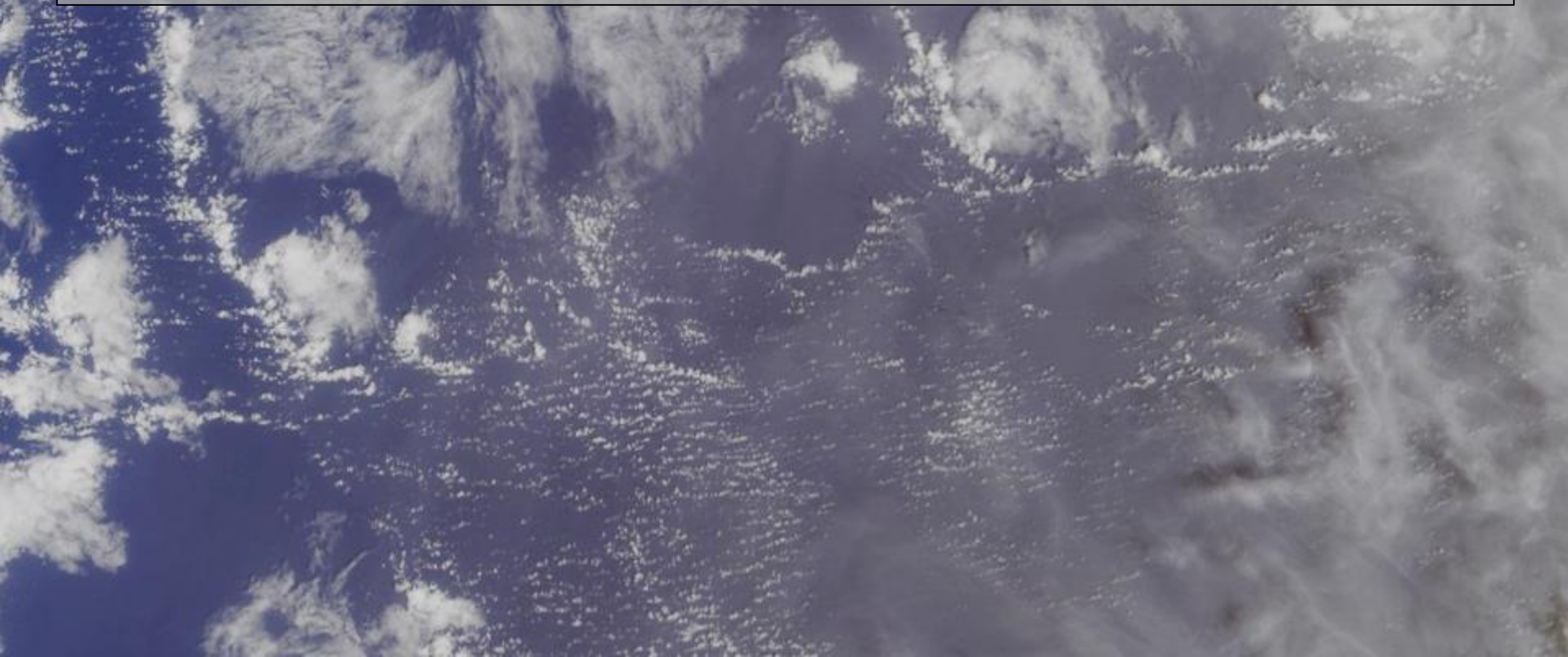
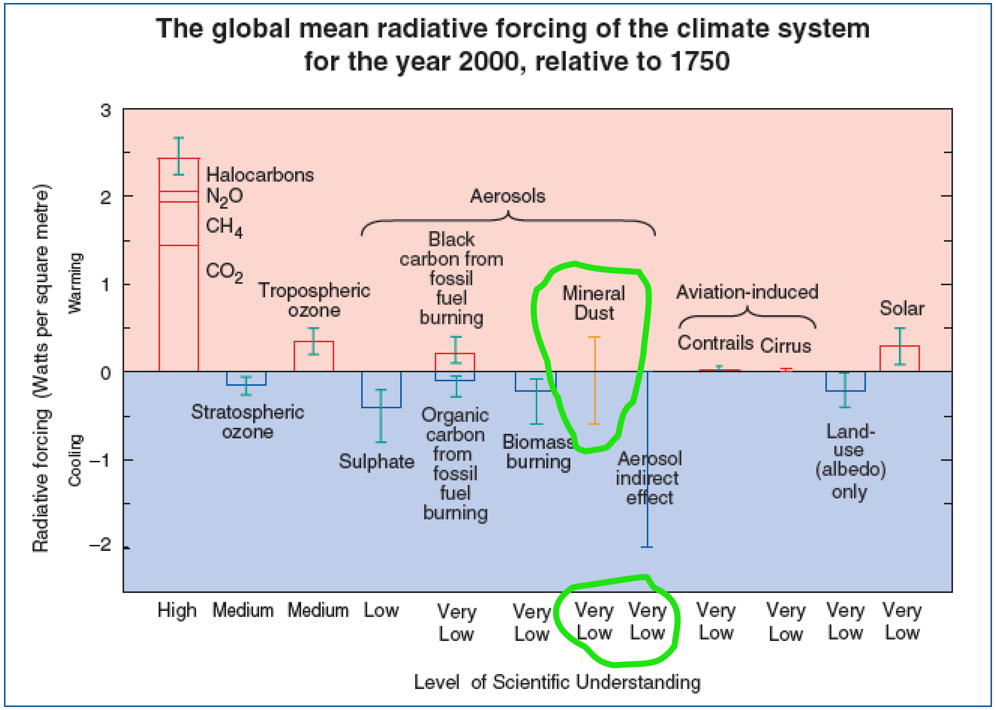
Remote Sensing of Aerosols From Satellites:
Why has it been do difficult to quantify Aerosol-Cloud Interactions for climate assessment, and How can we make Progress?

Ralph Kahn
NASA/Goddard Space Flight Center



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



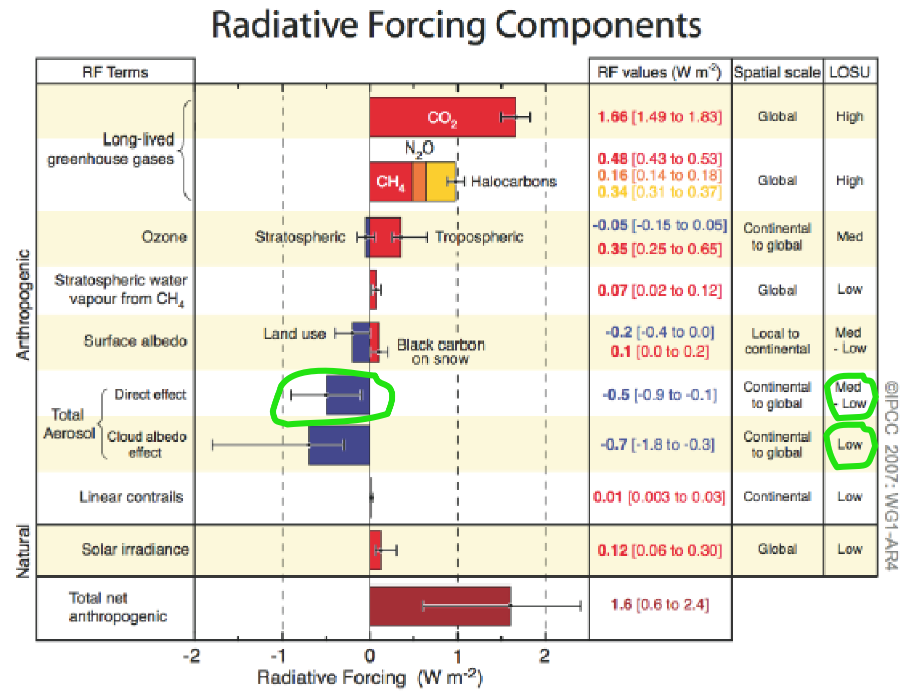
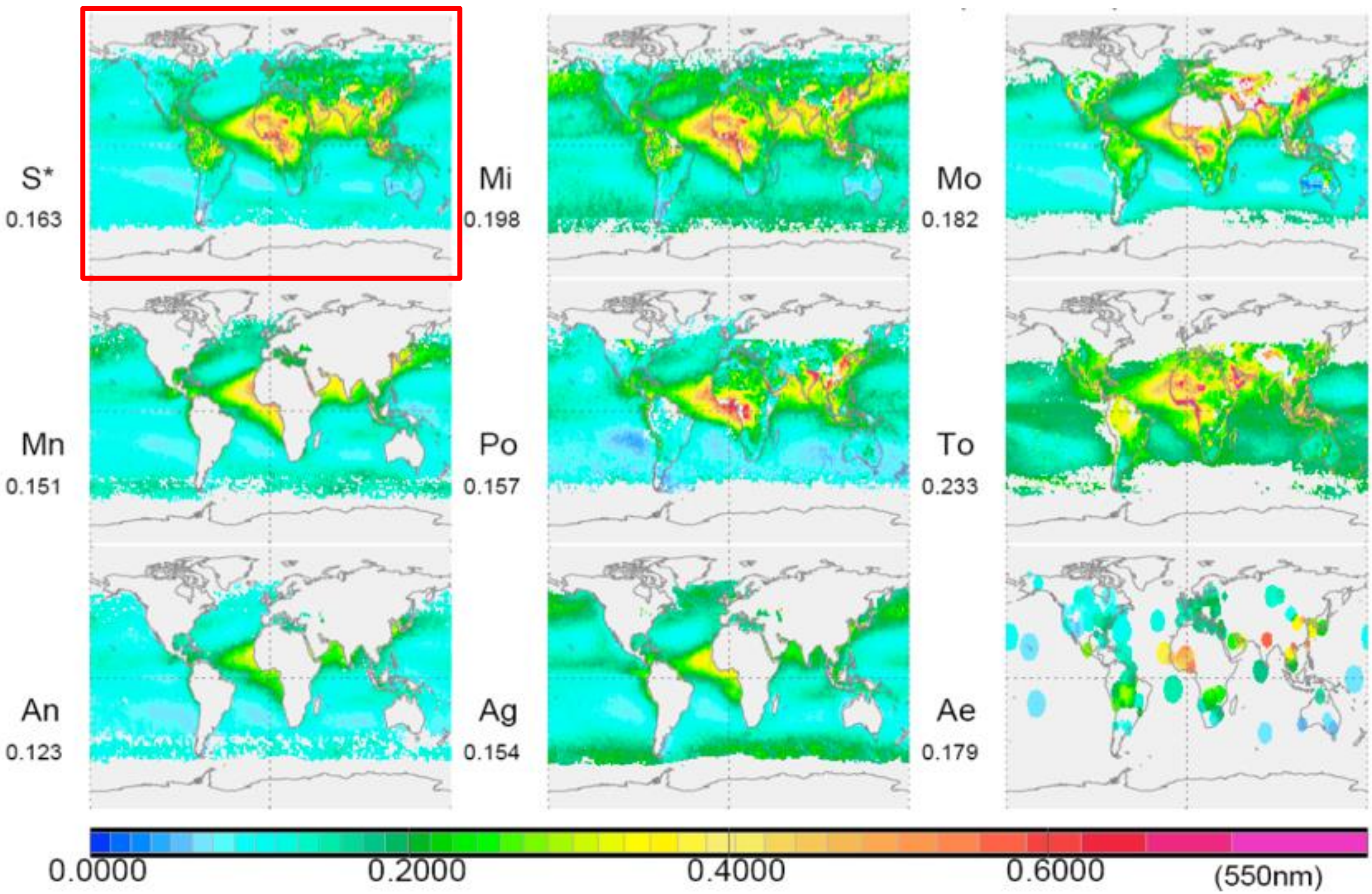


FIGURE SPM-2. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level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

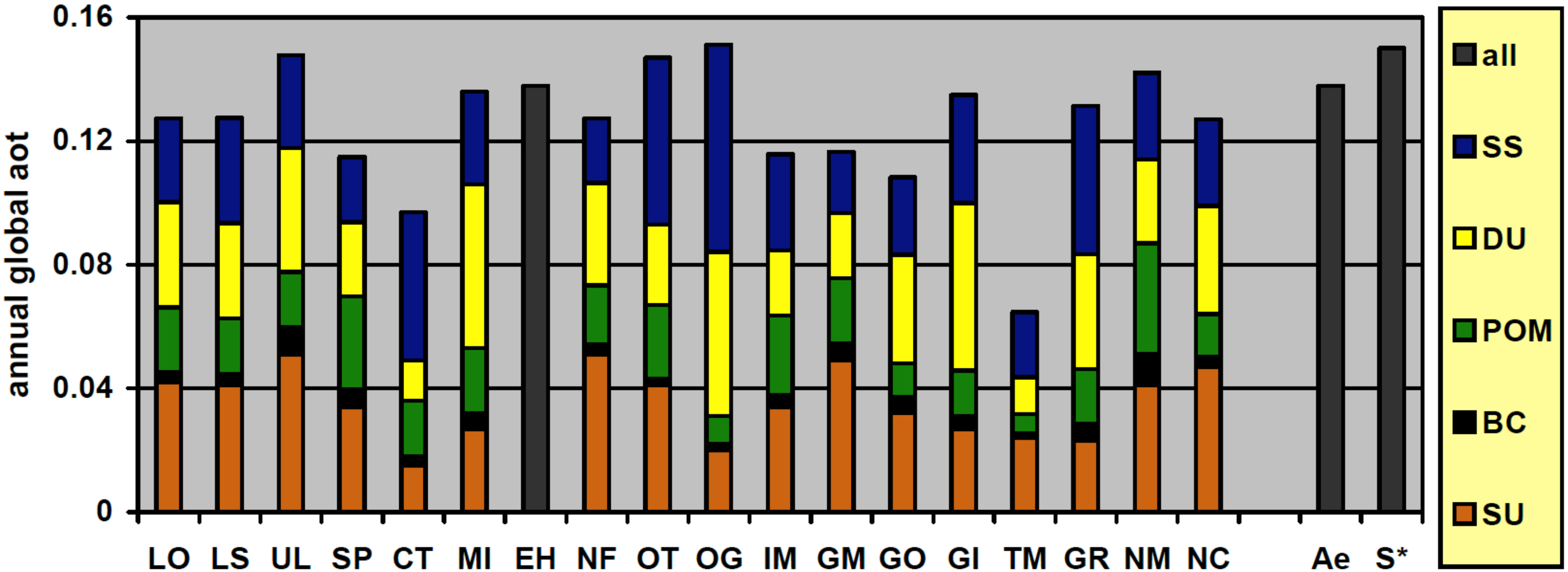
IPCC AR4, 2007
(EOS + ~ 6 years)

