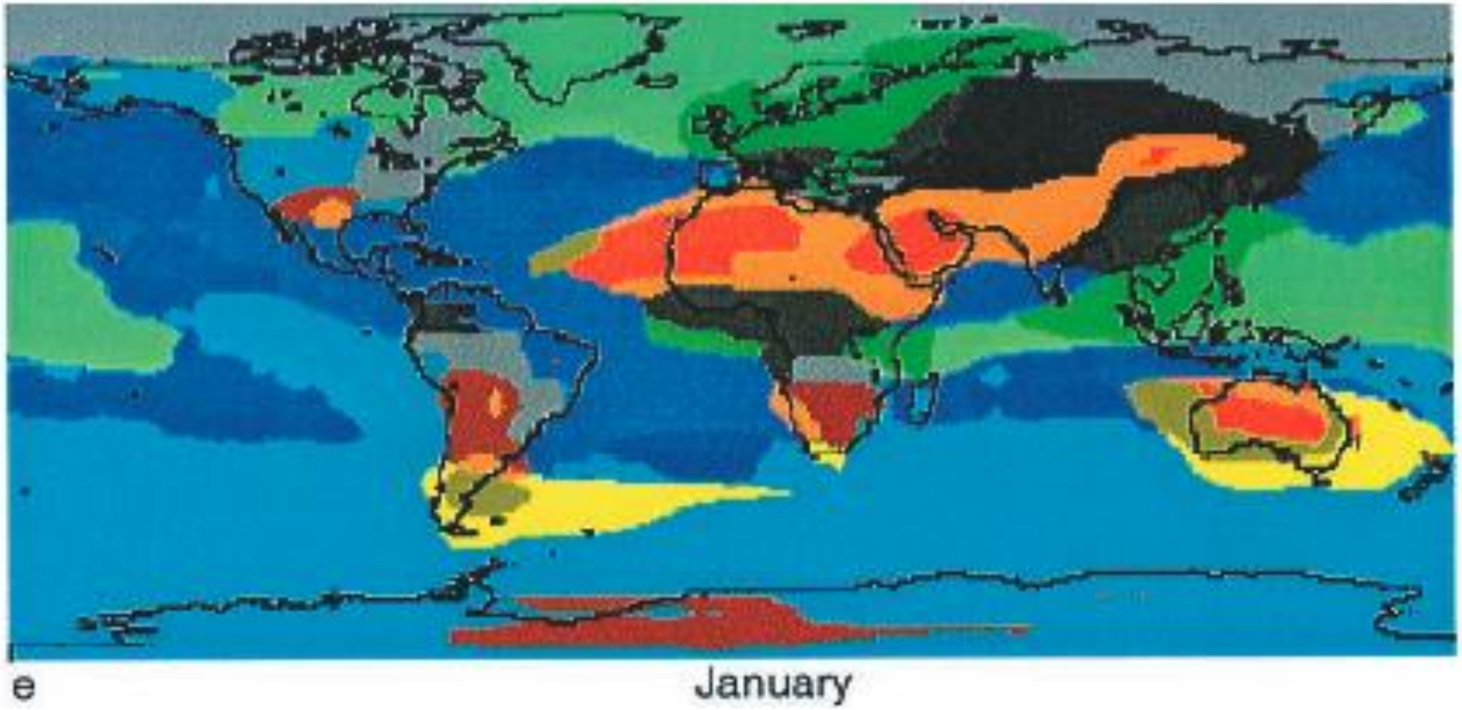
-Source in N Algeria for 2, 3 but not 1.

Kahn et al., Tellus 2009

We are aiming for Regional-to-Global

Aerosol-Air Mass-Type Discrimination

Something like this…

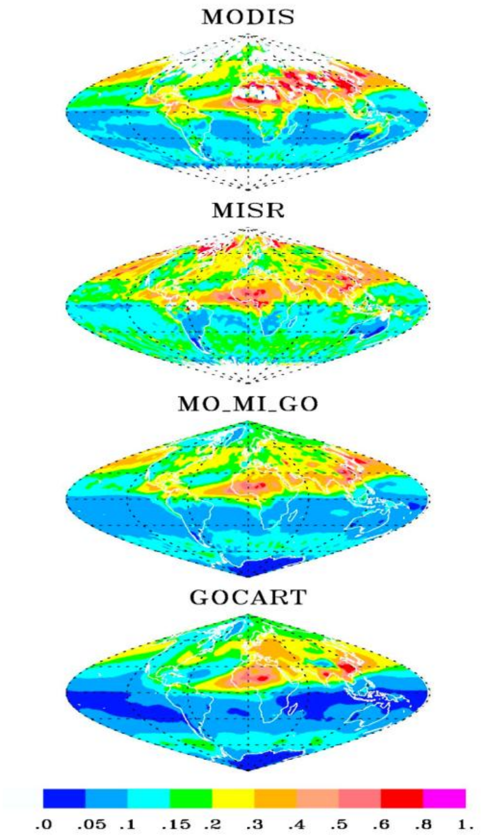


13 Groupings Based on Transport Model Aerosol Property Simulations

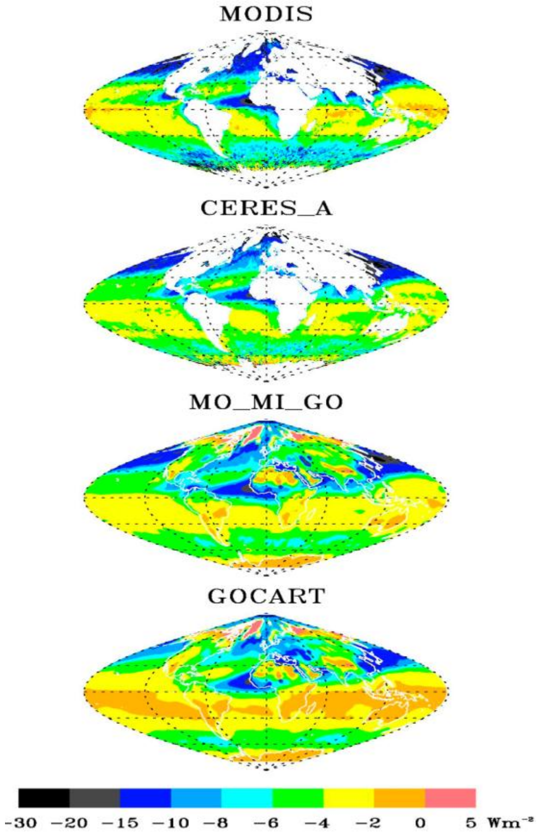
Kahn et al., JGR 2001

Constraints on Aspects of
Aerosol Climate Forcing

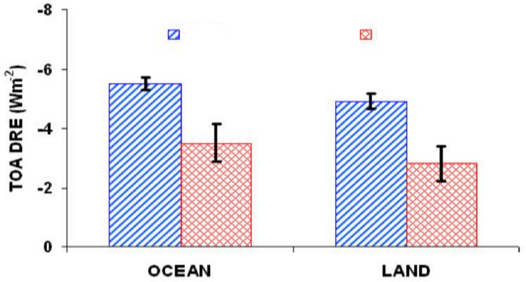
Global Aerosol Forcing Patterns: Measured, Modeled, & Merged



