Characterization of direct and indirect forcing of mineral dust using CALIPSO lidar data in conjunction with A-Train multi-sensor observations and a regional transport model WRF-DuMo

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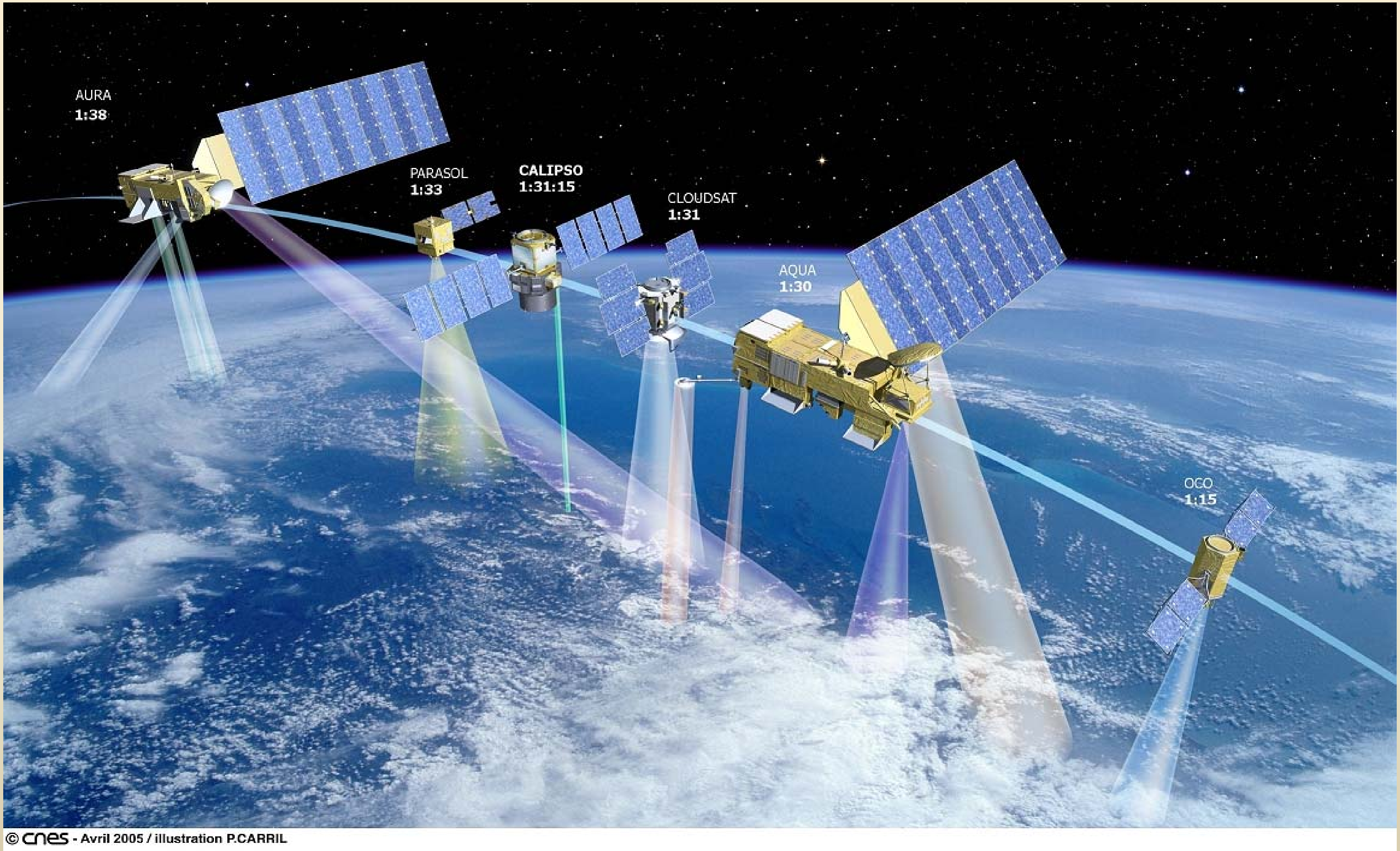
What the CALIPSO lidar can and cannot do…

to aid in dust studies

CALIPSO and A-Train provide unique observational capabilities to study dust:

Dust is readily observed by all passive and active sensors from the UV to thermal IR

CALIPSO: depolarization ratio, color ratio, and enhanced backscattering



Our goals: characterization of dust => process-level understanding

Regional (mesoscale) coupled modeling dust system WRF-DuMo

Terrestrial preprocessor ← Adjustable water/land cover mask to reproduce different (historical) LULC scenarios in Central and East Asia

WRF/Chem ← Flexible nesting capability

Driven by re-analysis data(NCEP or ECMWF)

Dust Module DuMo ← Choice of dust production scheme of different complexity:

simple schemes (prescribed erodible fraction);

MB95 (Marticorena and Bergametti)

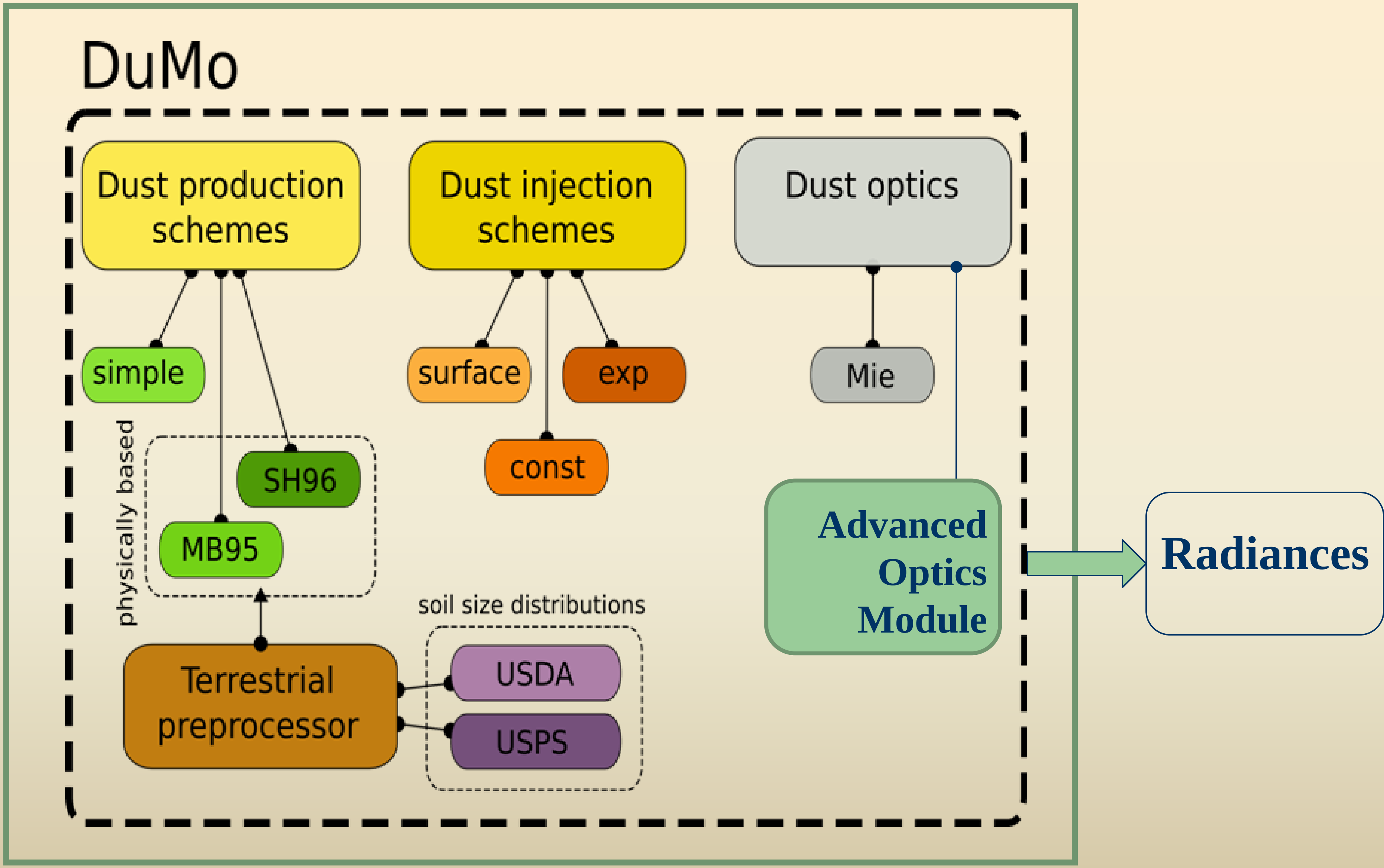
S04 (Shao)

Darmenova, Sokolik, Shao, Marticorena and Bergametti 2009, JGR: physically-based emission schemes