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



From: *Kinne et al. ACP 2006*

Constraining ARF – The Next Big Challenge



Ae= AERONET; S*= MISR-MODIS composite

Kinne et al., ACP 2006

Note: These are <u>not</u> yet updated to the CMIP5 (AR5) models

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

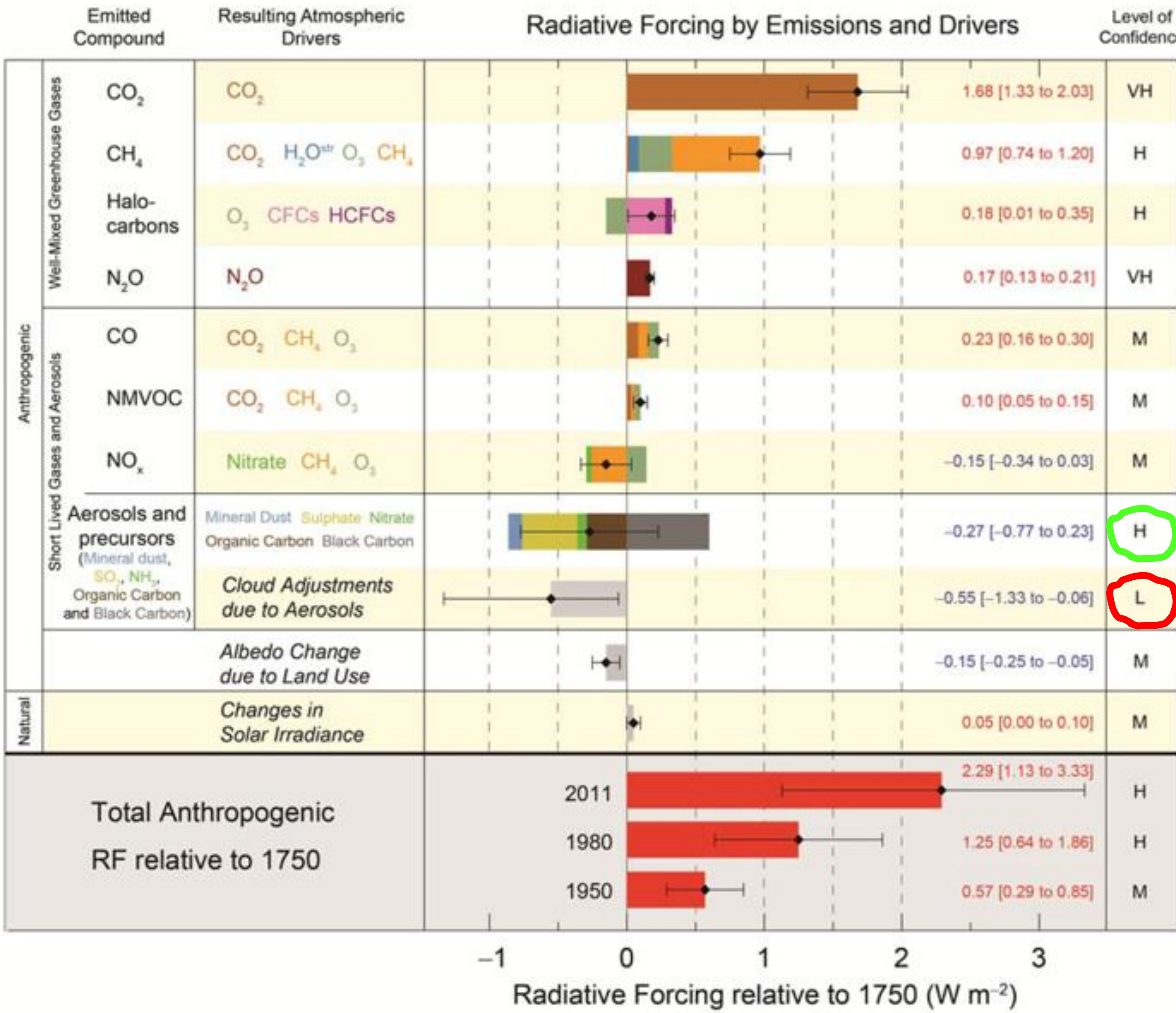
How Good is *Good Enough*?

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

-- ***For aerosol indirect effects, the aerosol type constraint requirements are more stringent***

CCSP - SAP 2.3, 2009

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*

Multi-angle Imaging SpectroRadiometer

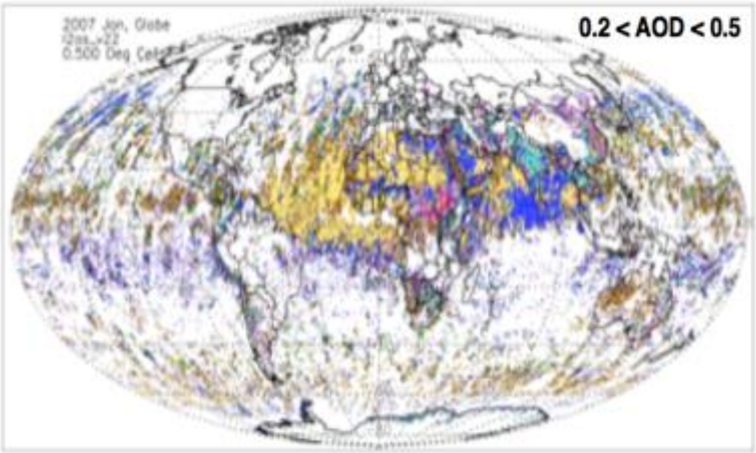
MISR

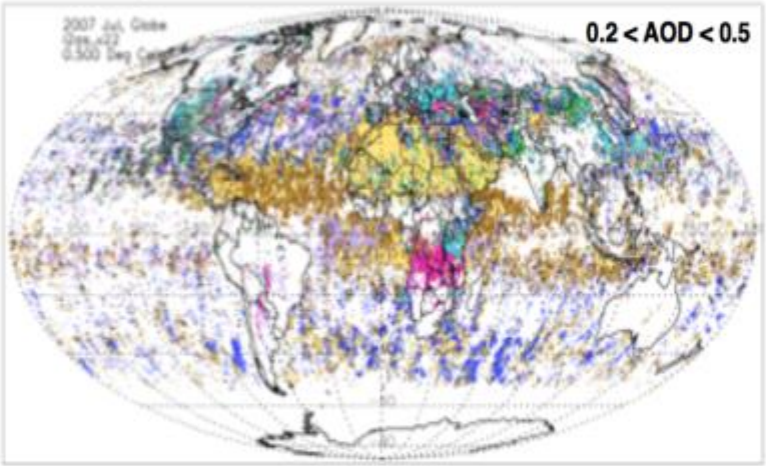
http://www-misr.jpl.nasa.gov

http://eosweb.larc.nasa.gov

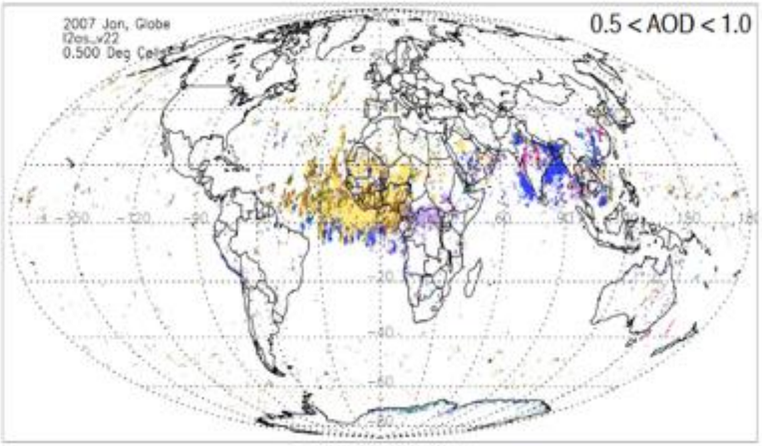
- **<u>Nine</u> CCD push-broom <u>cameras</u>**
- **<u>Nine</u> <u>view</u> <u>angles</u> at Earth surface: 70.5º forward to 70.5º aft**
- **<u>Four</u> <u>spectral</u> <u>bands</u> at each angle: 446, 558, 672, 866 nm**
- **Studies *Aerosols*, *Clouds*, & *Surface***

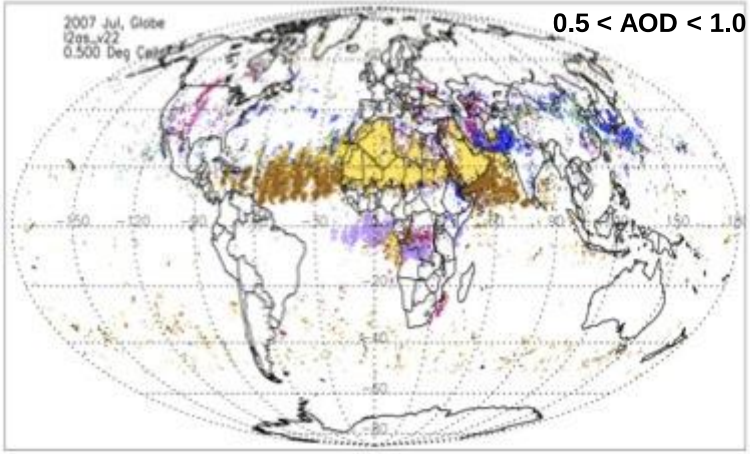
MISR Aerosol Type Discrimination





January 2007 | **July 2007**





1-10	11-20	21-30	31-40	41-50	51-62	63-70	71-74	Mixture Group

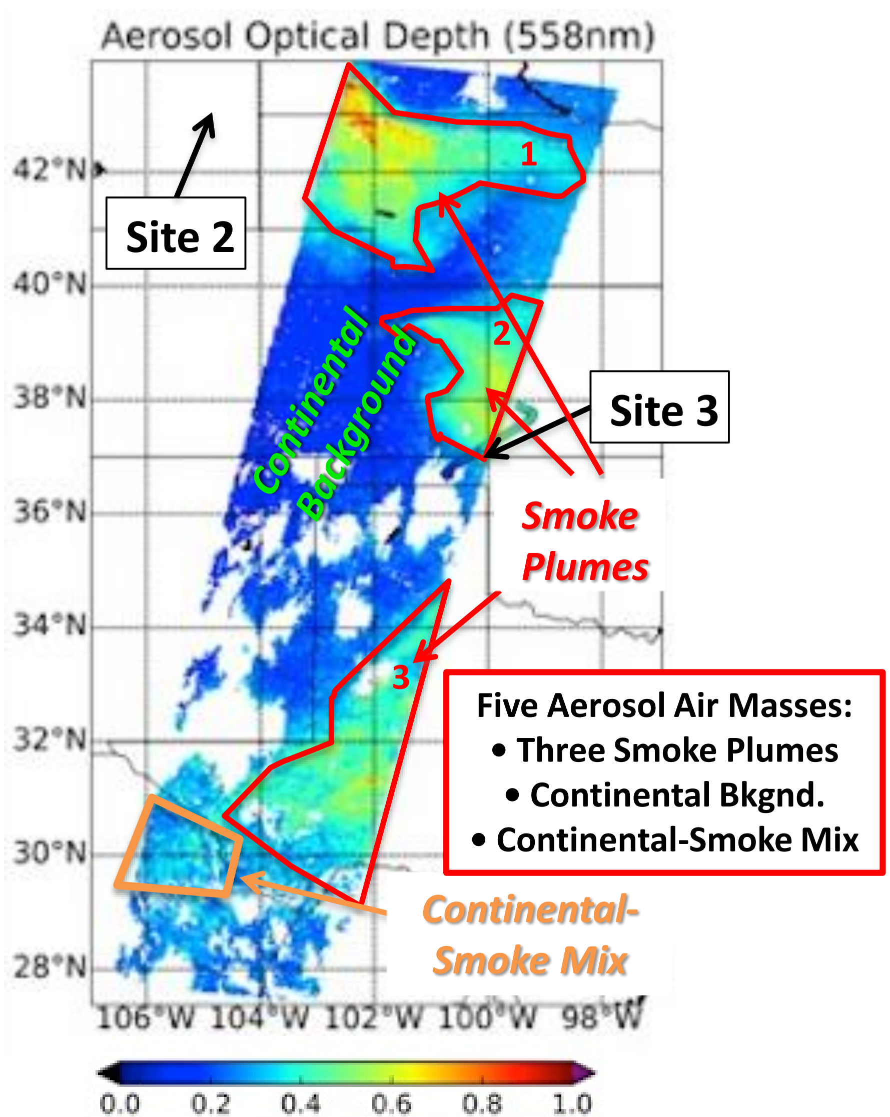
Spherical, non-absorbing

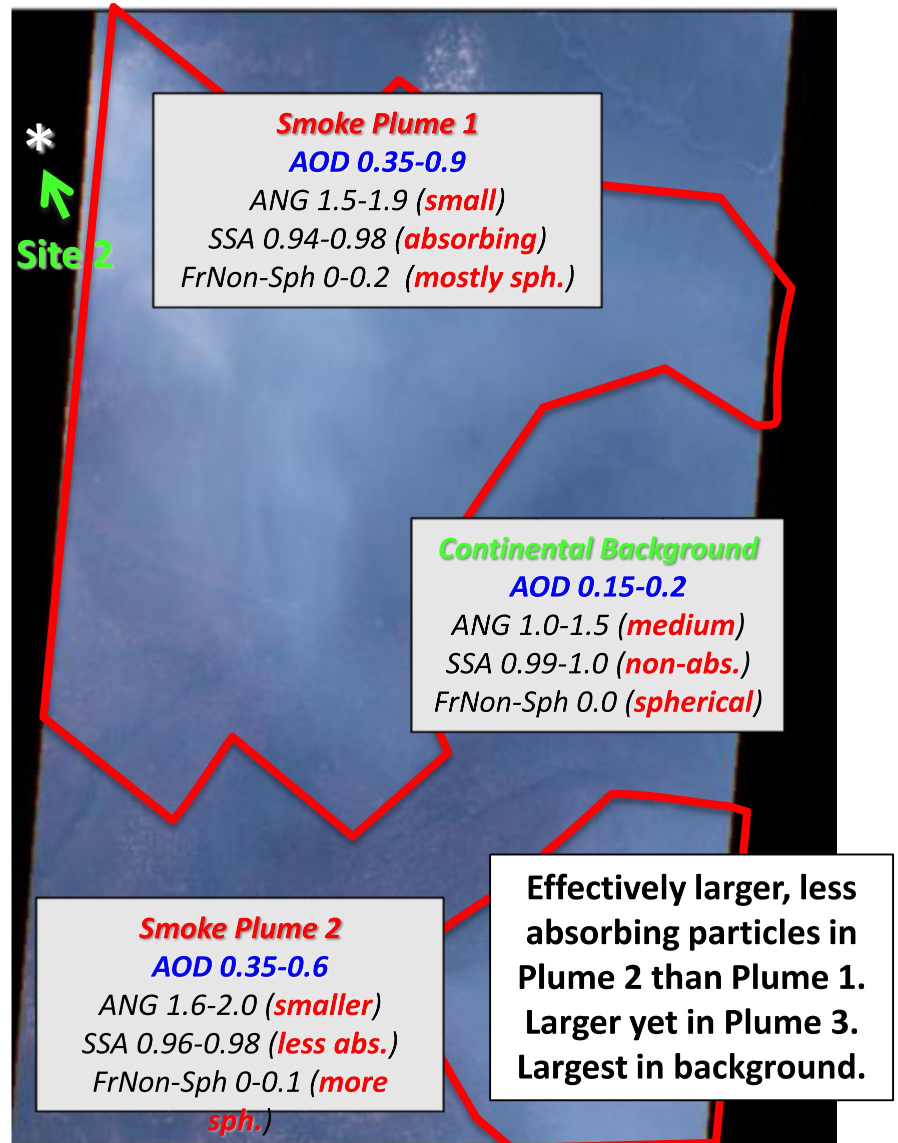
Spherical, absorbing

Non-spherical

Kahn & Gaitley JGR 2015

SEAC^{4}RS – MISR Overview 19 August 2013





Passive-remote-sensing ***Aerosol Type*** is a ***Total-Column-Effective***, ***Categorical*** variable!!

