Airborne Particles:

What We've Learned About Their Role in Climate From *Remote Sensing*, And Prospects for Future Advances

Ralph Kahn *NASA Goddard Space Flight Center*

Haboob, Khartoum Sudan 2007

Photo Credit: *Paul Currion on Flicker*

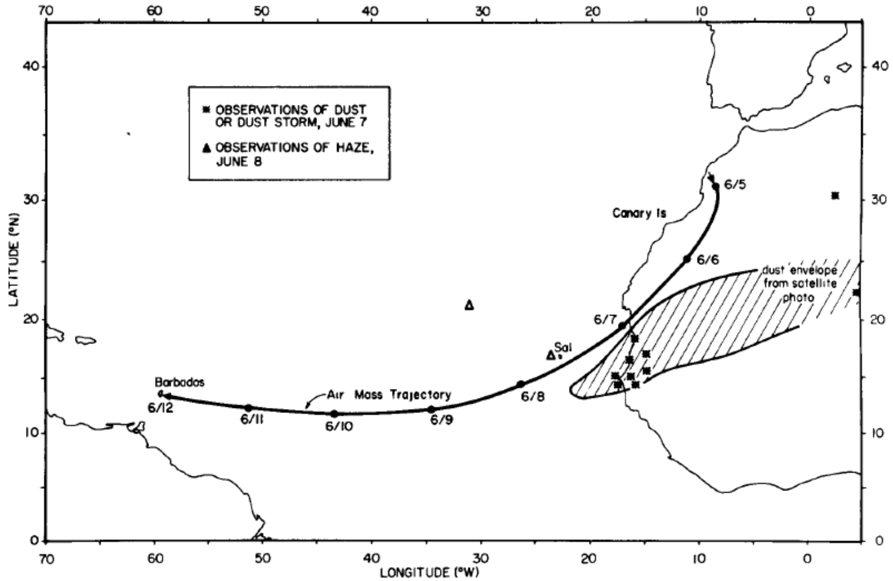
Mt. Etna Eruption 27-30 October 2002

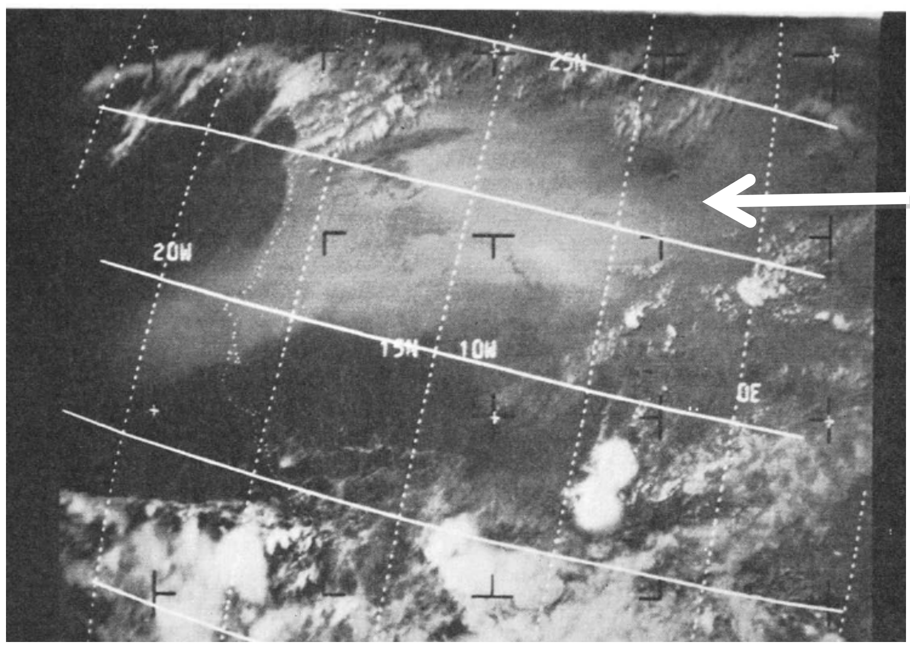
Station Fire near JPL, Pasadena CA August-September 2010

From: http://hometown-pasadena.com

Saharan Dust Plume *Tracked Across the Atlantic*

05-12 June 1967 *ESSA-5 Vidicon Imager*

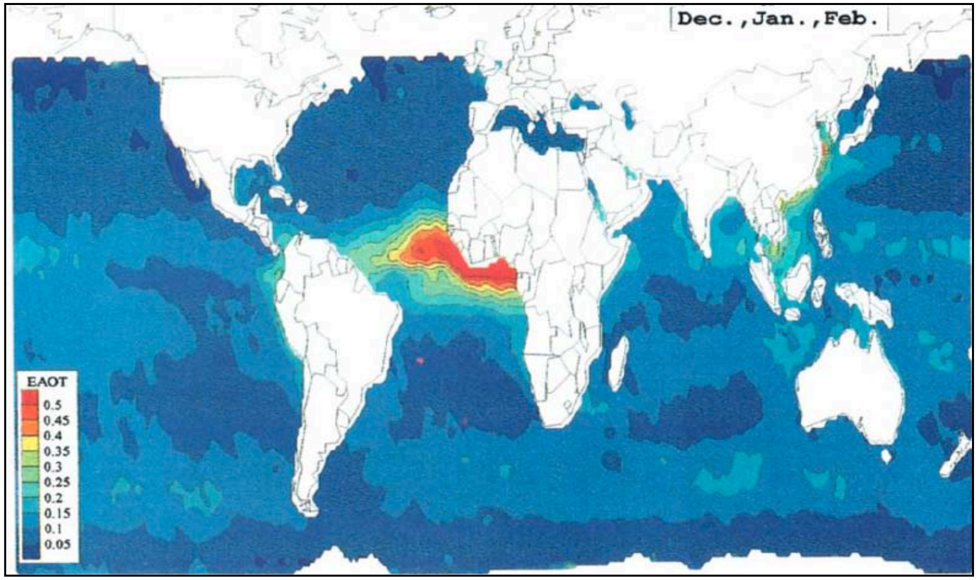




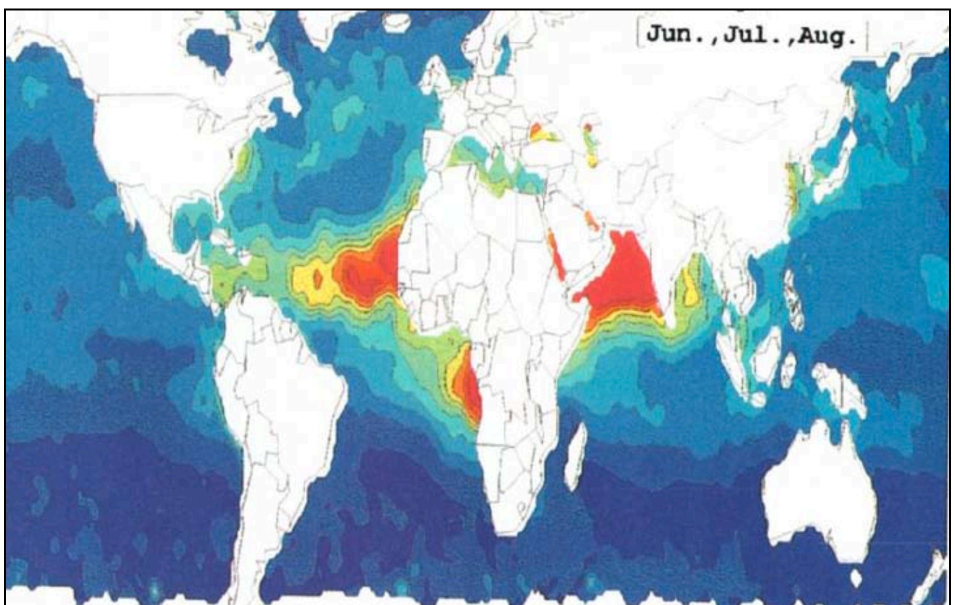
Over Mauritania, Western Sahara, and the eastern Atlantic
7 June 1967