Darmenov and Sokolik, 2009, ACPD

Kumar, Sokolik, and Nenes, 2009, ACP : dust –CCN activation

Regional (mesoscale) coupled modeling dust system WRF-DuMo



What the CALIPSO lidar can and cannot do…

Part. I Dust sources

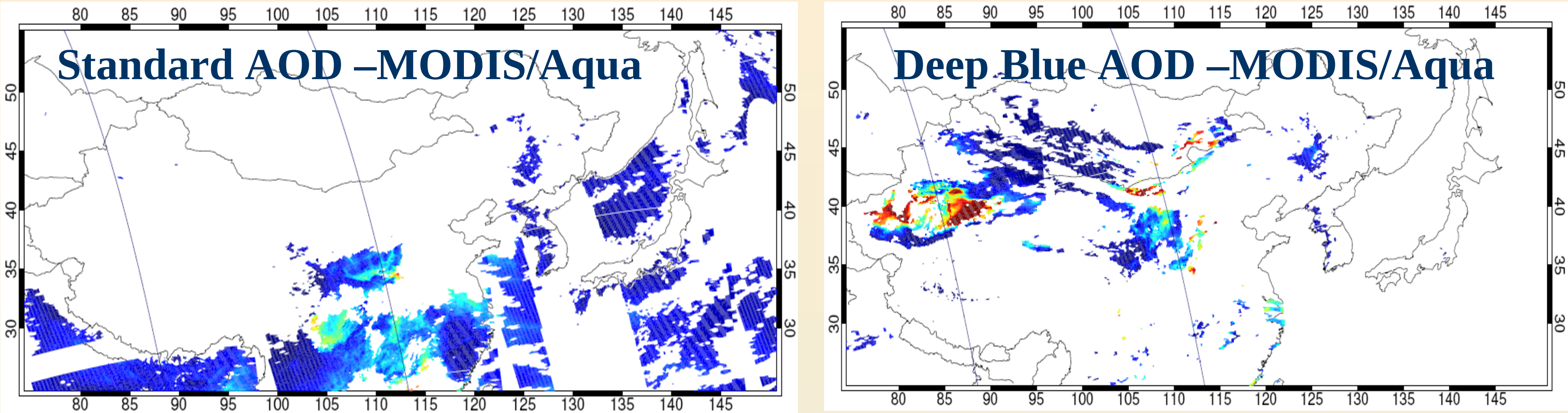
How much dust emitted?

Injection height?

Differences in regional, source-specific dust properties?
(e.g., nonsphericity)

Quantification of dust in source regions: A long-standing problem…

Hard to measure



March 30, 2007

Hard to model

$$F = C_{U10} U_{10}^3 \left(1 - \frac{U_{10th}}{U_{10}}\right)$$ → Injection height → Vertical mixing, deposition, etc. →

“Simple” scheme

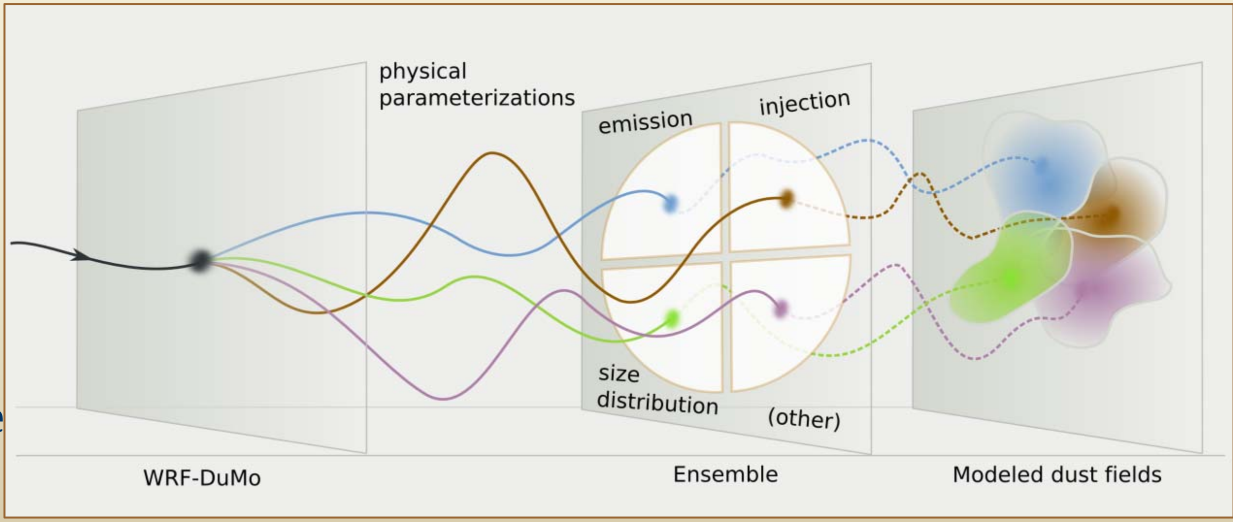
Ensemble-like predictions of 4D (3D+time) atmospheric dust fields:

Ensemble members:

- two physically-based dust emission schemes with varying input parameters
- varying injection schemes
- varying initial size-distribution of atmospheric dust aerosols (i.e., parameters of fine and coarse modes and their proportions)

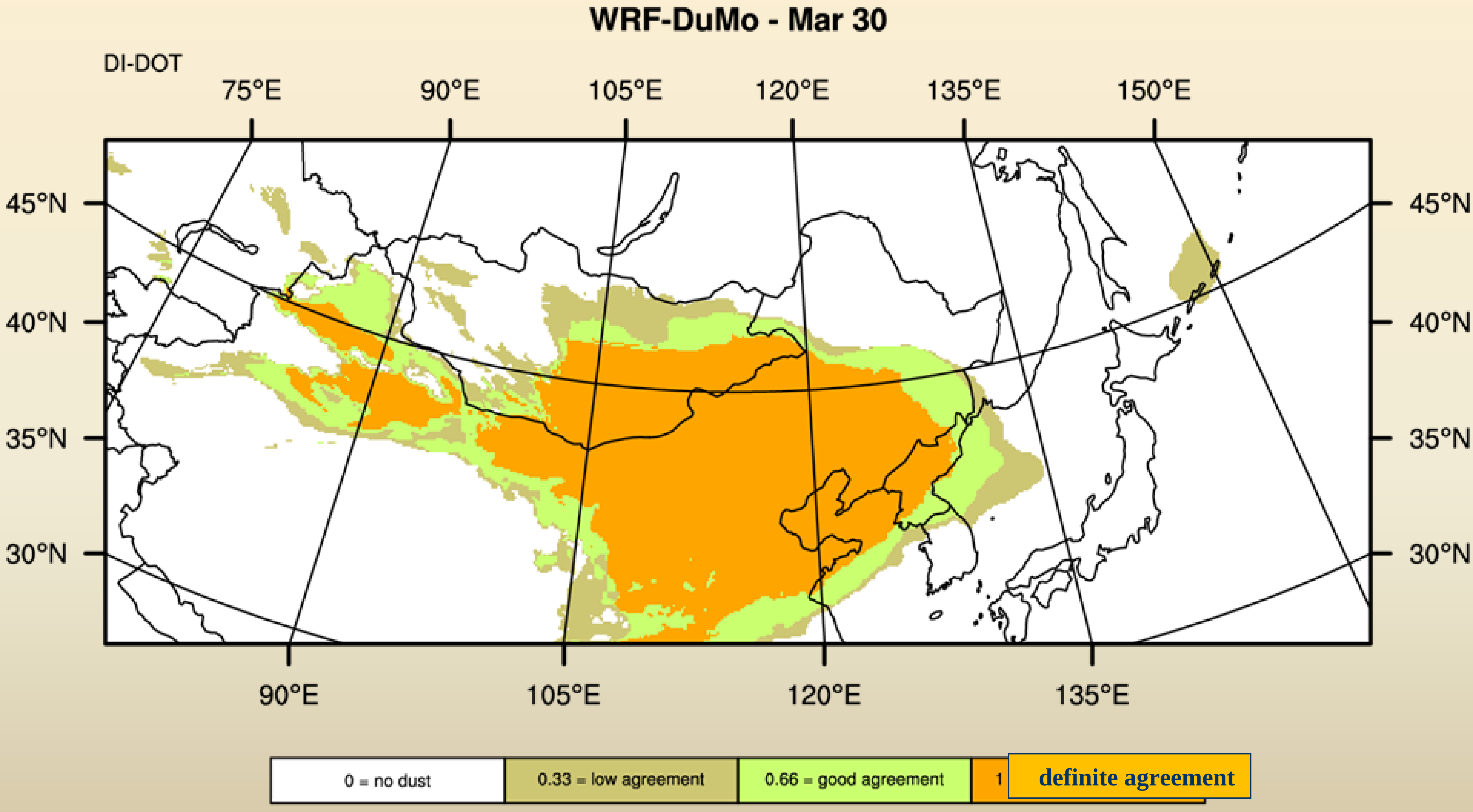
- Dust Index (probabilistic dust fields with assigned confidence levels)

- Modeled dust properties (e.g., visibility, optical depth, etc.) => impacts (radiative forcing, heating (cooling) rate etc.)