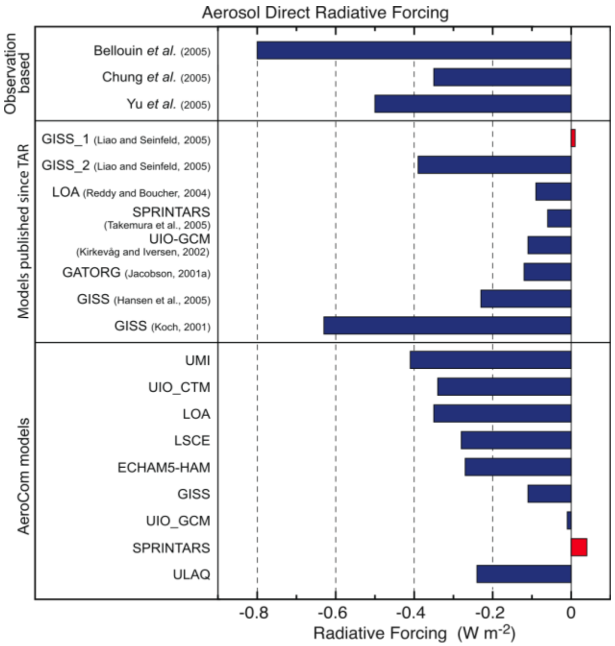
Seasonal (MAM)
Mid-vis AOD



Seasonal (MAM), Clear-sky
Diurnal-average TOA DARF



Annual, clear-sky, TOA DARF



Global, TOA, anthropogenic
DARF (Obs.-based shown at top)

Although spatial patterns are similar, *Model DARF* estimates are generally *smaller than observation*-based ones

From: *CCSP - SAP 2.3,* 2009

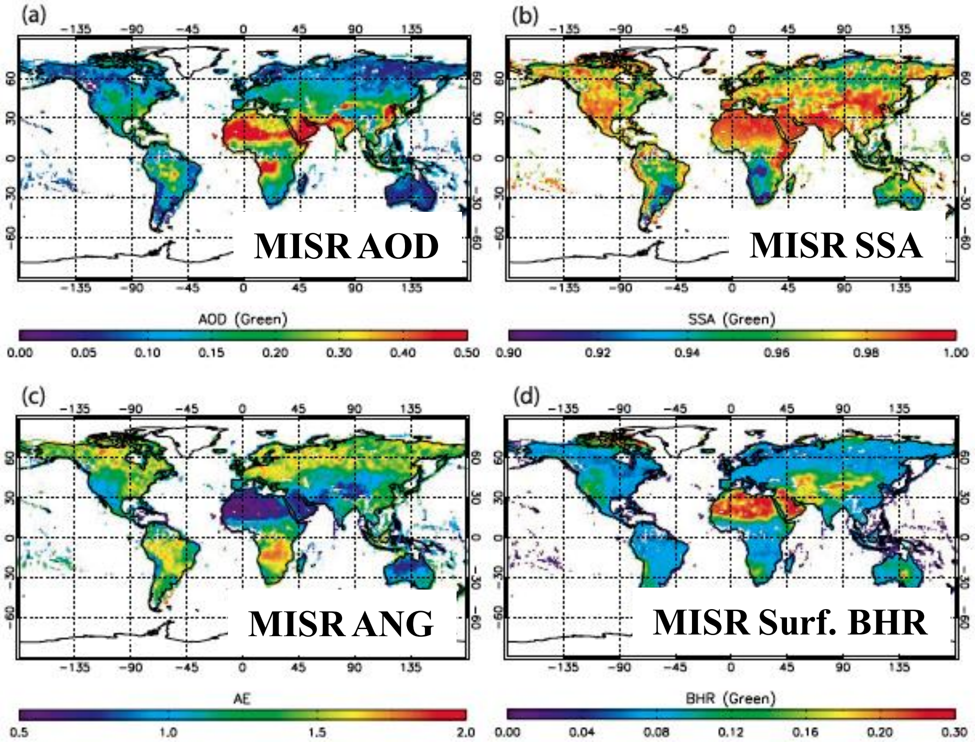
Over-Land Aerosol Short-wave Radiative Forcing w/Consistent Data

The slope of:

TOA albedo vs. AOD

For data stratified by:

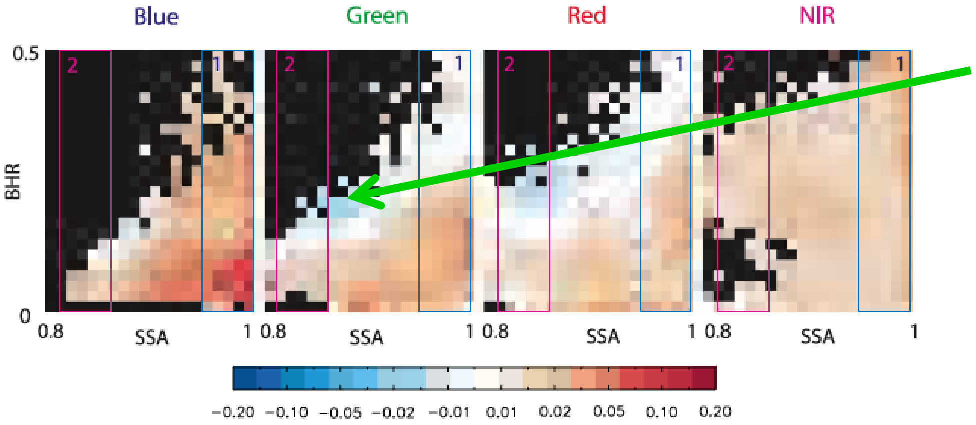
Surface BHR



Produces:

Spectral aerosol radiative efficiency

$(d\alpha_{TOA}/d\tau_{mid\text{-}vis})$

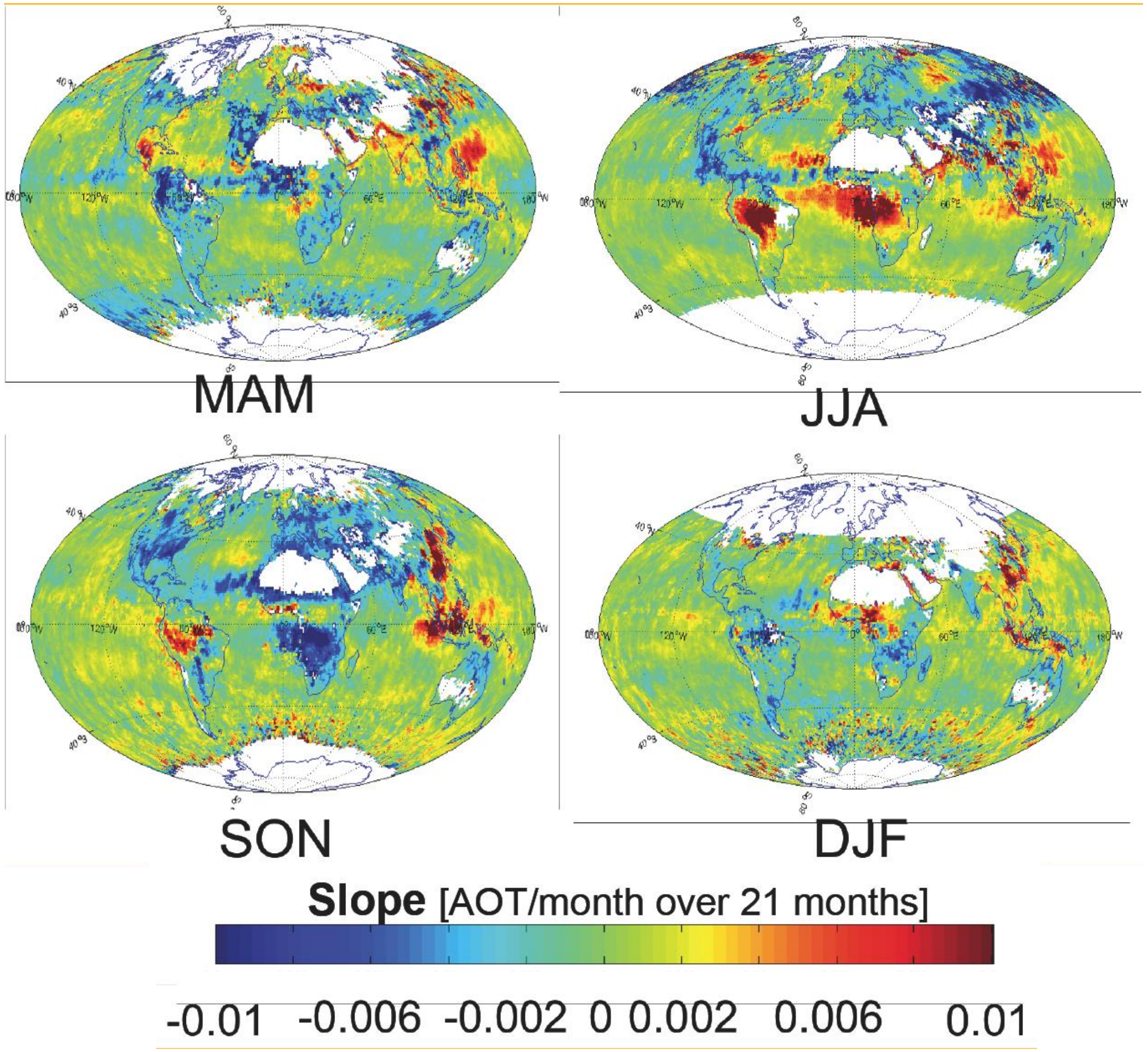


Bright surface + dark aerosol = decreasing albedo w/AOD

Depends on aerosol *microphysical* properties relative to surface albedo

Y. Chen et al. JGR 2009

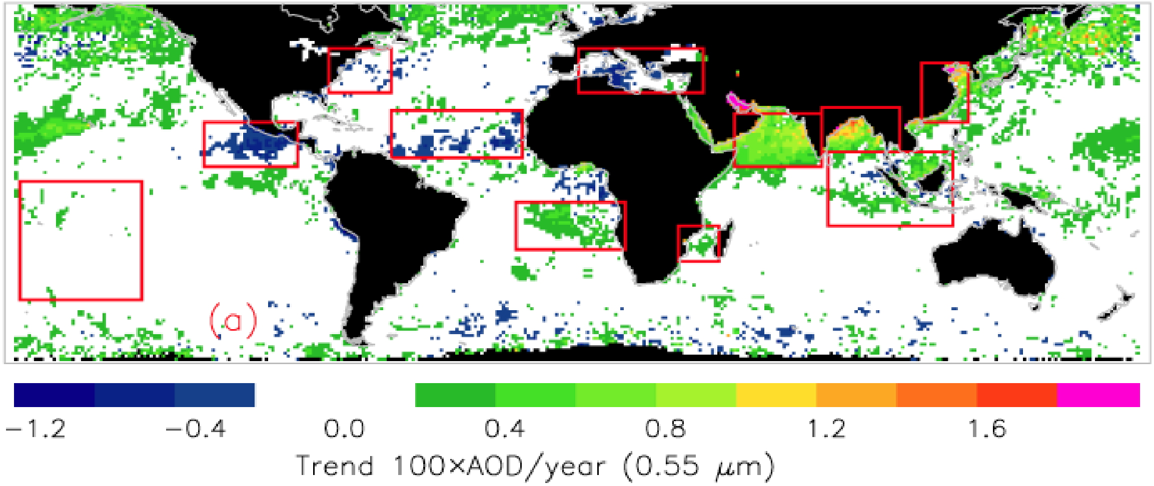
MODIS/Terra 7-Year Regional/Seasonal AOD Trends



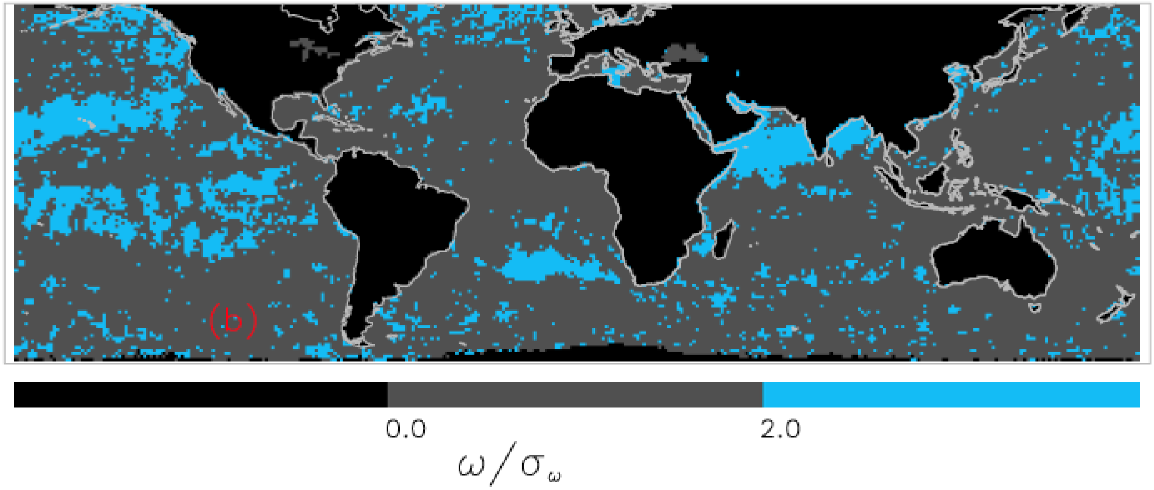
- Decrease over land, *except* E Asia + tropical Africa, S America, Indonesia burning seasons
- Increase over ocean, especially downwind of biomass burning areas

Remer et al.

MODIS 10-Year Global/Regional Over-Water AOD Trends



Trend



Statistical Significance

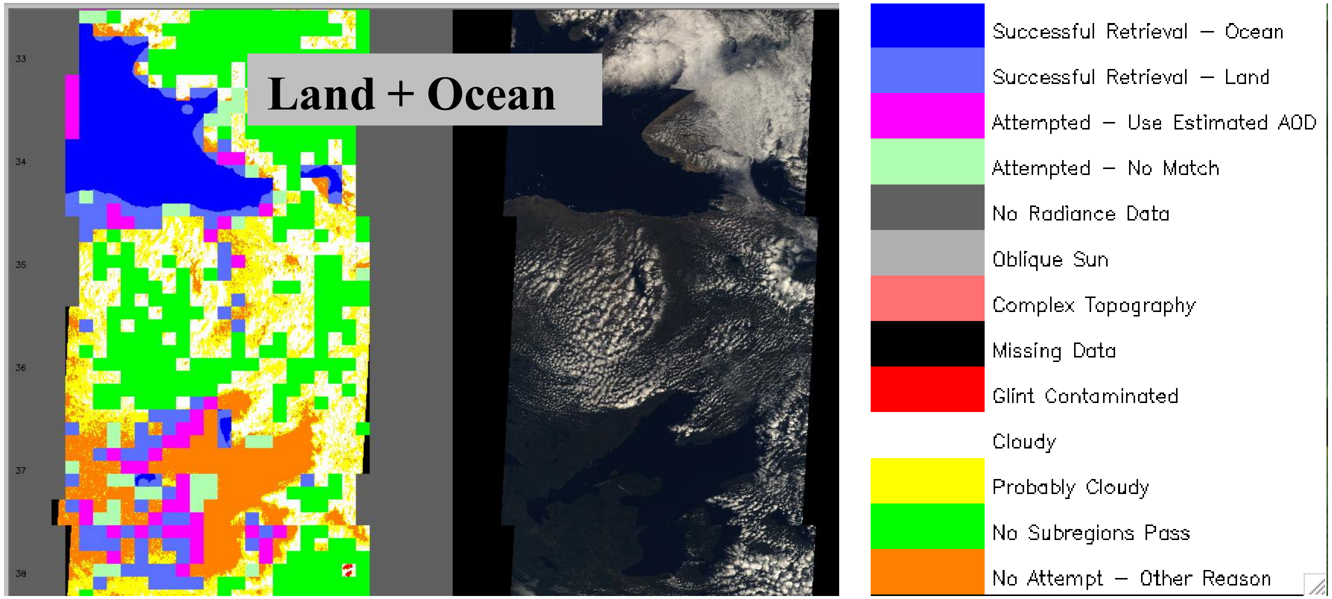
- Statistically ***negligible*** *(±0.003/decade)* ***global-average*** over-water AOD trend
- Statistically ***significant increases*** over the Bay of Bengal, E. Asia coast, Arabian Sea