From: *Prospero et al., Earth & Planet. Sci. Lett. 1970*

Global, Over-Ocean Column Aerosol Amount
July 1989 - June 1991 NOAA AVHRR



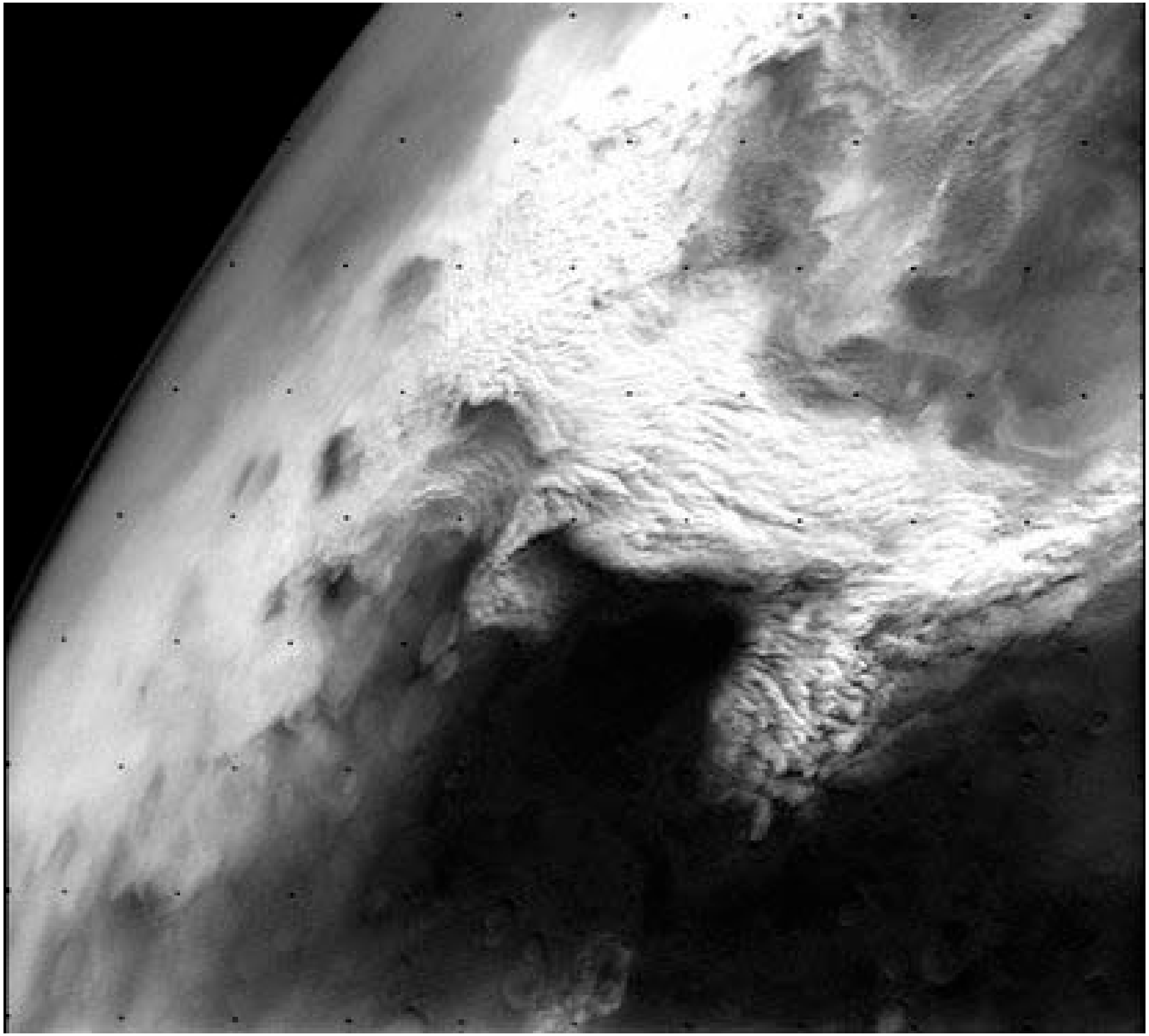
Northern Winter



Northern Summer

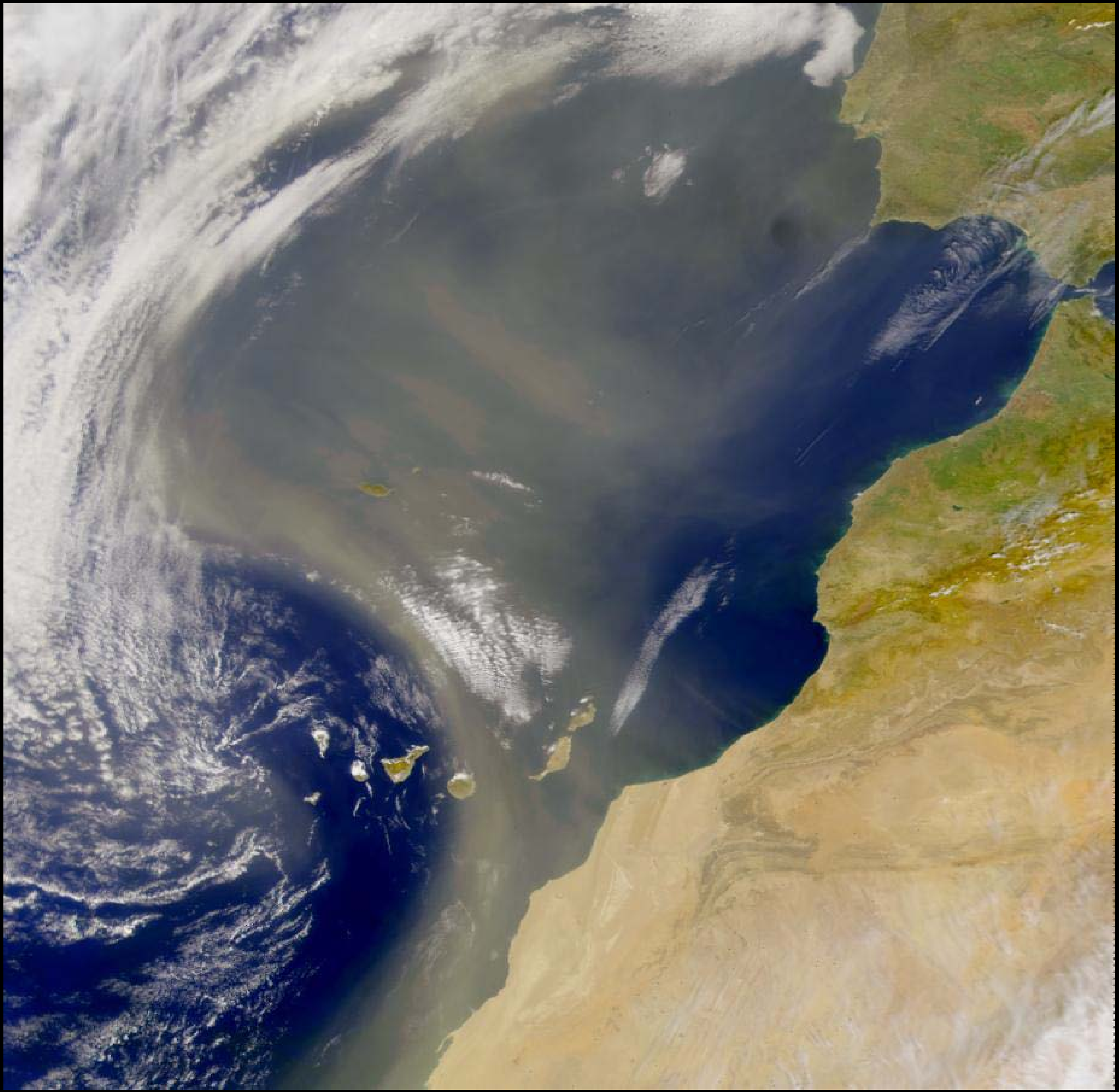
From: *Husar et al., JGR 1997*

Mars Dust Storm – Viking Orbiter 1976

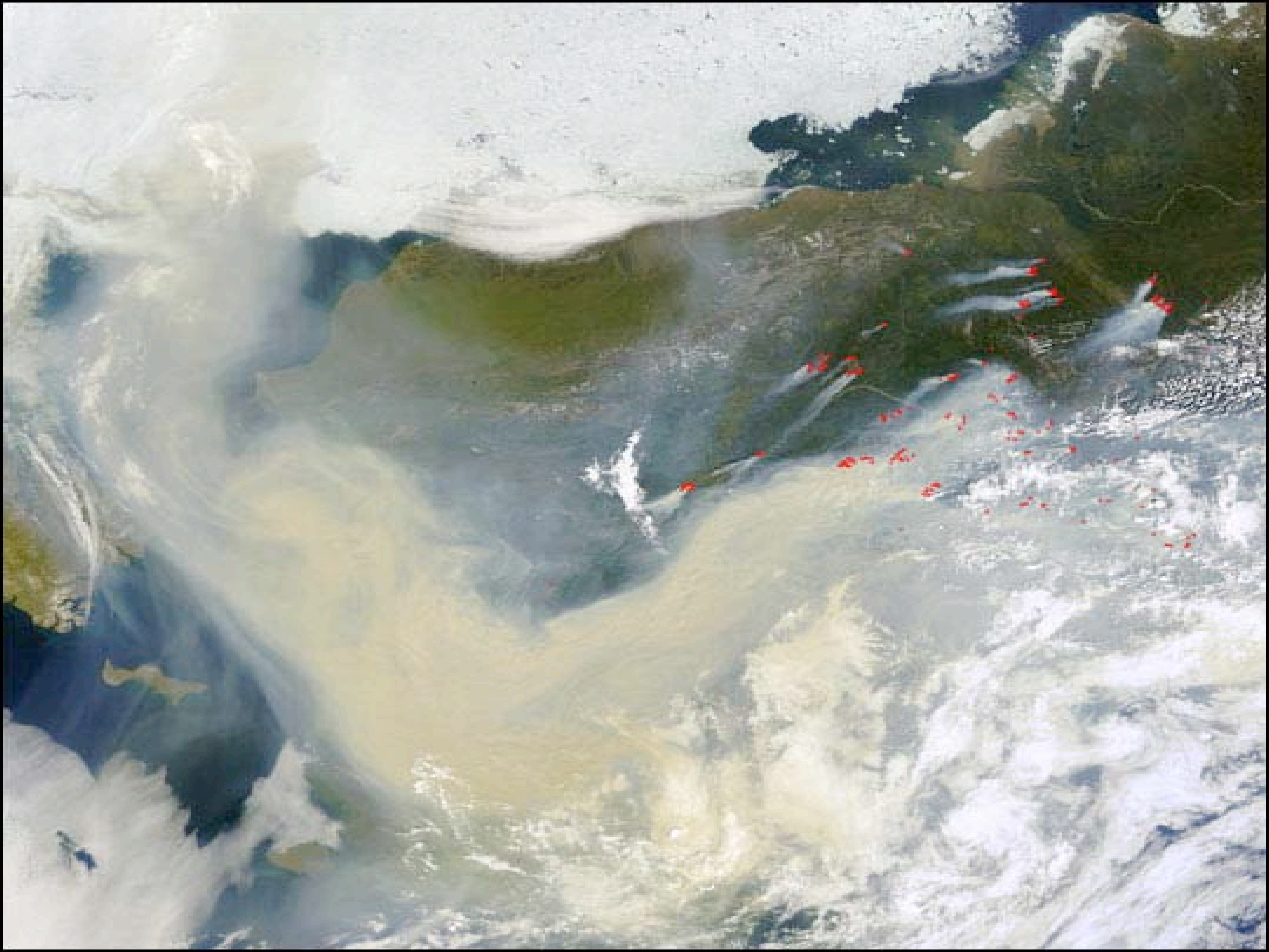


Martian Sky – Viking Lander 1, 1976

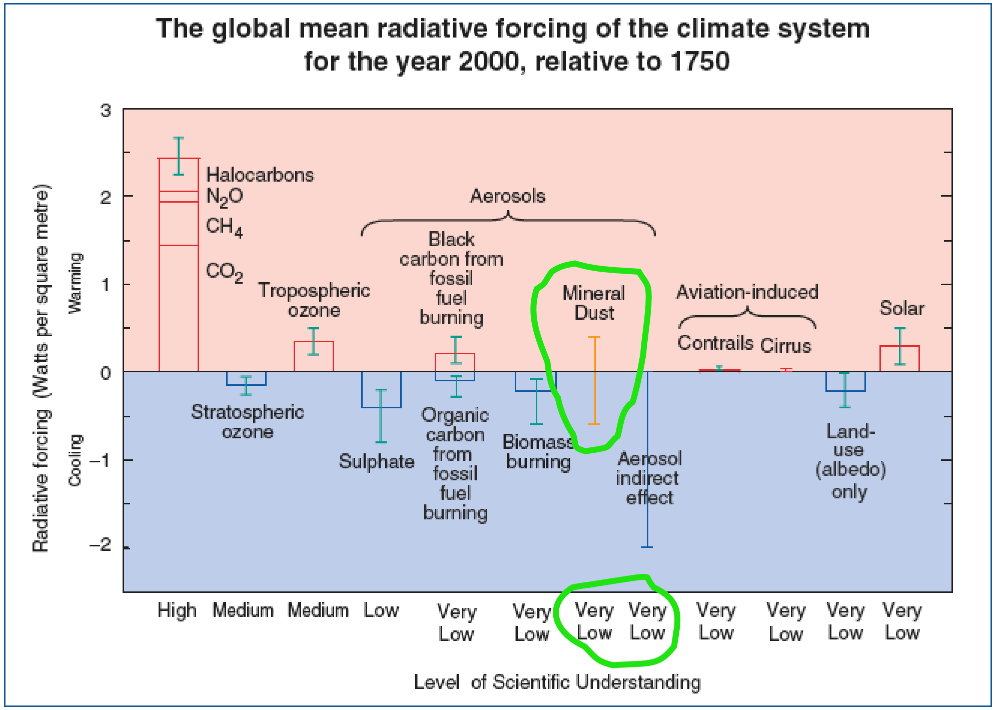
SeaWiFS – Sahara Dust over Canary Islands *06 March 1998*



MODIS – ***Fires in Alaska*** *01 July 2004 21:40 UTC*



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



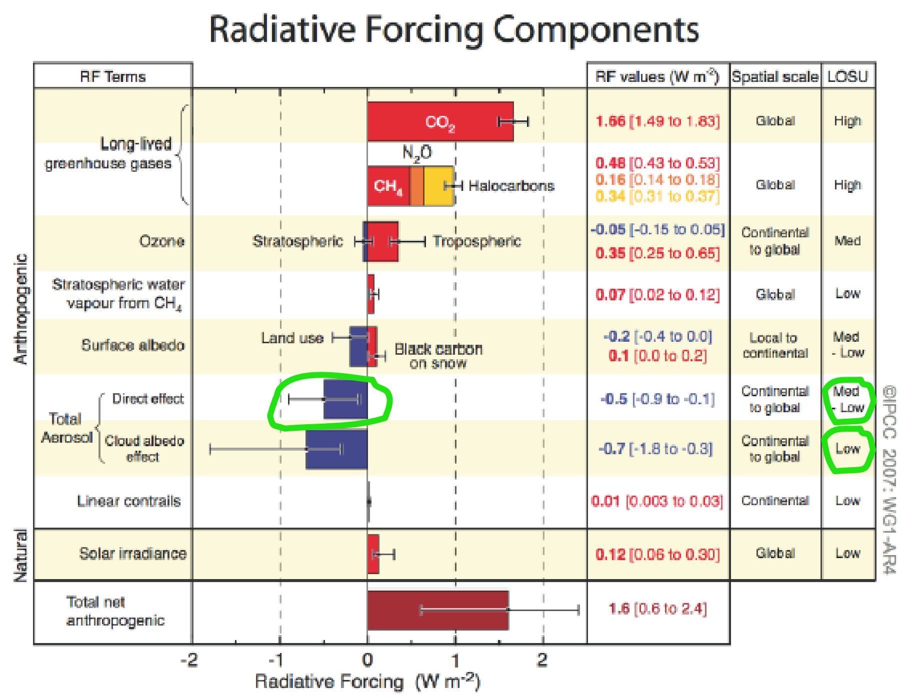
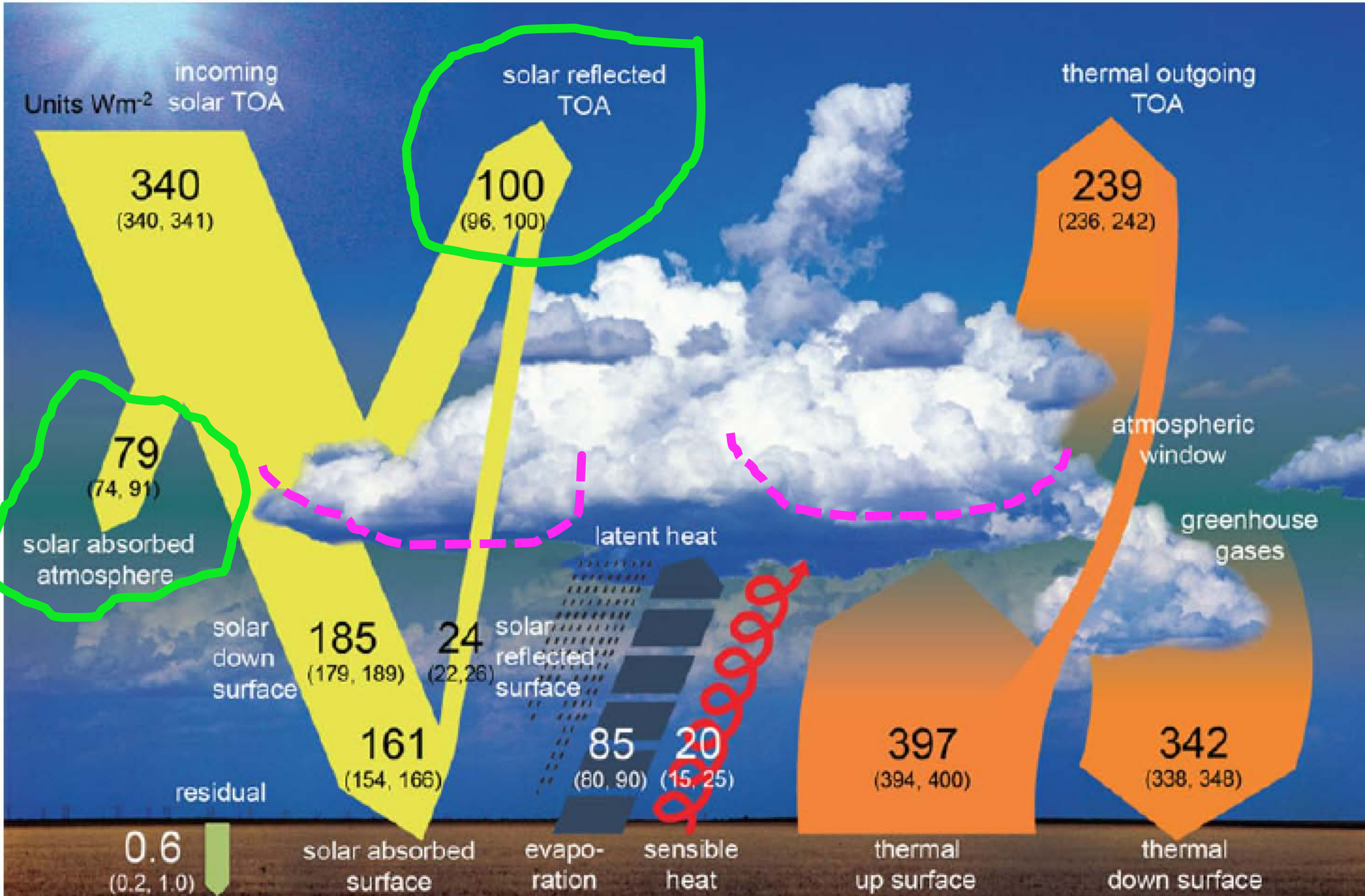