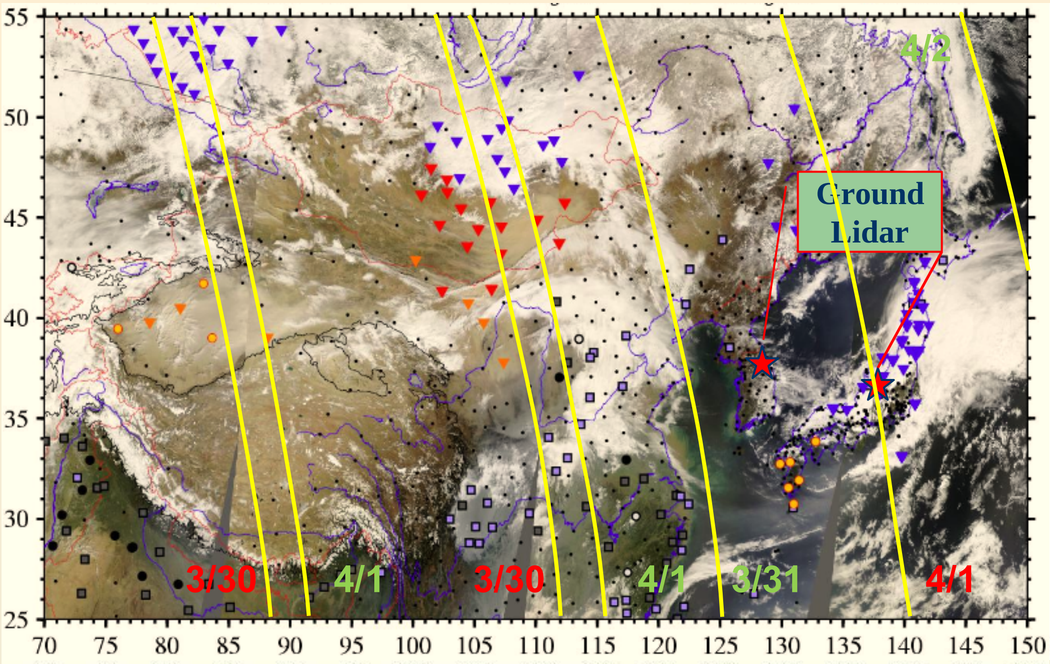


Darmenov and Sokolik, ACPD, 2009

Probabilistic Dust Index simulated with WRF-DuMo



Integrated analysis of CALIPSO, A-Train, and ground-based data

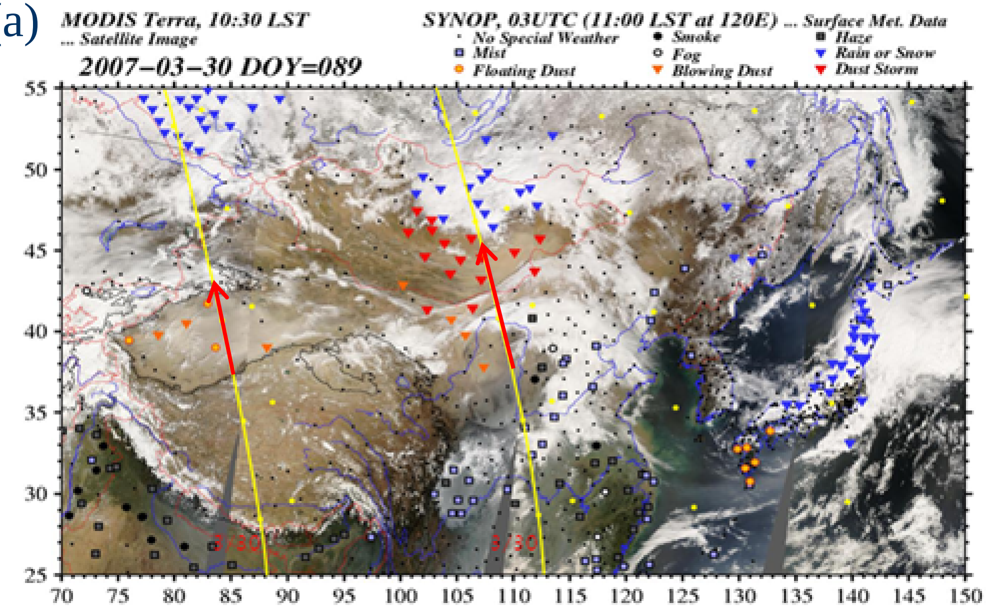


- EXAMPLE: Asian dust storms of 30 March - 4 April, 2007
- Region: The Taklamakan & Gobi deserts, and East Asia (Korea & Japan)
- Data Analysis
  - CALIOP orbit segments
  - MODIS: Red-green-blue channel (RGB) images; Standard AOD MODIS –Aqua; Deep Blue AOD MODIS-Aqua
  - OMI-AURA AI (Aerosol Index)
  - Ground-based meteorological data (WMO Synoptic data): archived by NOAA NCDC
  - Ground-based Lidar data: NIES (National Institute for Environmental Studies) Lidar network and Asian Dust Network (AD-Net)
  - The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory)
  - WRF-DuMo

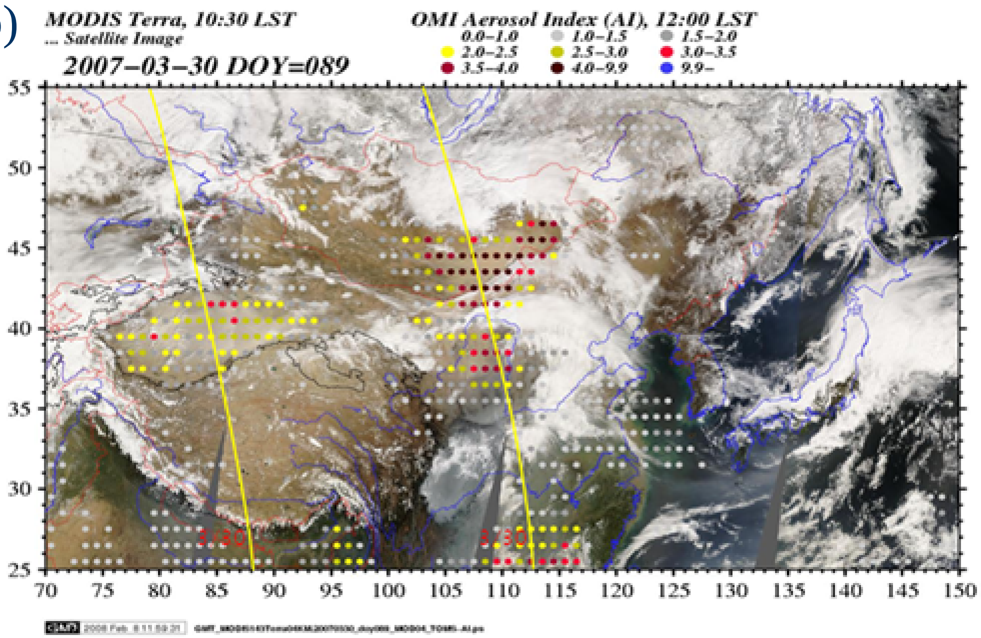
Choi, Sokolik, and Winker, 2009

Analysis of dust optical properties over the sources

(a)

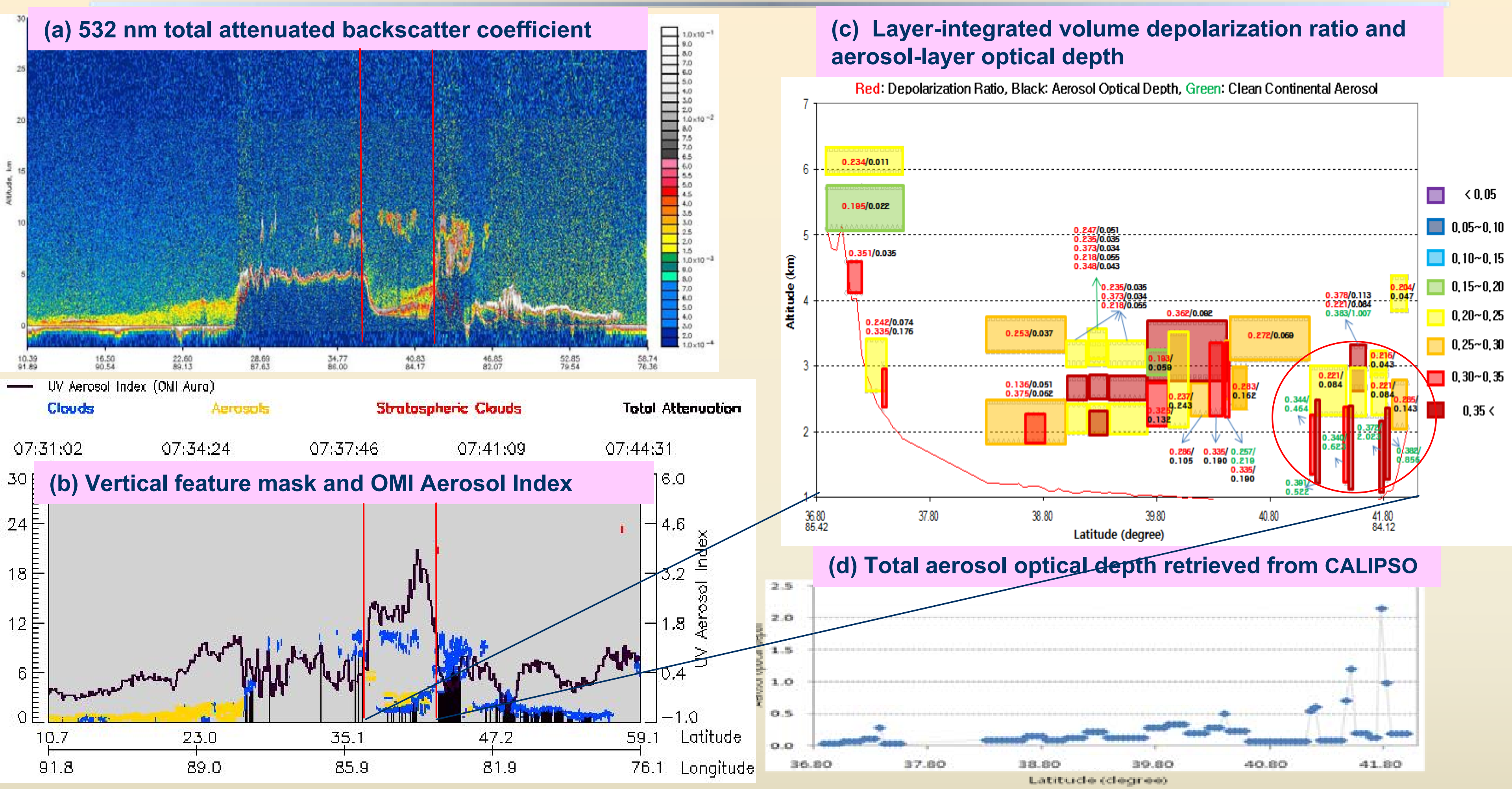


(b)



- Date: March 30, 2007
- (a) WMO (World Meteorological Organization) synoptic data
  - ▼(Dust storm): The Gobi Desert
  - ●(Floating Dust): The Taklamakan Desert
- (b) Aerosol Index (AI):
  - Aerosol Index much higher than 0.7 is a good indicator of the presence of dust (Prospero et al., 2002)
  - High values of Aerosol Index (AI) over both sources confirm that there was a high loading of dust in the atmosphere.

