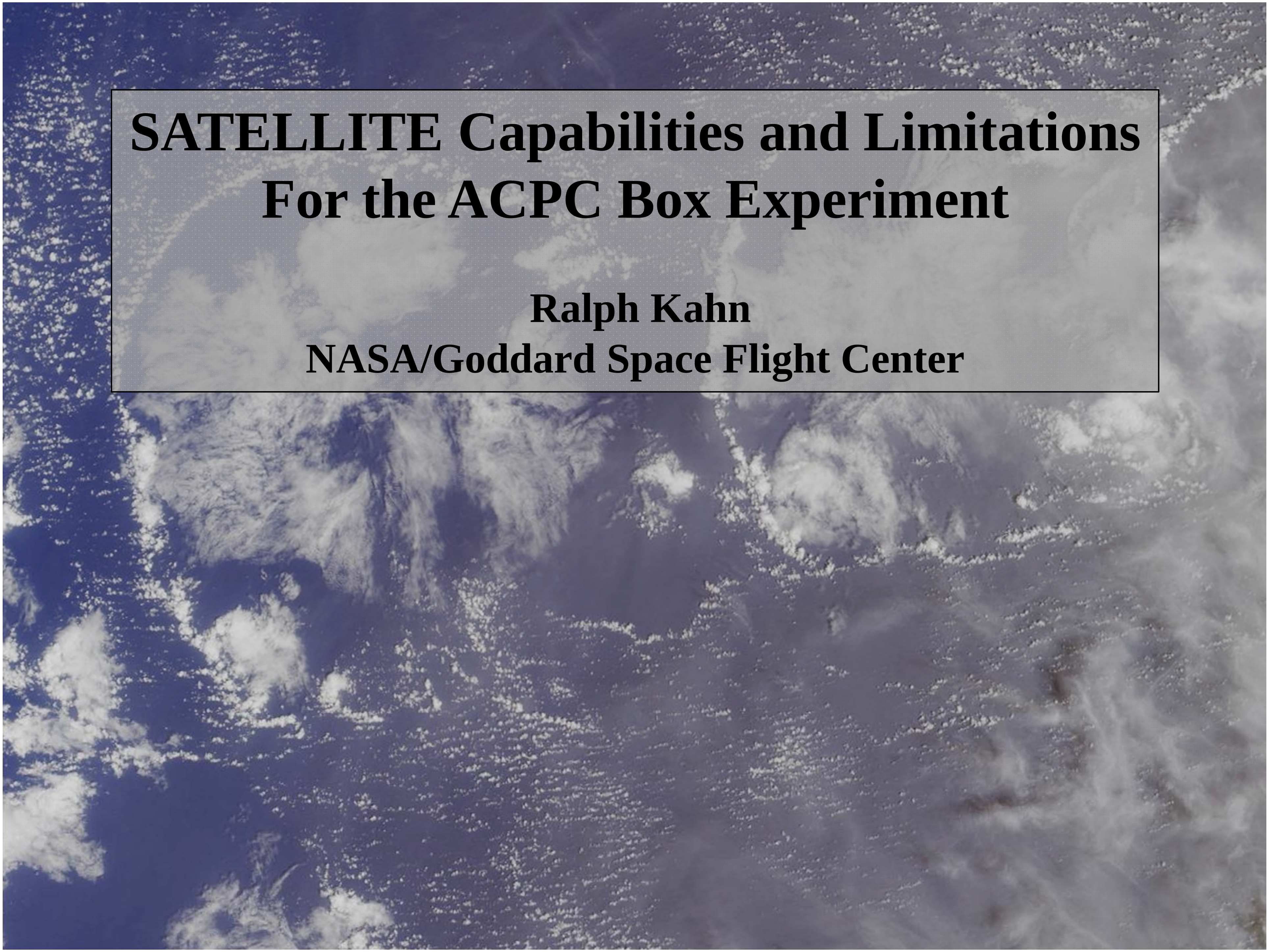


SATELLITE Capabilities and Limitations For the ACPC Box Experiment

Ralph Kahn
NASA/Goddard Space Flight Center

Overall Satellite ***Limitations***

- *Polar orbiters* provide ***snapshots only***
- Difficult to probe ***cloud base***
- Typically ~100s of meters or poorer ***horizontal resolution***
- *Passive instruments* offer little ***vertical information***
- *Active instruments* offer little ***spatial coverage***
- Little-to-no information about aerosol ***particle properties***
- Bigger issues retrieving aerosols ***in the presence of clouds!***
- Cloud property retrievals can be aliased ***by the presence of aerosols***

These points are summarized in ***Rosenfeld et al. Rev. Geophys. 2014***

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***

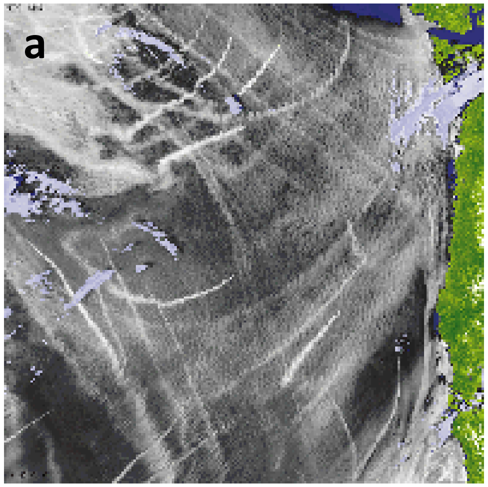
Satellites are fairly blunt instruments for studying aerosol-cloud interactions!!

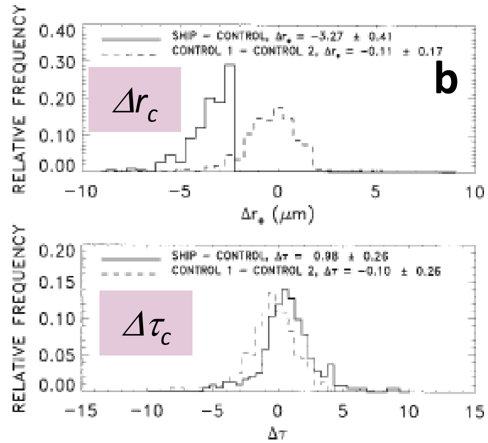
Satellite "Direct" Capabilities

- *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**

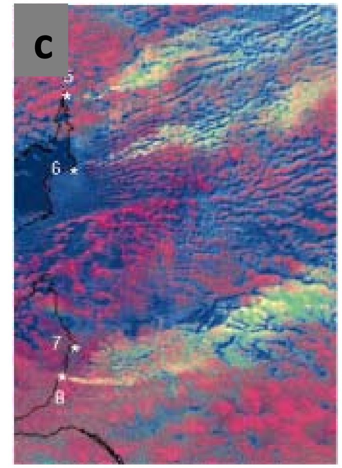
Need to be creative &
Play to the strengths of what satellites offer!!

Historical Examples

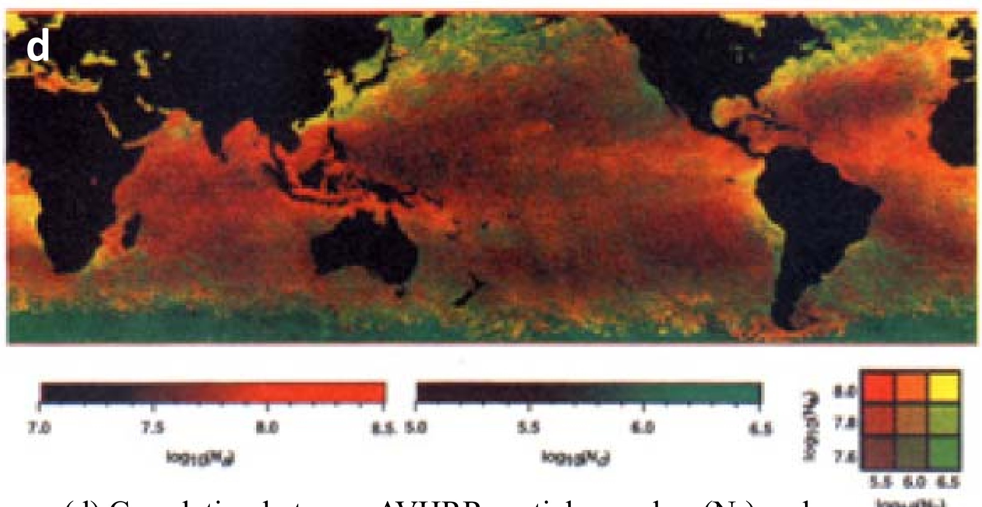




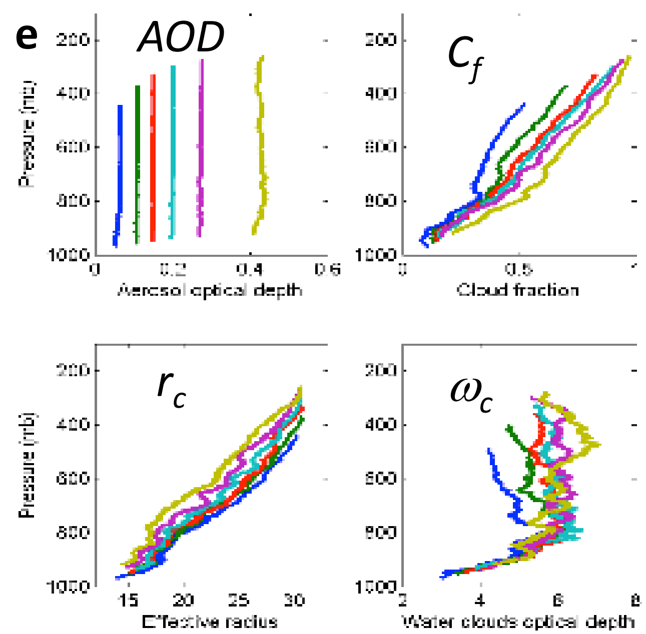
(a) Ship tracks off the coast of California, from AVHRR.
(b) Retrieved r_c and τ_c differences. [*Coakley & Walsh JAS 2002*].