FIGURE SPM-2. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level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

Global Energy Flows (W/m²)



Wild et al., BAMS 2012

Aerosol Contribution to Global Climate Forcing

• Cloud-free, global, ***Over-ocean***, vis, TOA DARF relative to zero aerosol: **-5.5 ± 0.2** W/m^2

This is a ***measurement-based*** value**,** with ***uncertainty based on diversity*** among estimates (actual uncertainties are probably larger)

• Taking 20% of aerosol to be anthropogenic, the ***human-induced component*** is: **-1.1 ± 0.4** W/m^2

• Global TOA ***anthropogenic total*** ARF relative to pre-industrial: **-1.3 (-2.2 to -0.5)** W/m^2

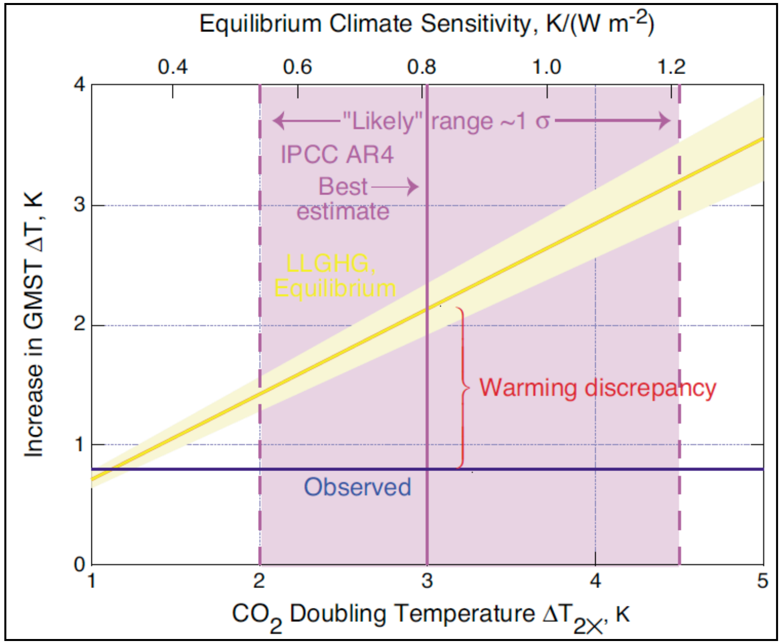
This is a ***model-based*** value**,** with ***uncertainty defined as diversity*** among estimates; (actual uncertainties are probably much larger)

• The models tend to agree on global AOD (as constrained by satellite & surface obs.), but differ on ***regional-scale AOD***, aerosol ***SSA***, and ***vertical distribution***

From: *CCSP - SAP 2.3*, 2009

How Good is "*Good Enough*"??

Climate Sensitivity, Aerosols, and Climate Prediction



Schwartz et al., 2010

$$F \times S = \Delta T$$

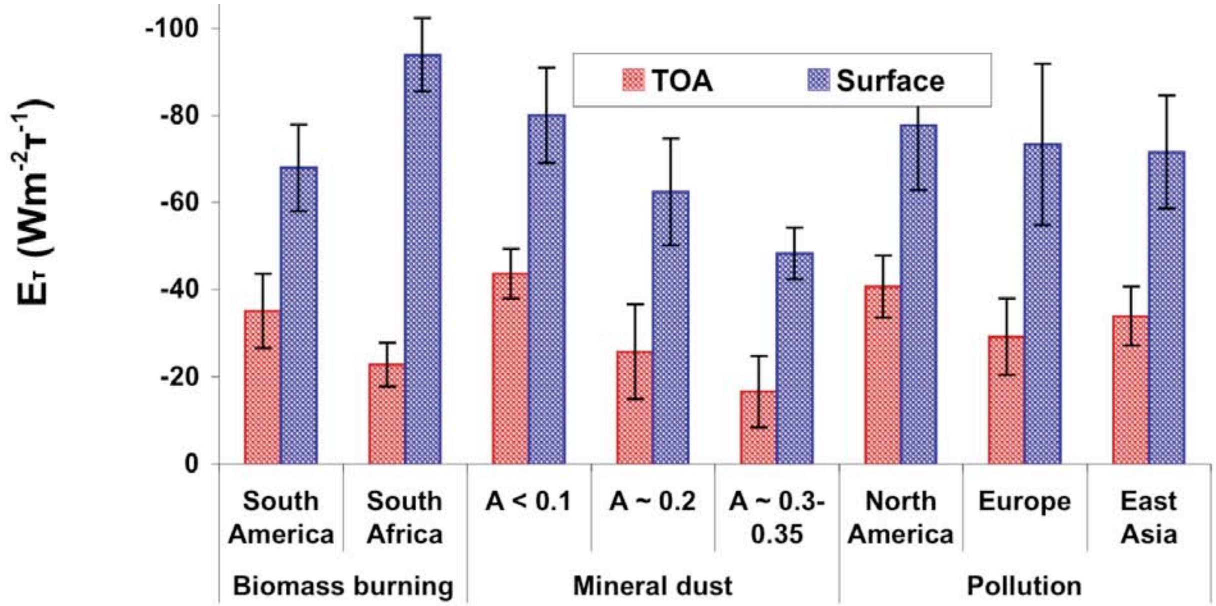
F: Effective Forcing; S: Climate Sensitivity; ΔT: Response

- ***Models are constrained by*** historical global mean surface temperature (***GMST***) ***change***
- Forcing by LL greenhouse gas increase since pre-industrial: ~ 2.6 W/m^2
- ΔGMST ***Expected***: ~ 2.1 K; ΔGMST ***Observed***: ~ 0.8 K
- ***Discrepancy dominated by Aerosol Forcing vs. S*** (disequilibrium, natural variation, etc. are less)
- ***Model Aerosol Forcing choices compensate for Climate Sensitivity differences*** (*Kiehl, GRL 2007*)

→ Aerosol forcing uncertainty directly impacts confidence in model predictions
From a policy perspective, this bears upon the *urgency of mitigation* efforts

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

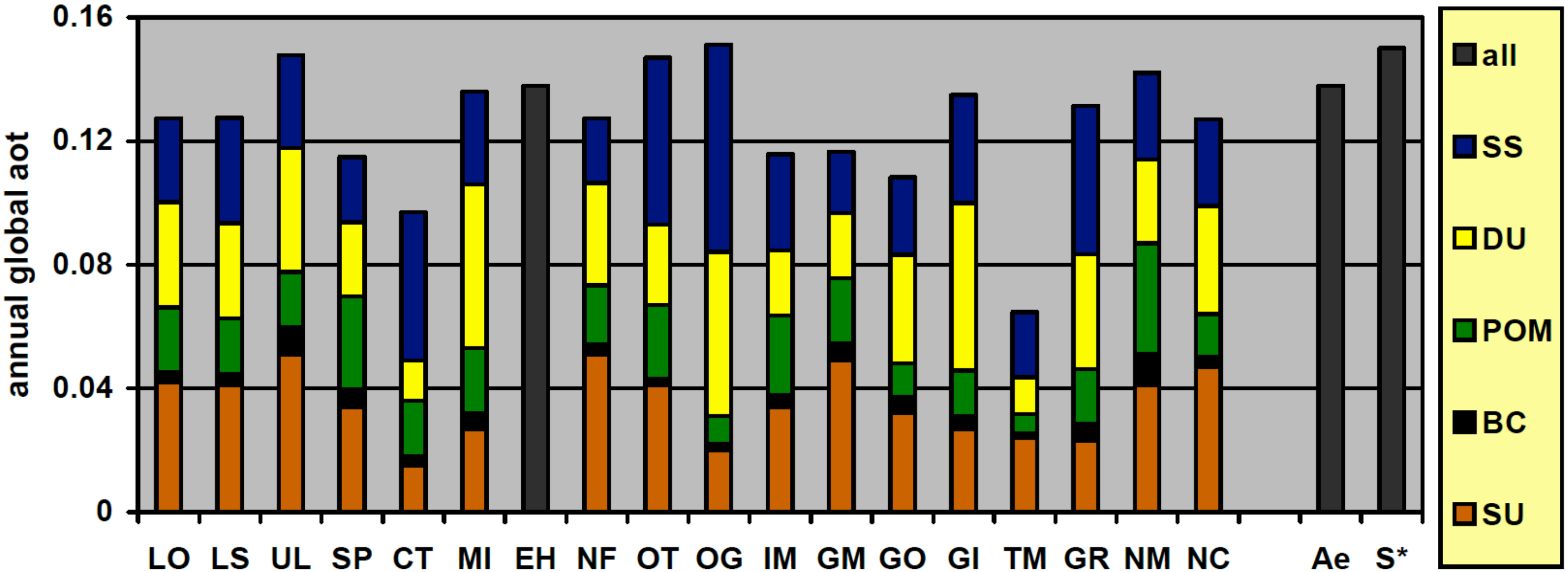
Direct Aerosol Radiative *Forcing Efficiency* per unit AOD



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

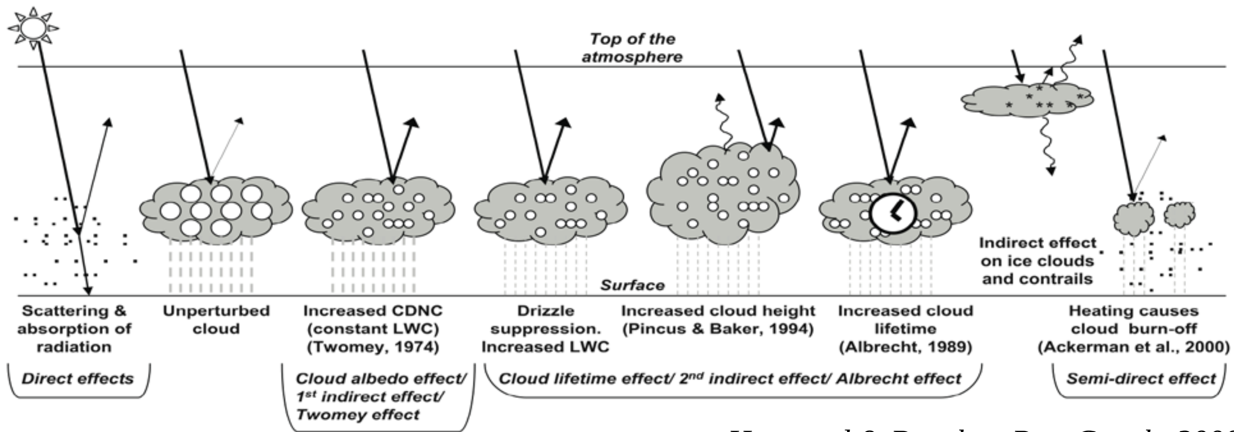
• The next big observational challenge: Producing ***monthly, global maps of Aerosol Type***