For Aerosol-Cloud Interactions – Overall Satellite ***Limitations***

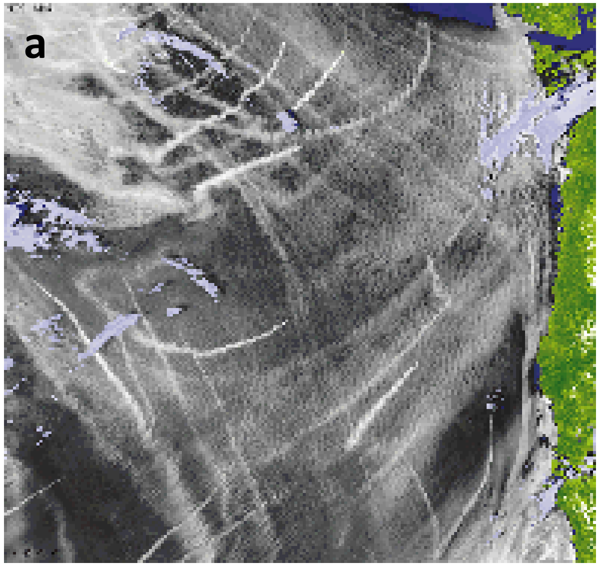
- *Polar orbiters* provide ***snapshots only***
- Difficult to probe ***cloud base***
- Typically ~100s of meters or poorer ***horizontal resolution***
- *Passive instruments (imagers)* offer little ***vertical information***
- *Active instruments (e.g., lidar)* offer little ***spatial coverage***
- Little information about aerosol ***particle microphysical properties***
- Bigger issues retrieving aerosols ***in the presence of clouds!***
- Cloud property retrievals can be aliased ***by the presence of aerosols***

Finer Points on Satellite Aerosol Retrieval *Limitations*

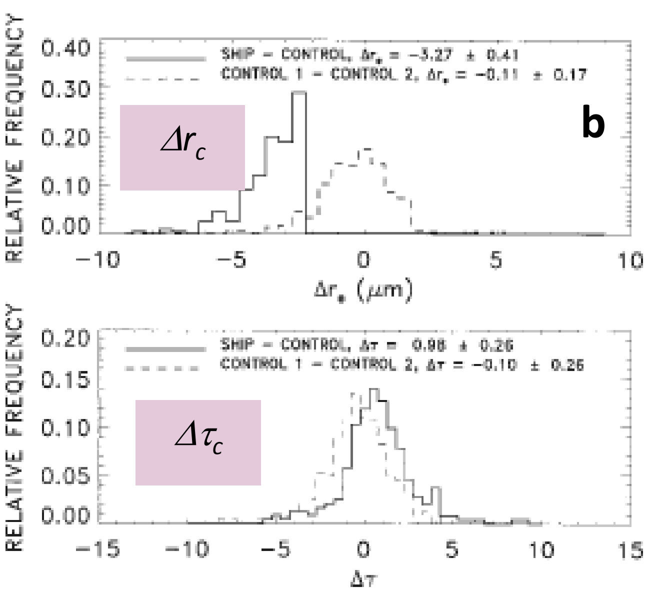
- Difficult to retrieve aerosols that are ***collocated with cloud***
  -- ***Cloud-scattered light*** & cloud "contamination" can affect near-cloud aerosol retrievals
- Rarely can detect aerosol in ***droplet-formation region*** below clouds – need cloud & aerosol ***vertical distributions***
- Aerosols smaller than about ***0.1 micron diameter*** look like atmospheric gas molecules – must ***infer CCN*** number
- Must deduce aerosol ***hygroscopicity*** (composition) from qualitative "type" – size, shape, and SSA constraints
- Environmental (Meteorological) Coupling – Factors can ***co-vary***
  -- LWP can decrease as aerosol number concentration increases (also depends on atm. stability)
- Many aerosol-cloud interaction time & spatial scales do not match ***satellite sampling***

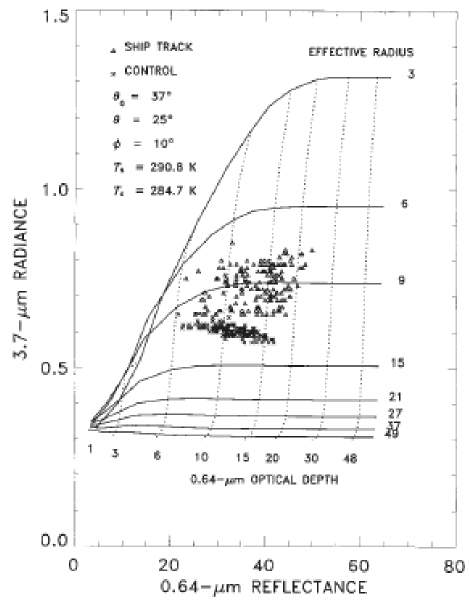
Satellites are fairly blunt instruments for studying aerosol-cloud interactions!!

Aerosol Effects on Clouds – ‘Controlled’ Situations

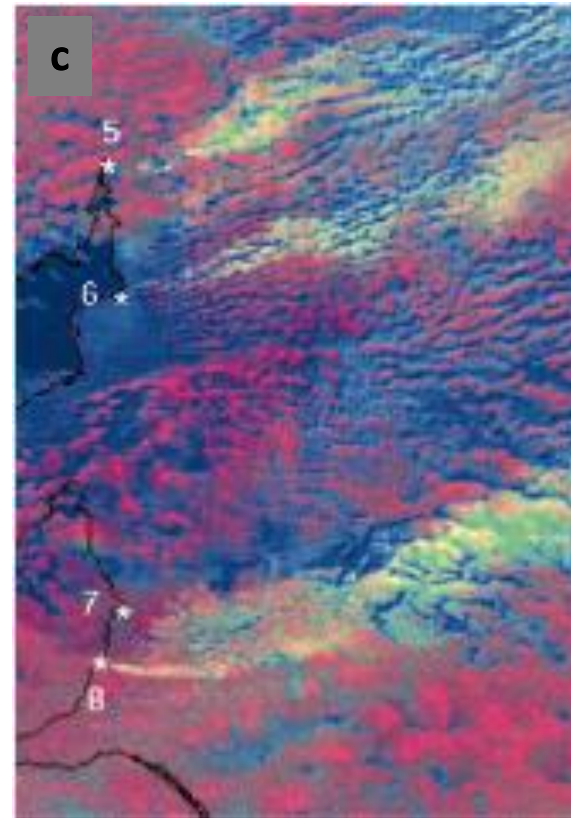


- Statically stable conditions
- Fairly uniform stratiform





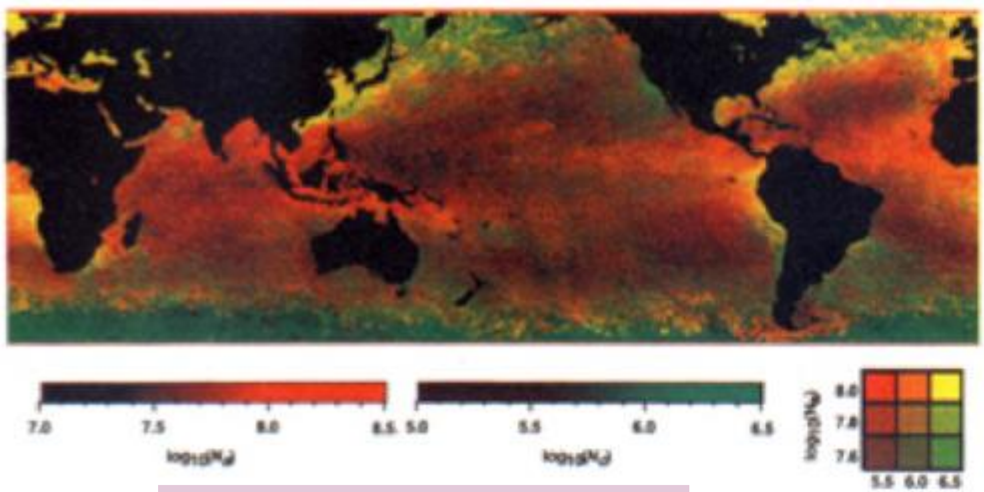
τ_c and r_c from 0.64 and 3.7-micron AVHRR (plane-parallel RT)



False-color AVHRR [Blue – 11 µm; Red – 0.67 µm; Green – 3.7 µm] Red indicates large droplets, yellow signifies smaller droplets [*Rosenfeld, Sci. 2000*]

(a) Ship tracks off the coast of California, from AVHRR.
(b) Retrieved r_c and τ_c differences. [*Coakley & Walsh JAS 2002*]

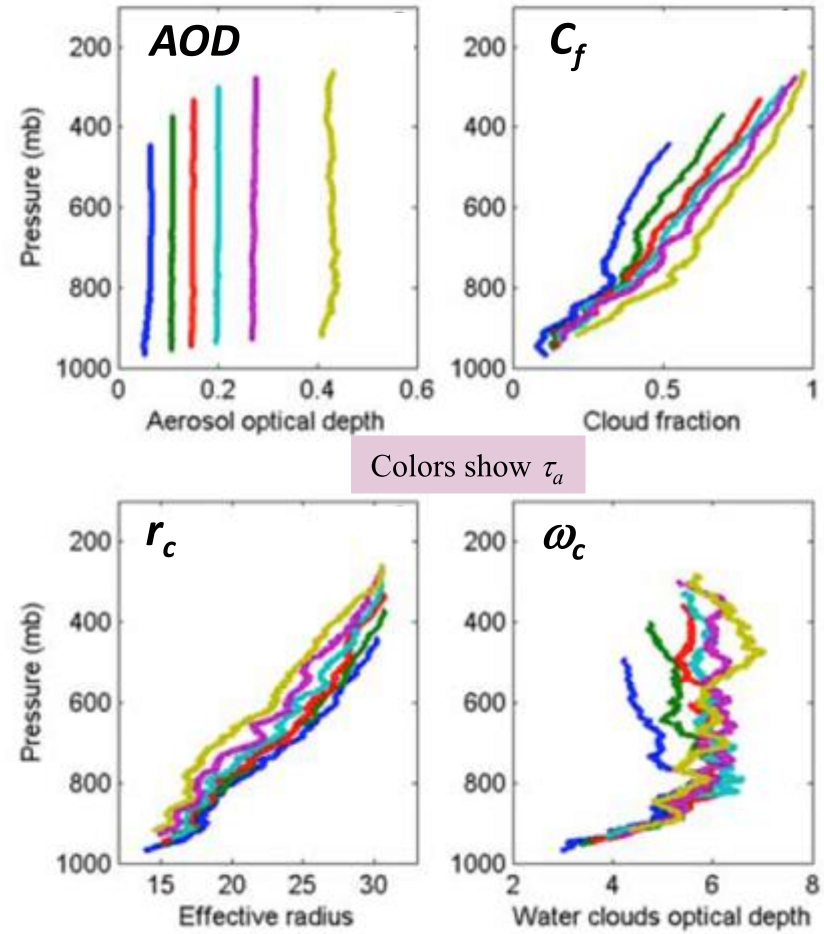
Aerosol Effects on Clouds – Correlation Studies



Log N_a (*red*) vs. Log N_c (*green*)
Yellow= N_a, N_c large
Red= N_a large, N_c small
Green= N_a small, N_c large

Correlation between AVHRR particle number N_a (fixed r_a; *AI* (= τ_a x *ANG*) and cloud droplet (N_c) concentrations, for 4 months in 1990; $N_a \sim \tau_c$; **$N_a \sim 1/r_c$ in low cloud** (yellow) regions [*Nakajima et al., GRL 2001*].

- [*Feingold et al. JGR 2001*] ***Drop size effect saturates*** at $\tau_a \sim 0.4, 0.8$, depending on conditions (SCAR-B, Brazil)
- [*Ackerman et al., Sci. 2000*] INDOEX – absorbing aerosol can ***dissipate clouds***

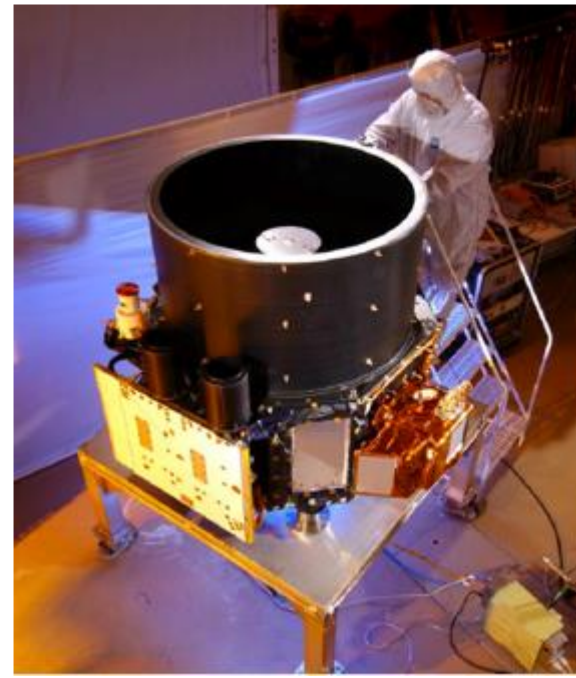


Atlantic convective ***cloud invigoration*** from MODIS [*Koren et al. GRL 2005*]

- $1/r_c \sim N_c \sim N_a \sim \tau_a$ [Cloud radius effect]
- r_c decrease → early precip. inhibited → higher cloud tops, cloud fraction, glaciation
- C_f, T_c, τ_c (water clouds) all increase with τ_a

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)

Vertical Range (km)	Horizontal Resolution (km)	Vertical Resolution (m)
30.1 – 40	5	300
20.2 - 30.1	1.7	180
8.2 – 20.2	1.	60
-0.5 – 8.2	0.33	30