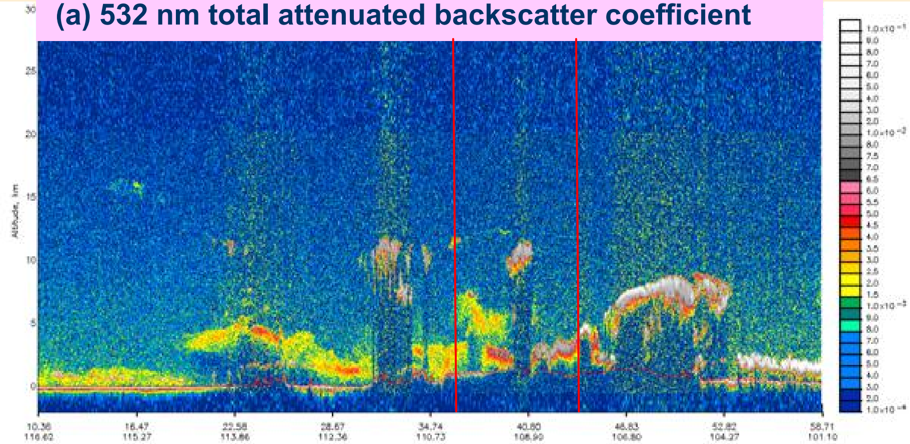
Analysis of dust optical properties over the Taklamakan



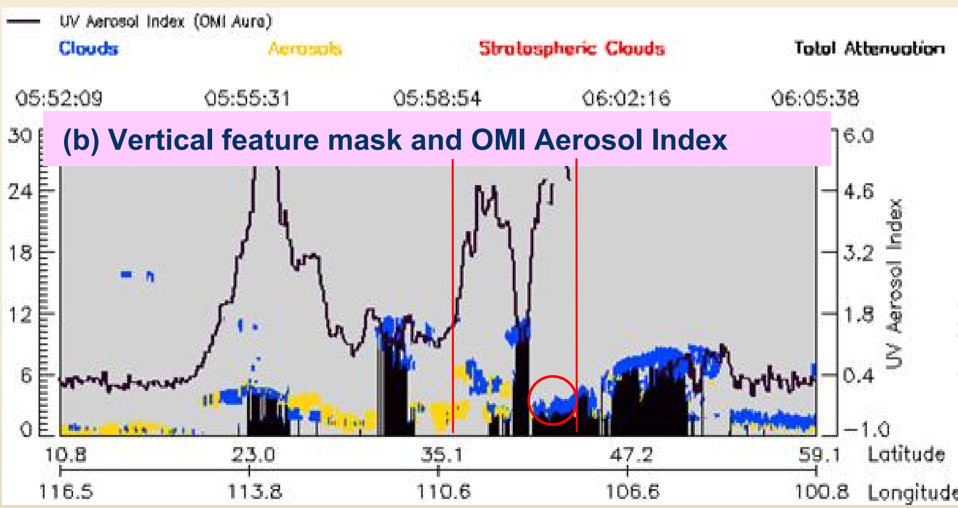
- Height (2~4 km), $\delta_{v,layer}$ (0.136~0.378), average (0.26)
  - Green color: clean continental aerosol => classification error
- Aerosol optical depth (version 2): unrealistically low

Analysis of dust optical properties over the Gobi

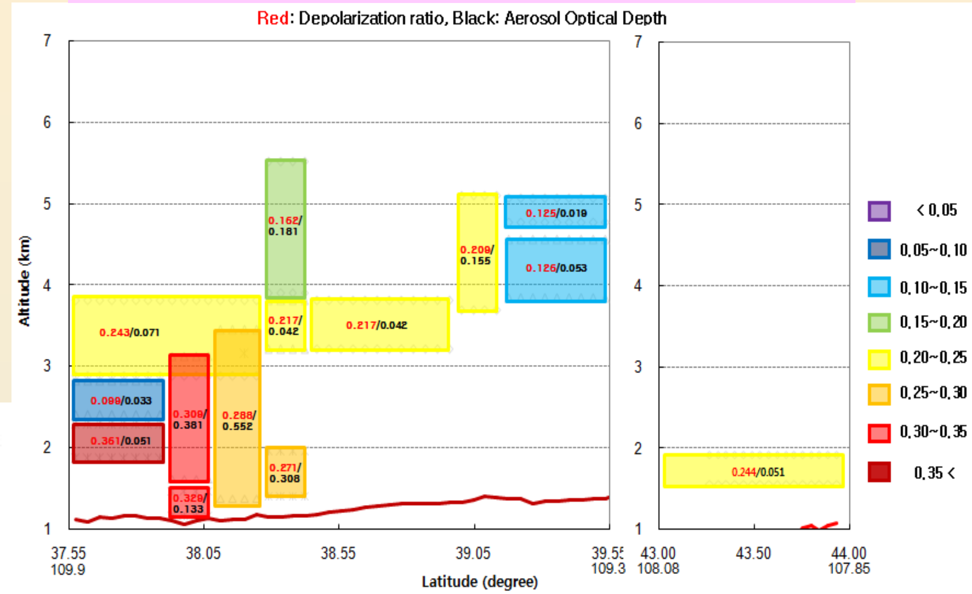
(a) 532 nm total attenuated backscatter coefficient



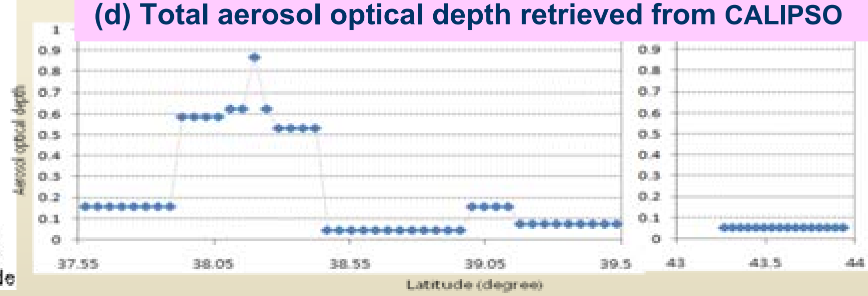
(b) Vertical feature mask and OMI Aerosol Index



(c) Layer-integrated volume depolarization ratio and aerosol- optical depth



(d) Total aerosol optical depth retrieved from CALIPSO

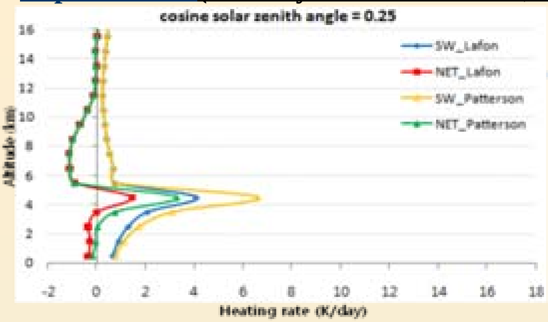


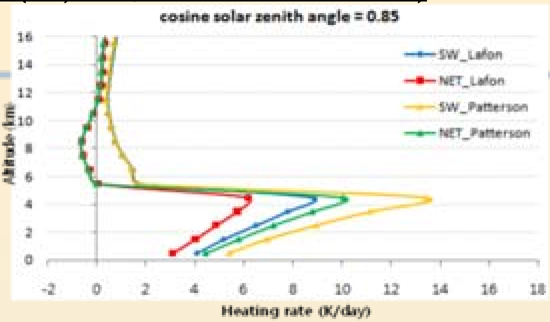
- Vertical feature mask: dust is wrongly classified as clouds.

- $\delta_{v,layer}$ has very high values near the surface (higher than 0.35) and lower values at 3-4 km. (might suggest that the coarse dust particles are not well mixed vertically)
  - The nonsphericity effect is similar between Taklamakan dust and Gobi dust.