Zhang & Reid, ACP 2010

MISR Retrieval Status Distribution

Overall, about **15%** of Earth's surface produces successful MISR automatic aerosol retrievals (about the same fraction for MODIS)

Dark blue = Ocean retrieval
Light blue = Land retrieval



Kahn, Nelson, Garay et al., TGARS, 2009

From experience with MISR & MODIS:

For global, ~ 1° × 1° AOD, in general, MISR data need to be aggregated to ***~ 3-month sampling*** *to converge with MODIS*

Key Attributes of the MISR **Version 22** Aerosol Product

- **AOT Coverage** – ***Global but limited sampling*** on a monthly basis
- **AOT Accuracy** – Maintained even when particle property information is poor
- **Particle Size** – ***2-3 groupings reliably***; quantitative results vary w/conditions
- **Particle Shape** – ***spherical vs. non-spherical robust***, except for coarse dust
- **Particle SSA** – useful for ***qualitative*** distinctions
- **Aerosol Type Information** – diminished when ***AOT < 0.15*** or 0.2
- **Particle Property Retrievals** – ***improvement expected*** w/algorithm upgrades
- **Aerosol Air-mass Types** – ***more robust*** than individual properties
- ***Sensitivity to particle properties varies enormously with conditions***!

PLEASE READ THE QUALITY STATEMENT!!!

… and more details are in publications referenced therein

Current MISR & MODIS Mid-Visible AOD Sensitivities

- MISR: **0.05 or 20% * AOD** overall; ***better over dark water***

[*Kahn et al*., 2005; 2010]

- MODIS: **0.05 or 20% * AOD** over land
  0.03 or 5% * AOD over dark water

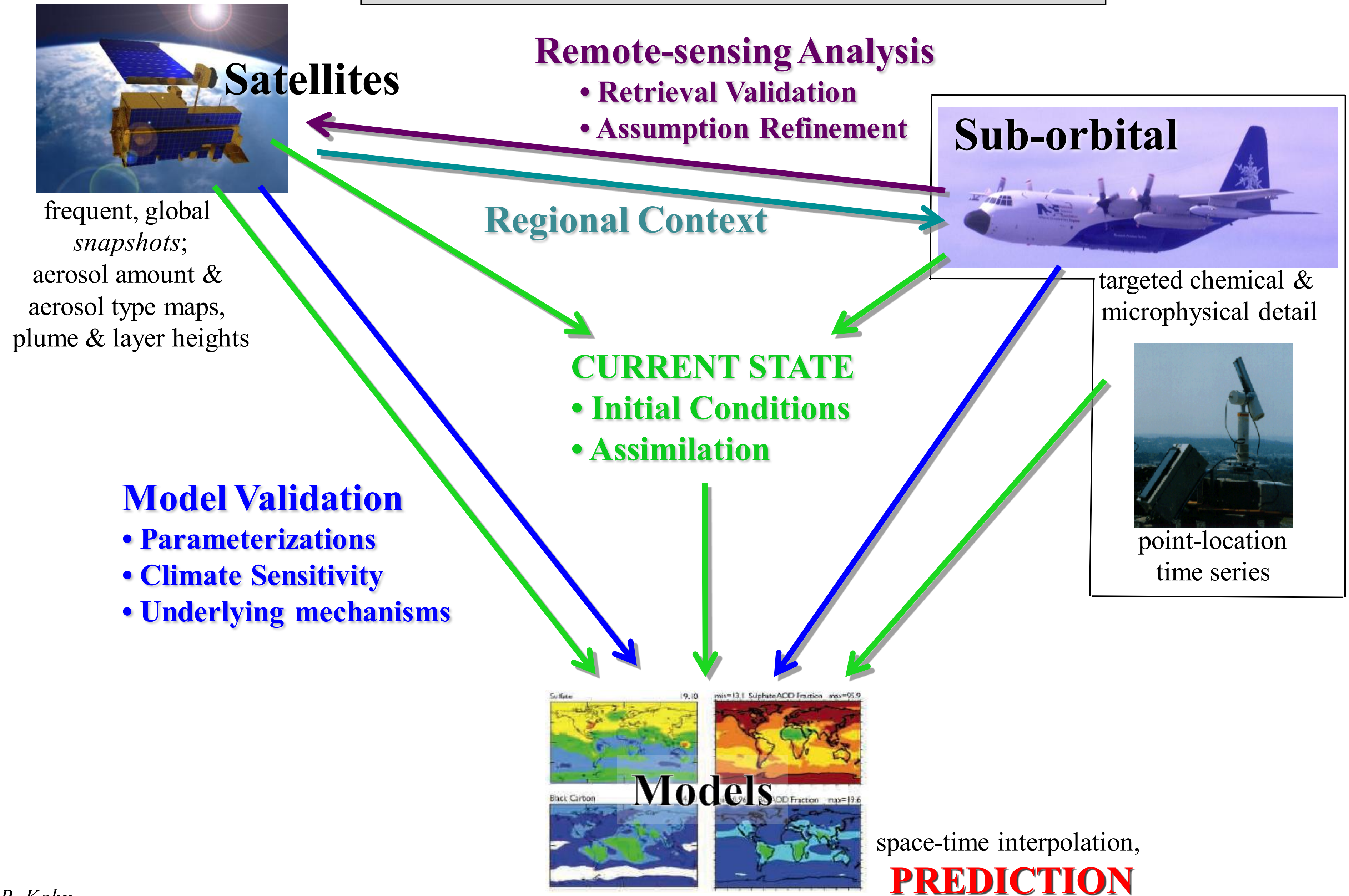
[*Remer et al*. 2005; 2008; *Levy et al*. 2010]

Based on AERONET coincidences (cloud screened by ***both*** sensors)

→ ***Direct Aerosol Radiative Forcing (DARF): Need AOD to <~ 0.02***

→ ***Particle Properties are Categorical rather than continuous Quantities***

Aerosol-Climate Prediction



Satellites

frequent, global *snapshots*;
aerosol amount &
aerosol type maps,
plume & layer heights

Remote-sensing Analysis
- **Retrieval Validation**
- **Assumption Refinement**

Regional Context

Sub-orbital

targeted chemical &
microphysical detail

point-location
time series

CURRENT STATE
- **Initial Conditions**
- **Assimilation**

Model Validation
- **Parameterizations**
- **Climate Sensitivity**
- **Underlying mechanisms**

Models

space-time interpolation,
PREDICTION

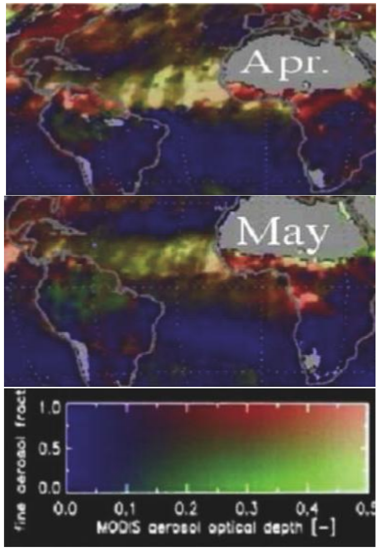
R. Kahn

Next Steps

- **Global Aerosol-Air-Mass-Type Maps**
  - Upgraded ***MISR*** retrievals + ***future missions***
- **Aerosol Size, SSA, Shape PDFs for Major Sources**
  - Systematic ***aircraft*** + surface measurements, of global scope
- **Aerosol Source Strength**
  - ***MODIS*** + MISR AOD snapshots as constraints on model sources (***Forward*** and/or ***Inverse Modeling***, ***Data Assimilation***)
- **Aerosol Vertical Distribution**
  - ***CALIOP*** global lidar (downwind) + MISR stereo (near-source)
- **Aerosol Transports**
  - Global AOD Maps: ***MODIS*** + ***MISR*** + ***TOMS/OMI*** + ***POLDER*** + …
- Plan for ***Future Satellite Missions***