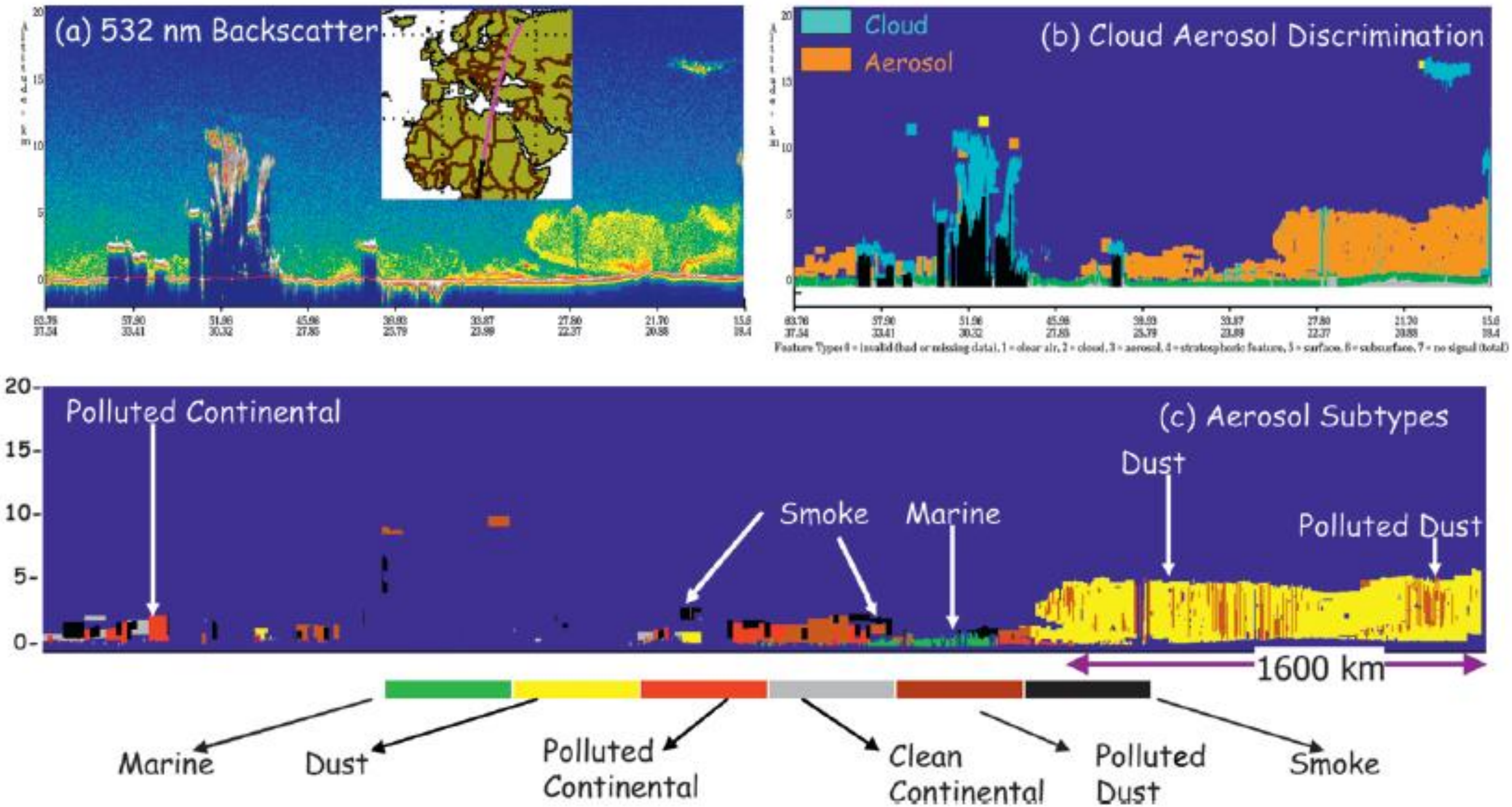


Launched April 2006

- 15 orbits per day, ~100 m wide sampling ***curtain***; averaged to 333 m
- 532 and 1064 nm + polarization (at 532 nm); to ~40 km elevation
- Layer height for AOD ≥ 10^{-2}; AOD for layers having AOD ≤ 3
- For low AOD, need the higher S/N of ***nighttime,*** 532 nm observations

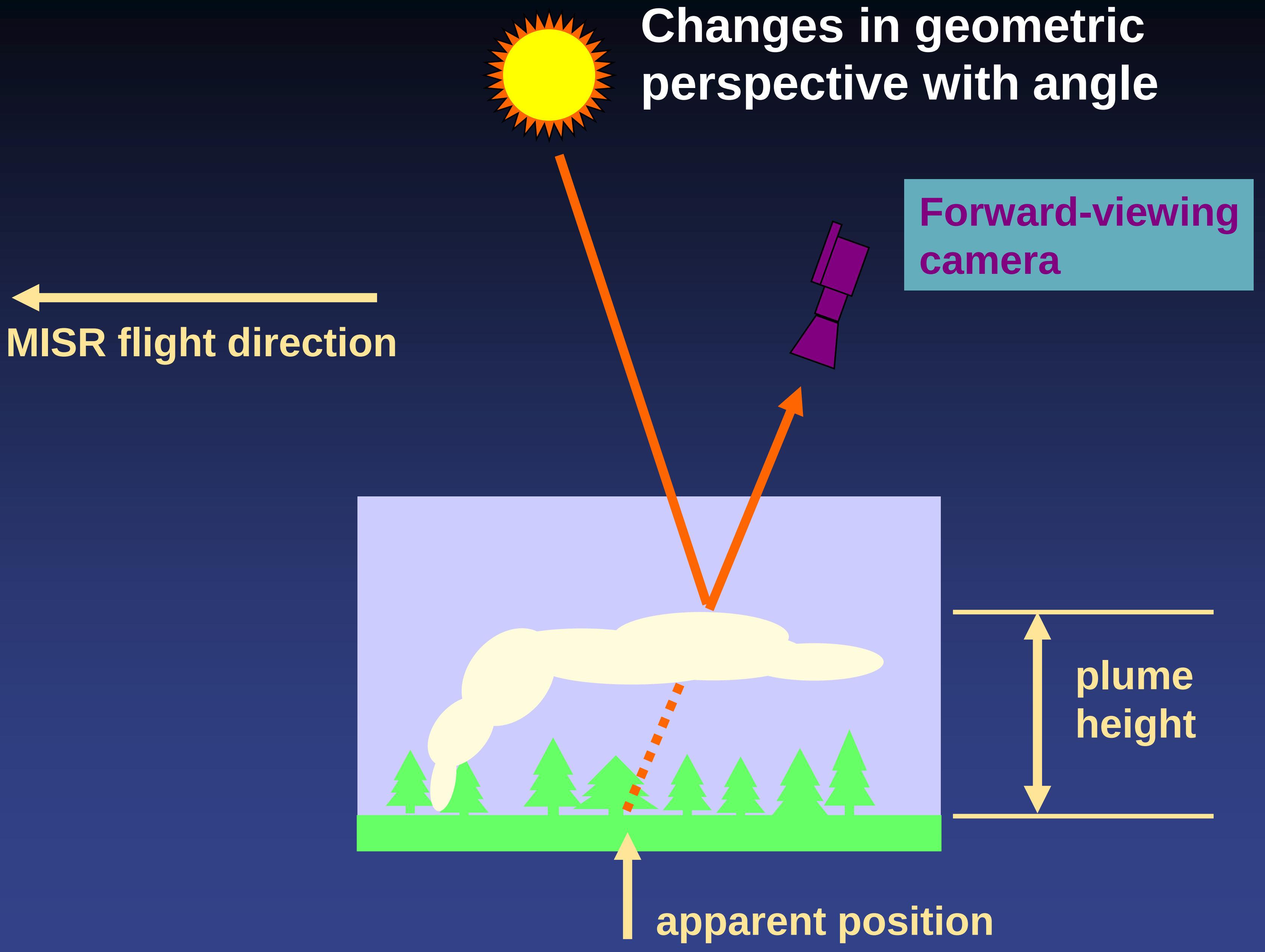
Winker et al., JAOT 2009

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)



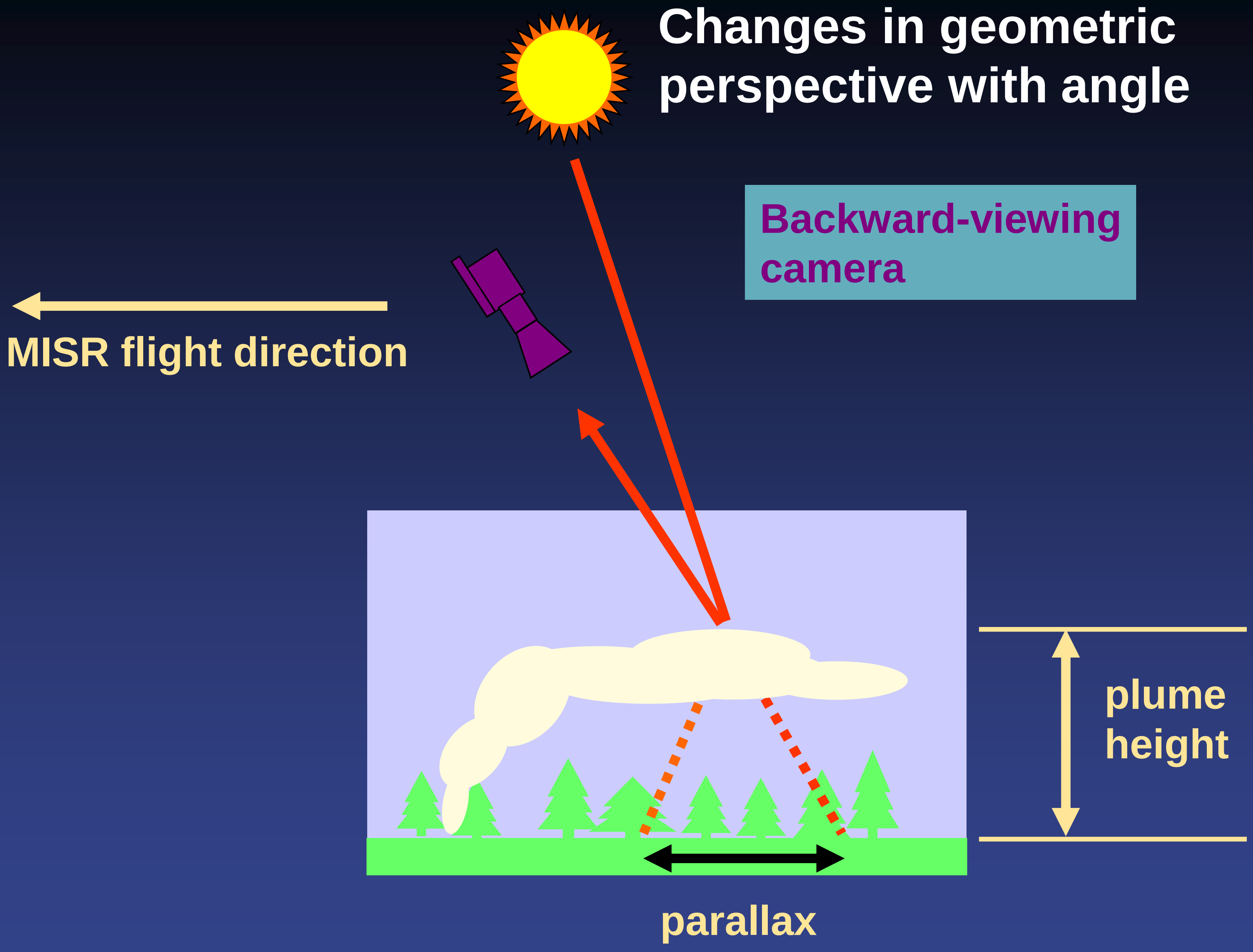
Omar et al., JAOT 2009

Changes in geometric perspective with angle



Diner 2003

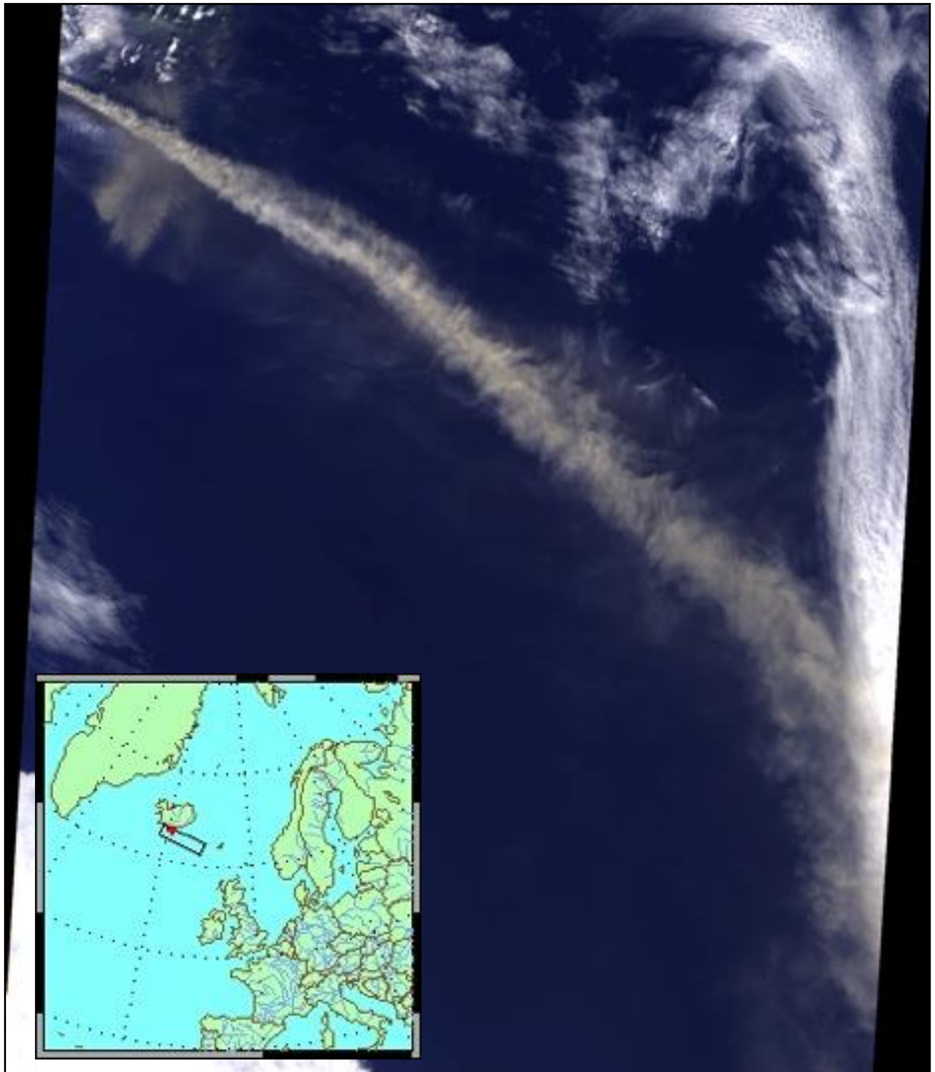
Changes in geometric perspective with angle