(c) False-color AVHRR: Red indicates large droplets, yellow signifies smaller droplets [*Rosenfeld, Sci. 2000*]



(d) Correlation between AVHRR particle number (N_a) and cloud droplet (N_c) concentrations, for 4 months in 1990; Yellow indicates high N_c with large N_a; red indicates high N_c despite small N_a. [*Nakajima et al., GRL 2001*]



(e) Atlantic convective cloud invigoration from MODIS; aerosol optical depth (AOD), cloud fraction (C_f), cloud droplet effective radius (r_c), water optical depth (ω_c) vs. height; p_c encoded in colors, increasing from blue to green. [*Koren et al. GRL 2007*]

Table 1. The Measured Parameters, Measuring Instruments, and Achievable Accuracy for the Box Experiments[a]

Parameter	Marine Sc	Trade Wind Cumuli	Deep Convective	Achievable Accuracy	Instrument	Platform
* Radiation						
Satellite measurements of TOA radiation, separated to cloud-free and cloudy conditions	H	H	H	2 W m^{-2} for SW instantaneous grid point measurement; 3.7 W m^{-2} for LW [*Loeb et al.*, 2009 JC]	MODIS, CERES	Satellite
Surface downwelling radiation measurements during cloud-free and cloudy conditions	H	H	H	LW: 1%; SW: 2% (daily) [*Wild et al.*, 2013] +3 W/m^2 representativeness error of a point observation for regional (1°) means [*Hakuba et al.*, 2013]	Pyranometer (SW total), Pyrheliometer (SW direct), Pyrgeometer (LW)	Surface
* Satellite measurements of water vapor, with emphasis on upper tropospheric vapor that is detrained from anvils.	L	L	H	10–30% [*Hegglin et al.*, 2008; *Stiller et al.*, 2012 and references therein]	ACE-FTS, MIPAS, AURA-MLS, AIRS	Satellite
* Satellite measurements of CO_2 and CH_4. (near-surface-sensitive column-averaged dry air mole fractions)	M	M	M	CO_2 0.5–1%, CH4 1% [*Buchwitz et al.*, 2014]	CO_2, CH_4: SCIAMACHY, GOSAT	Satellite
* Tropospheric ozone: Tropospheric column or layer averaged mixing ratio				Tropospheric ozone: 10–20% [*Zhang et al.*, 2010; *Boynard et al.*, 2009]	Tropospheric ozone: TES, OMI, IASI	
* Satellite measurements of cloud top temperatures, albedo and emissivity.	H	H	H	Temperature: ~ ± 5 K for optically thin clouds ±1 K for optically thick clouds	AIRS and TOVS (T and Emissivity) CERES (Albedo)	EOS Aqua (AIRS) Various NOAA polar-orbiting satellites (TOVS)
*				Emissivity: ±0.05 for effective emissivity > 0.50; ±0.15 for emissivity < 0.50 Albedo: No absolute uncertainty reported; Stability better than 1%/year SW TOA Flux ~ 4% for all-sky, 2–3% over thick cloud	MISR-MODIS-CERES (TOA Flux)	EOS Terra and Aqua (MODIS, CERES) EOS Terra (MISR)
Nonradiative heat transfer:						
Surface sensible and latent heat fluxes. Atmospheric and oceanic heat storage and transport; atmospheric vertical profiles of latent heating.	H	H	H	Sensible and latent heat fluxes: ~15–20% half-hourly (~5% daily) random error, order of 10–20% surface energy balance closure deficit [*Kessomkiat et al.*, 2013]	Sonic anemometer for fluxes	
* Calculation of heat advection, based on the atmospheric motions and soundings, and accounting for the latent heating.	H	H	H	0.25 K d^{-1} of atmospheric heating		Soundings and satellites, aircraft
* Air motions:						
Air motions: The changes in air mass fluxes at the lateral boundaries determine the forcing of circulation systems. This requires the documentation of lateral mass and latent and sensible energy fluxes.	H	H	H	Divergence of 0.01 kg m^{-3} h^{-1}		Soundings and satellites, aircraft
	M	M	M	5 m/s, 30 km		Satellite

Rosenfeld et al. Rev. Geophys. 2014

Table 1. (continued)

Parameter	Marine Sc	Trade Wind Cumuli	Deep Convective	Achievable Accuracy	Instrument	Platform
* Satellite-retrieved winds at various heights, based on tracking clouds and moisture features (Atmospheric Motion Vectors).						
Doppler S-Band radar measurements (clear air motions)	H	H	H	1 km, 1 m/s		Surface radars
Hydrological cycle						
Precipitation measurements are required for obtaining a vertical profile of the latent heat and moisture fluxes.	H	H	H	10% of the rainfall accumulation	Polarimetric Radar and rain gauges	Surface and satellite radars
3D coverage of Doppler and polarimetric hydrometeor type and size measurements	M	M	H	20% of MVD	Polarimetric radar	Surface radar
3D evolution of drizzle in MSC, with a cloud radar	H	M	M	Sensitivity of −15 dBZ	Cloud radars	Surface and satellite radars
Separate to convective and stratiform components	—	—	H	10% of the rainfall accumulation	Radar data analysis	
Hydrologic measurements of soil moisture, runoff, and stream flows.	NA	NA	M	10%	Stream flows	
Measurements of evaporation and evapotranspiration.	H	H	H	see latent heat flux: ~15–20% half-hourly (~5% daily) random error) [*Kessomkiat et al.*, 2013]	Link to latent heat	
* Atmospheric height-dependent moisture convergence, as measured by the sounding network and satellite measurements of moisture soundings.	H	H	H	0.0001 kg m^{-3} h^{-1}	Link to soundings lateral fluxes	
Aerosols and their precursors:						
Measurements of precursor gases	M	M	M	For most inorganic precursors gasses typically better than 5%: e.g., 1% or 0.2 ppb for SO_2	Monitor instruments	Airplane, surface
Aerosol size distribution	H	H	H	±10% in number size distribution in submicron ranges from 20 to 200 nm [*Wiedensohler et al.*, 2012], decreasing accuracy (±30%) at higher particle sizes. Total particle number concentrations better than ±5%.	SMPS or DMPS APS, PCASP (supermicron)	Airplane, lidar, surface
Measurements of size-resolved aerosol chemistry	M	M	M	At best 0.1 μg/m^3 for size specific speciation, 25% for PM1 [*Canagaratna et al.*, 2007]. Lower detection limit varying with species, 0.03 μg m^{-3} (nitrate, sulfate, and chloride) up to 0.5 μg m^{-3} (organics) [*Drewnick et al.*, 2009]	AMS, time of flight mass spectrometer	Airplane, surface
Measurements of aerosol hygroscopicity and CCN-activity	M	M	M	Better than ±20% in hygroscopicity parameter [*Su et al.*, 2010]. For hygroscopic growth factor, typically ±0.05 [*Swietlicki et al.*, 2008]. For hygroscopic growth factor, typically ±0.05 [*Swietlicki et al.*, 2008]	CCNC, HTDMA	Airplane, surface
CCN activation spectra including giant CCN	H	H	H	Similar to aerosol hygroscopicity, above	DMPS, SMPS, CCNC, PCASP	Airplane, surface
Ice nucleating activity of the aerosols	N/A	N/A	H	Better than order of magnitude in the activated fraction [*Jones et al.*, 2011],	INC	Airplane, surface

Rosenfeld et al. Rev. Geophys. 2014

Table 1. (continued)

Parameter	Marine Sc	Trade Wind Cumuli	Deep Convective	Achievable Accuracy	Instrument	Platform
				14% for activated fraction in deposition freezing [*Kanji et al.*, 2013]		
Surface sun photometers (spectral AOD)	M	M	M	Cimel 0.01 [*Eck et al.*, 2010], Microtops 0.02 [*Ichoku et al.*, 2002]	sun photometers (Cimel)	Airplane, surface
* Satellite measurements of aerosol parameters: AOD, SSA, spectral AOD, depolarization ratio, UVAAI.	H	H	H	AOD: The larger of 0.05 or 20% over land; the larger of 0.03 or 10% over dark water. SSA—qualitative two-to-four bins between very absorbing and nonabsorbing. Particle size—qualitative fine/coarse ratio over water from MODIS; qualitative, three-to-five size bins from MISR UVAI—Precision of 0.1 for AI > 0.8 over ocean, and for AI > 0.5 over land. from OMI [*Torres et al.*, 2013]		Satellite
Cloud-aerosol interactions						
The aerosol direct and cloud-mediated effects on the radiative and latent heat budget of the atmosphere, and the resultant changes in the atmospheric motions that feed back to the clouds, precipitation and aerosols. The great challenge here is disentangling the aerosols from meteorological effects on clouds and their radiative effects.						
Cloud cover, optical depth, albedo and radiative effects under different aerosol conditions in as similar meteorology as possible. Study of adjacent clouds in and out of aerosol plumes can be effective.	H	H	H	LWP, r_e, N_d, cloud optical depth for convective and layer clouds	Data processing	
For layer clouds: satellite retrieved cloud top effective radius, liquid water path and cloud drop concentrations. Validation with aircraft measurements and cloud radar	H	H	H	LWP, r_e, N_d, cloud optical depth for convective and layer clouds	Data processing	
For convective clouds: satellite-retrieved vertical profiles of cloud particle effective radius and thermodynamic phase. Validation with aircraft measurements.	H	H	H	10% of the effective radius	Data processing	
Cloud base updraft spectra, by vertically pointing radar and lidar, and by aircraft and UAVs.	H	H	H	On the order of 0.1 m s^{-1}	Radar, lidar	Surface and aircraft
Cloud base CCN, as obtained from cloud base updrafts and drop number concentrations.	H	H	H	30% of drop concentrations at cloud base	Data processing	
Secondary activation of aerosols in deep convective clouds. This can be inferred by the satellite retrieved vertical profiles of cloud particle effective radius, and validated in more detailed by aircraft.	N/A	M	M	30% of small drop and ice concentrations at any level	Data processing	