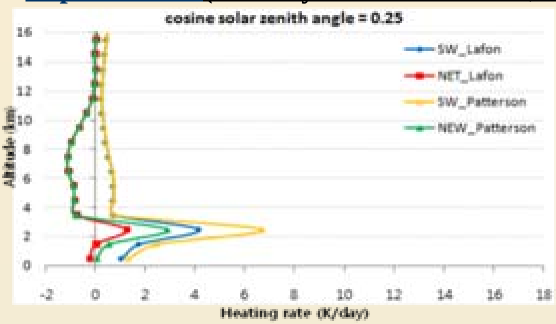
Heating rates

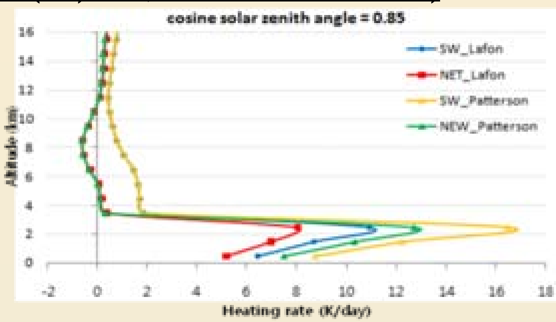
Experiment 1 (Dust layer extent: 0-5 km, AOD(0.5)= 2.5, Surface Albedo= 0.22)



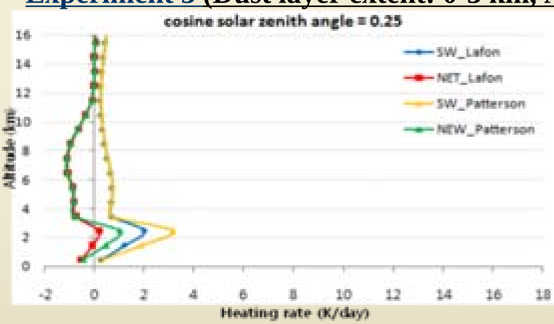


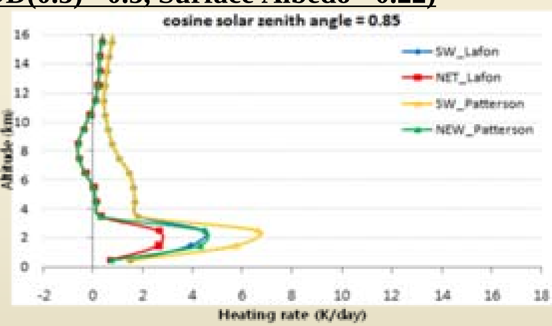
Experiment 2 (Dust layer extent: 0-3 km, AOD(0.5)= 2.5, Surface Albedo= 0.22)





Experiment 3 (Dust layer extent: 0-3 km, AOD(0.5)= 0.5, Surface Albedo= 0.22)





The cosine of solar zenith angle: 0.25 (low sun) & 0.85 (local noon)

- The profiles and values of heating/ cooling rates are strongly affected by a dust layer location.
  - The maximum rates: at the top of each layer.
- Comparing experiments 2& 3:
  - Increasing dust loadings increases both SW heating rates and IR cooling rates.
  - But net rates are positive, except cases with the low solar angle.

- The magnitude of the OPAC model net heating rates is ~30% larger than Asian dust (Lafon et al. 2006).
  - The radiative impact of Asian dust on the atmospheric dynamics and thermodynamics was likely overestimated by past studies.

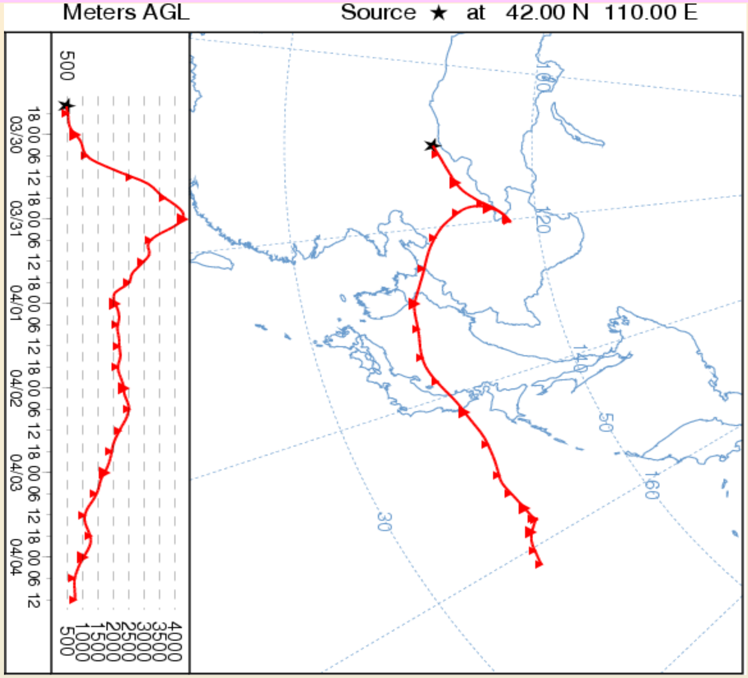
What the CALIPSO lidar can and cannot do…

Part. II Mid-rangeTransport

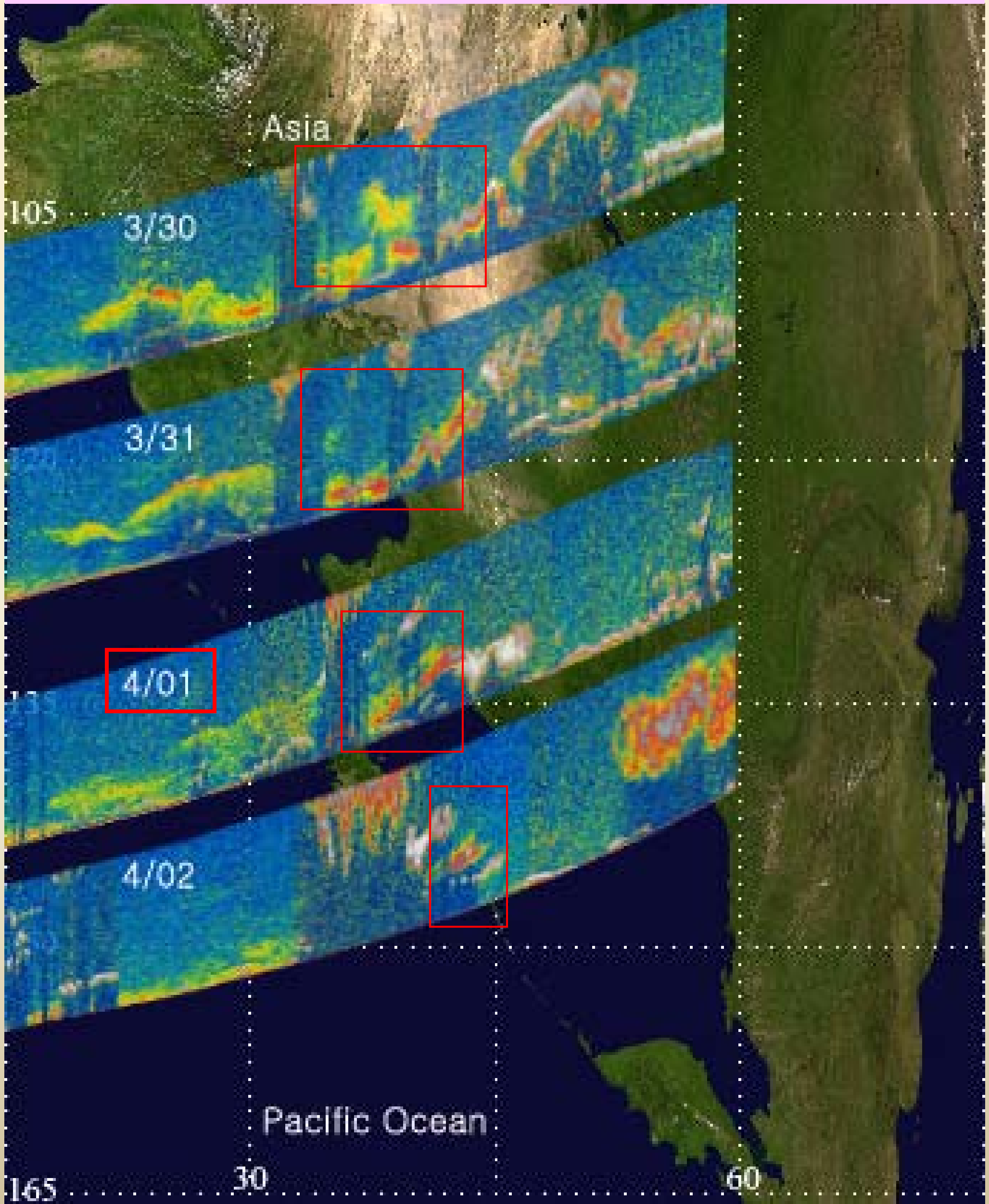
Dynamics of dust vertical profiles (single layer vs. multiple layers, dust-clouds layering)
Are there significant changes in dust properties (dust ageing)?

Analyses of Mid-Range Transport of Asian Dust

(a) Forward trajectories from NOAA HYSPLIT model



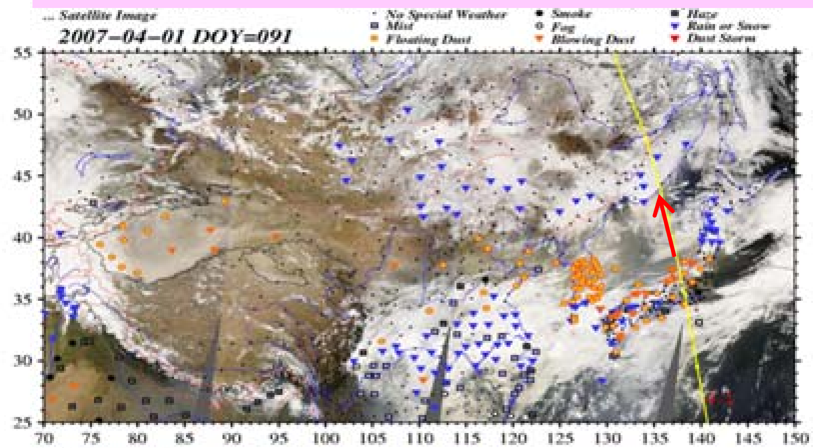
(b) Reconstructed dust transport



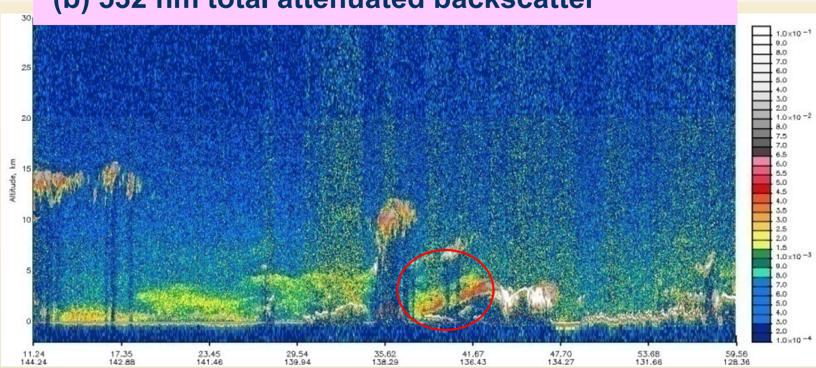
- Dust event: March 30~April 2
- Regions: The Gobi ~ Japan
- HYSPLIT back trajectories
- The vertical structure of Asian dust changes during the transport.
- Dust layers are mixed with clouds.