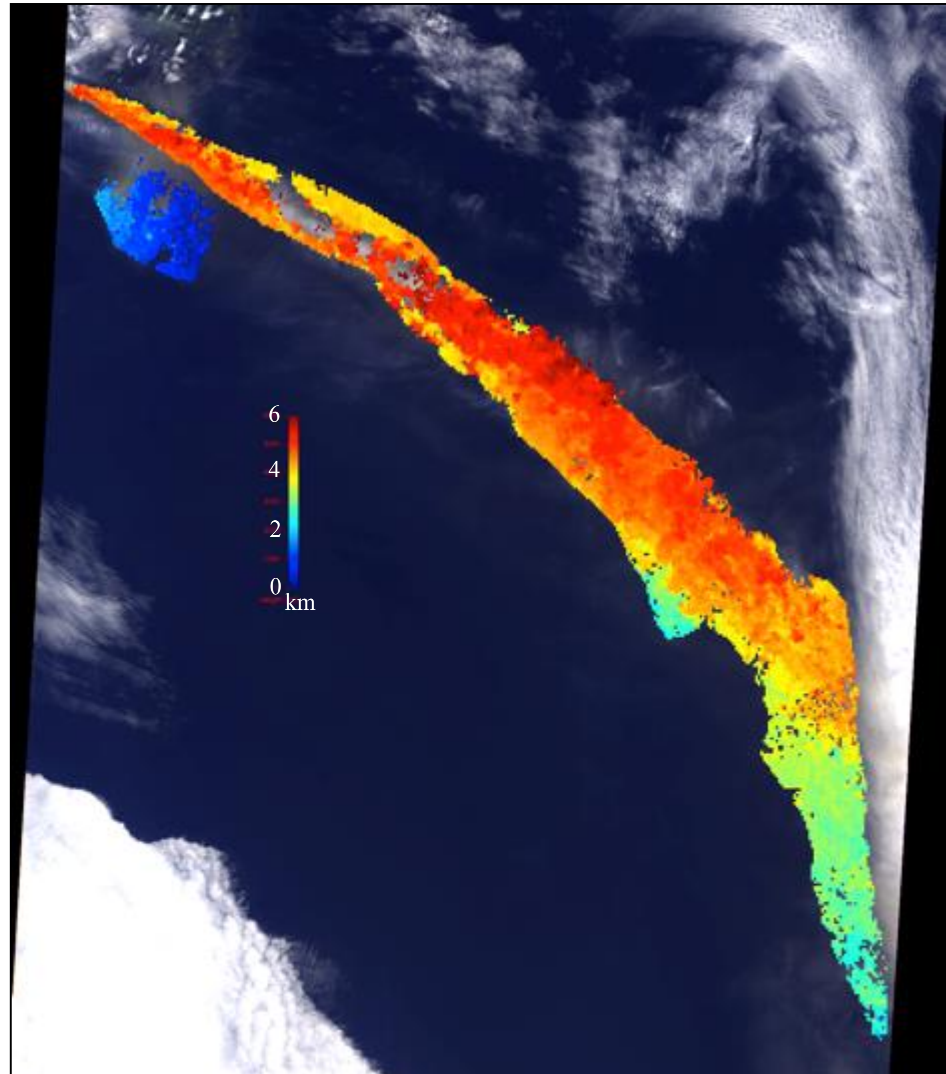


Diner 2003

MISR Stereo-Derived Plume Heights

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

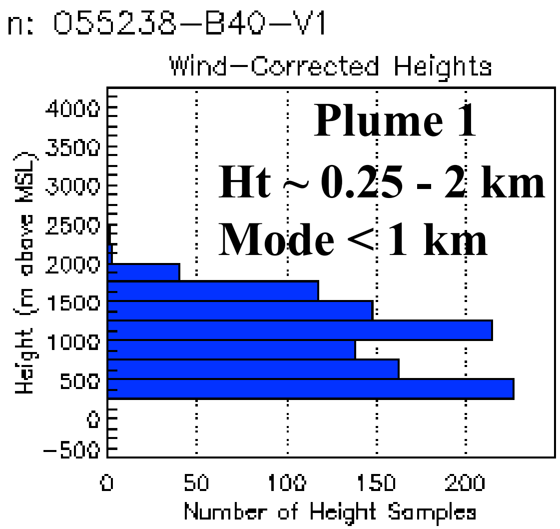




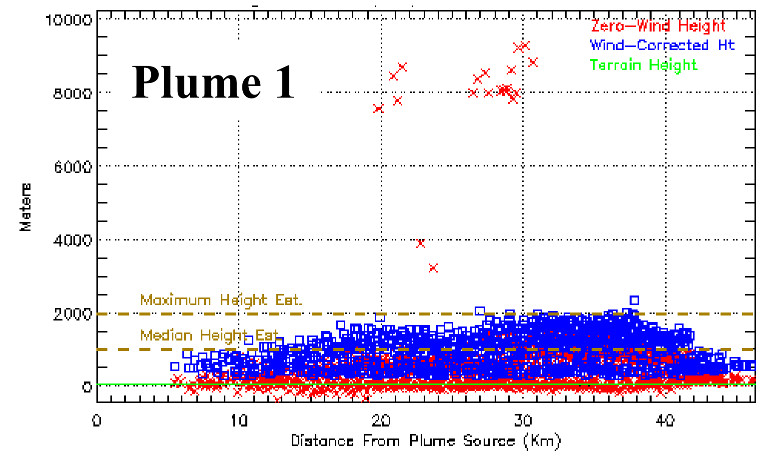
D. Nelson and the MISR Team, JPL and GSFC

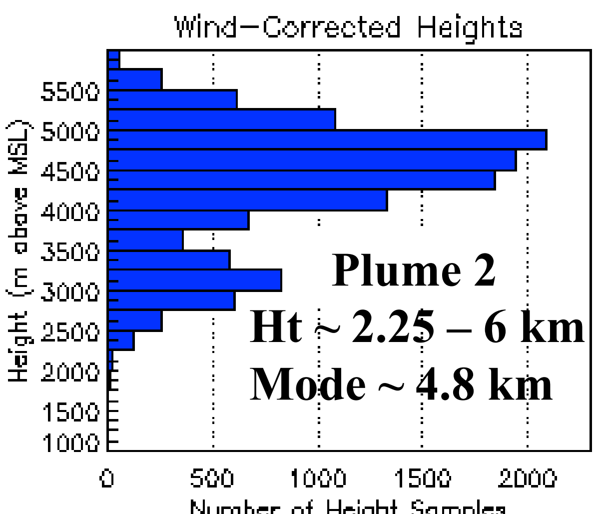
MISR Stereo-Derived Plume Heights

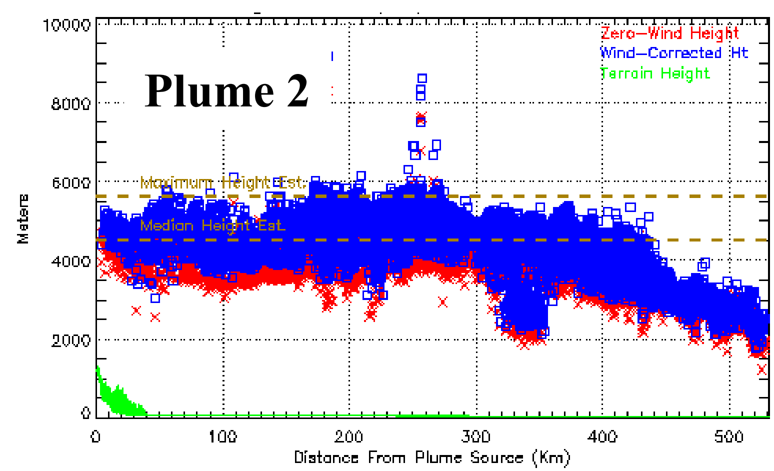
07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39



Height: **Blue** = Wind-corrected



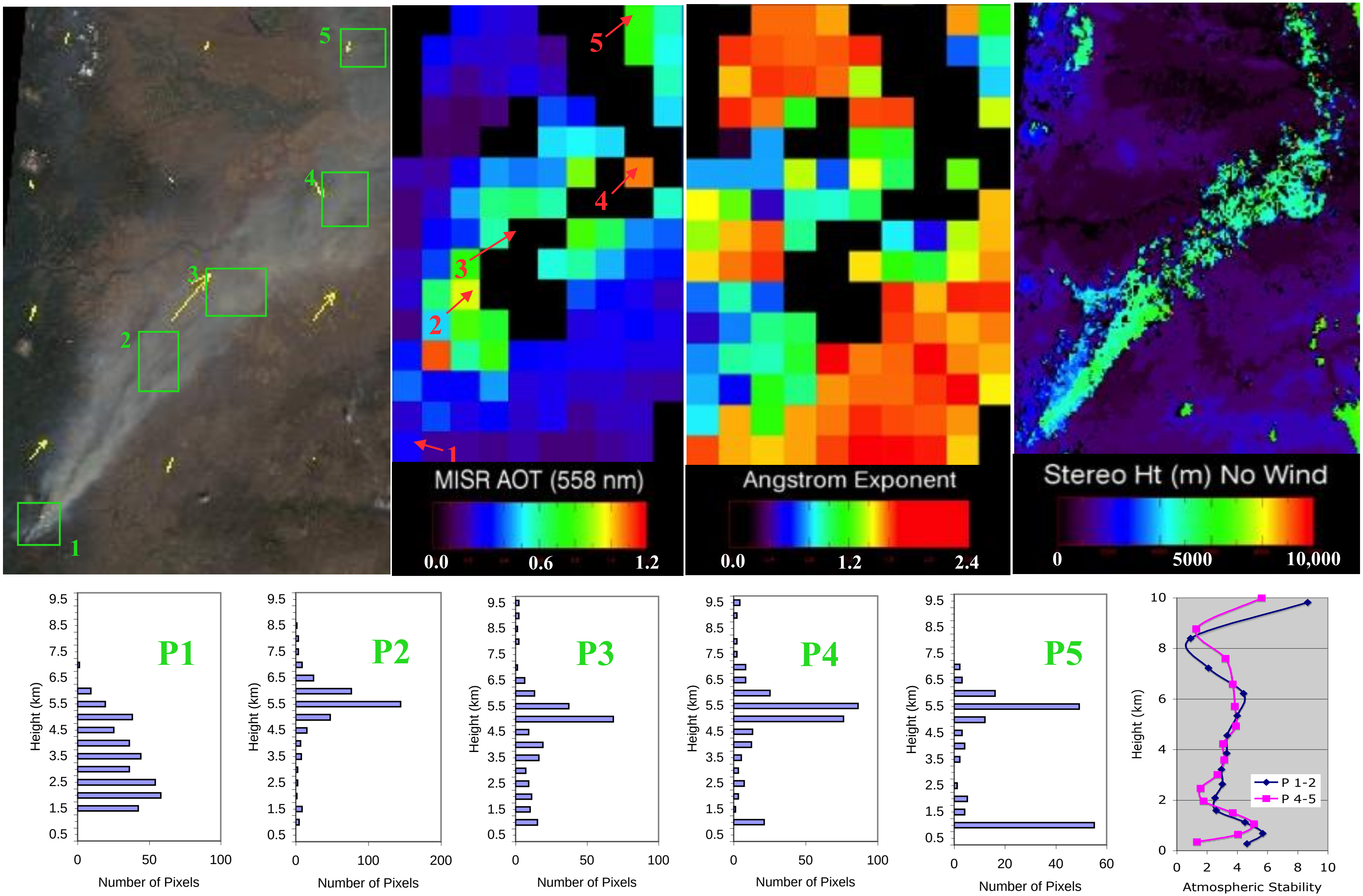




D. Nelson and the MISR Team

Oregon Fire Sept 04 2003

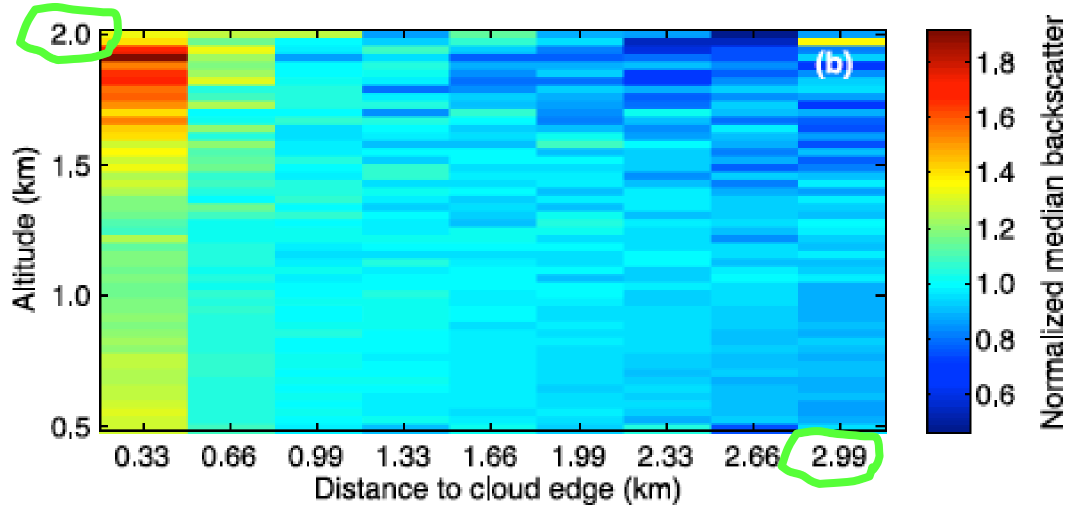
Orbit 19753 Blks 53-55 MISR Aerosols V17, Heights V13 (no winds)

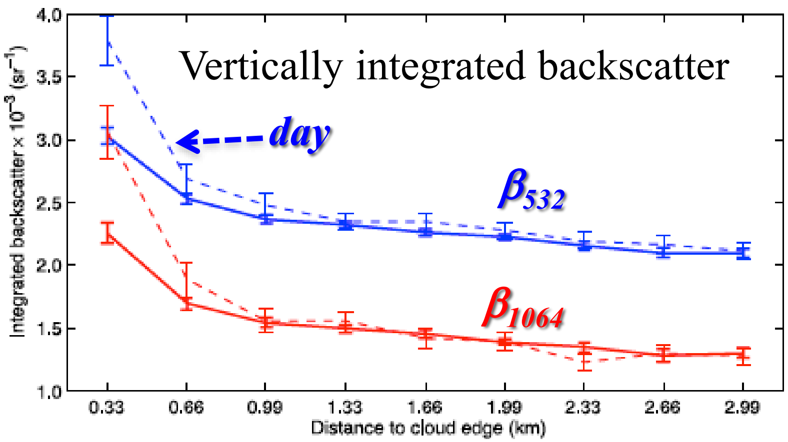


Kahn, et al., JGR 2007

Aerosol Properties Near Cloud

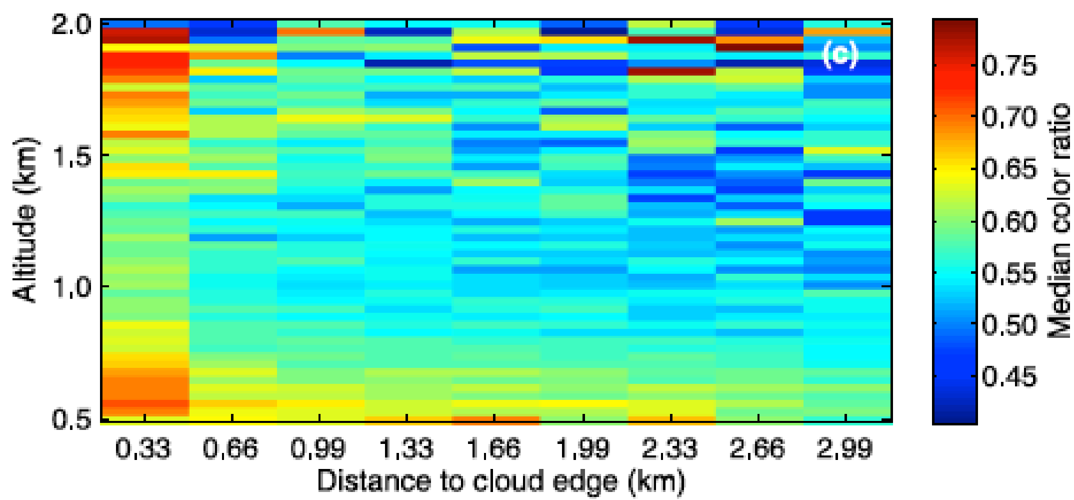
CALIPSO nighttime 532 nm backscatter, normalized over 2.99 km. ***Enhanced aerosol opacity*** near cloud edge, especially at ***cloud top and bottom***.