Rosenfeld et al. Rev. Geophys. 2014

Table 1. (continued)

Parameter	Marine Sc	Trade Wind Cumuli	Deep Convective	Achievable Accuracy	Instrument	Platform
New particle formation	M	M	M	Qualitative in smallest sizes (diameter < 3 nm), similar to particle number size distribution measurements in larger sizes [*Kulmala et al.*, 2012]	AIS, NAIS, DMPS, PSM	Surface and aircraft
Vertical profile of hydrometeor types, concentrations and sizes, by surface and space borne radars.	M	M	H	20% of MVD	link to polarimetric radar measurements	
Detrained aerosols from the clouds at various heights, as measured by aircraft.	M	M	M	Similar to the size distribution measurements (above)	SMPS, PCASP	aircraft
Scales						
Horizontal along wind	1500 km	500 km	500 km			
Horizontal across wind	200 km	200 km	500 km?			
Vertical resolution	50 m	100 m	100..400 m			
Horizontal resolution	50 m	100 m	1000 m			
Temporal scale	3 days	1 day	1 day			
Potential locations	Offshore California, Offshore Chile, Canary Islands or Cape Verde	South China Sea, Gulf of Mexico	Indonesia, Amazonas, Congo			

[a]The importance codes in columns 2–4 are as follows: High (essential, must be included), M (important to be included), L (low priority). Instrument names are as follows: AIS, Aerosol and Air Ion Spectrometer; AMS, Aerosol Mass Spectrometer; CCNC,Cloud Condensation Nuclei Counter; Cimel, Sun photometer; DMPS, Differential Mobility Particle Sizer; HTDMA, Hygroscopic Tandem Differential Mobility Analyzer; INC, Ice Nuclei Counter; NAIS, Nanometer aerosol and Air Ion Spectrometer; PCASP, Passive Cavity Aerosol Spectrometer Probe; PSM, Particle Size Magnifier; SMPS, Scanning Mobility Particle Sizer.

Hoped-for Satellite Products; *Rosenfeld et al*. 2014*

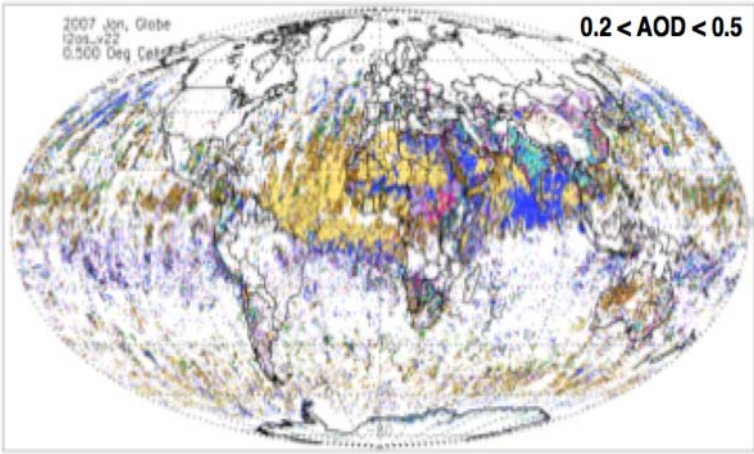
- TOA ***radiation*** – cloud-free & cloudy conditions
- Precipitable ***water vapor***
- Upper tropospheric ***water vapor***
- CO_2 and other ***greenhouse gases***
- Cloud-top ***temperature***, ***albedo***, ***emissivity***
- Cloud-top r_{c_eff} and ***thermodynamic phase***
- Height-resolved ***winds***
- ***Moisture soundings***
- *AOD*, *SSA*, *ANG*, *polarization* – ***Aerosol Type***
- Cloud ***vertical profile*** r_{c_eff} and ***thermodynamic phase***
- ***Vertical profile hydrometeor type***
- ***Composition & longevity of supercooled cloud layers***
- ***Cirrus radiative effects and dependence on CCN, IN***

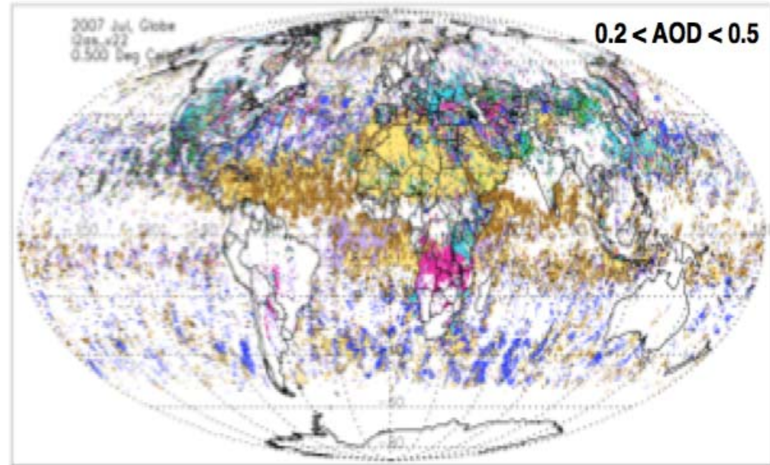
Indirect or multi-platform

* *Table 1*

Would you believe the answer if it were a surprise?