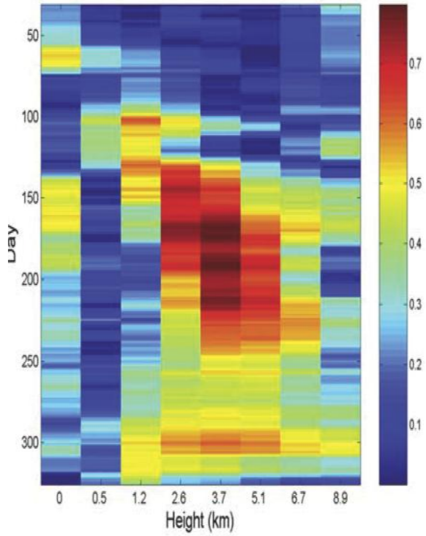
Backup Slides

Aerosol Material Fluxes: Atlantic Dust & Asian Pollution



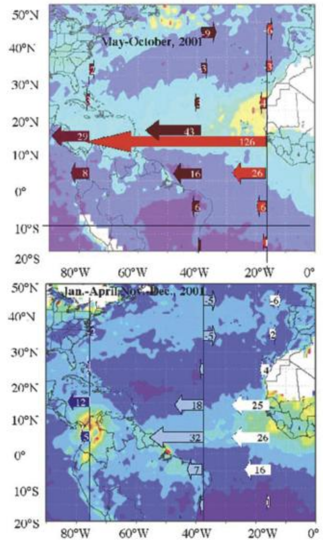
MODIS AOD & Type

Low AOD, **Fine BioBurn**, **Coarse Dust**



NCEP **W Wind** - MODIS **AOD**

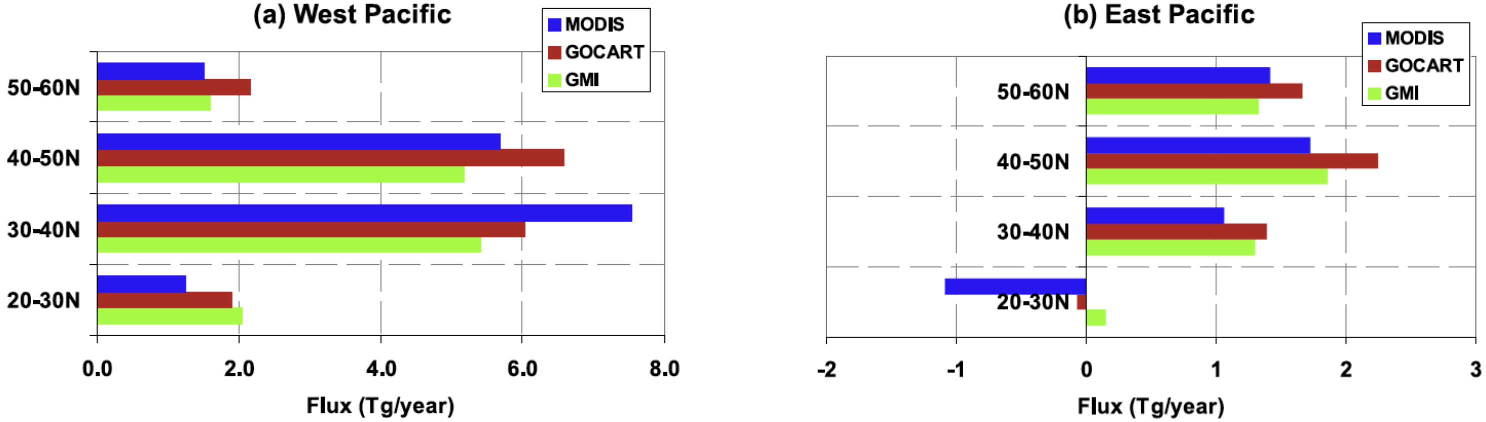
Correlation 2.6-5 km; May-October



Dust Transport Estimate (Tg)

May-October (Top) January-April (Bot)