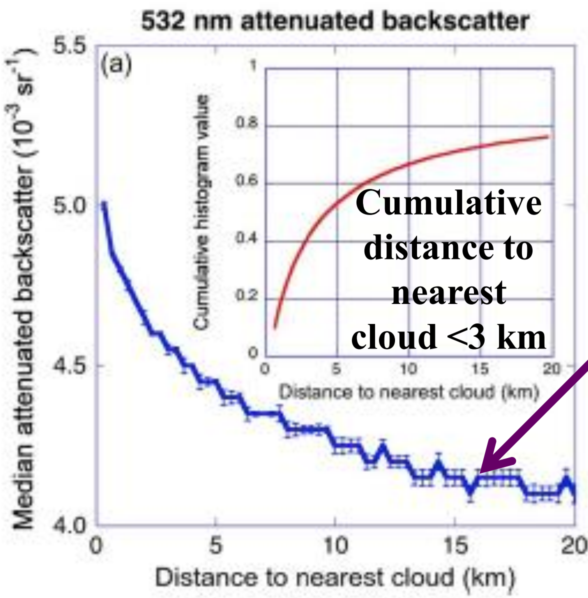
Detrainment at cloud top??
Hygroscopic growth at cloud bottom??
Collision Coalescence (R↑; N, σ↓)?

CALIPSO median nighttime 1064/532 nm color ratio. ***Larger particles*** near cloud edge, especially at cloud top and bottom.



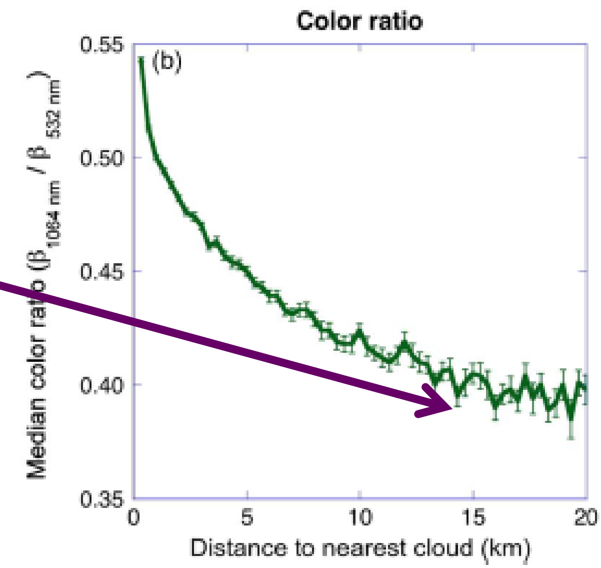
Tackett & Di Girolamo GRL 2009

Aerosol Properties Near Cloud



Cumulative distance to nearest cloud <3 km

Backscatter & color ratio enhanced to ~15 km



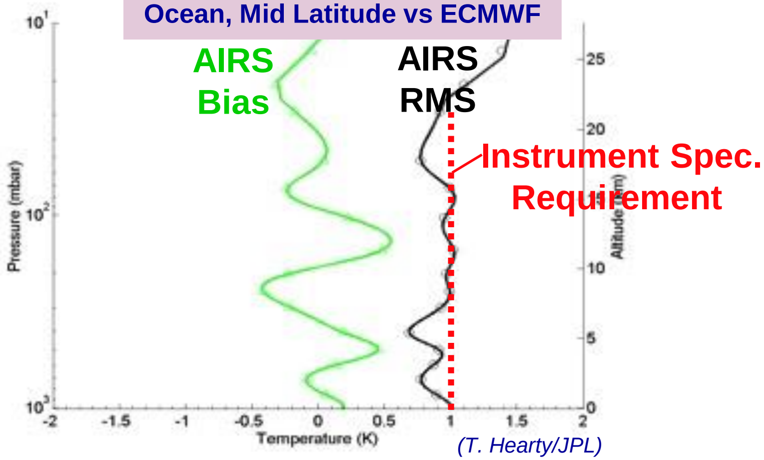
Global data
Sept. – Oct. 2008

Varnai & Marshak, GRL 2011

AIRS - Temperature & Water Vapor Profiles

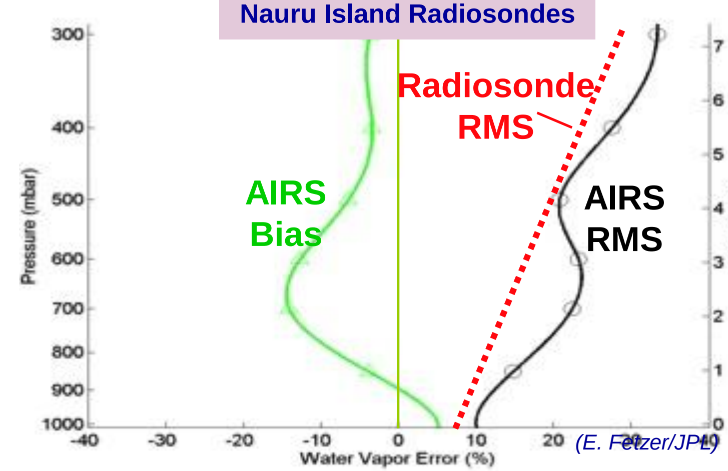
Temperature Profiles Accurate to 1K/km to 30 mb

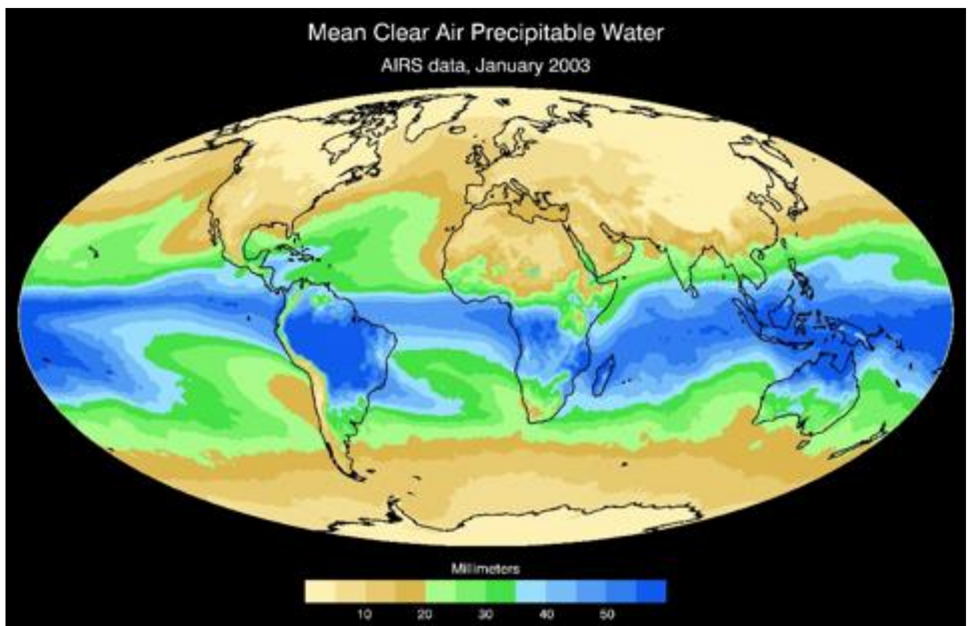
Ocean, Mid Latitude vs ECMWF



Water Vapor Profiles Match Observations 15%/2km

Nauru Island Radiosondes





15 km nadir footprint

Satellite Capabilities

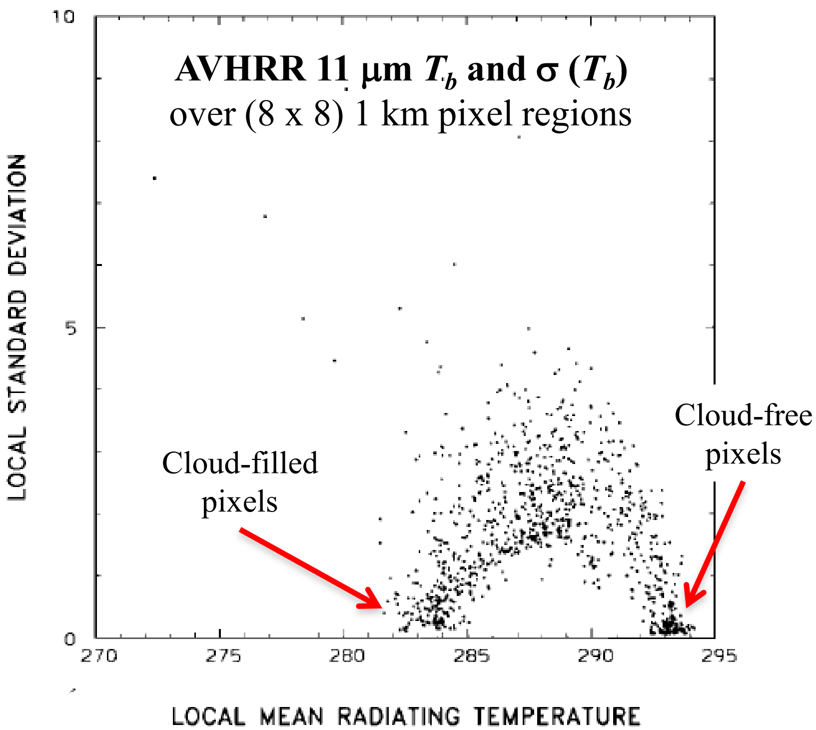
- *Polar orbiting imagers* provide ***frequent, global coverage***
- *Geostationary platforms* offer ***high temporal resolution***
- *Multi-angle imagers* offer ***aerosol plume height & cloud-top mapping***
- *Passive instruments* can retrieve total-column ***aerosol amount (AOD)***
- *Active instruments* determine aerosol & some cloud ***vertical structure***
- *UV imagers* and *active sensors can* retrieve ***aerosol above cloud***
- *Multi-angle*, *spectral*, *polarized* imagers obtain ***some aerosol type info.***
- *Active sensors* can obtain ***some aerosol type info., day & night***
- Satellite trace-gas retrievals offer ***clues about aerosol type***
- *Vis-IR imagers* can retrieve ***cloud phase***, r_c, T_c, p_c, τ_c, α_c, C_f, **LWP**

Need to be creative &
Play to the strengths of what satellites offer!!

Assessing Some Satellite-Retrieval Issues

Partly Filled Pixels

[*Coakley & Bretherton JGR 1982*]



- Can obtain cloud-fraction for single-layer clouds
- Multi-layered clouds can be identified by distinct T_b
- The challenge is selecting a spatial scale for aggregation

Sampling Bias Example

[*Rosenfeld & Feingold GRL 2003*]

First Indirect Effect: $IE \sim -d\ ln\ r_c / d\ ln\ \tau_a$

<u>AVHRR</u>

[*IE* ~ 0.17] over ocean (*Nakajima et al. 2001*)

- Partly filled pixels, surface contributions → r_c *errors*
- Disfavors: thin & broken cloud, especially over land

<u>POLDER</u> (*Breon et al., 2002*)

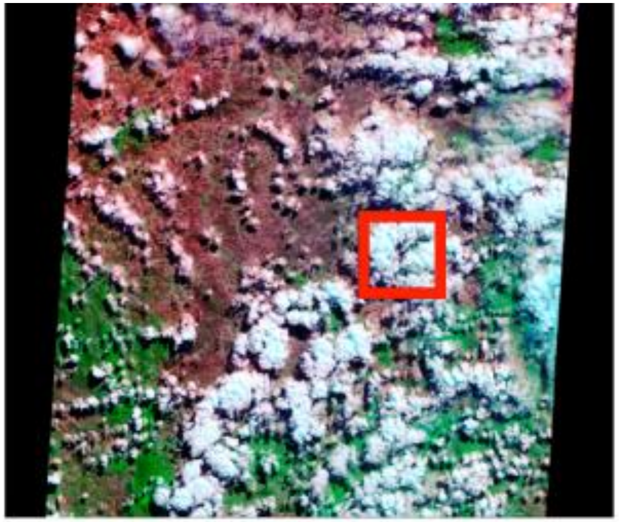
[*IE* ~ 0.085] over ocean; [*IE* ~ 0.04] over land

- Uses "glory" to get r_c →
  favors more mono-disperse, less turbulent clouds
- Disfavors: thick convective clouds, variable height & r_c

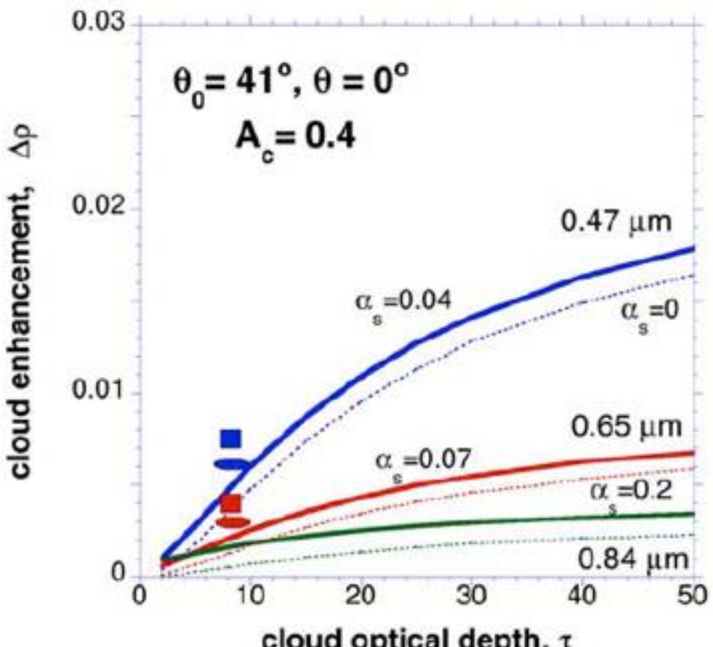
Thinner clouds →
smaller updrafts, less activation, smaller *IE*