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

Aerosols "Indirect" Forcing of Clouds

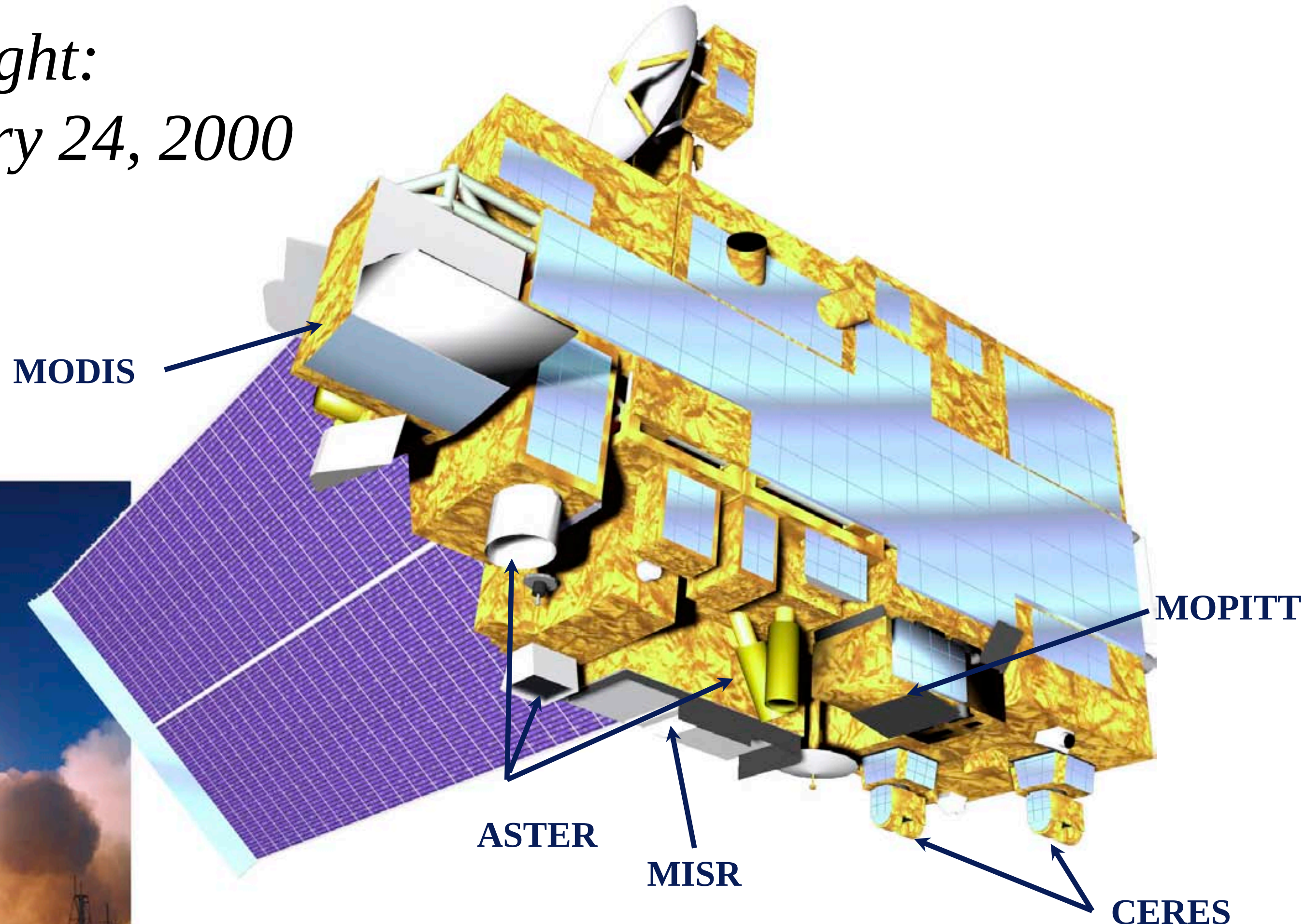


Haywood & Boucher, Rev. Geoph. 2000

- **Aerosol *Particle Size* Matters**
  - -- Not easy for remote-sensing techniques to observe ***the smallest, most numerous*** CCN
  - -- Deducing small-size CCN from larger-particle distribution depends sensitively on ambient RH
- **Aerosol *Particle Composition* Probably Matters Too**
  - -- Remote-sensing not very sensitive to particle chemistry (***polarization*** should help)
- ***Location*, Location, Location**
  - -- Satellite remote-sensing cannot observe aerosol ***below*** most clouds; difficult observing aerosol near clouds as well
- ***Clouds, Ambient Meteorology*** Affect Aerosol Retrievals

The NASA Earth Observing System's Terra Satellite

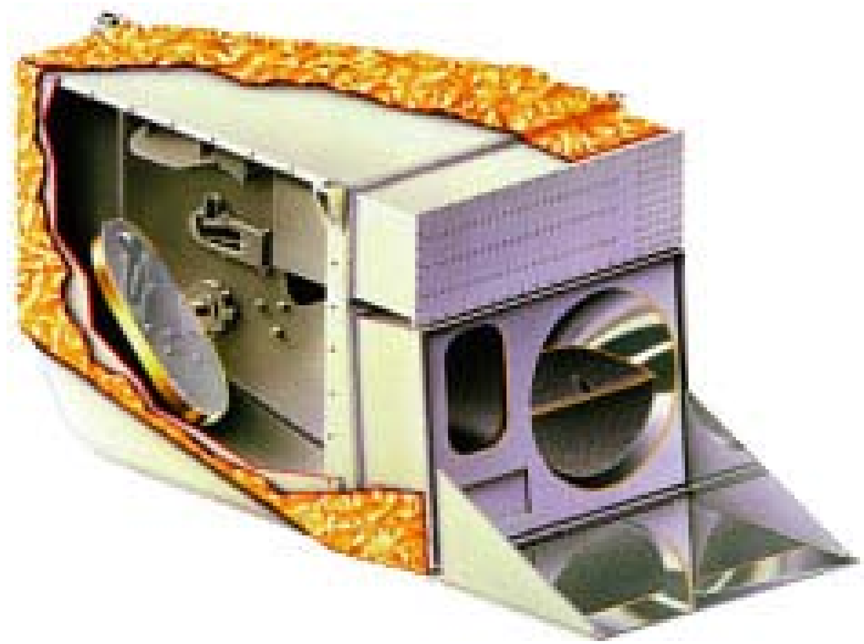
First Light:
February 24, 2000



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

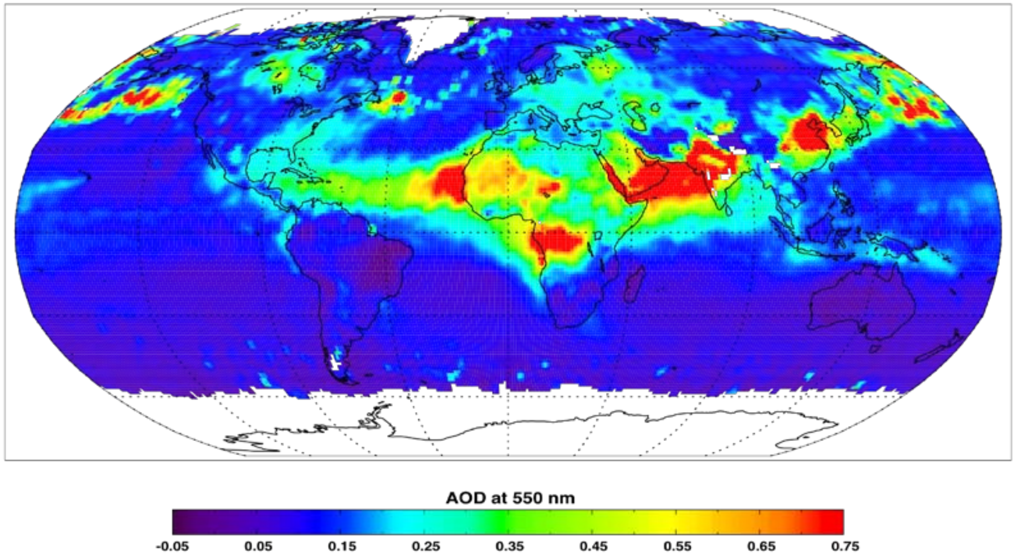


Improved over AVHRR:
- Calibration
- Spatial Resolution
- Spectral Range & # Bands