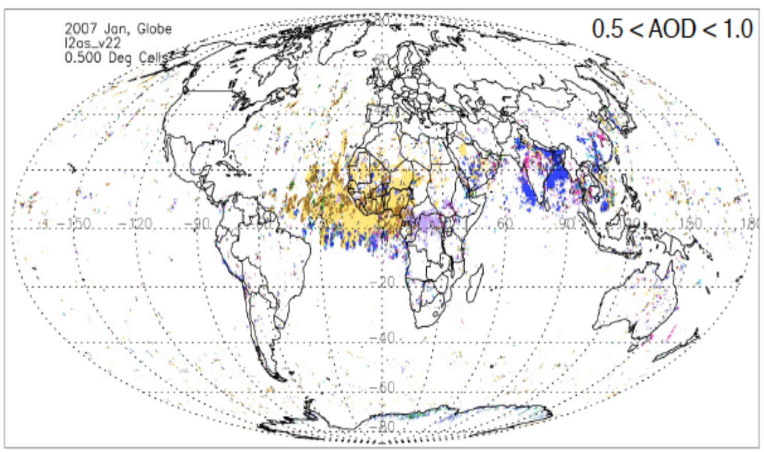
MISR Aerosol Type Discrimination

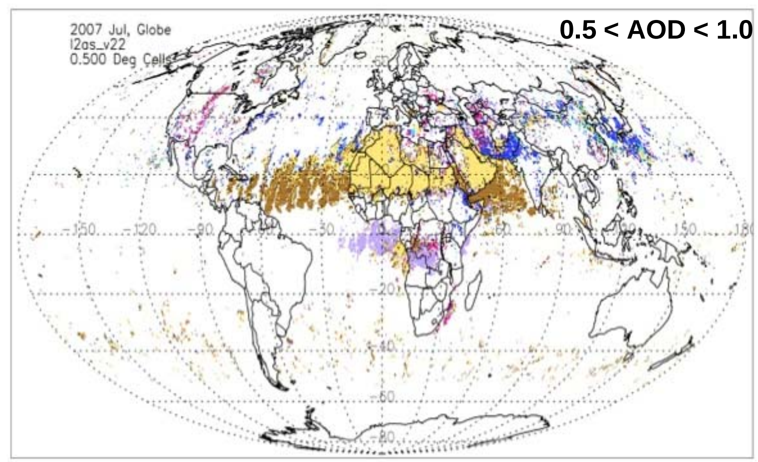




January 2007

July 2007





Mixture Group

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

Spherical, non-absorbing

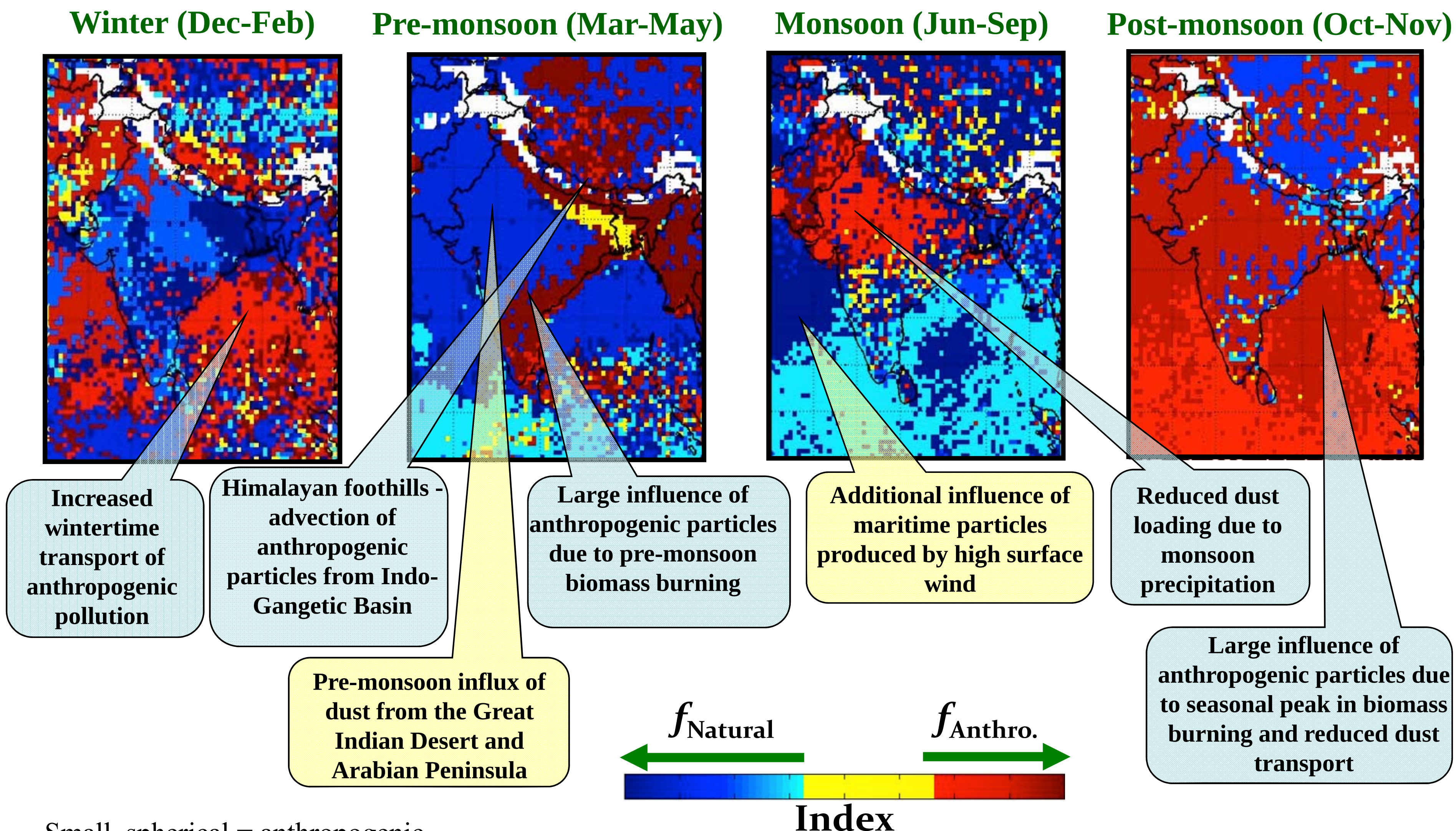
Spherical, absorbing

Non-spherical

Kahn & Gaitley JGR in press

Seasonal Change in ***Aerosol Type*** over India

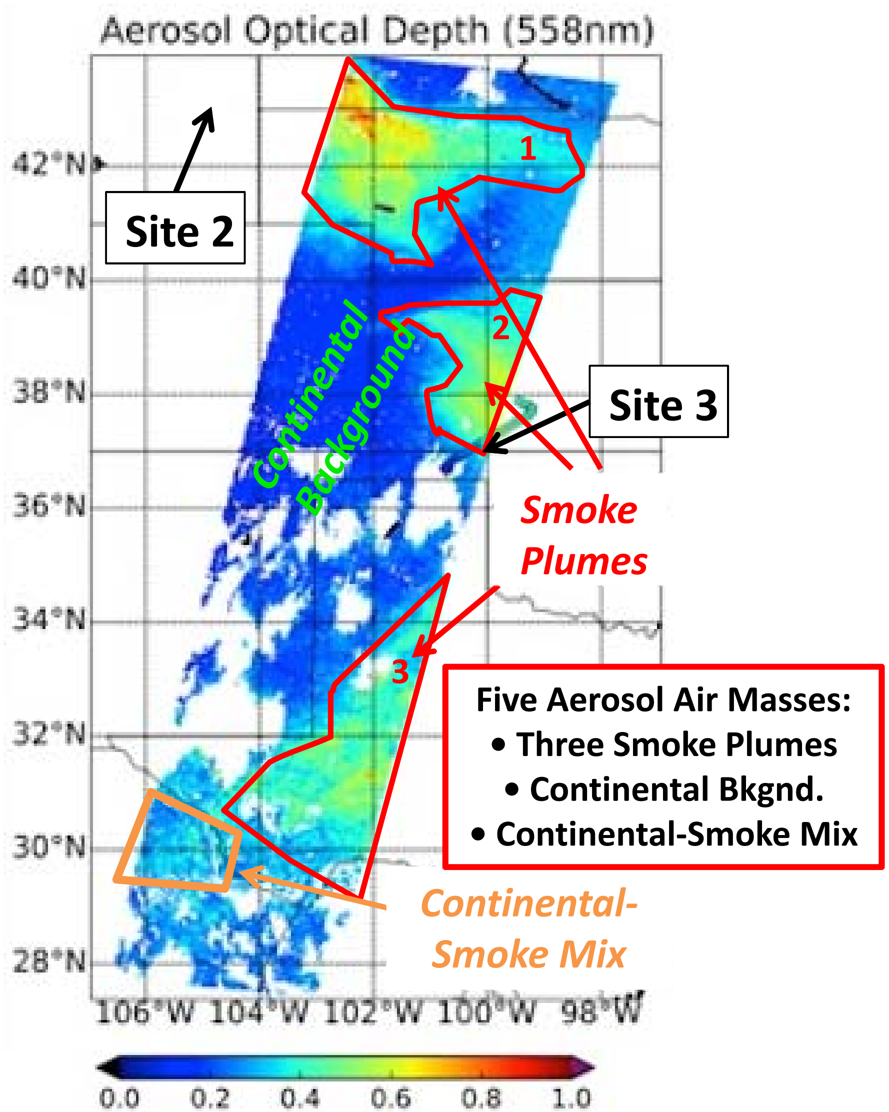
Anthropogenic vs. Natural based on MISR-retrieved Particle Size & Shape