So POLDER might produce artificially low regional *IE*

3-D Light Scattering Effects on Remote Sensing



ASTER false-color image
Brazil, 09 August, 2001



Simulated cloud → Rayleigh scattered light enhancement vs. τ_c

- Using the image geometry
- For three wavelengths
- For different surf. reflectances (α_s)

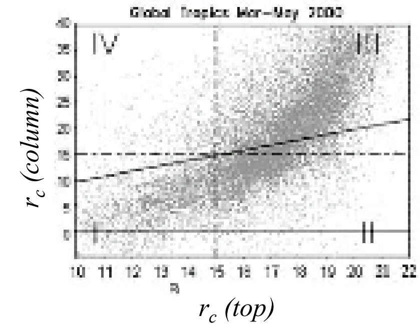
Refl. in "clear" pixels used for MODIS AOD Retrievals (***squares***)

Refl. in pixels 3 km away from cloud (***ovals***) [*Wen et al.* 2007]

Marshak et al., JGR 2008

Vertical Structure, and Confounding Meteorology
r_c – Cloud 'Top' vs. Cloud Column, & *LTS*

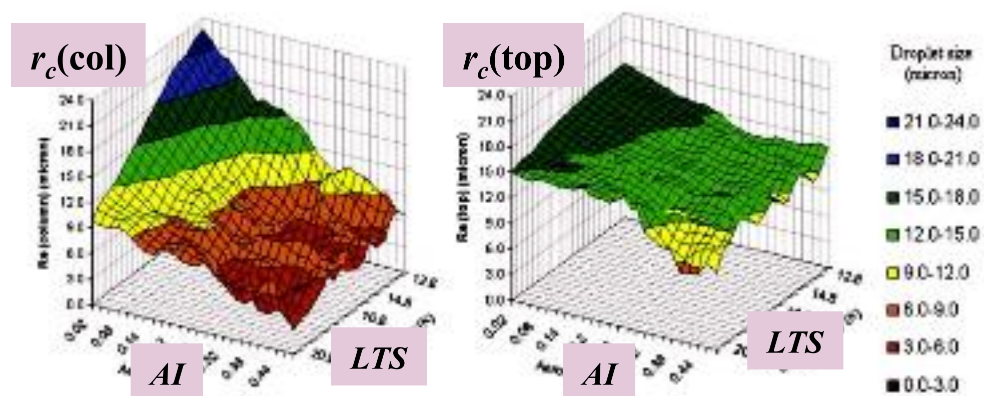
- **TRMM** data, March-May, 2000; 37˚N to 37˚S
- Vis-IR Radiance Imager (**VIRS**) for r_c**(top)**, τ_c
- Microwave Imager (**TMI**) for r_c**(col)**, ***LWP*** (19, 37GHz)
- Warm clouds only ($T_c > 273$ K)
- VIRS to find cloud-filled TMI pixels
- ***AI*** from **MODIS**
- **Lower Trop. Stability** (***LTS***) from **NCEP**



	r_c(top) vs.	r_c(col) (microns)	
I.	<15	<15	[non-ppt.]
II.	>15	<15	[transition]
III.	>15	>15	[ppt.]

- ***IE*** appears **larger** for r_c**(col)** than r_c(top)
- **Higher *LTS*** and/or ***AI*** ~ **reduced** r_c and **suppressed rain conditions**
- **Aerosol effect ~ 50% larger** than *LTS* effect
- TMI ***LWP* decreases with reduced** r_c → **net change in cloud albedo SMALL**

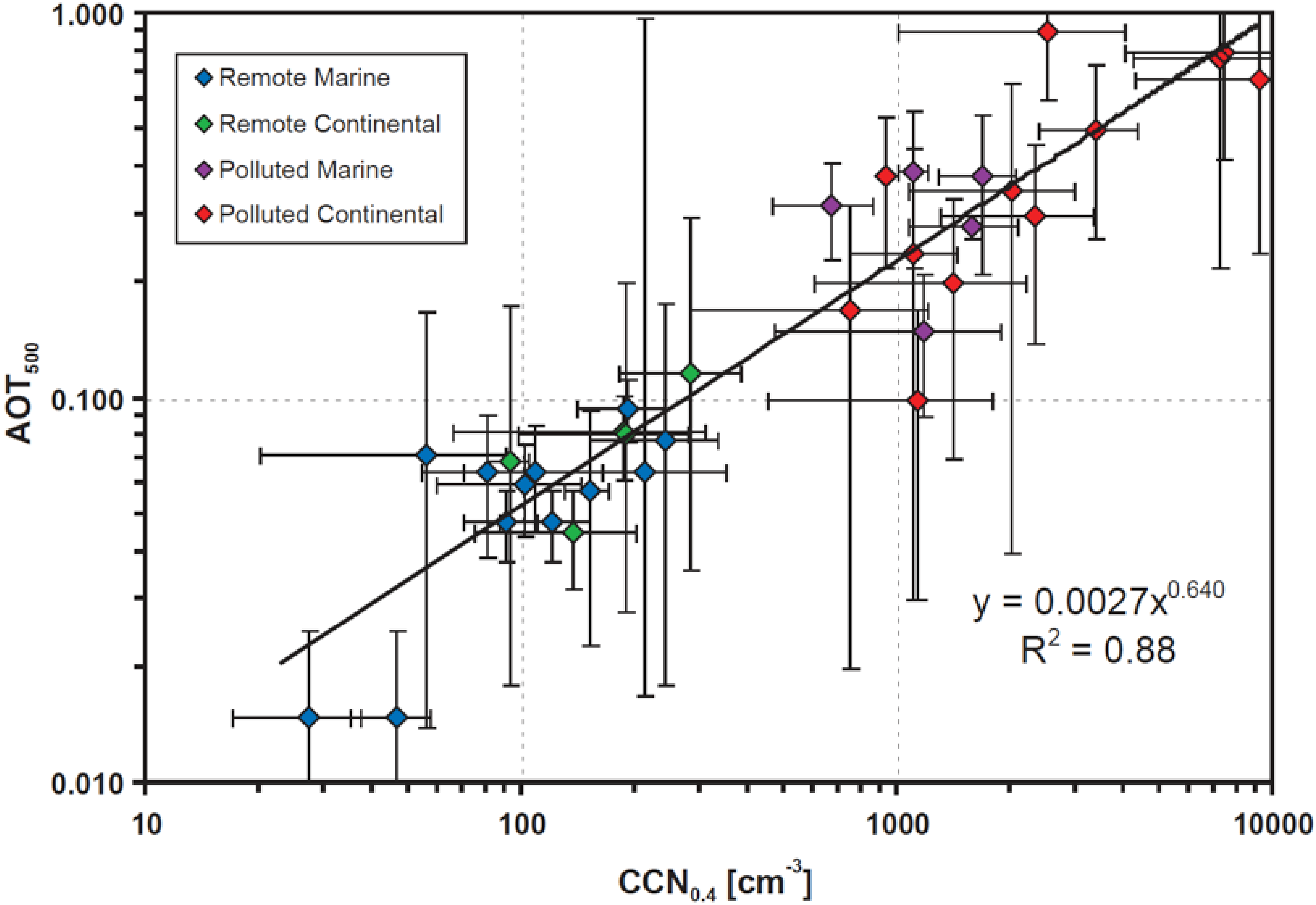
[dα_c/d*LTS* ~9%; *LTS* **effect dominates**]



r_c vs. *AI* vs. *LTS*

Matsui et al., GRL 2004

Correlation Between AOD from Space and CCN in Remote & Polluted Regions



Andreae ACP 2009

Using ***AI* (= τ_a x *ANG*)** to Estimate ***CCN***

Kapustin, Clarke, et al., JGR 2006

• <u>Test</u> <u>Idea</u>: Smaller particles more likely to become *CCN; **Ang*** is a smaller quantity for larger particles

• ACE-Asia, Trace-P *in situ* **field data** – *CCN* proxy

• **AI does not work quantitatively in general**, but can **<u>if the data are stratified</u>** by:

-- ***RH*** in the aerosol layer(s) observed by satellites

-- **Aerosol Type** (hygroscopicity; pollution, BB, dust)

-- **Aerosol Size** (*Ang* is not unique for bi-modal dist.)

Practically, in addition to t_a and *Ang*, this requires:

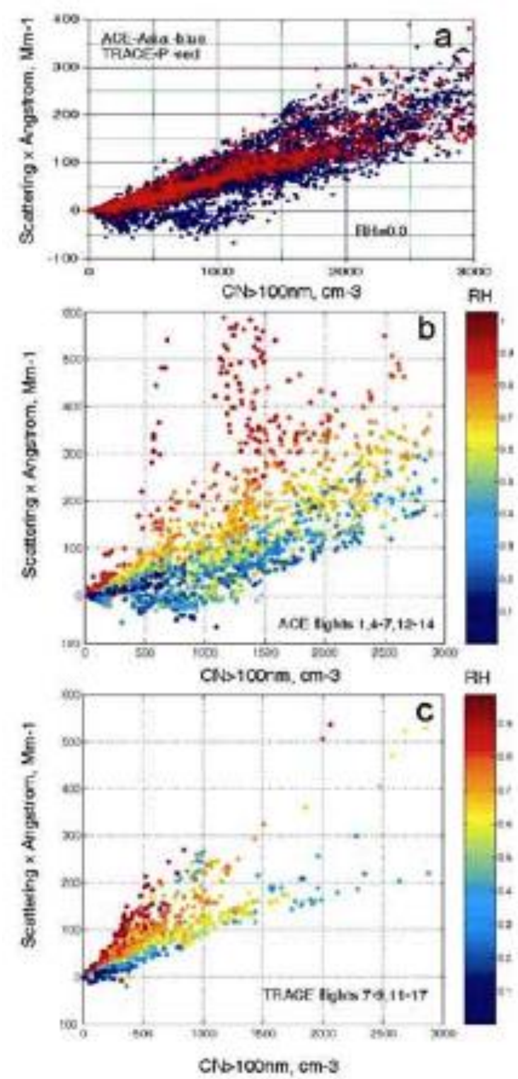
-- Vertical **humidity structure**

-- **Height-resolved** aerosol **type**

-- **Height-resolved size** dist.

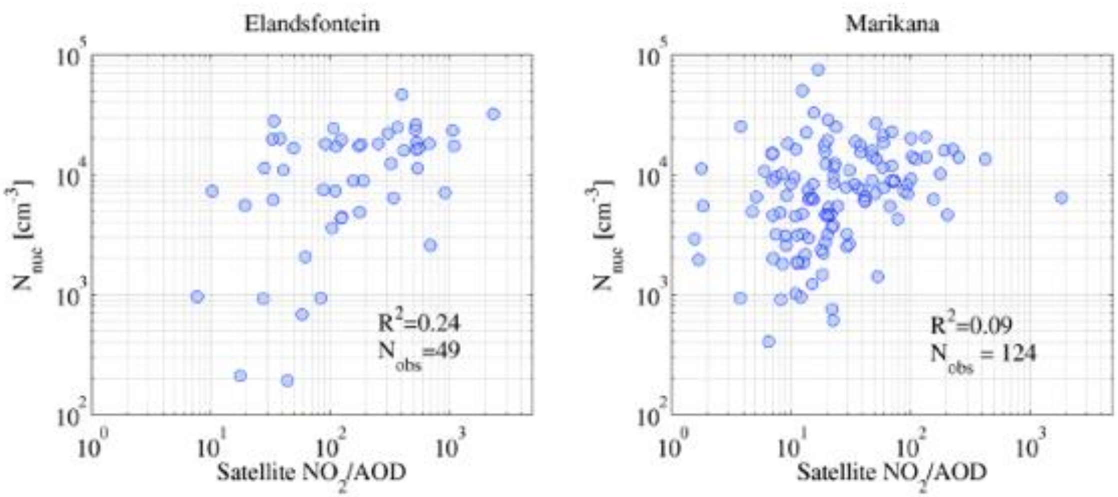
[extrapolated to small sizes(?)]

This study includes enough detail to assess *AI* ~ N_a *<u>and</u>* *AI* ~ *CCN*



AI vs. *in situ CCN* proxy
(a) all ACE (blue) & Trace-P, **<u>dry</u>**
(b) ACE - OPC-only, amb. *RH*
(c) TP - OPC-only, amb. *RH*

Satellite-Derived Proxies for CCN



Satellite NO_2/AOD proxy vs. *in situ* nucleation particle concentration

Sundstrom et al., ACP 2015

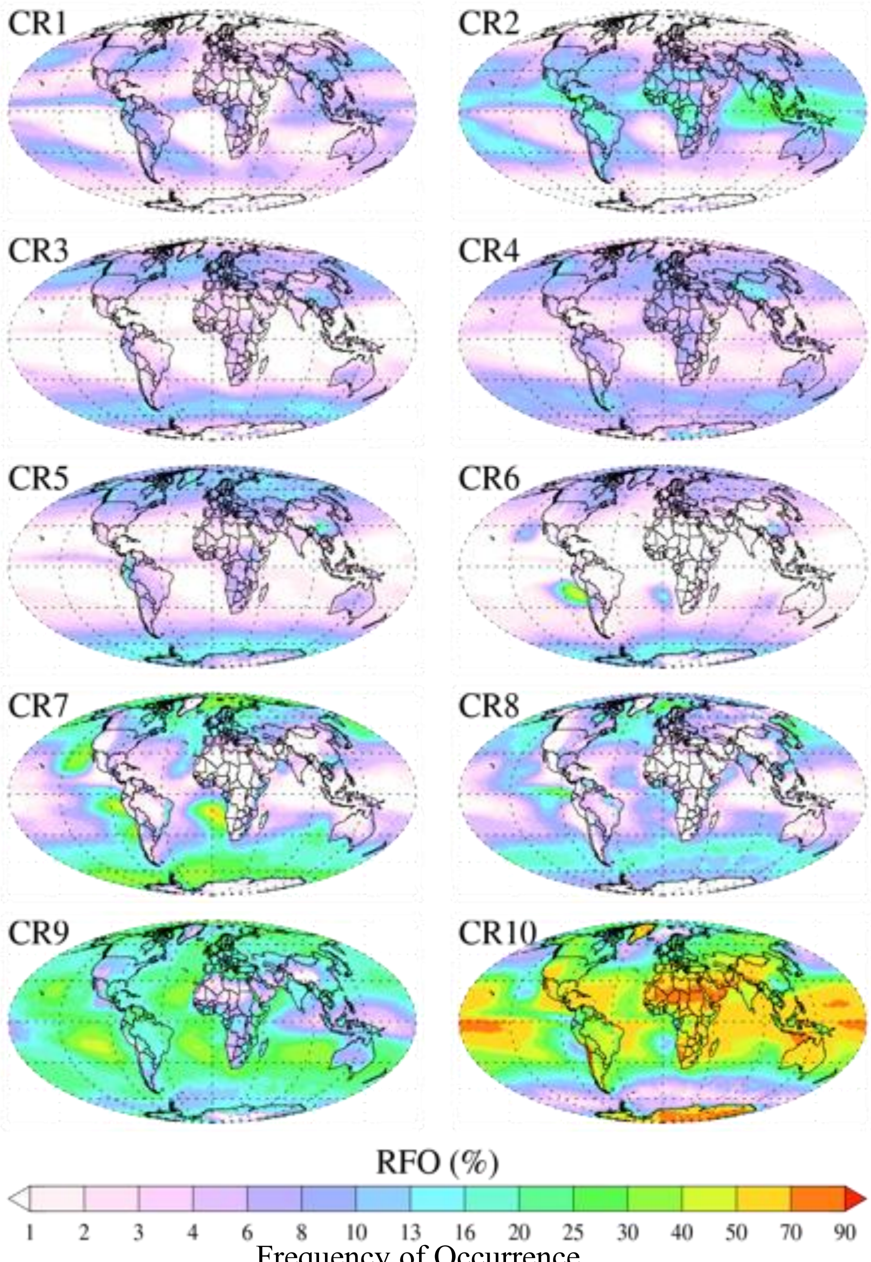
- OMI NO_2 Column
- OMI SO_2 Column (mainly near-surface)
- *OMI* UVB (310 nm) Surface noontime irradiance to form secondary sulfate
- *MODIS* AOD [*attempt* to represent the condensation ***sink*** for nucleation particles]