The 1 April 2007 Case: Asian dust over Japan

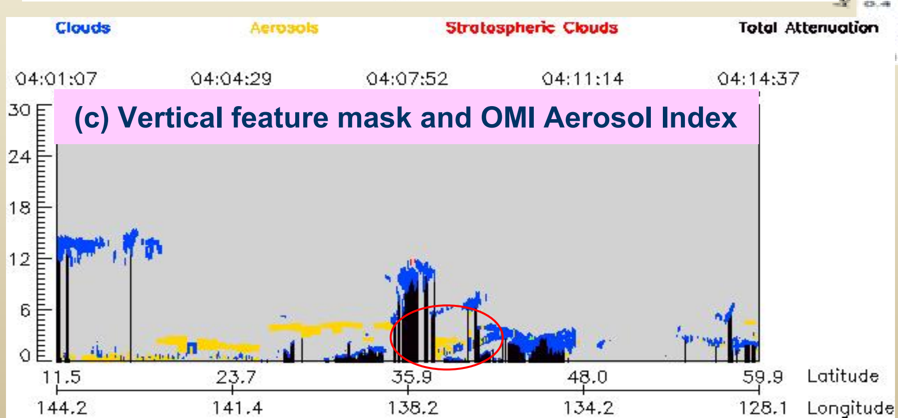
(a) Integrated images (Visibility, MODIS-Terra, orbit of CALIPSO)



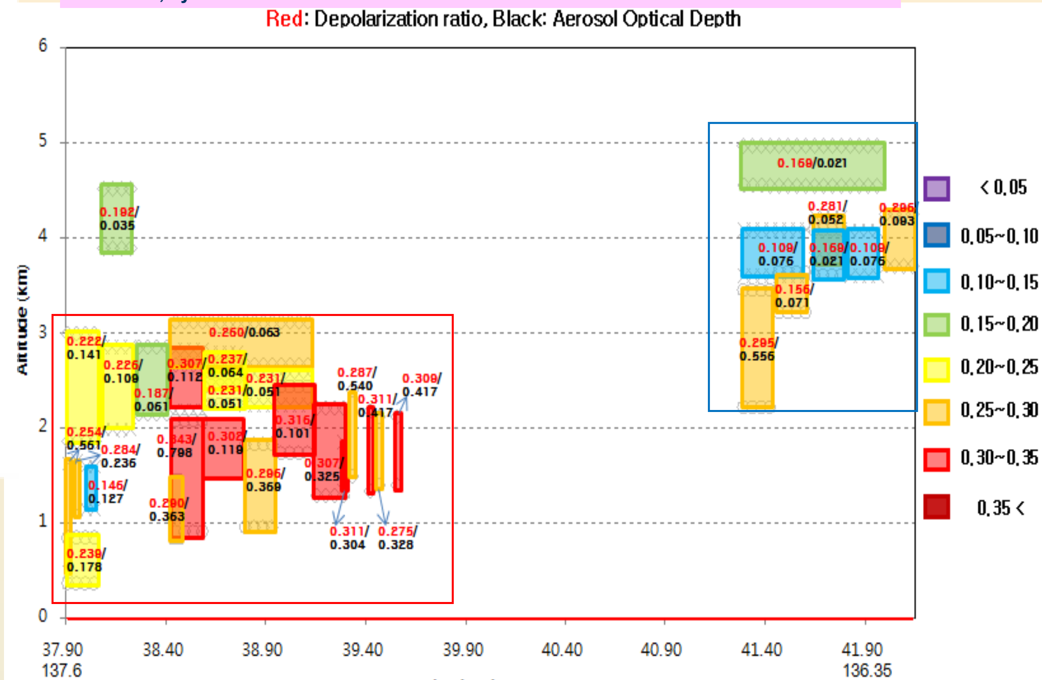
(b) 532 nm total attenuated backscatter



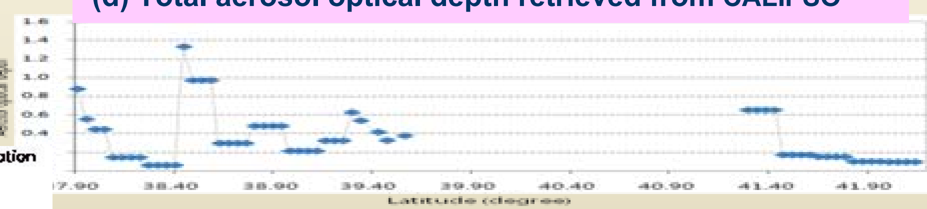
(c) Vertical feature mask and OMI Aerosol Index



(c) $\delta_{v,layer}$ and aerosol-layer optical depth

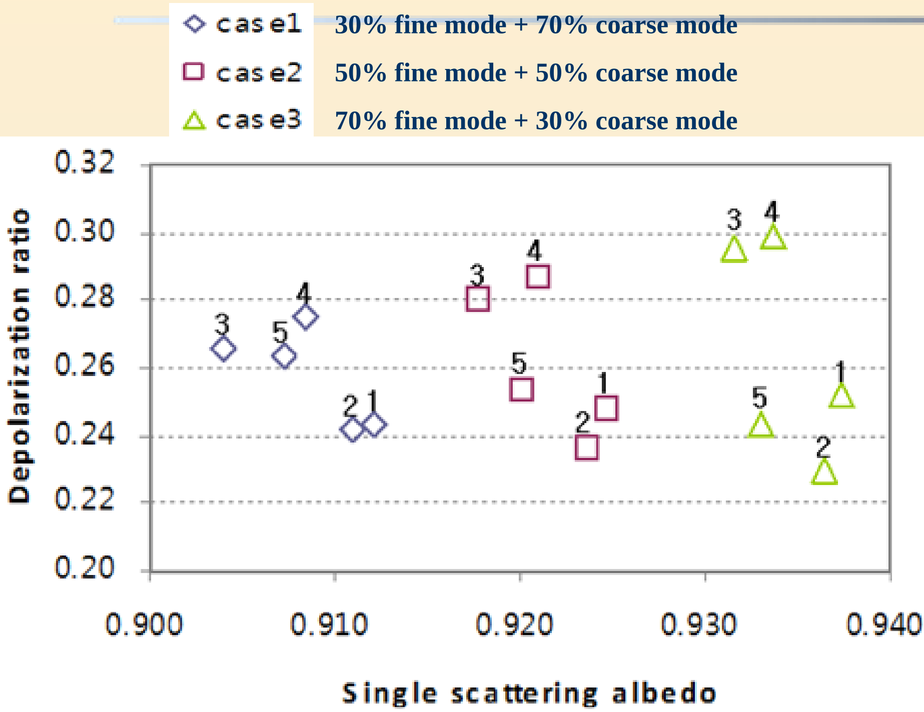


(d) Total aerosol optical depth retrieved from CALIPSO

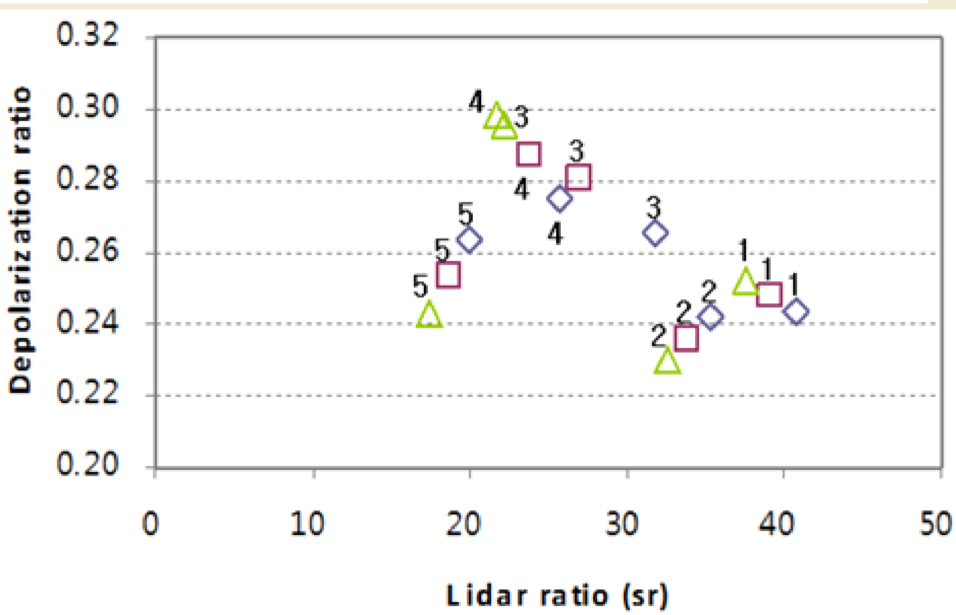


- $\delta_{v,\ layer}$/AOD in red rectangle: 0.231~0.343 / 1.4
  - Similar to ones observed over source
- $\delta_{v,\ layer}$/AOD in blue rectangle: 0.1~0.15 (Low)
- Aged dust: either low or high depolarization
- Different mechanisms might control the aging of dust

Optical Modeling: T-matrix Method + IGOM



- The aspect ratio(ε’): the ratio of the largest to the smallest particle dimensions
  - Axial ratio(ε) = a/b, ε’=ε is for prolate spheroids and ε’=1/ε for oblate spheroids
  - Mixtures 1 & 2: Dubovik et al.(2006)
  - Mixture 3: Wiegner et al. (2008) for Saharan dust
  - Mixtures 4 & 5: Okada et al. (2001) for Asian dust



- Particle depolarization ratio (δ_a) has relatively low sensitivity to the size distribution.