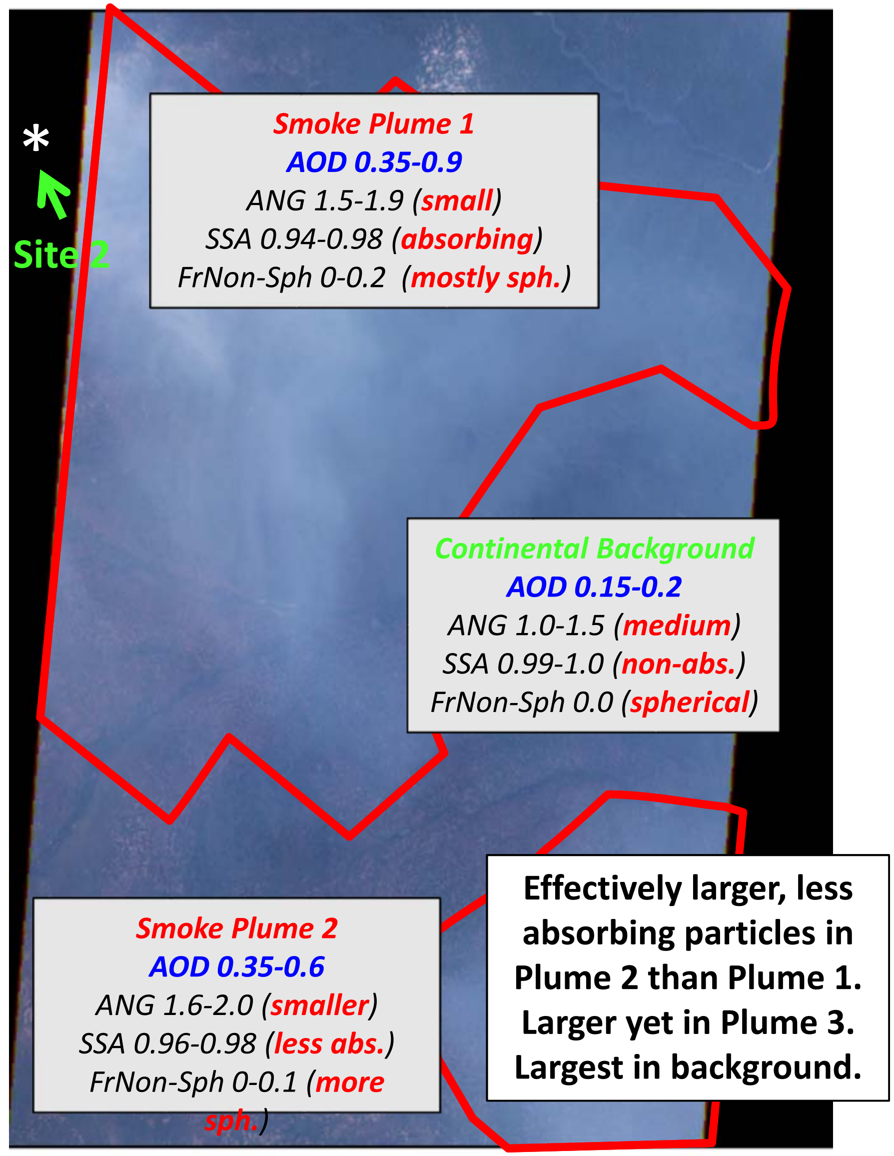


Small, spherical = anthropogenic
Large, non-spherical = natural

Dey & Di Girolamo JGR 2010

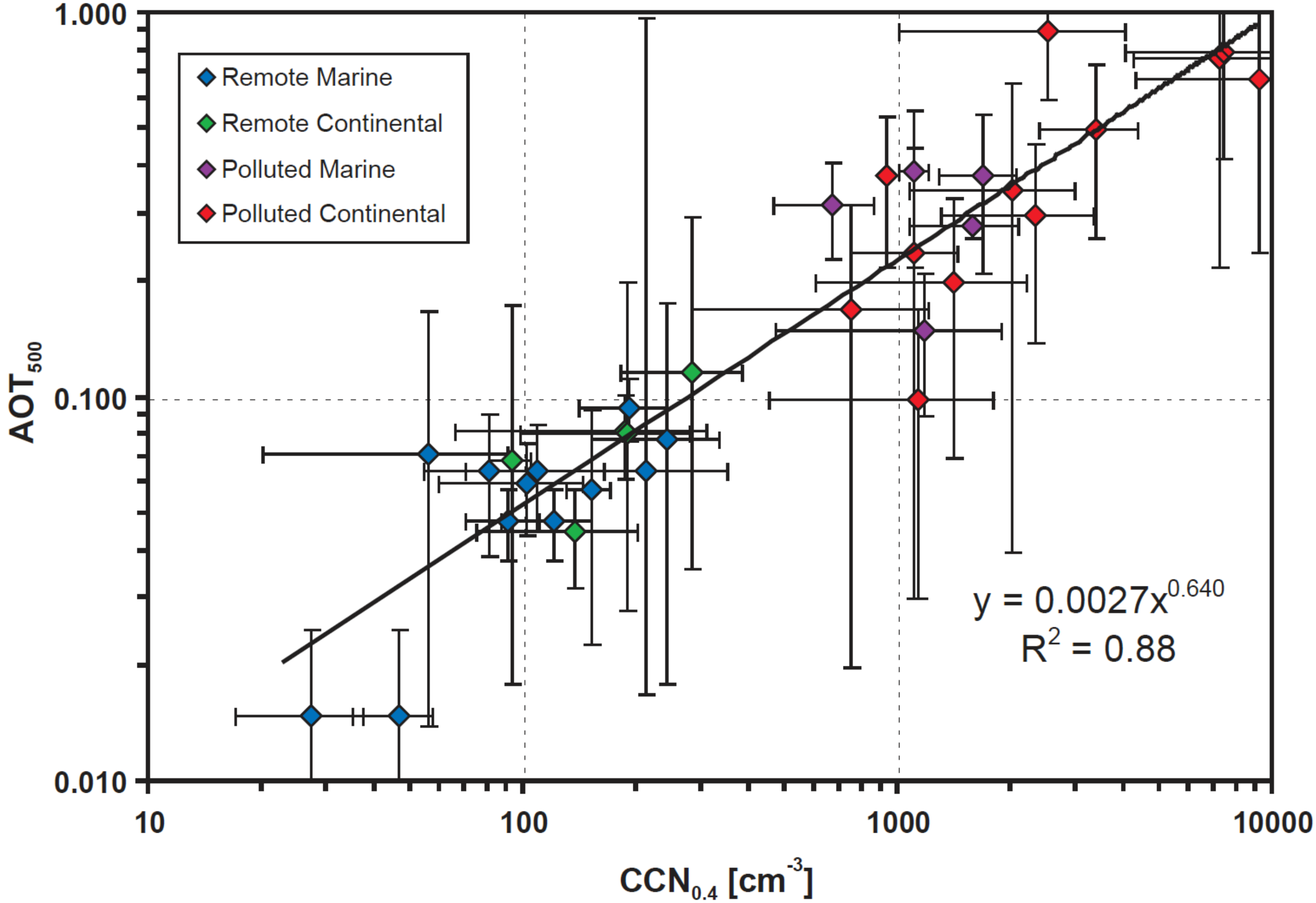
SEAC⁴RS – *MISR Overview* 19 August 2013





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

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

• Test Idea: 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

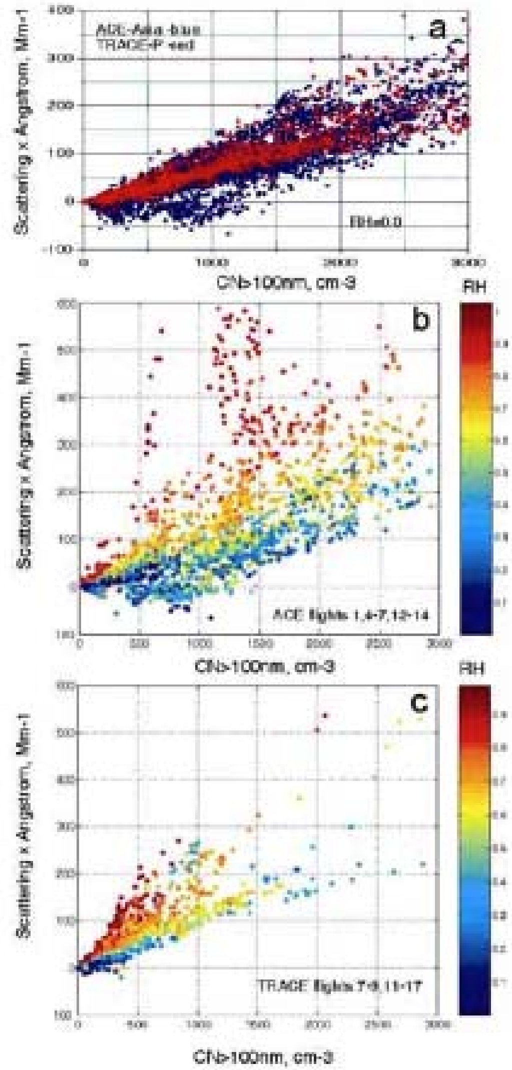
• **AI does not work quantitatively in general**, but can **if the data are stratified** by:

-- ***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 τ_a and *Ang*, this requires:

-- Vertical **humidity structure**
-- **Height-resolved** aerosol **type**
-- **Height-resolved size** dist.
[extrapolated to small sizes(?)]

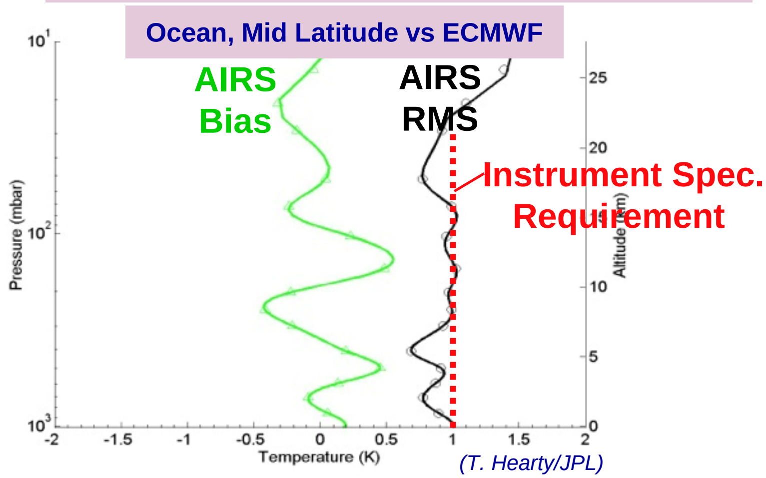
This study includes enough detail to assess *AI* ~ N_a *and* *AI* ~ *CCN*



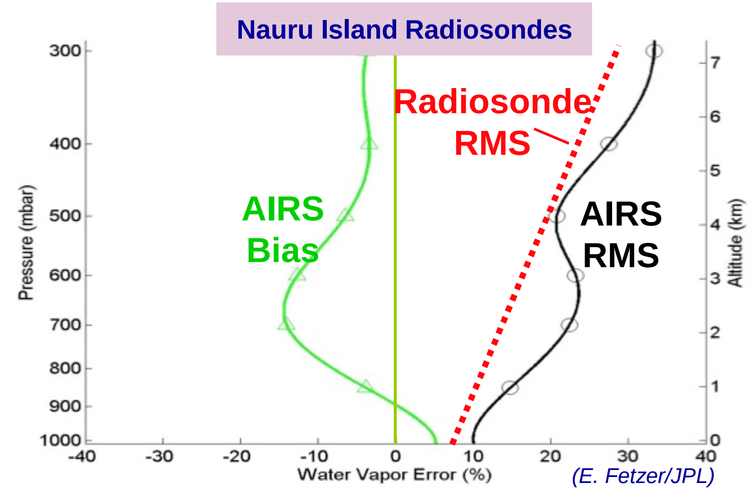
AI vs. *in situ CCN* proxy
(a) all ACE (blue) & Trace-P, **dry**
(b) ACE - OPC-only, amb. *RH*
(c) TP - OPC-only, amb. *RH*

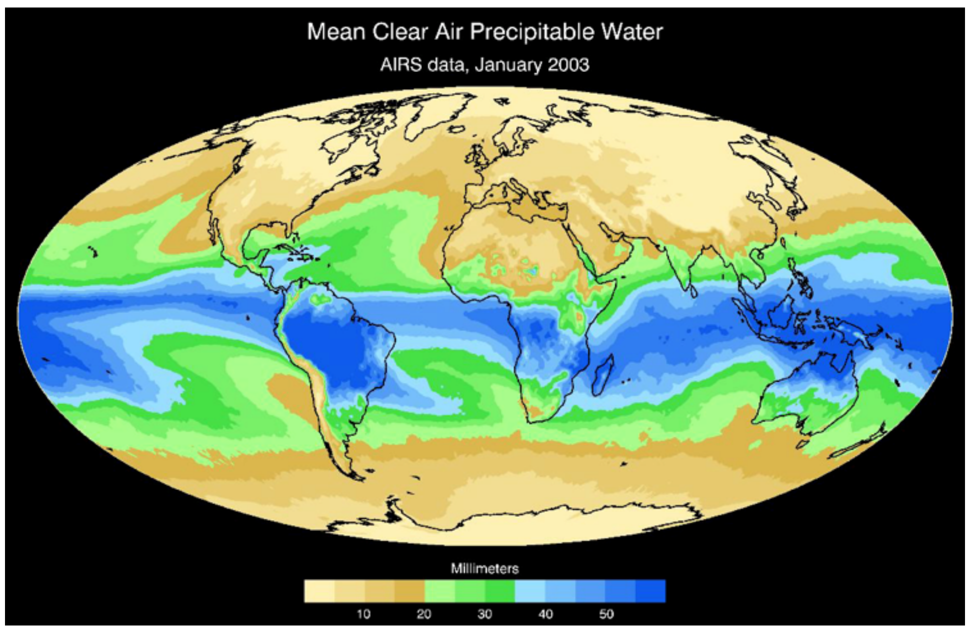
AIRS - Temperature & Water Vapor Profiles