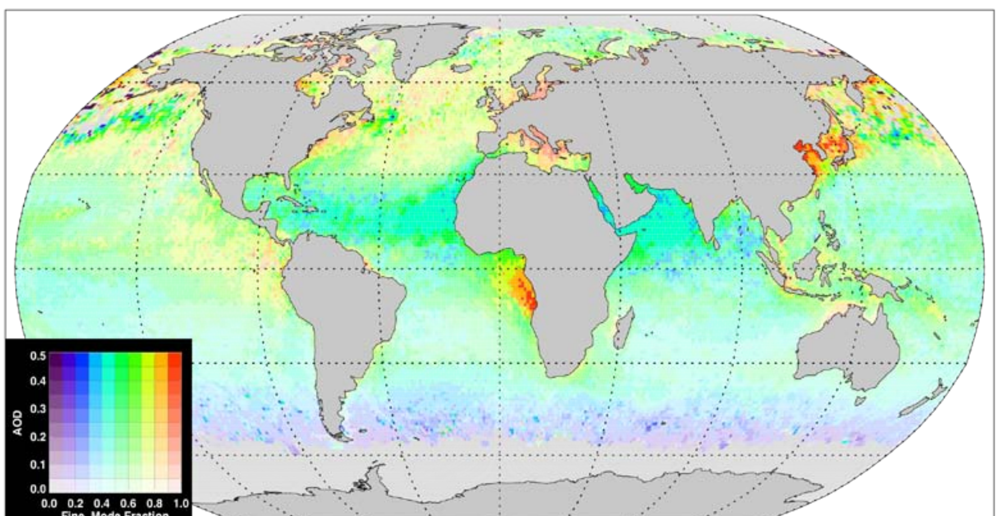
MODIS Team, NASA/GSFC

Global, Monthly Average ***MODIS Aerosol Products***

July 2010



Mid-visible
Aerosol Optical Depth

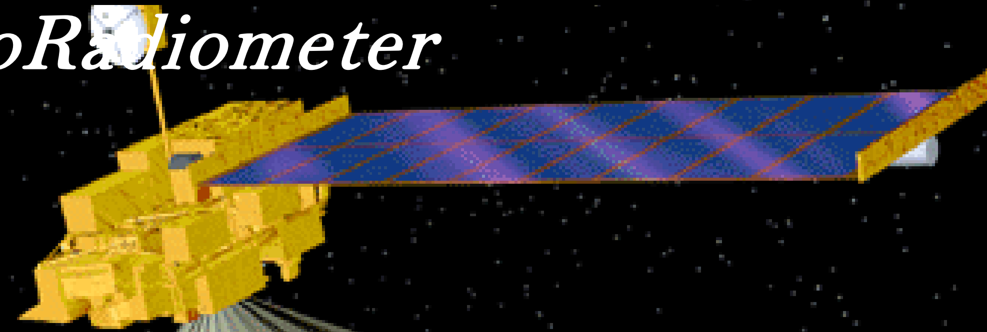


Fine-mode Fraction, with AOD encoded as color saturation

From: *MODIS Team, NASA GSFC*

Multi-angle Imaging SpectroRadiometer

MISR

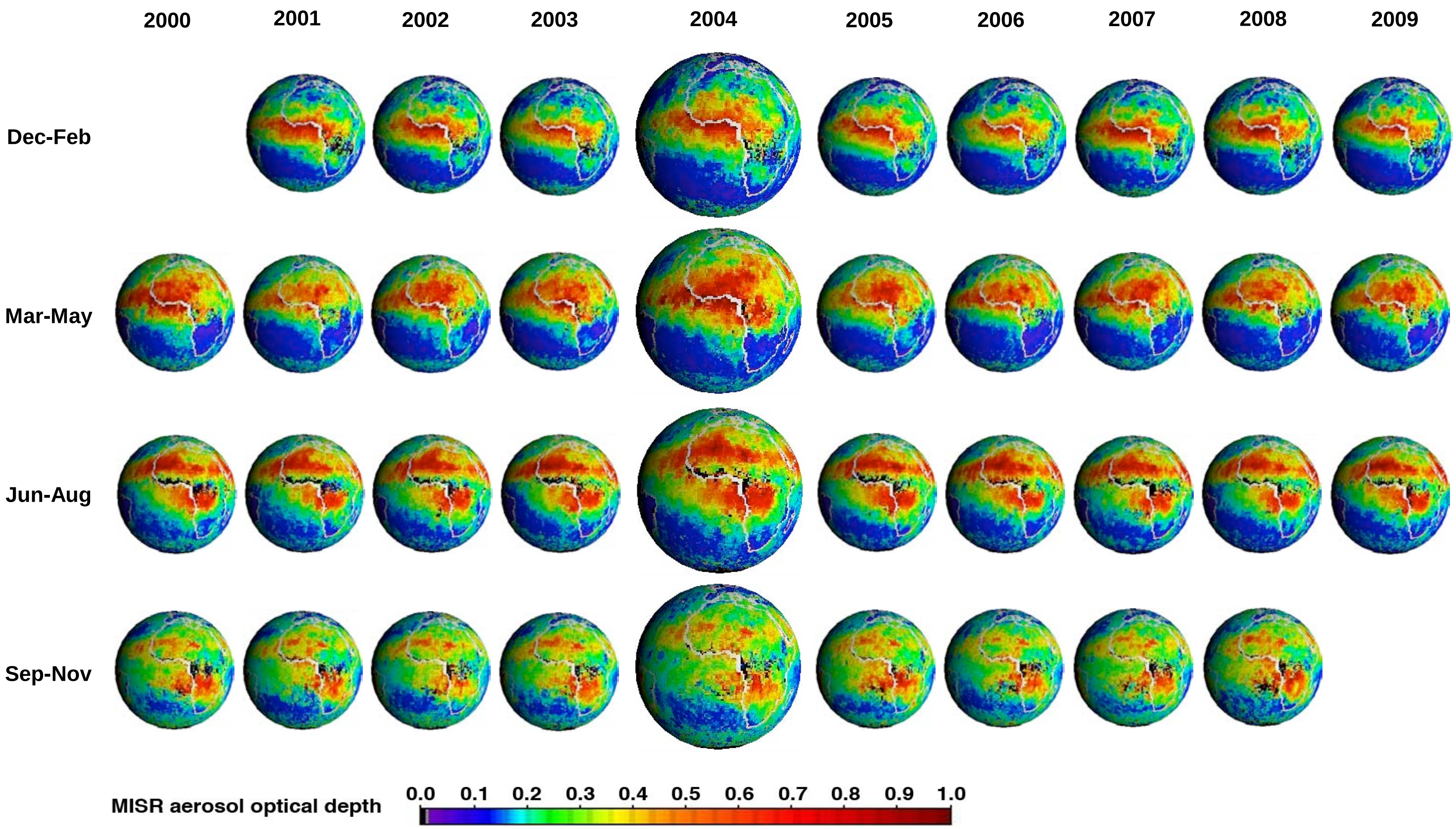


http://www-misr.jpl.nasa.gov

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*

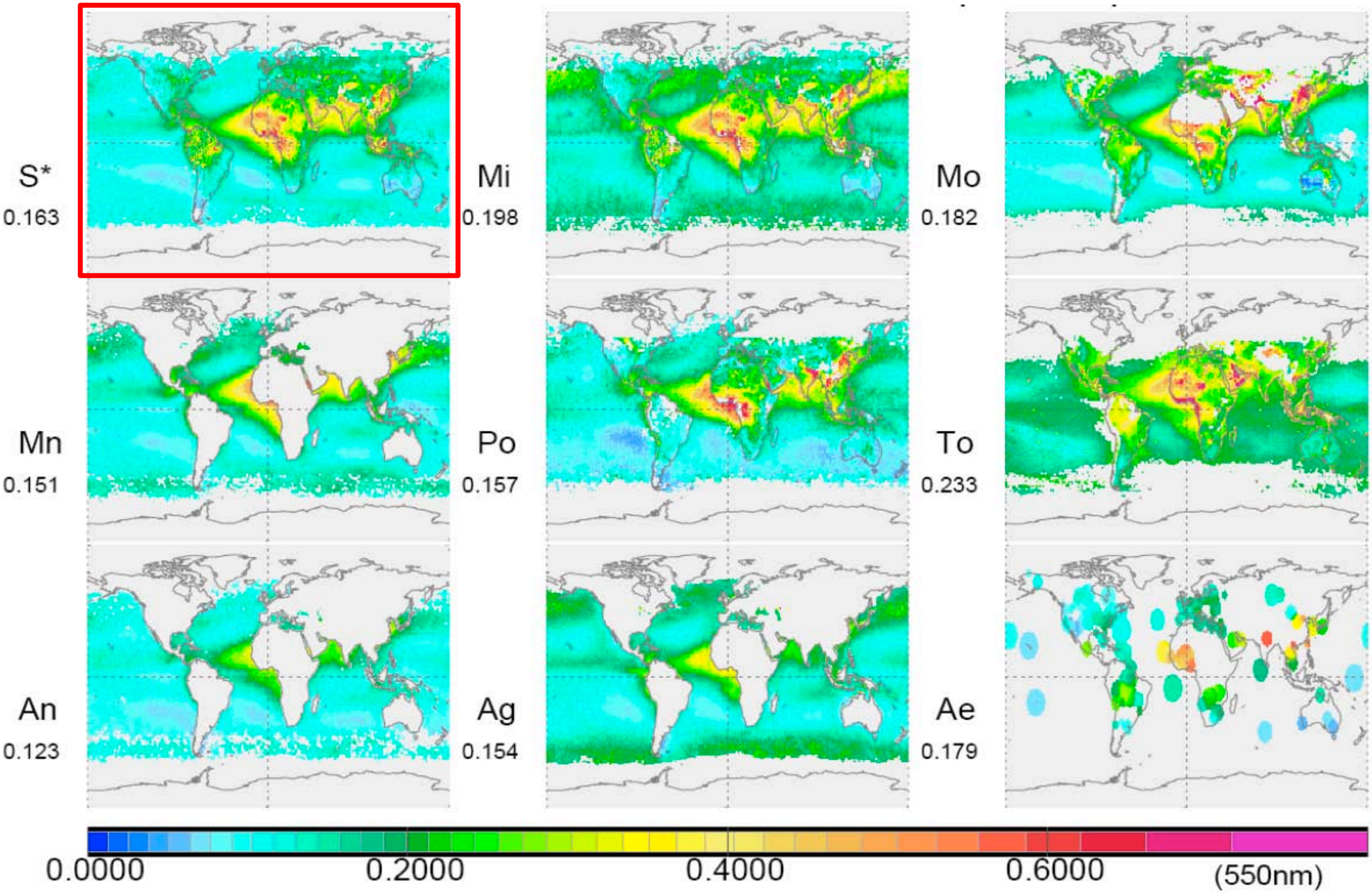
Ten Years of Seasonally Averaged Mid-visible Aerosol Optical Depth from MISR



…includes bright desert dust source regions

MISR Team, JPL and GSFC

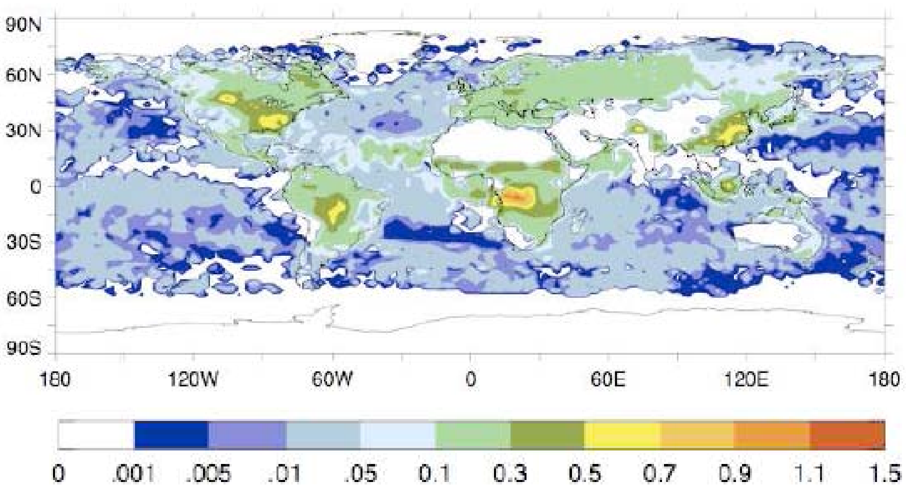
Multi-year Annual Average *Aerosol Optical Depth* from Different Measurements + *Synthesis* (S*)



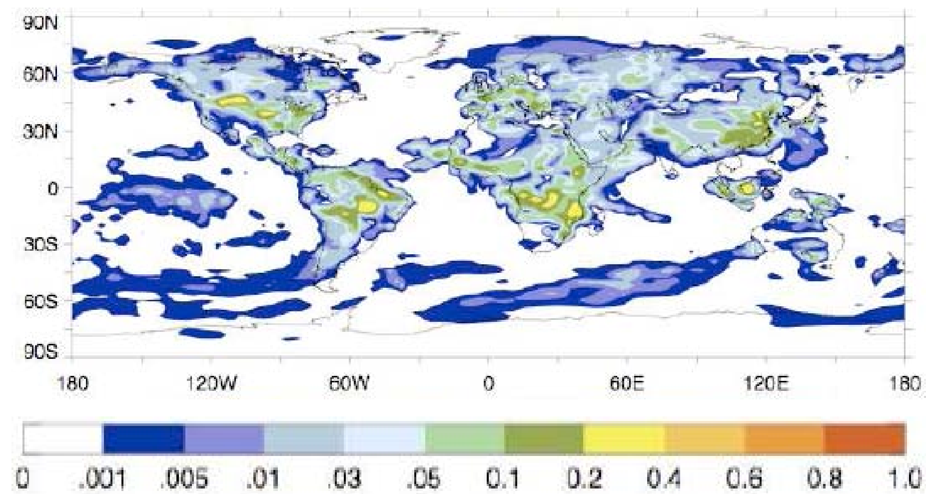
From: *Kinne et al. ACP 2006*

Aerosol Source Characterization
by Combining Measurements and Models

MODIS Fine-mode AOD (550 nm), August 18-30 2000

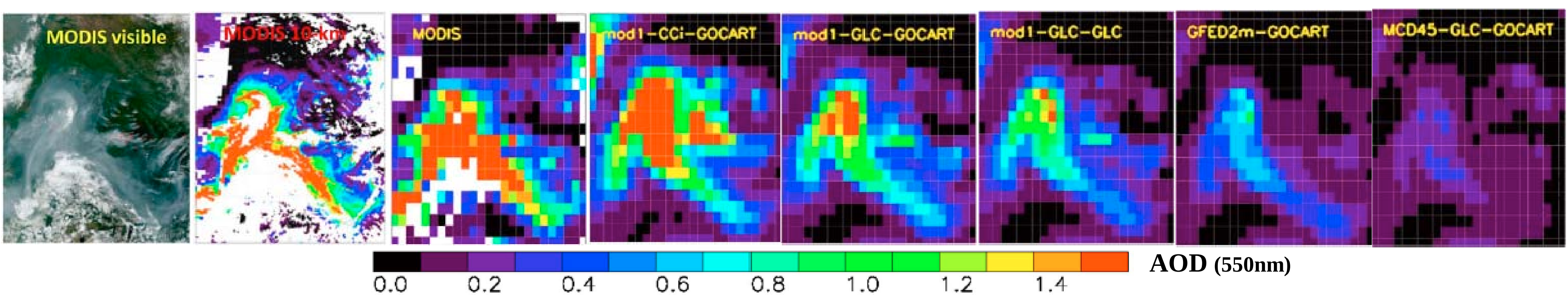


GoCART *Inverse-Model-Retrieved* Emissions (10^7 kg/day)



From: *Dubovik et al., ACP 2008*

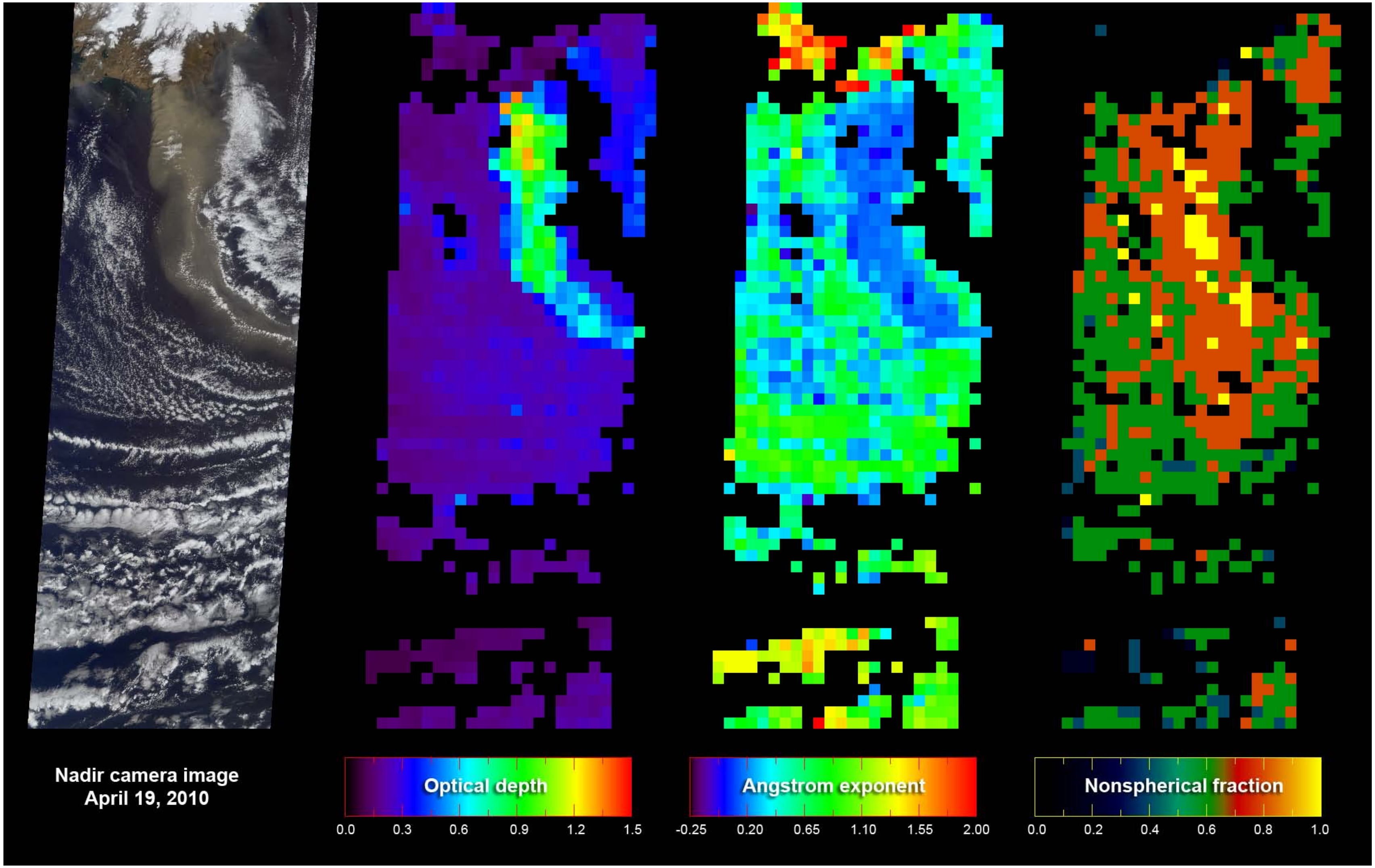
MODIS July 2006 Siberian Smoke Plume Image + AOD, and 5 GoCART *Forward-Model Simulations* with different source strengths