- The CALIPSO lidar ratio for desert dust is S_a=38.1 sr, which corresponds to $\delta_a > 0.24$.
- δ_a higher than 0.3, observed by CALIPSO for Asian dust, are indicative of lower S_a.
- None of cases can produce δ_a: <0.2 and >0.3.

⇒ Limitations of the assumption on spheroids.

⇒ Need the DDA approach

What the CALIPSO lidar can and cannot do…

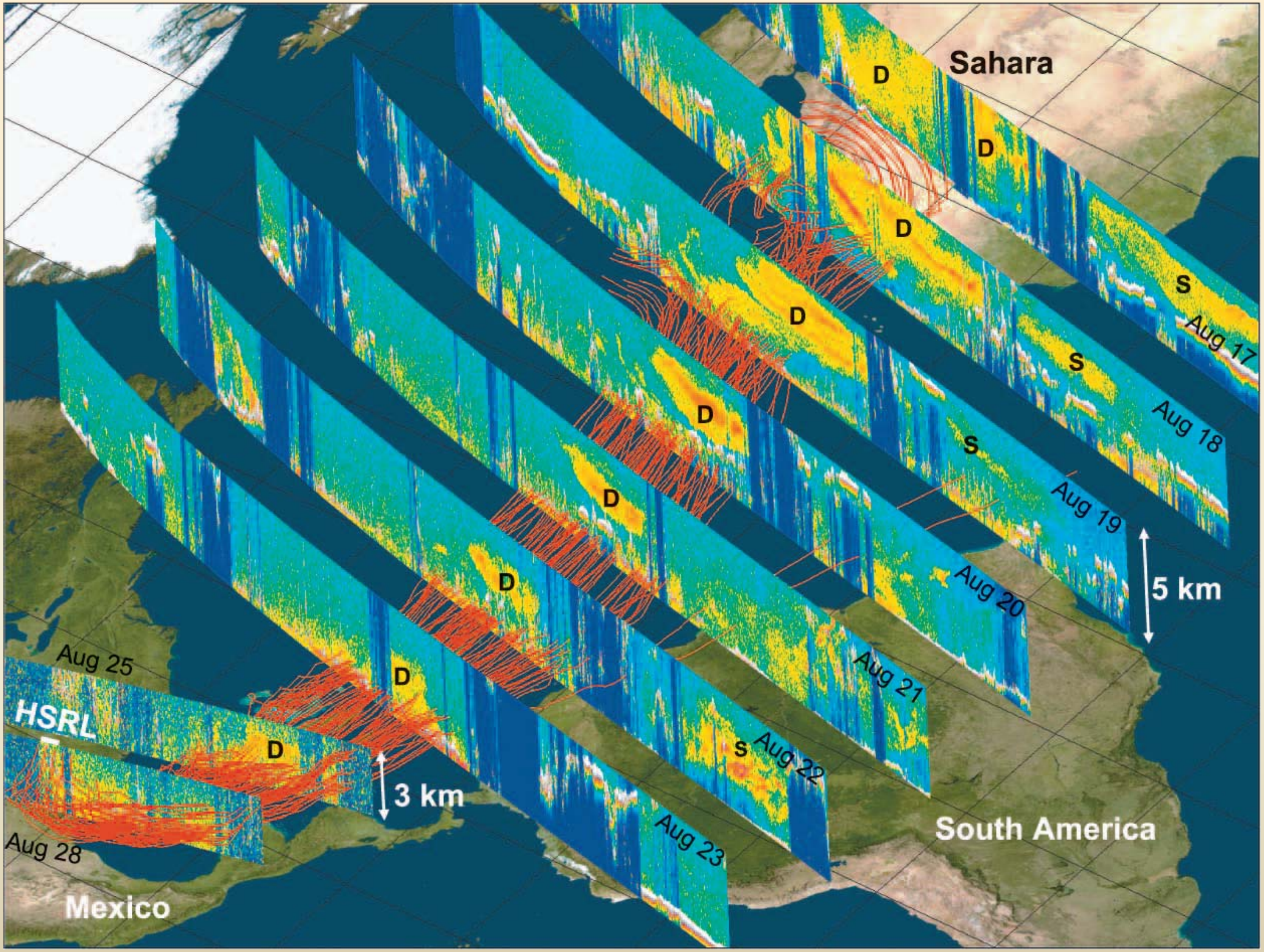
Part. III Dust transport

CALIPSO+AIRS => Size-resolved composition
Spectral IR forcing and cooling rates

Effect of particle nonsphericity in the IR spectrum…
a good fit with spheroids of ε= 5 for clays and quartz

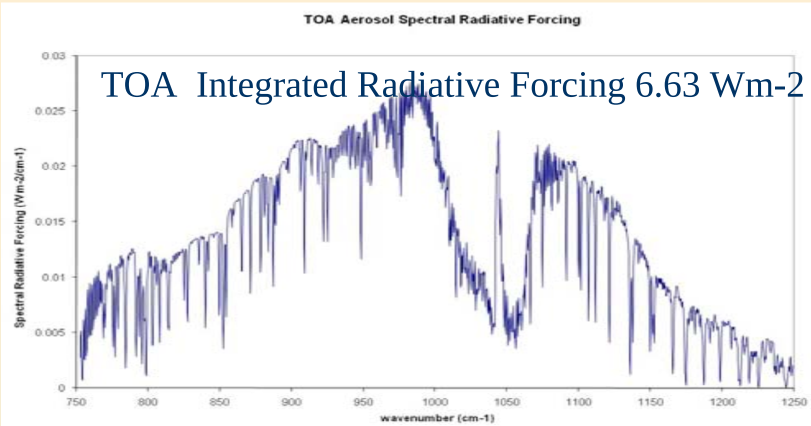
Boer&Sokolik

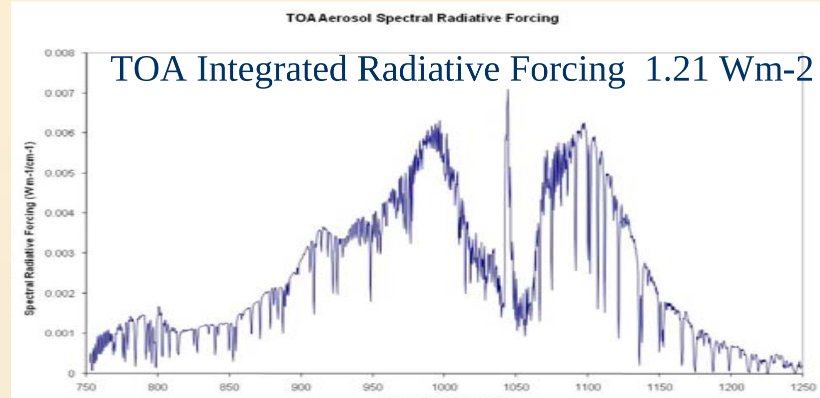
Saharan dust trans-Atlantic event (Aug. 17-23, 2006)

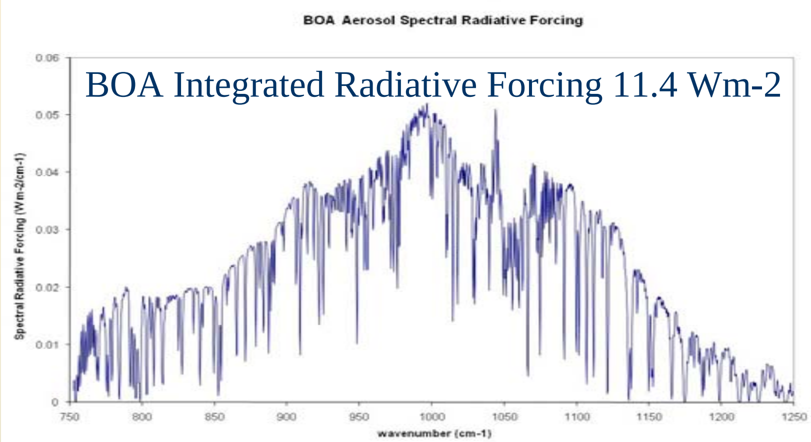


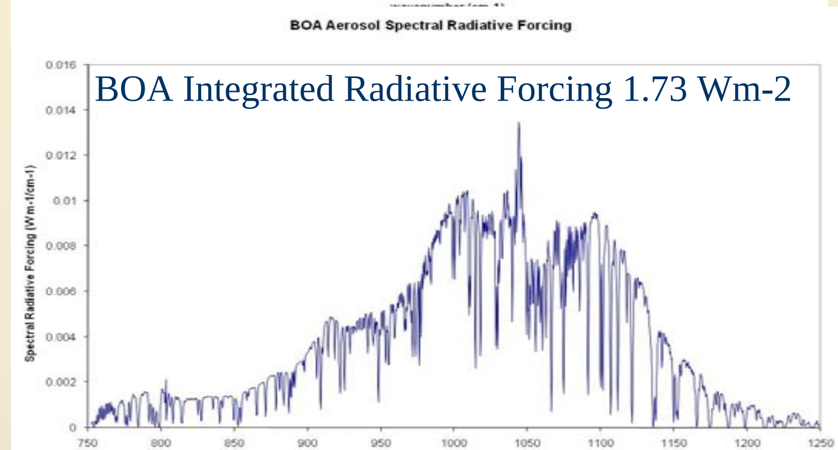
Liu et al. (2008)