Temperature Profiles Accurate to 1K/km to 30 mb



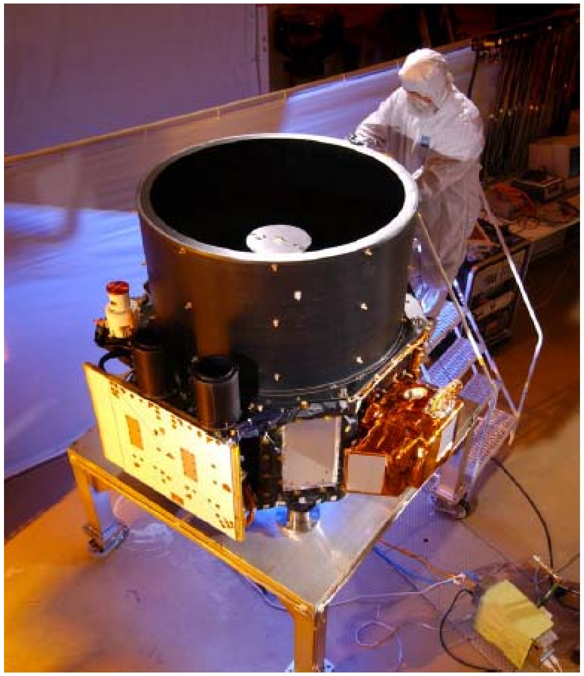
Water Vapor Profiles Match Observations 15%/2km





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

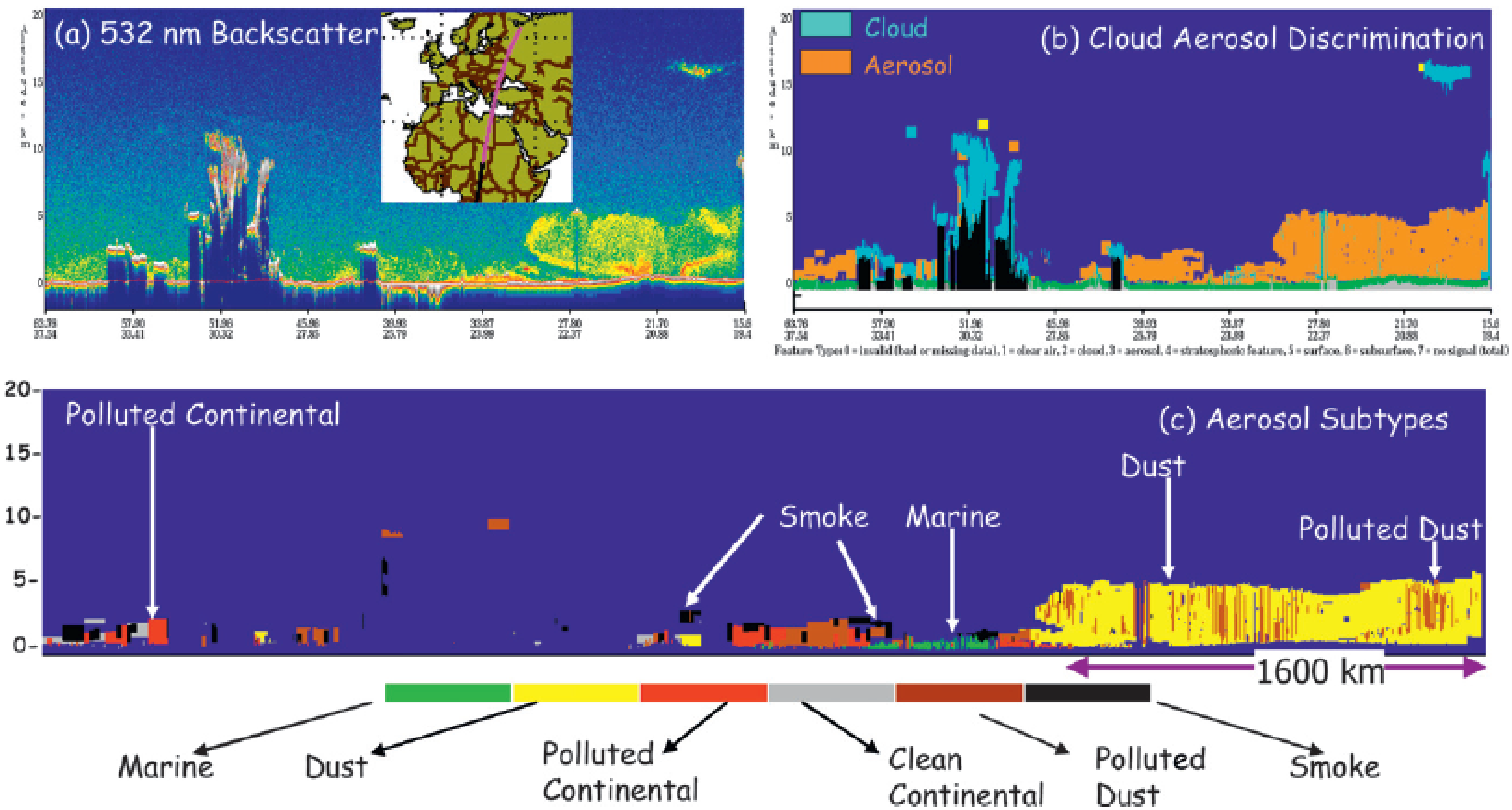


Launched April 2006

- Lower AOD sensitivity than SAGE
- But ***higher space-time resolution*** than SAGE
- 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

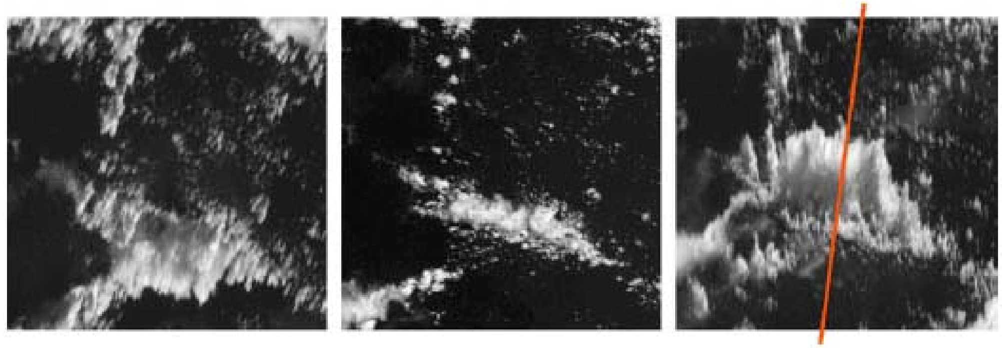
Winker et al., JAOT 2009

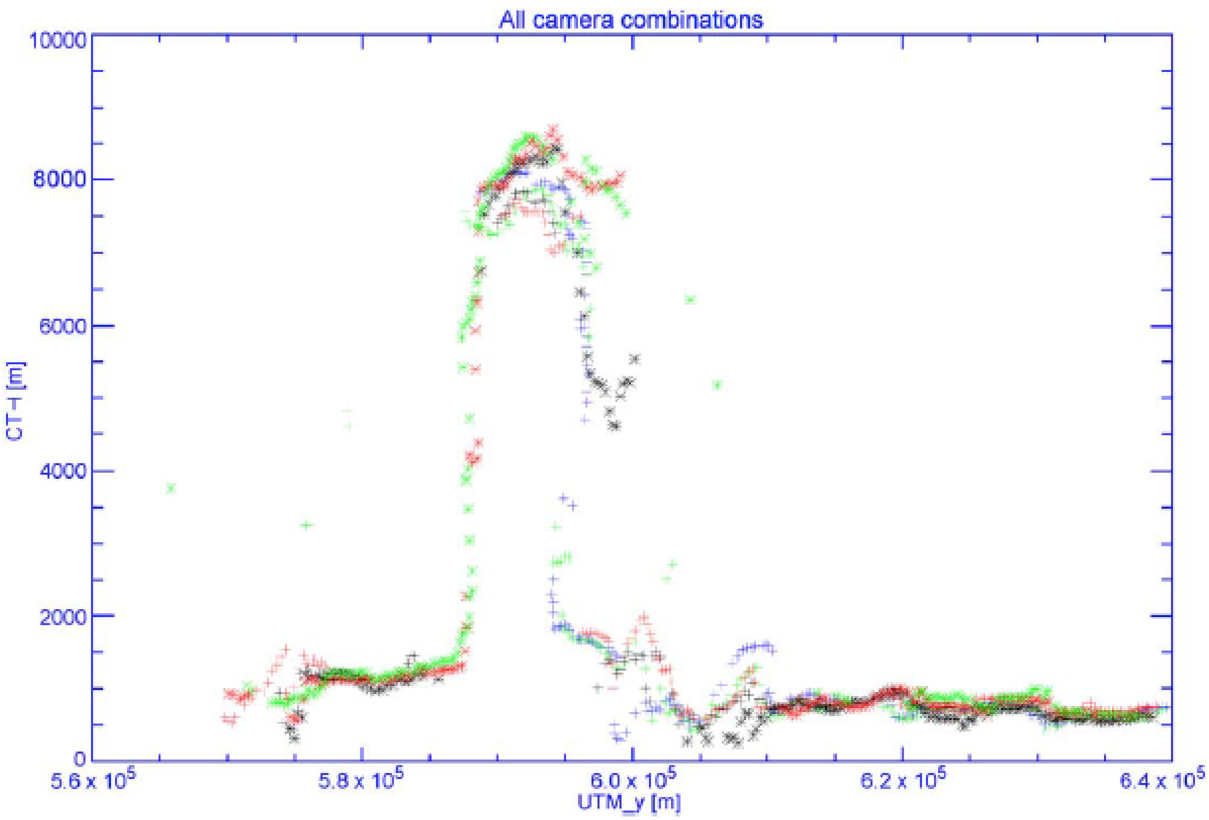
The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)