From: *Petrenko et al., JGR 2012*

MISR-Derived Ash Plume Aerosol Amount & Properties

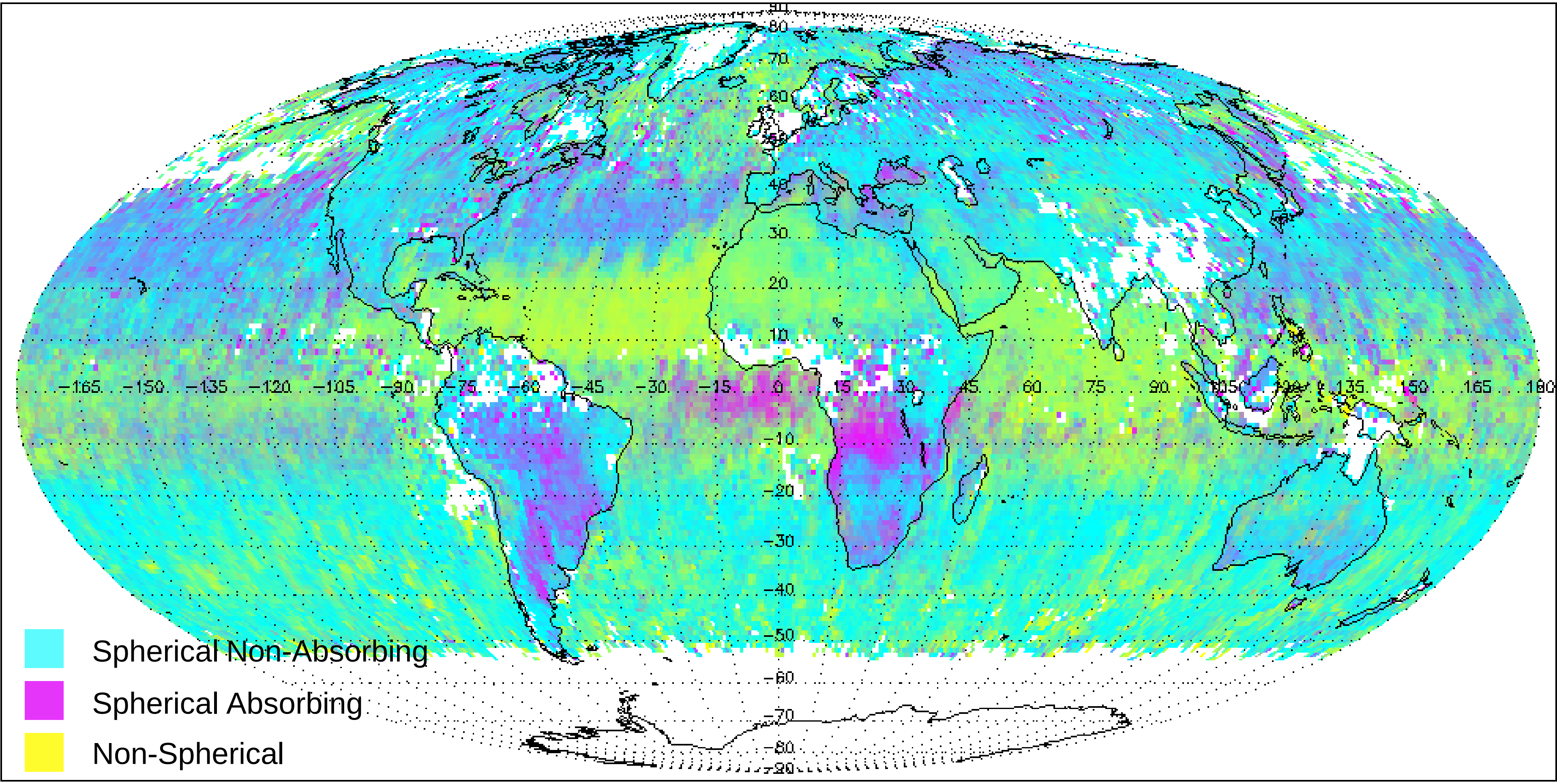
Eyjafjalljökull Volcano 19 April 2010



MISR Team, JPL and GSFC

MISR ***Aerosol Type*** Distribution

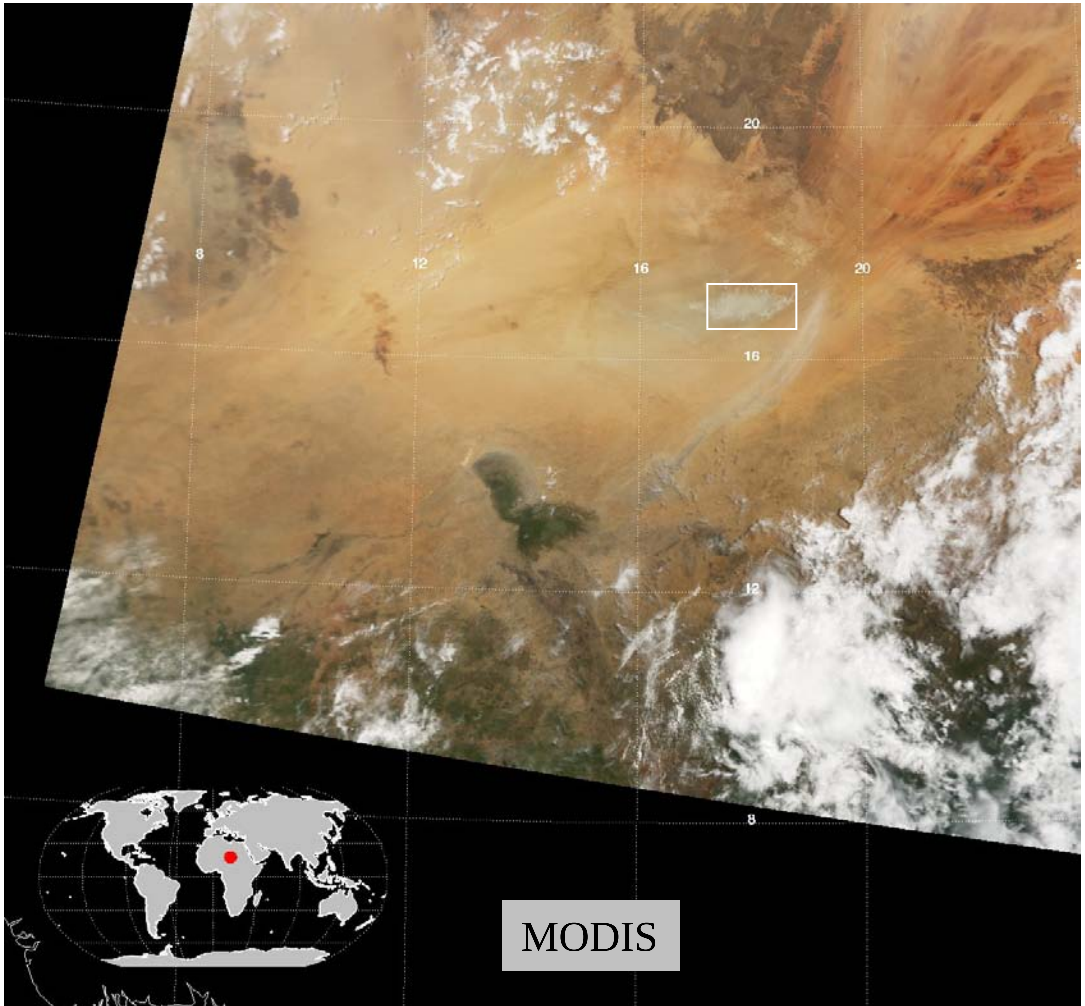
MISR Version 22, July 2007

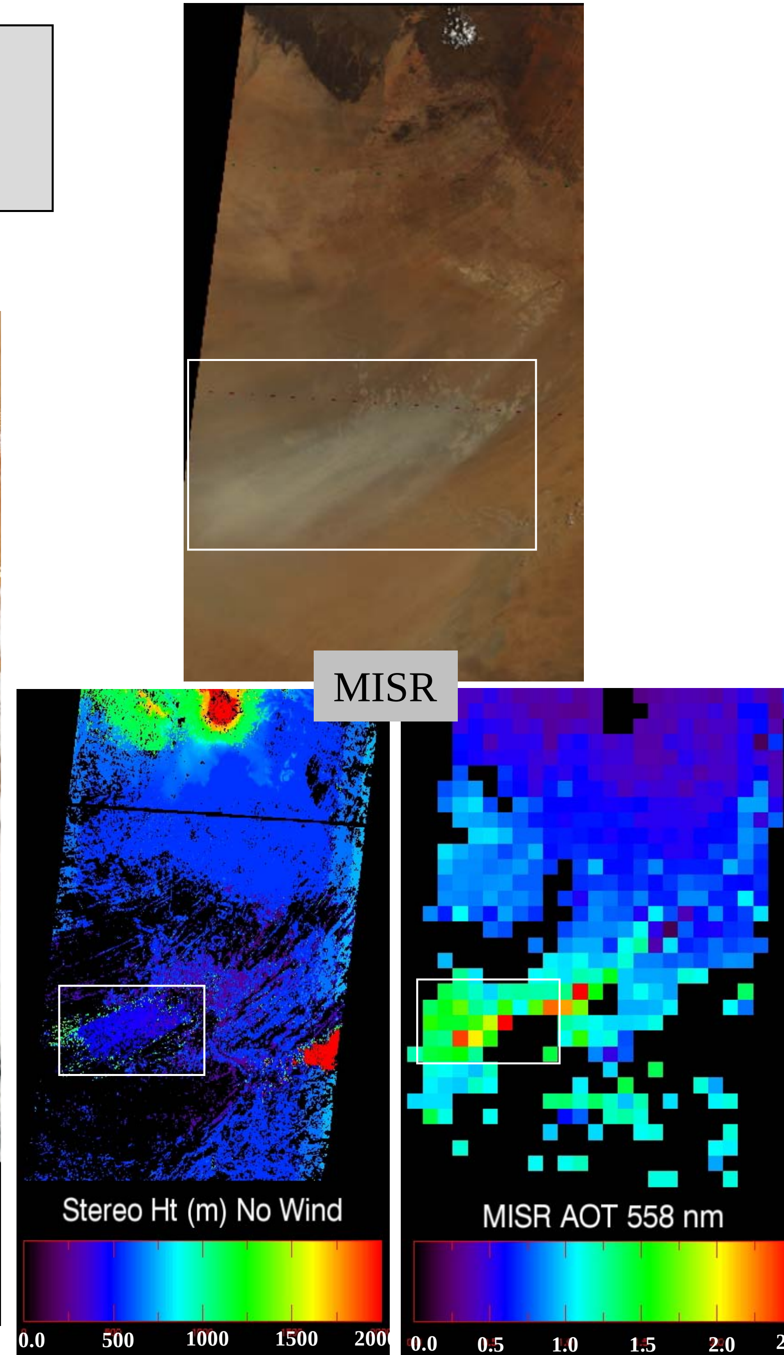


Kahn, Gaitley, Garay, et al., JGR 2010

Saharan Dust Source Plume

Bodele Depression Chad June 3, 2005 Orbit 29038



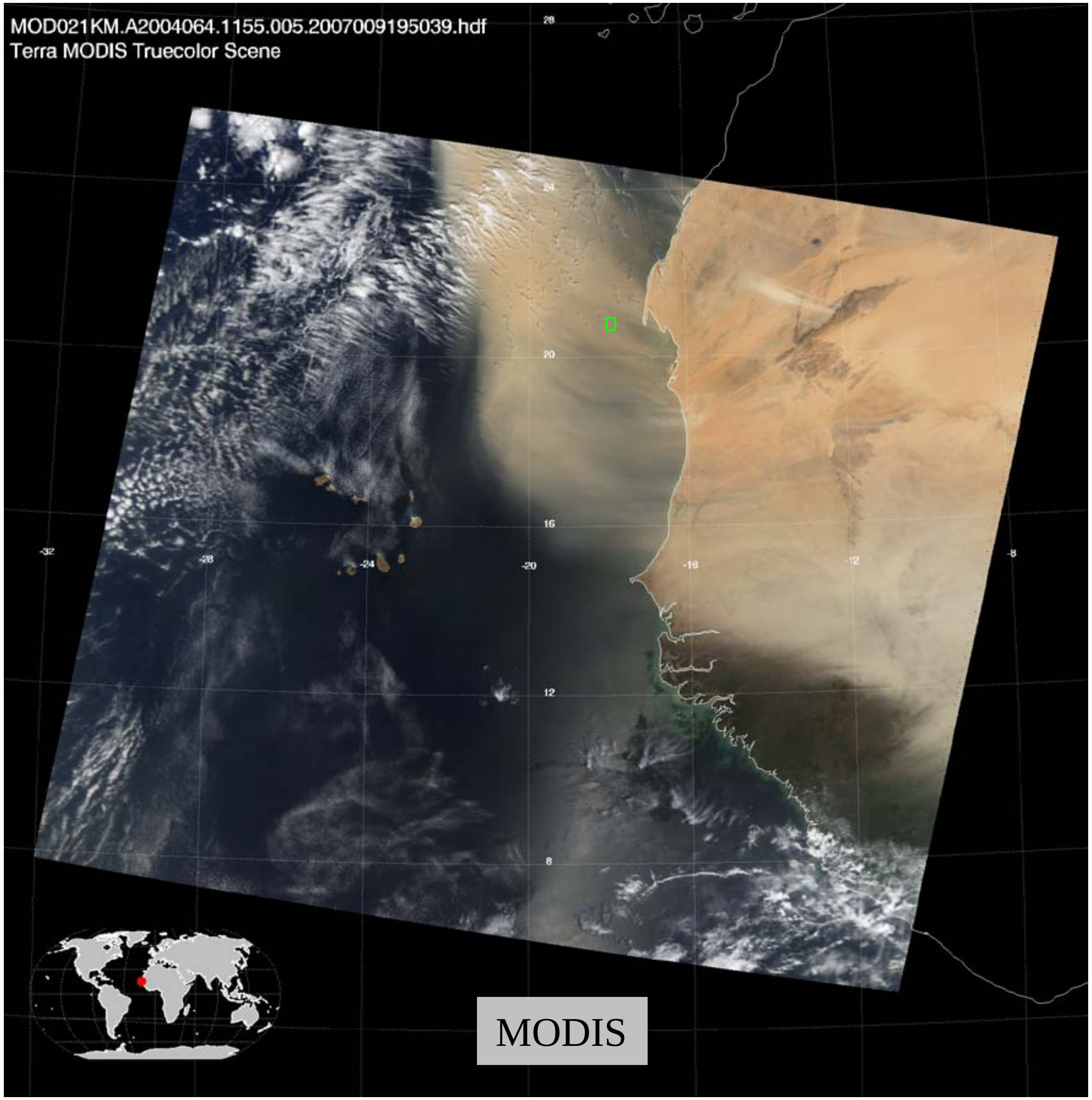


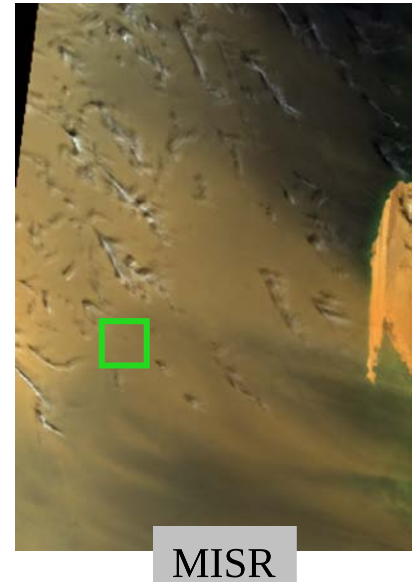
Dust is injected near-surface…

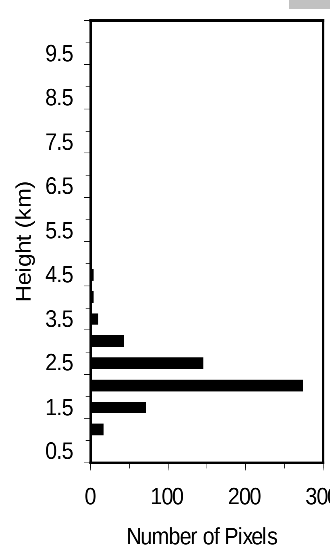
Kahn et al., JGR 2007