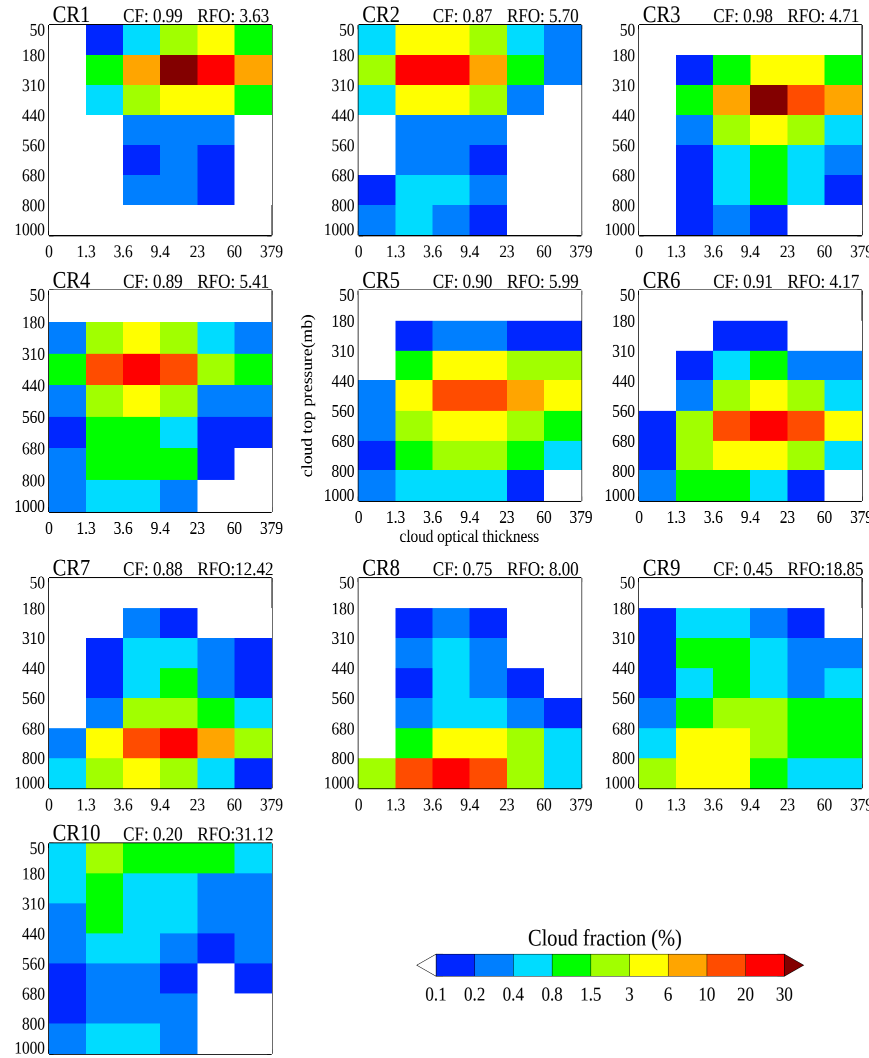
These are quantities we can retrieve from satellites, though they are not necessarily the ones we really want

→Ambiguity in vertical distributions of formation areas and sinks
→Lack of information about diurnal variation from satellites
→The 2-D spatial distribution of proxies compares ~ better with *in situ* observations for S. Africa, except where gas column concentrations are low

Would you believe the answer if it were a surprise?

MODIS global cloud regimes



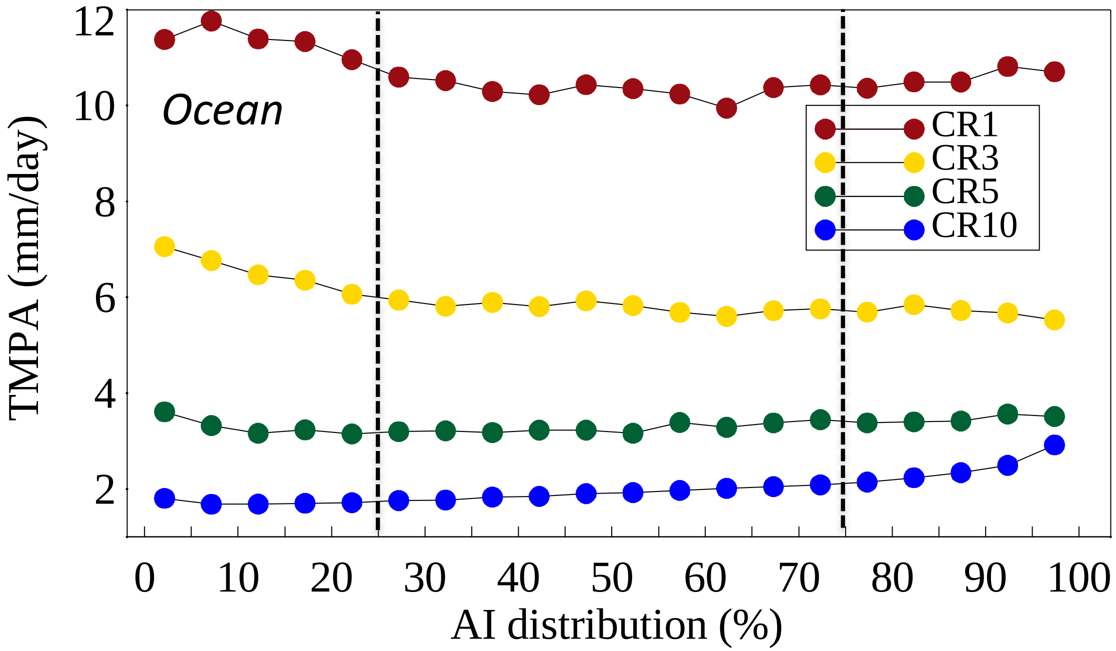


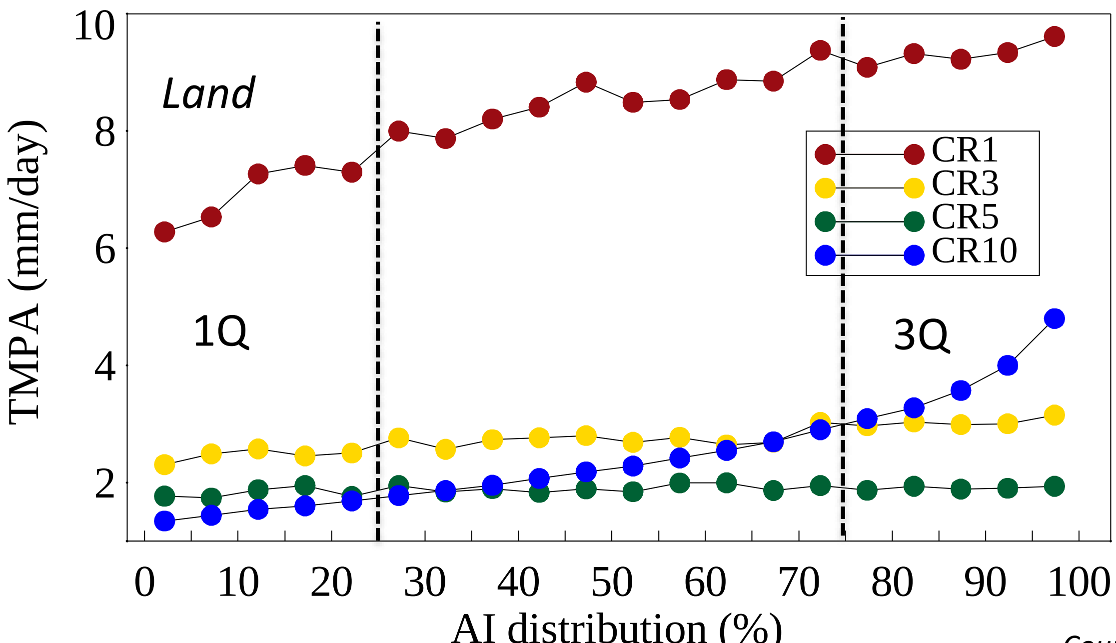
CTP vs. TAU Cluster Analysis

(10 “Cloud Regimes”; MOIDS V5.1)

Courtesy of Lazaros Oreopoulos

Precipitation vs AI per CR (50° S to 50° N)





Relationship between precipitation & Aerosol Index, stratified by cloud regime (CR) and Land/Ocean

Courtesy of Lazaros Oreopoulos

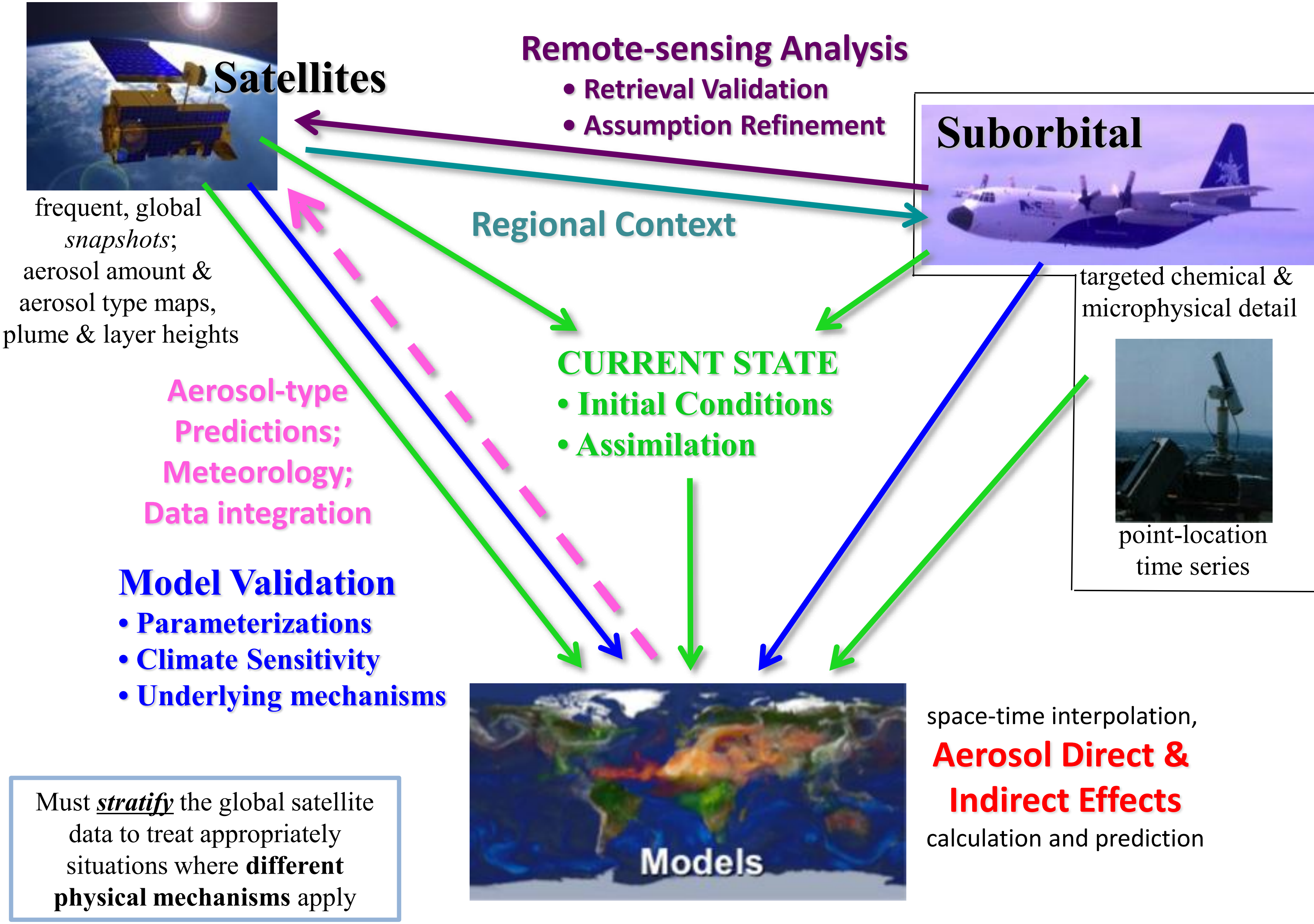
Summary

Observed trends when going from low aerosol index (1Q) to high (3Q)

	CR_{ice} Land/Ocean (CR 1, 2, 3)		CR_{liq} Land/Ocean (CR 6, 7, 8)		CR_{10}
Precip.	⇑ (red)	⇓	-		⇑
C_f	-		⇑ (blue)		⇑
CTH	⇑ (red)		⇑	-	⇑
τ_c	⇑ (red)	⇓	⇑ (blue)		⇑
r_e	⇓	-	⇓ (blue)		⇑
PrecipNZ	⇑ (red)	⇓	-	⇓ (blue)	⇑

red arrow: consistent with invigoration; blue arrow: consistent with 1st and 2nd indirect effect

Courtesy of Lazaros Oreopoulos



Adapted from: Kahn, Survy. Geophys.

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 15+ 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*

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***, ***Chemical Type***, and ***Mass Extinction Efficiency*** (MEE)
- ***Process Data Routinely*** at central site; instrument PIs develop & deliver algorithms, upgrade as needed; data distributed via central web site
- Peer-reviewed Paper 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