Omar et al., JAOT 2009

MISR Stereo Imaging Cloud-top Height



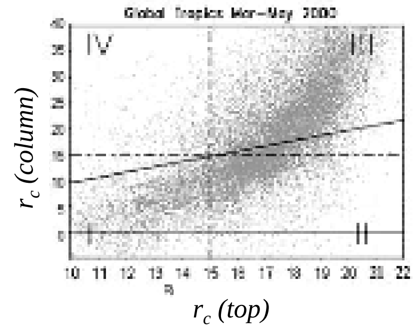


Colors indicate different camera combinations used

Seiz & Davies, RSE 2006

VERTICAL STRUCTURE
r_c – CLOUD 'TOP' VS. CLOUD COLUMN, & *LTS*

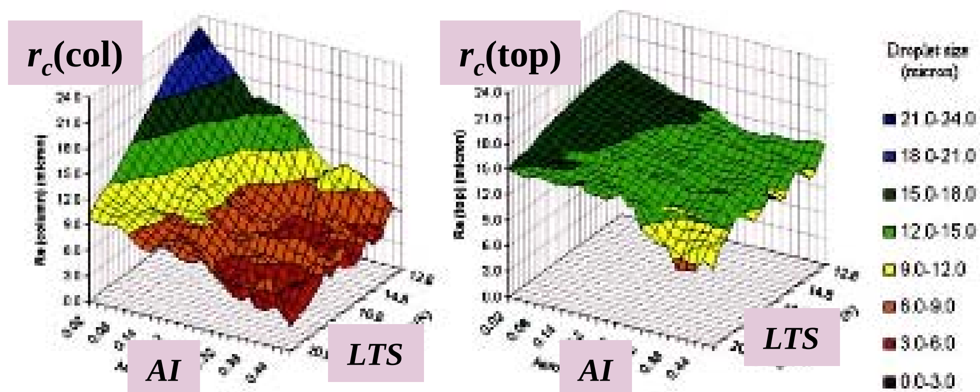
- **TRMM** data, March-May, 2000; 37˚N to 37˚S
- Vis-IR Radiance Imager (**VIRS**) for ***r*$_c$(top), τ_c**
- Microwave Imager (**TMI**) for ***r*$_c$(col), *LWP*** (19, 37GHz)
- Warm clouds only (T_c > 273 K)
- VIRS to find cloud-filled TMI pixels
- ***AI*** from **MODIS**
- **Lower Trop. Stability**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

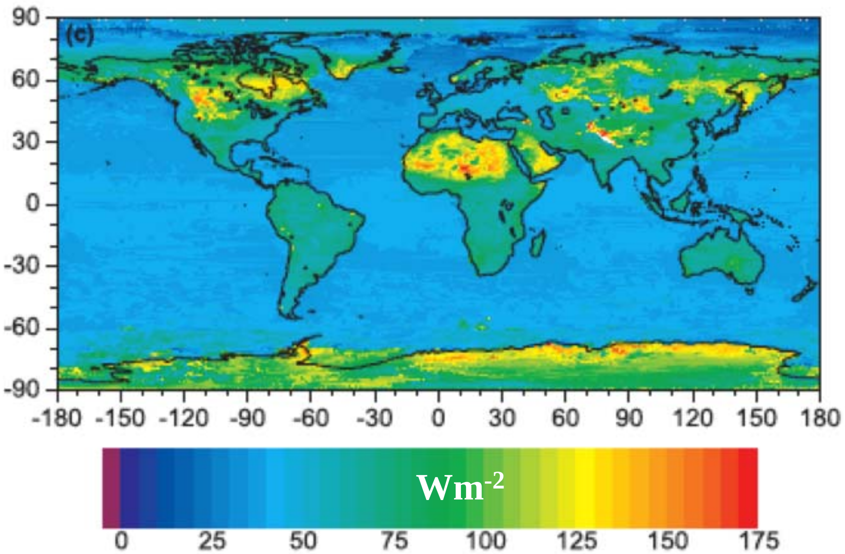


r_c vs. *AI* vs. *LTS*

Matsui et al., GRL 2004

The Clouds and the Earth's Radiant Energy System (CERES) Short-Wave (SW) Albedo

- Instruments on 3 satellites (Terra, Aqua, S-NPP) [formerly TRMM; future JPSS-1, 2]
- **Channels**: SW (0.3-5 μm), IR (8-12 μm); Total (0.3-200 μm)
- **Daily global coverage in across-track mode** (+ along-track & rotating az options)
- **Spatial Resolution**: ~ 20 km at nadir

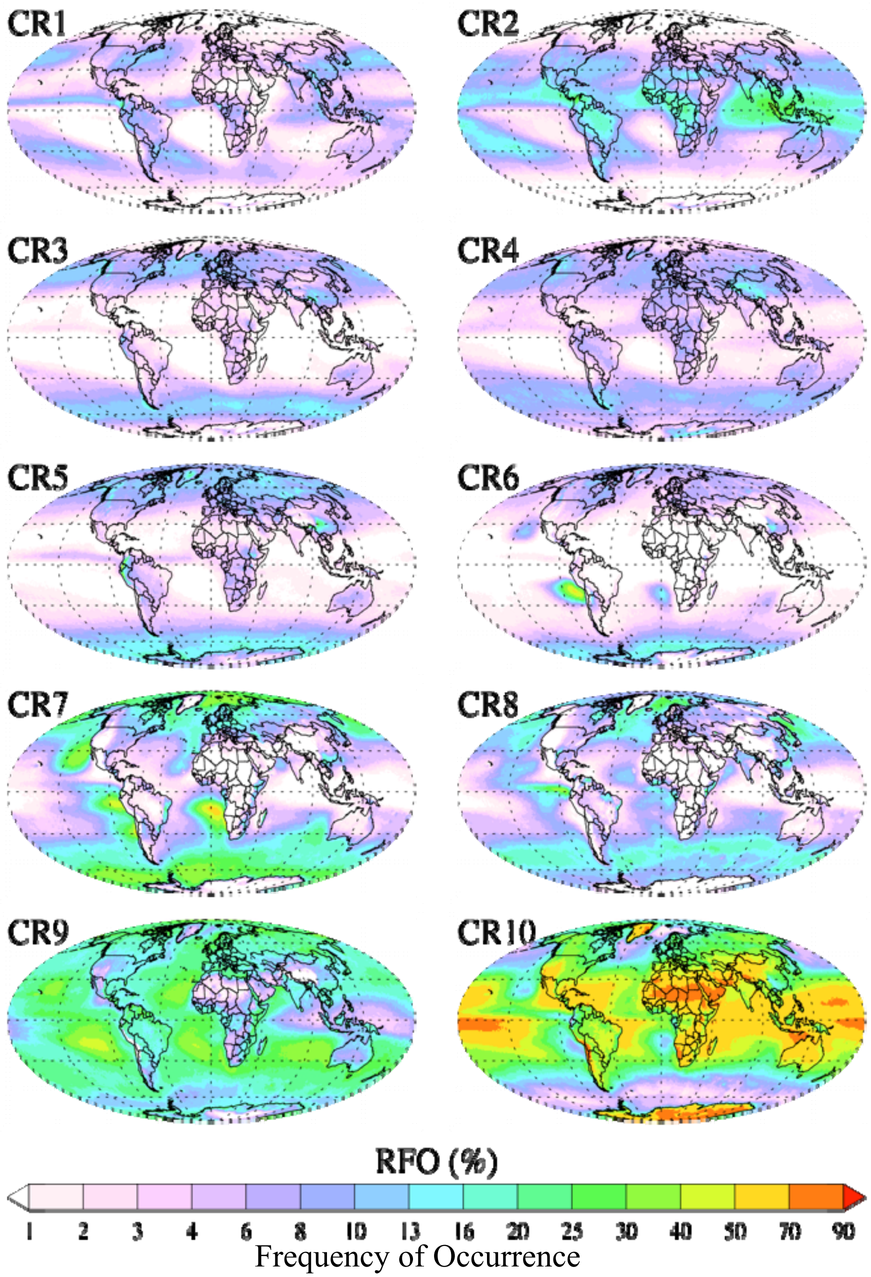


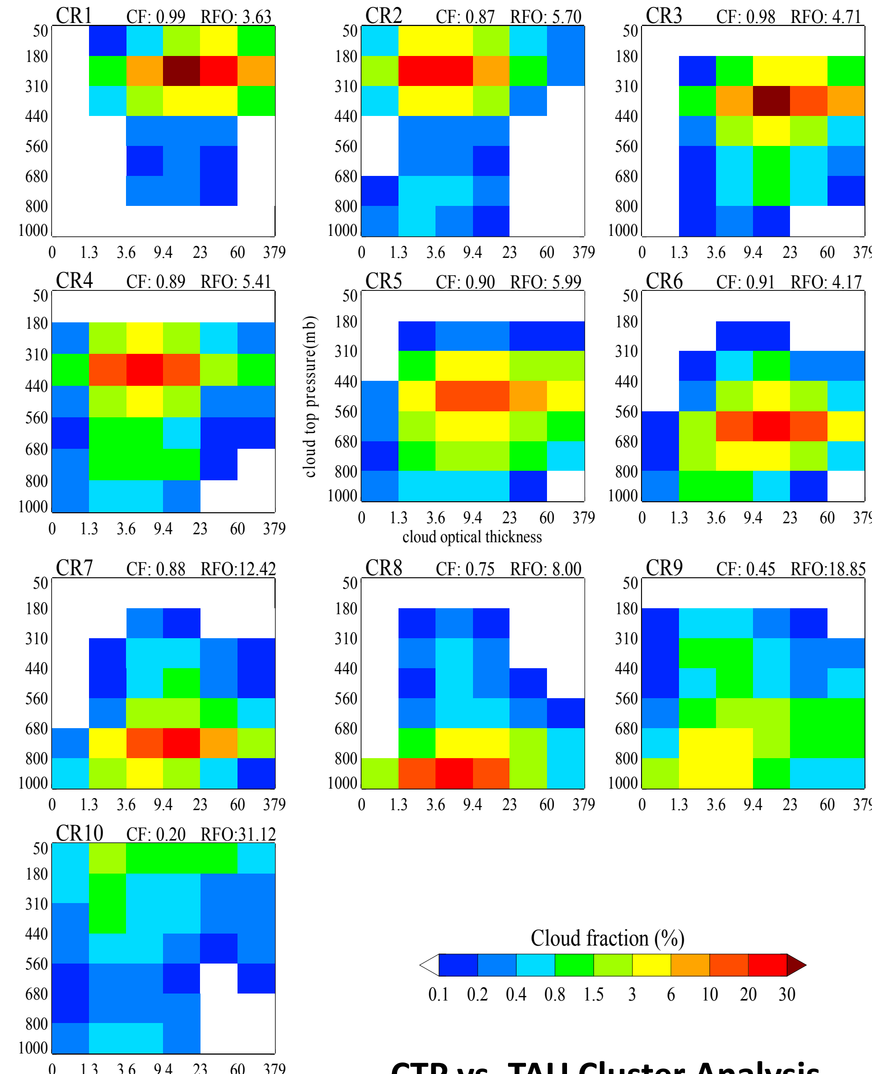
March 2002 CERES SW TOA Clear-sky flux (w/MODIS cloud-clearing)