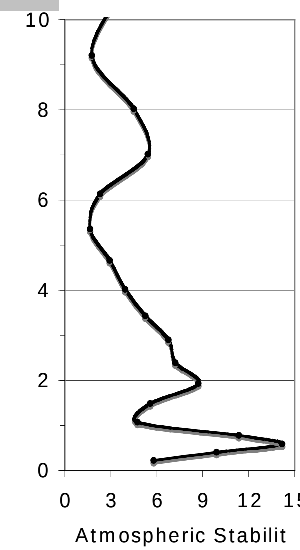
Transported Dust Plume

Atlantic, off Mauritania March 4, 2004 Orbit 22399







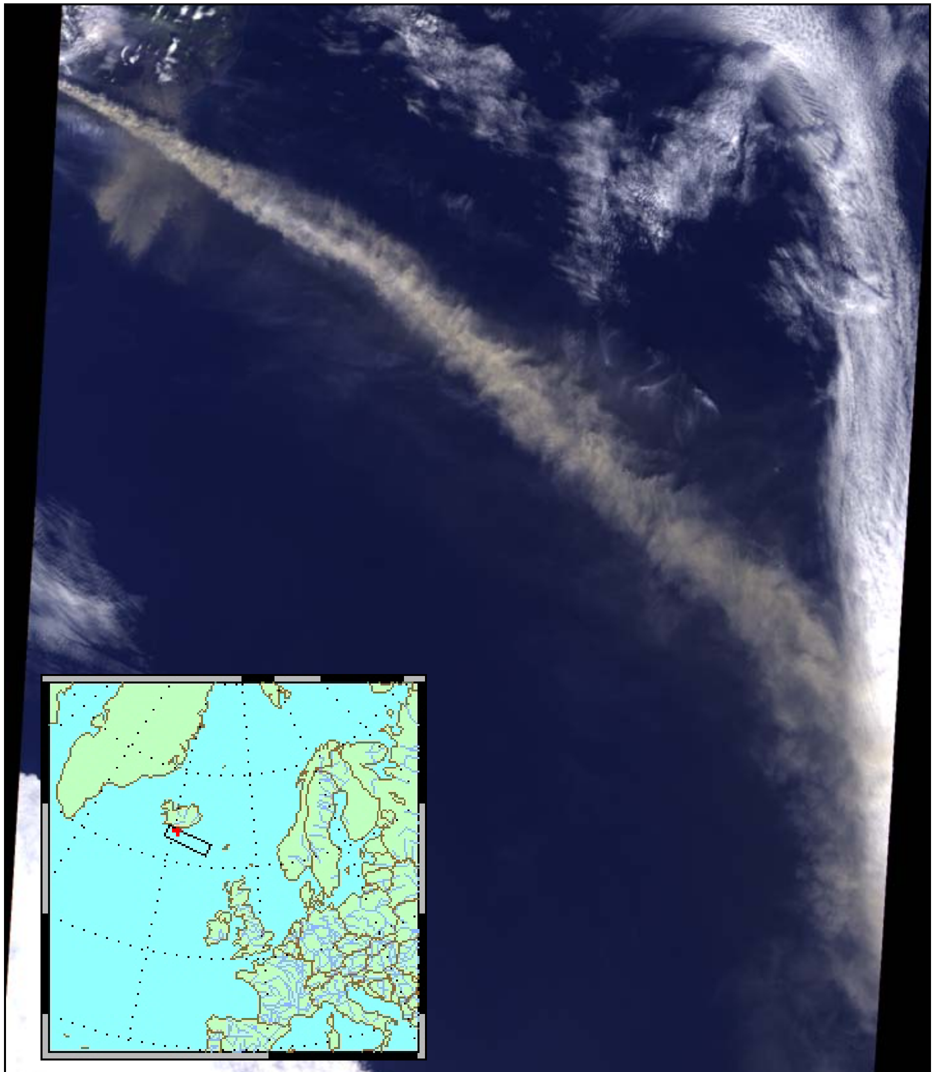


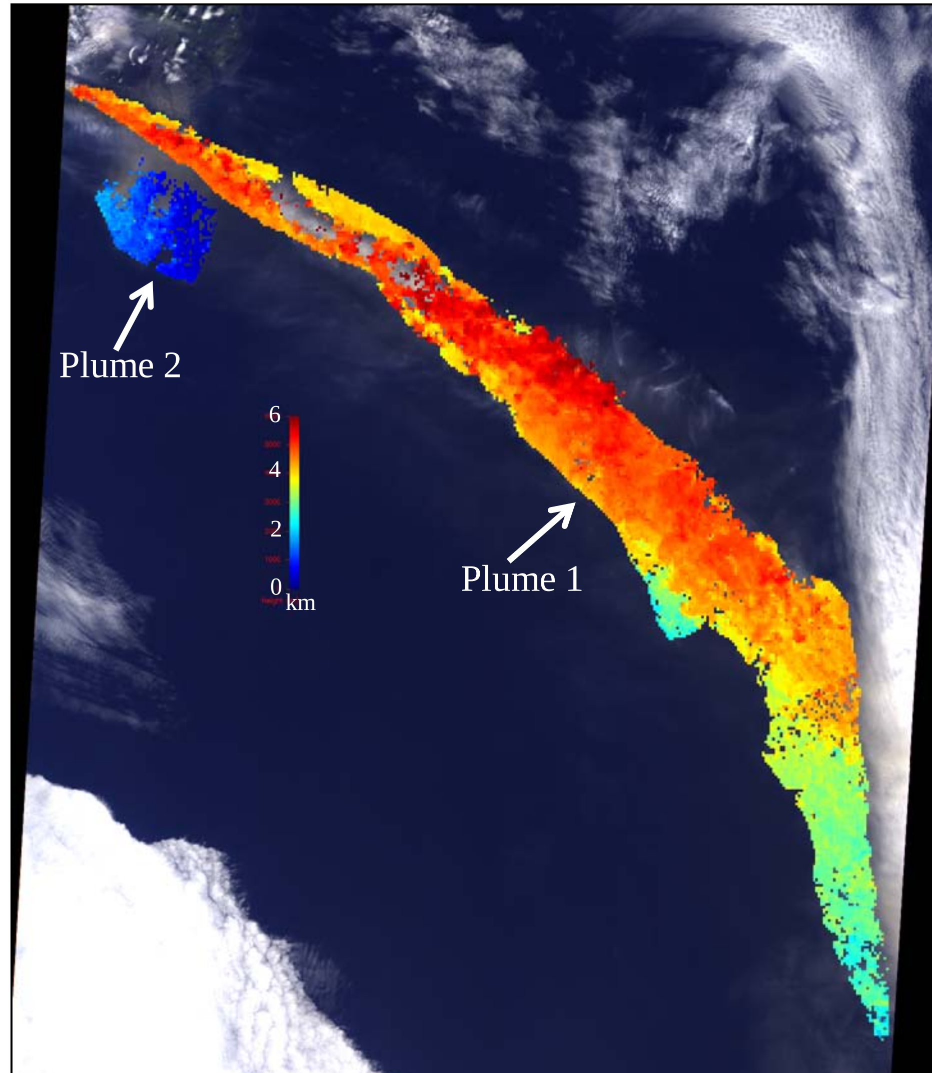
Transported dust finds elevated layer of relative stability…

Kahn et al., JGR 2007

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

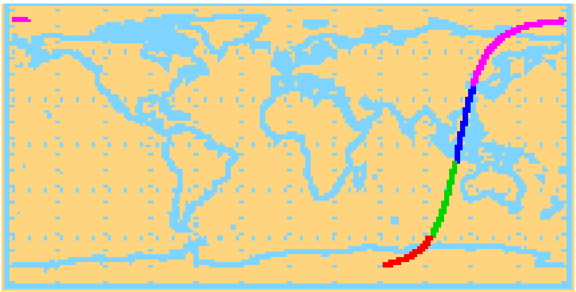
***07 May 2010** Orbit 55238 Path 216 Blk 40 UT 12:39*

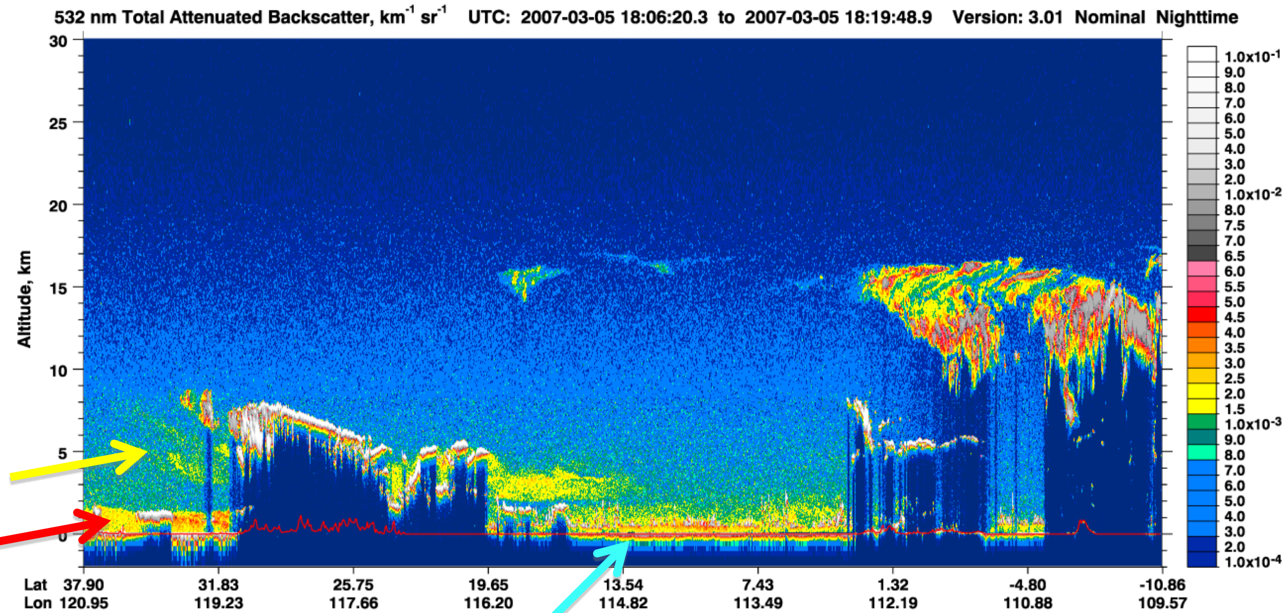




D. Nelson and the MISR Team, JPL and GSFC

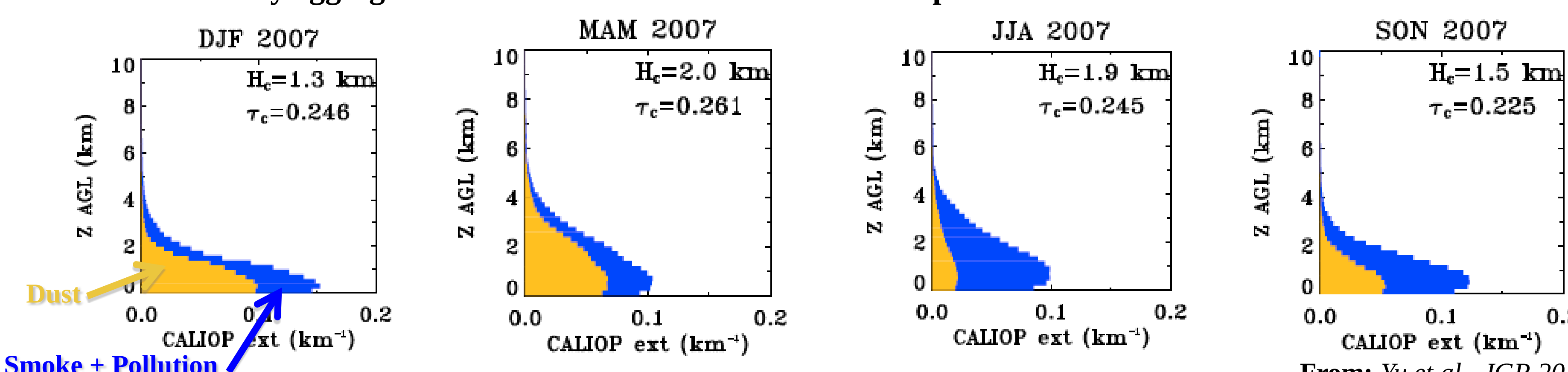
CALIPSO Lidar Aerosol Layer Height "Curtains"