Kaufman et al., JGR 2005

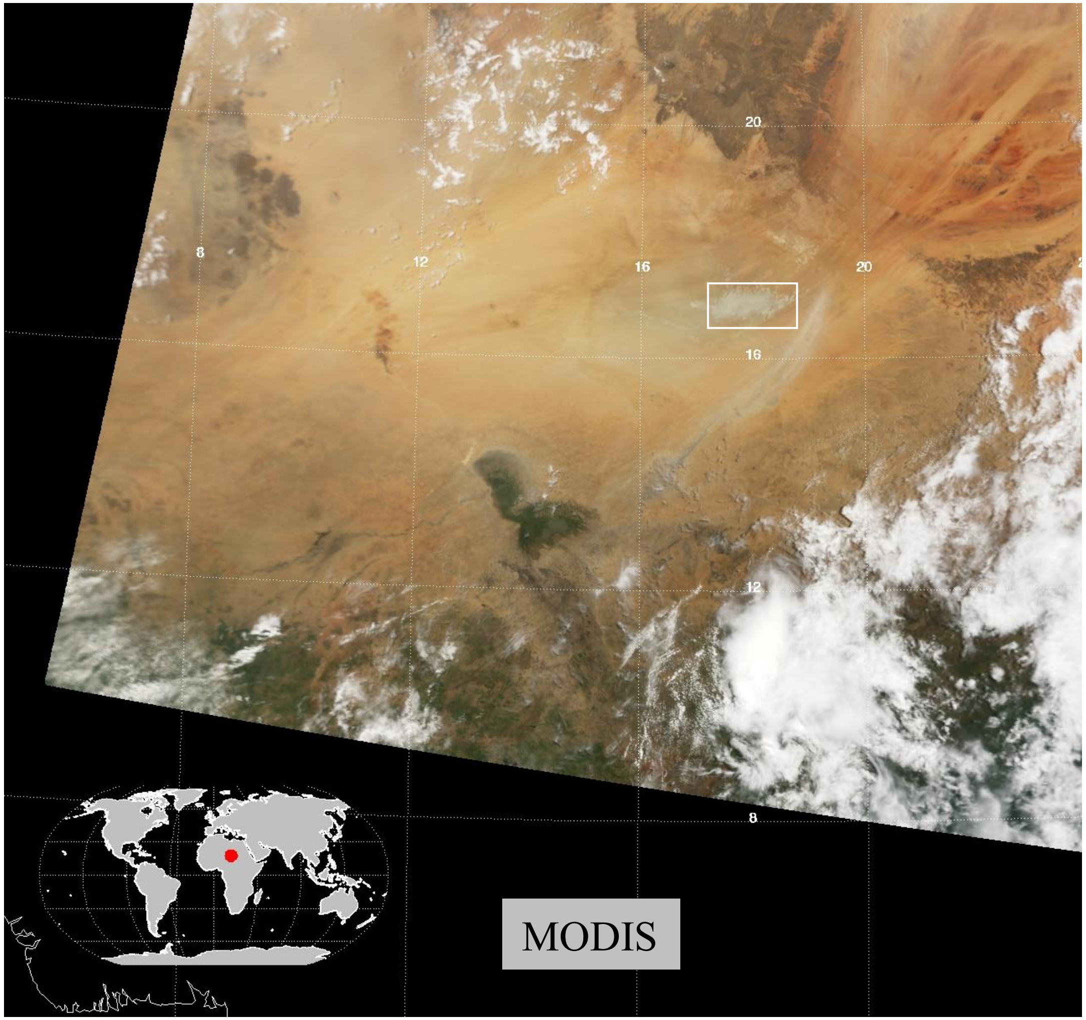


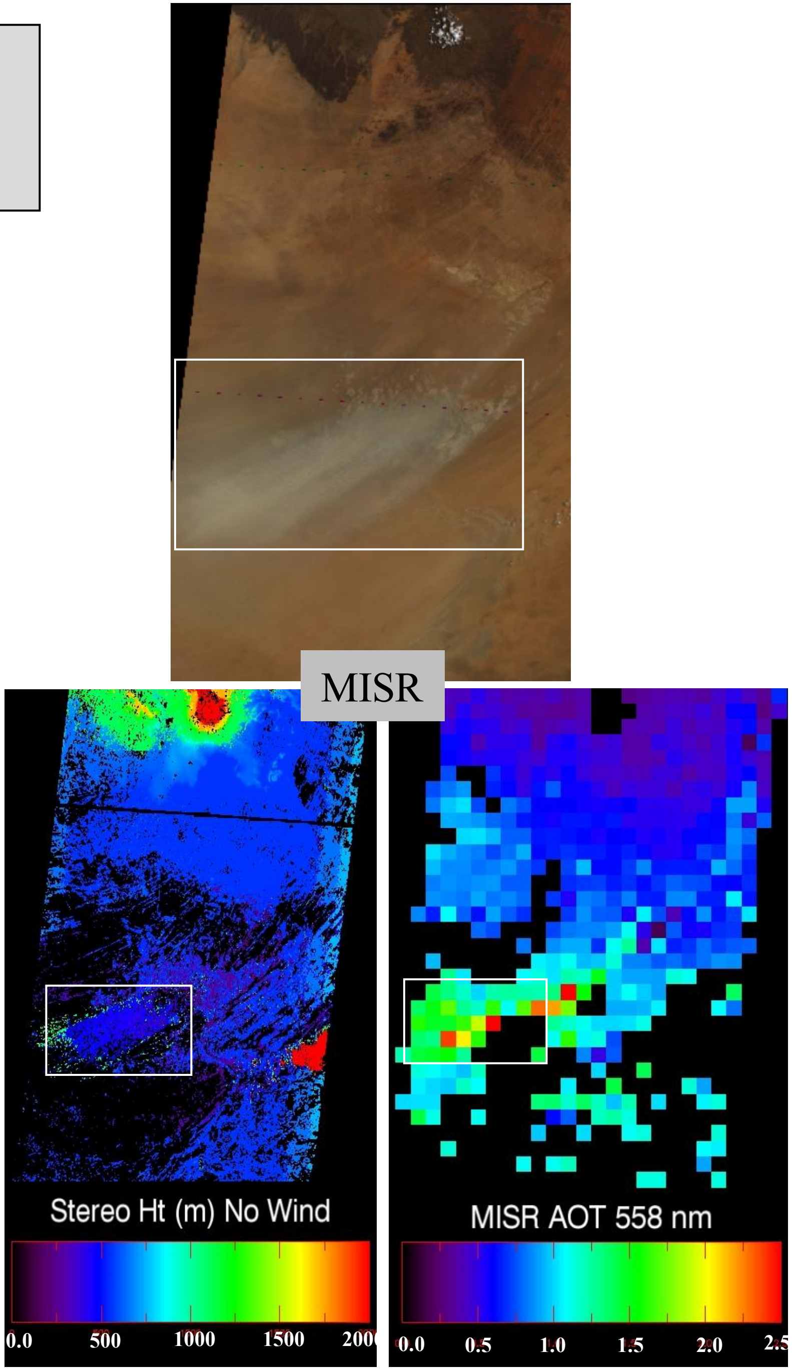
MODIS AOD & type, **Field Campaign** aerosol properties & vertical distribution, GEOS model winds; Compared with GOCART and GMI model Fine-particle mass fluxes