CERES SW Albedo **Absolute Calibration accuracy:** ~1%
Instantaneous SW TOA Flux **Uncertainty**: ~ 4% for all-sky
Stability: ~0.3 Wm^{-2}/decade (0.001/decade in ***global*** albedo)

Loeb et al., JGR 2006; J. Clim. 2009; Surv. Geophys. 2012

MODIS global cloud regimes



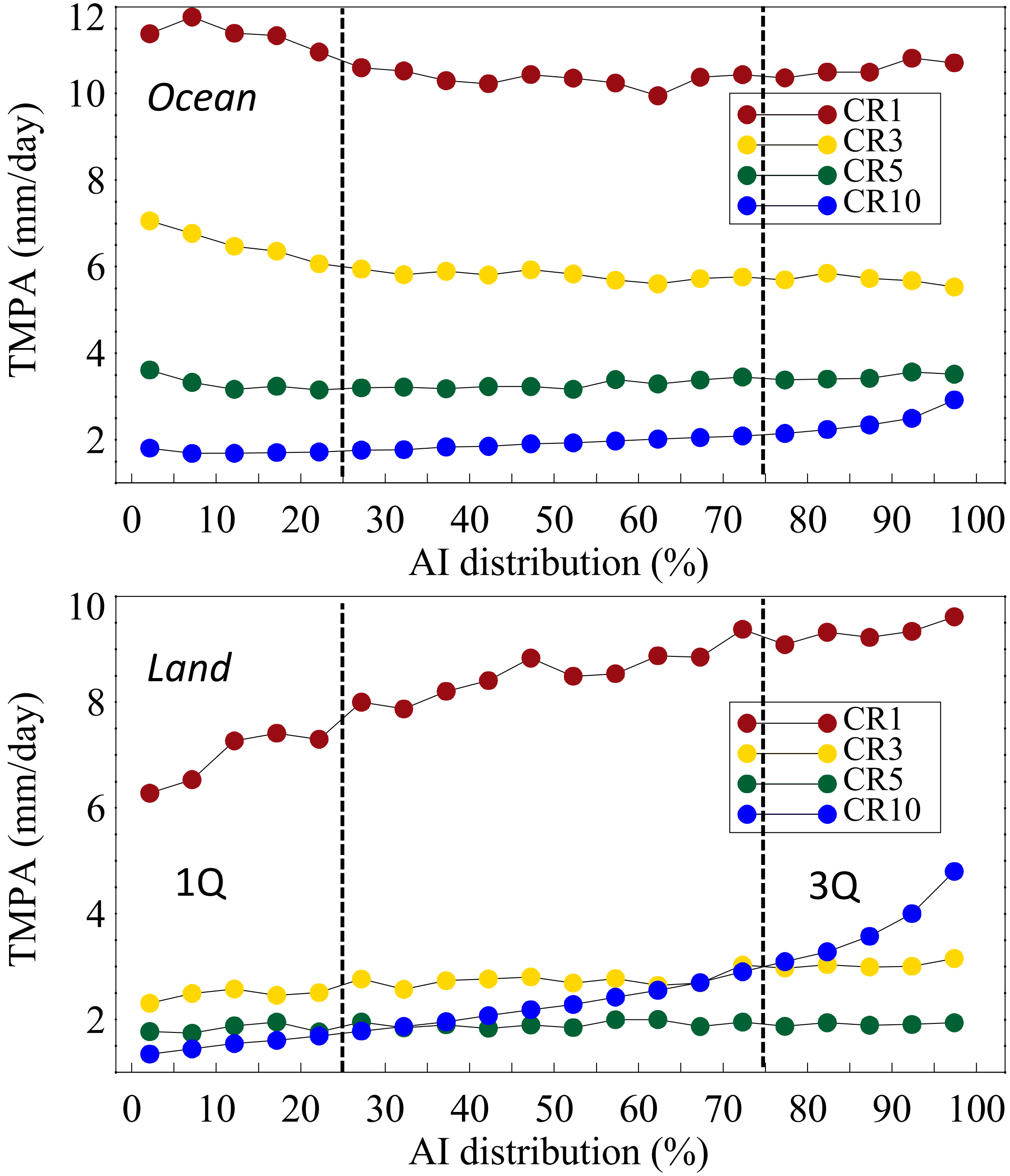


CTP vs. TAU Cluster Analysis

(10 “Cloud Regimes”; MOIDS V5.1)

Courtesy of Lazaros Oreopoulos

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



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}
Prcp	⇑	⇓	–		⇑
CF	–		⇑		⇑
CTH	⇑		⇑	–	⇑
Tau	⇑	⇓	⇑		⇑
Re	⇓	–	⇓		⇑
PrcpNZ	⇑	⇓	–	⇓	⇑

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

Courtesy of Lazaros Oreopoulos

Box Model Considerations

• **Spatial Domain:** 5° x 5° (~500 km)
3-D Spatial Resolution: ~10 – a few 100 m

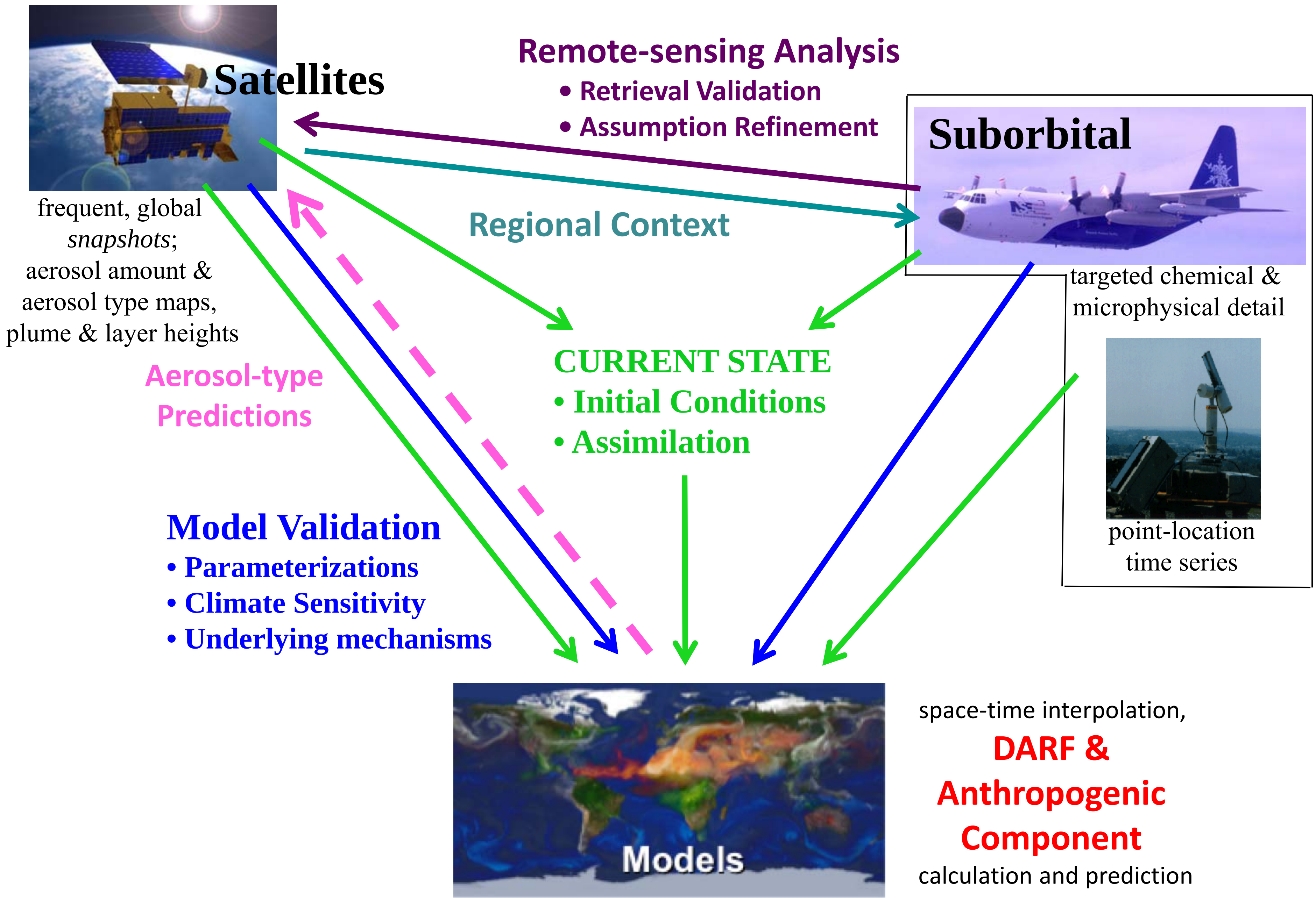
• **Temporal Coverage:** (at least) 24 hours, multiple times
Temporal Resolution: ~ (at least) 1-3 hours

• ***Need top, bottom, and *side* fluxes***

Satellites *Cannot* Provide All This

But satellites can provide ***context*** over the domain
… and some ***validation*** of the modeling

What is the ***fractional coverage*** of different cloud types in the domain?
How do the TOA ***radiative fluxes vary*** with atmospheric conditions?
What are the ***background AOD*** and aerosol type gradients?
What are the cloud-top, aerosol layer, and aerosol ***plume heights***?



Kahn, Survy. Geophys. 2012