From: *CALIPSO Team, NASA Langley Research Center*

Seasonally aggregated dust & non-dust vertical extinction profiles over Eastern China for 2007



From: *Yu et al., JGR 2010*

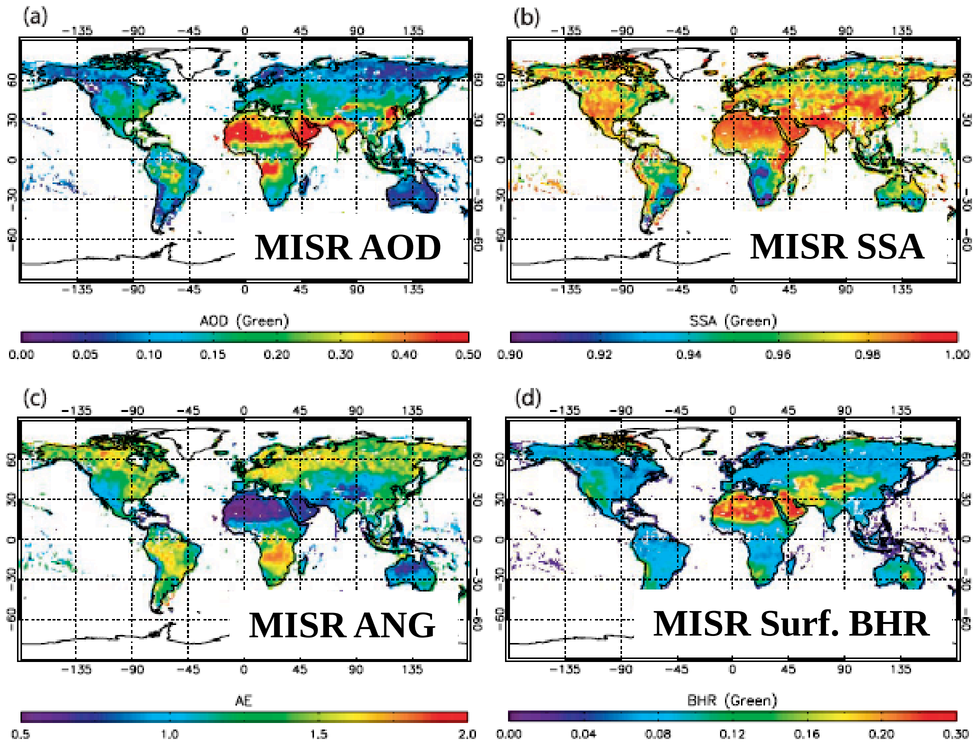
Over-Land Aerosol Short-wave Radiative Forcing w/Consistent Data

The slope of:

TOA albedo vs. AOD

For data stratified by:

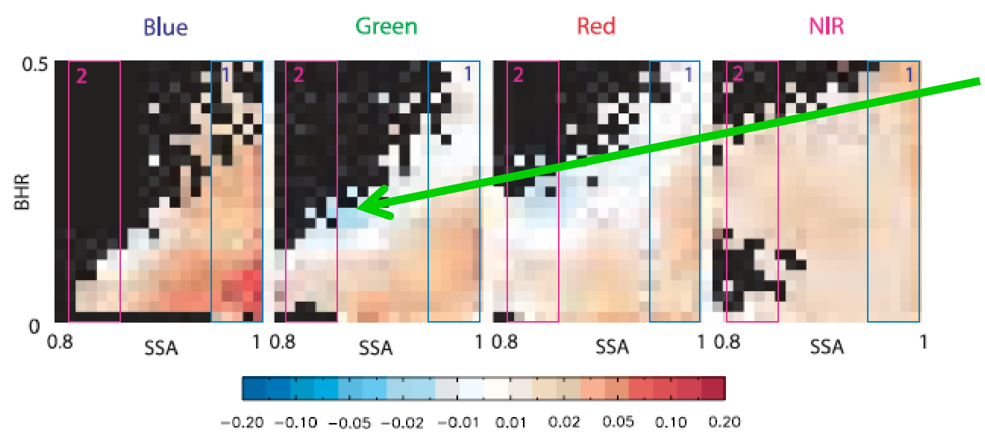
Surface BHR



Produces:

Spectral aerosol radiative efficiency

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

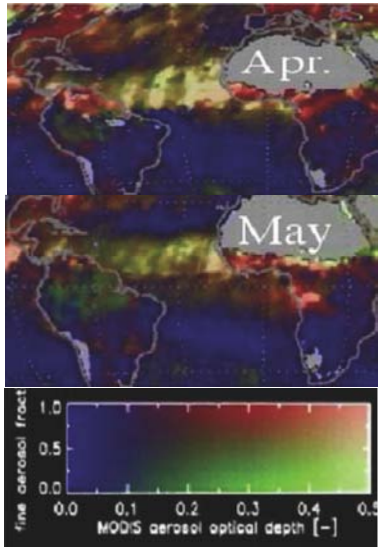


Bright surface + dark aerosol = decreasing albedo w/AOD

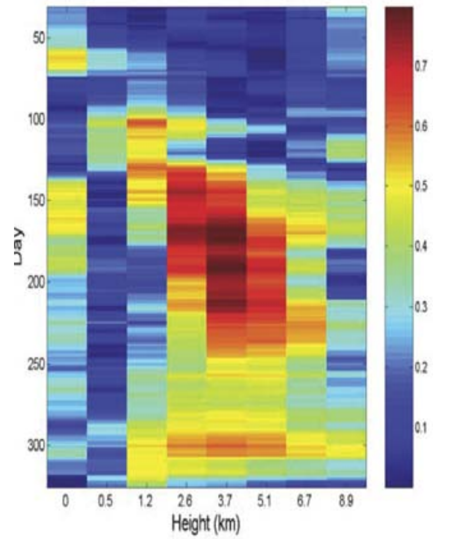
Depends on aerosol *microphysical* properties relative to surface albedo

Y. Chen et al. JGR 2009

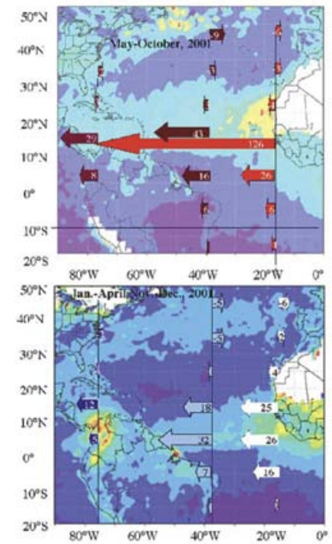
Aerosol Material Fluxes: Atlantic Dust & Asian Pollution



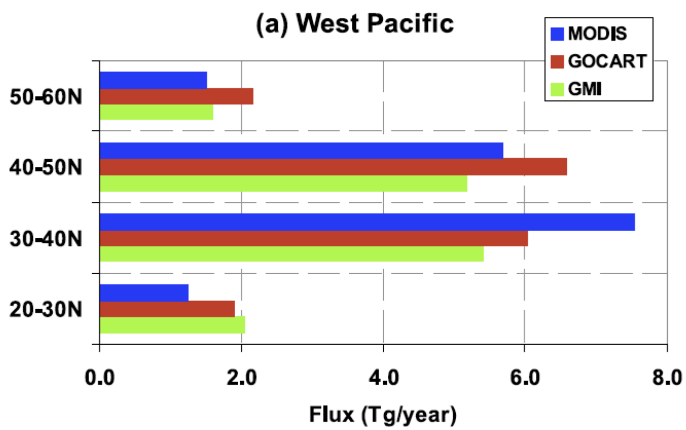
MODIS AOD & Type
Low AOD, **Fine BioBurn**, **Coarse Dust**

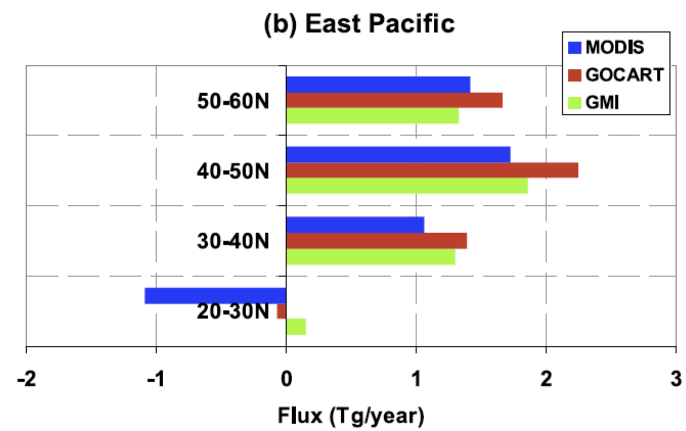


NCEP **W Wind** - MODIS **AOD**
Correlation 2.6-5 km; May-October



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

Current MISR & MODIS Mid-Visible AOD Sensitivities

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

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

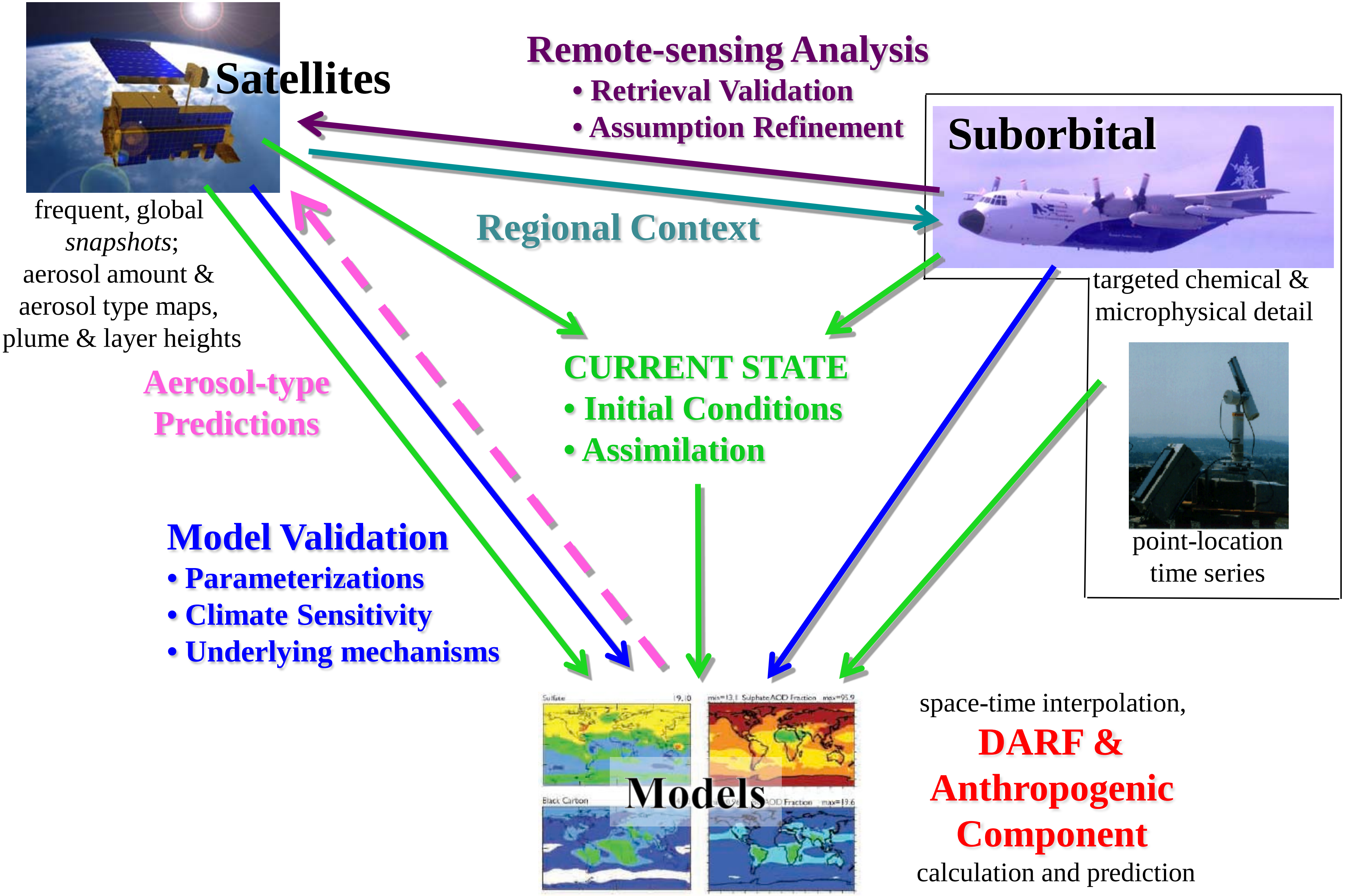
- MODIS: **0.05 or 20% * AOD** over land
  0.03 or 5% * AOD over dark water

[*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***



Kahn, Survy. Geophys. 2012

Comparative Planetology and the Atmosphere of Earth

1. **Comparative Planetology** – Discovering how planetary atmospheres are similar, and how they are different, expands our appreciation of Earth itself, by placing specific attributes of our planet into a larger context.
   -- *Radiative and Dynamical Scaling Laws*

2. **Subtle Earth Effects** – Some phenomena in Earth's atmosphere are of much greater physical importance in the atmospheres of other planets.
   -- *Venus' Greenhouse*; *Jupiter's Magnetosphere*

3. **Data Available Only from Other Planets** – Data of comparable or higher quality relevant to Earth can sometimes be found in other places.
   -- *Inner solar system climate record from Mars (and the Moon?)*

4. **New Ideas** – Inspiration leading to a habit of out-of-the-box thinking…

NASA 1989