Yu et al., JGR 2008

Saharan Dust Source Plume

Bodele Depression Chad June 3, 2005 Orbit 29038



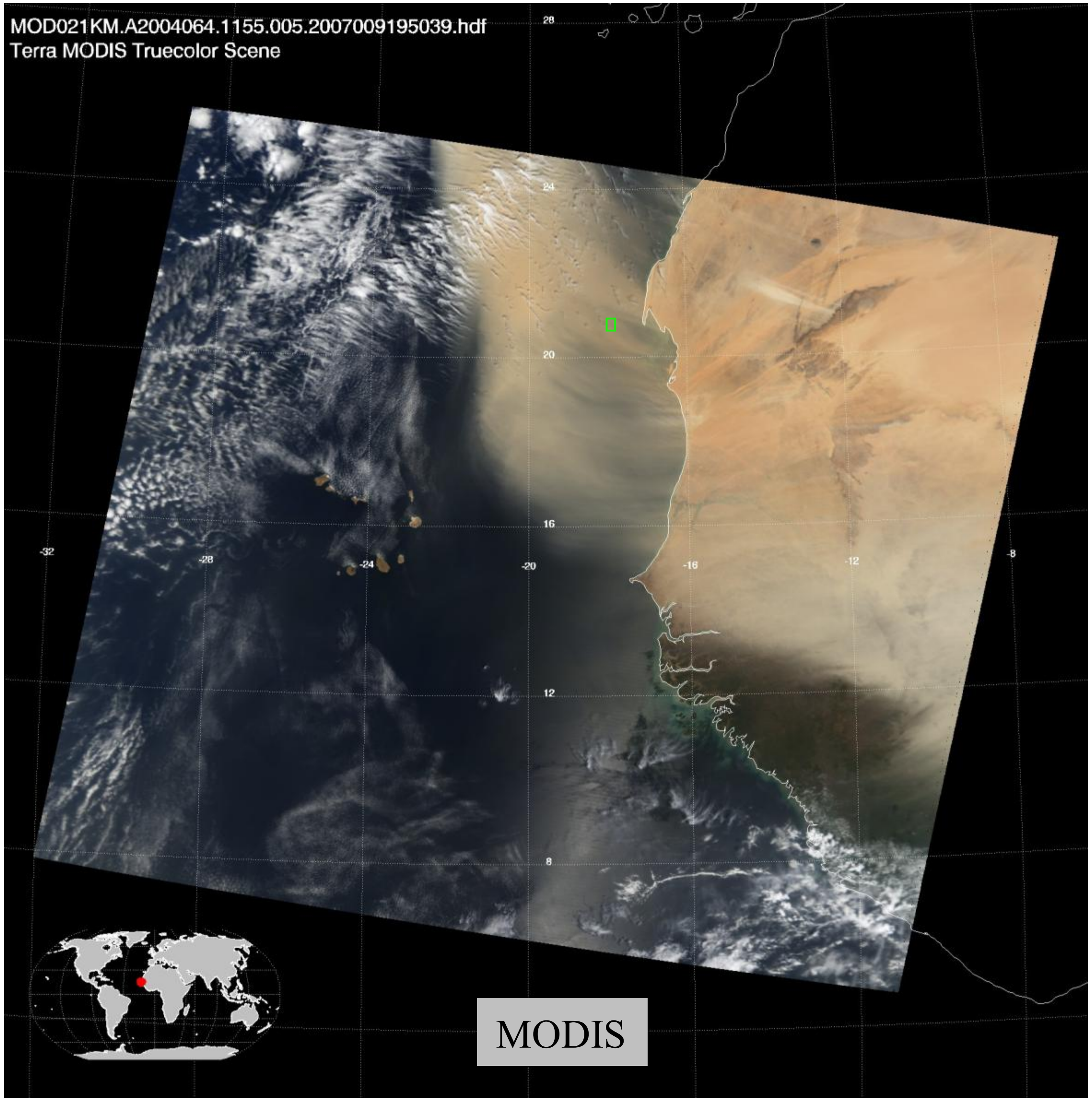


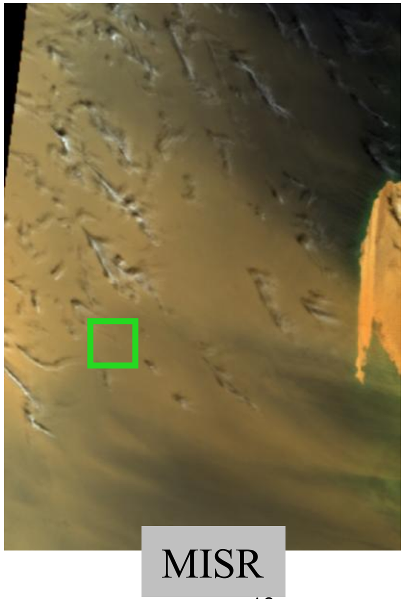
Dust is injected near-surface…

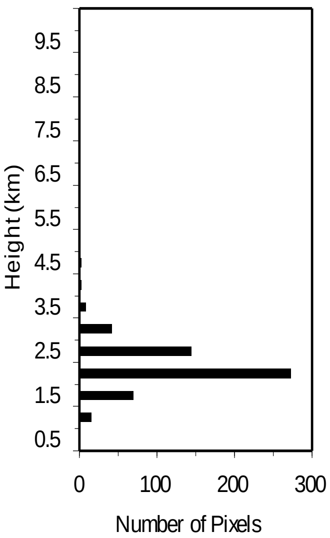
Kahn et al., JGR 2007

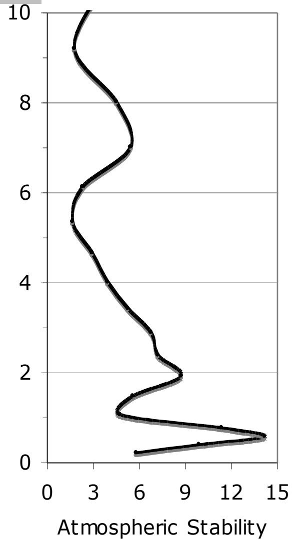
Transported Dust Plume

Atlantic, off Mauritania March 4, 2004 Orbit 22399







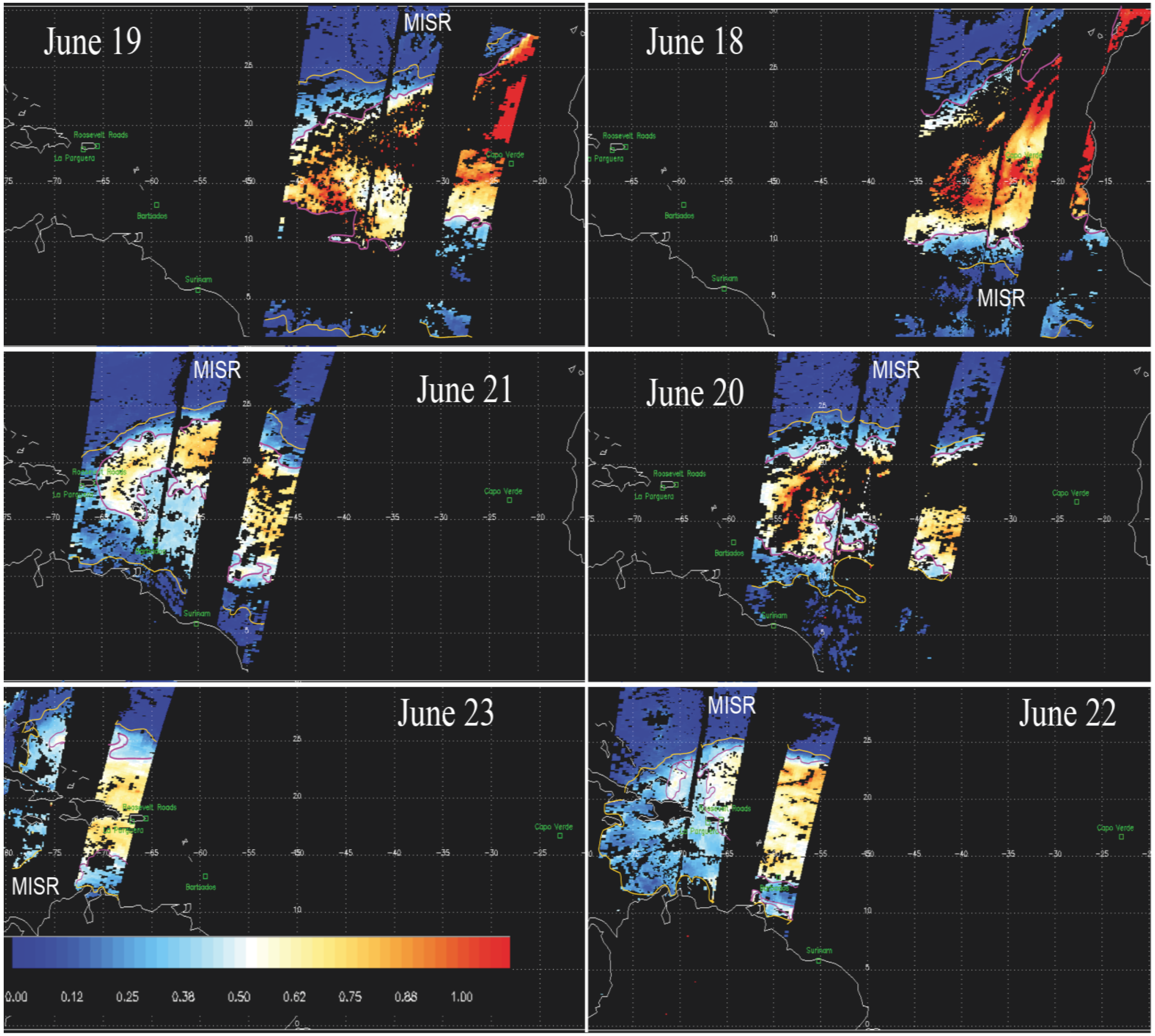


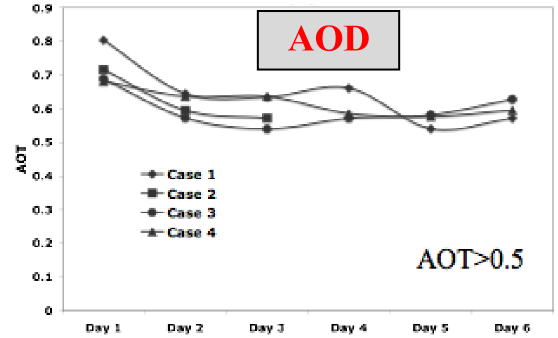
Transported dust finds elevated layer of relative stability…

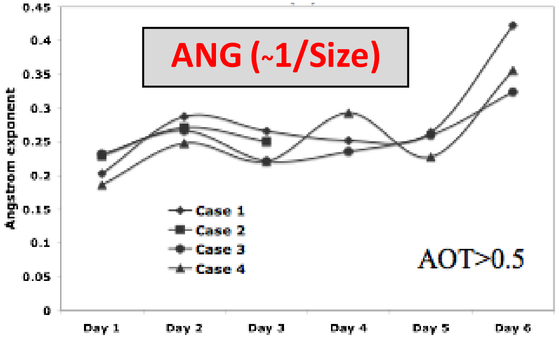
Kahn et al., JGR 2007

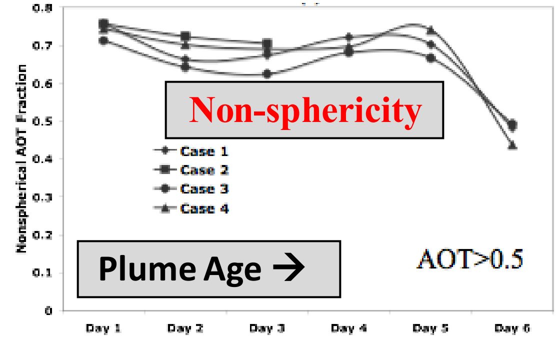
Constraining Aerosol Sources, Transports, & Sinks

Complementary MISR & MODIS AOD; Saharan Dust Plume over Atlantic June 19-23, 2000





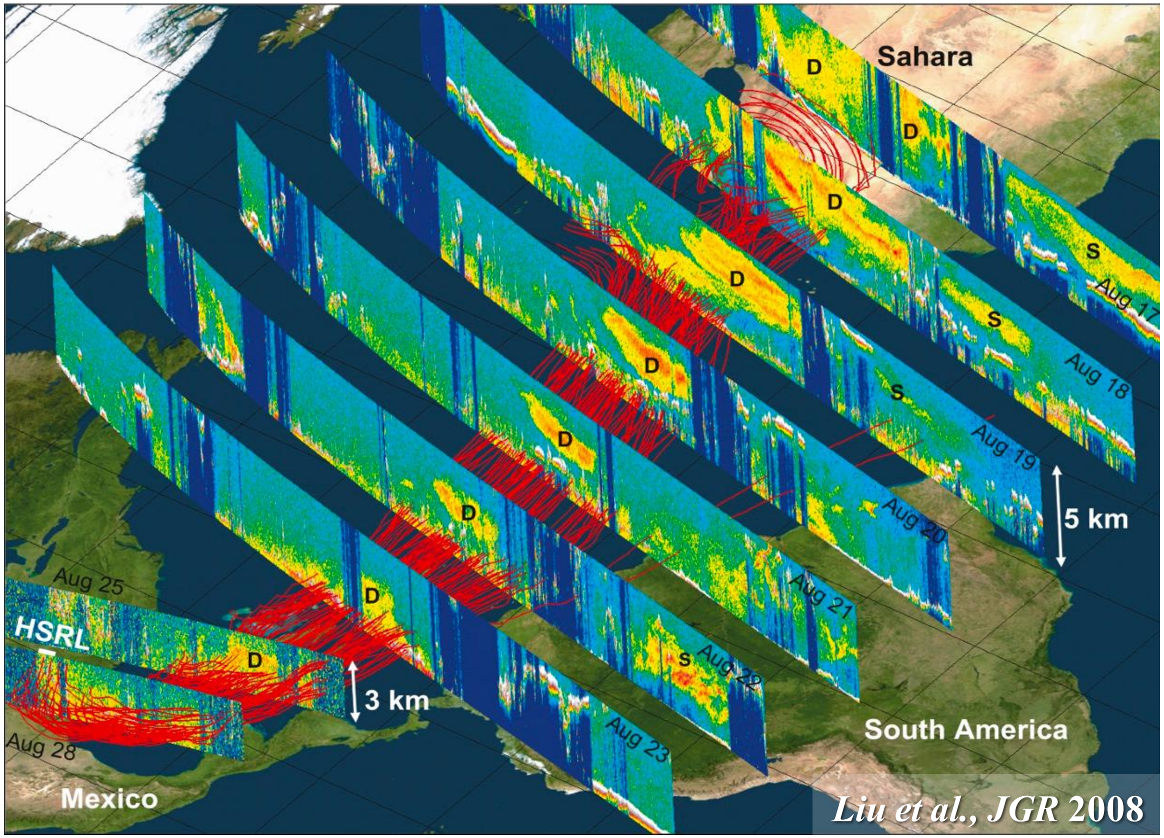




Contours: AOT=0.15 (yellow); AOT=0.5 (purple)

Kalashnikova and Kahn, JGR 2008

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

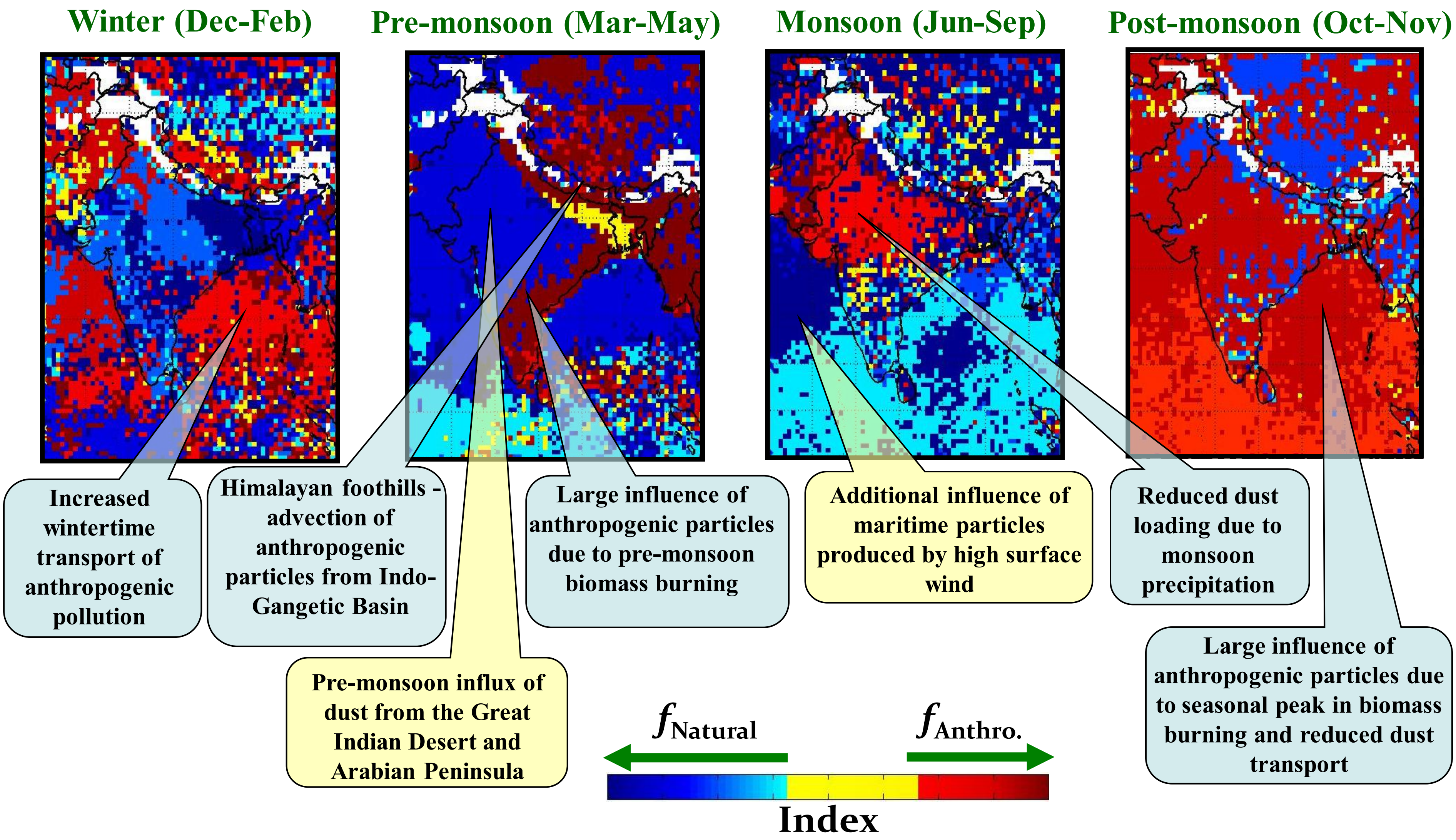


August 2007 Saharan dust "D" and smoke "S" event
mapped by CALIPSO 532 nm backscatter, with superposed
model back trajectories and airborne HSRL observations

Piecing together the bigger picture. Consistency requires –

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

Seasonal Changes in Anthropogenic and Natural Aerosol Types Over India



Winter (Dec-Feb)

Pre-monsoon (Mar-May)

Monsoon (Jun-Sep)

Post-monsoon (Oct-Nov)

Increased wintertime transport of anthropogenic pollution

Himalayan foothills - advection of anthropogenic particles from Indo-Gangetic Basin

Large influence of anthropogenic particles due to pre-monsoon biomass burning

Additional influence of maritime particles produced by high surface wind

Reduced dust loading due to monsoon precipitation

Pre-monsoon influx of dust from the Great Indian Desert and Arabian Peninsula

Large influence of anthropogenic particles due to seasonal peak in biomass burning and reduced dust transport

Index uses MISR-retrieved particle shape and size constraints to separate natural from anthorpogenic aerosol

Dey & Di Girolamo JGR 2010