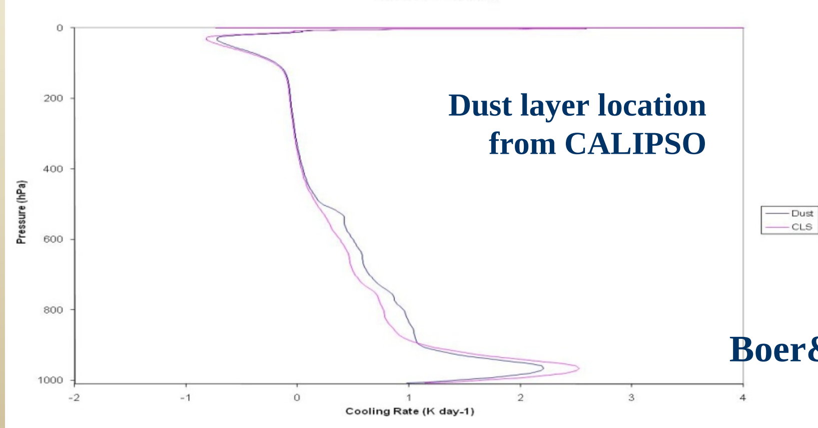
Dust IR radiative forcing derived from AIRS: Saharan dust 20&23 Aug., 2006

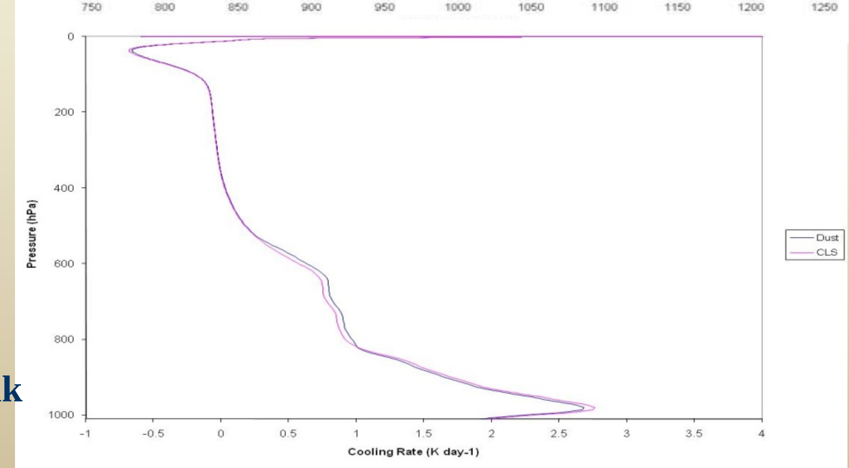








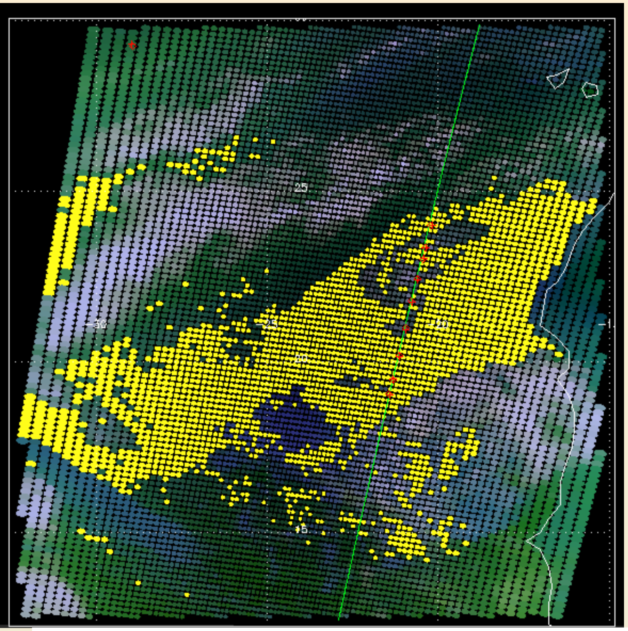


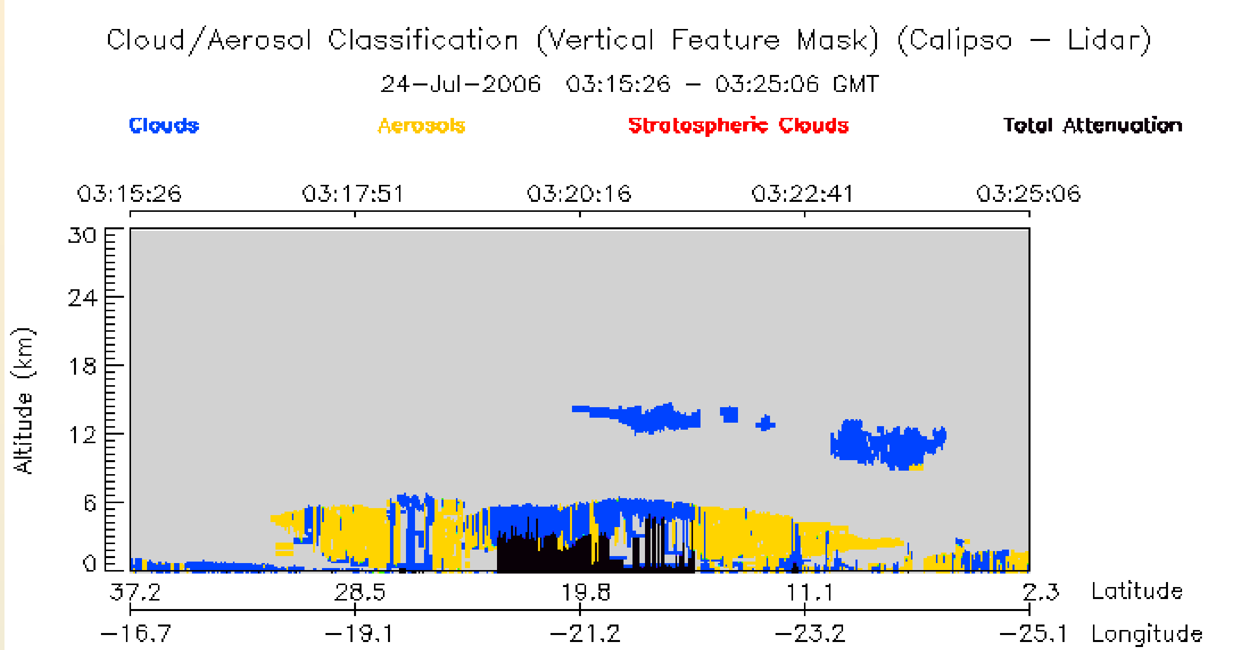


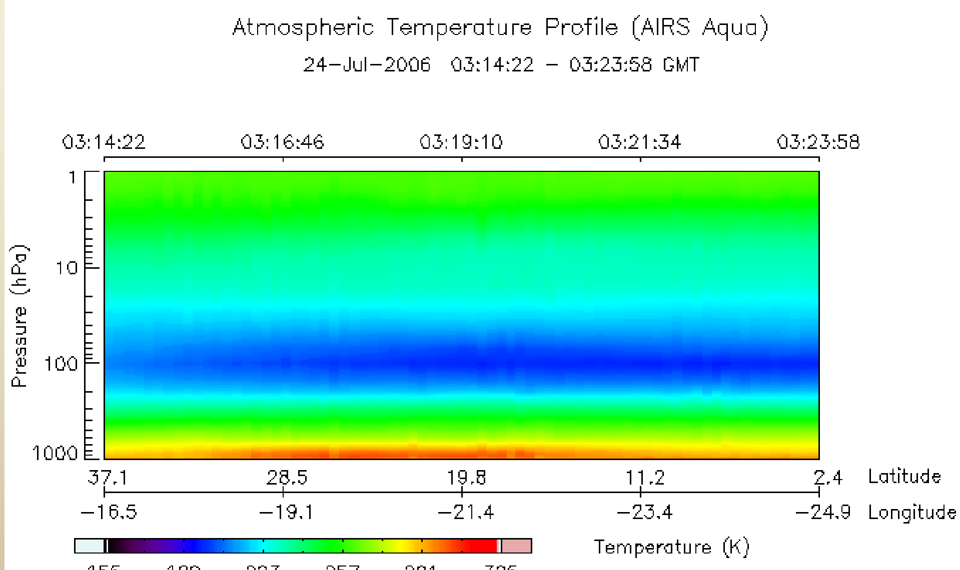
Boer&Sokolik

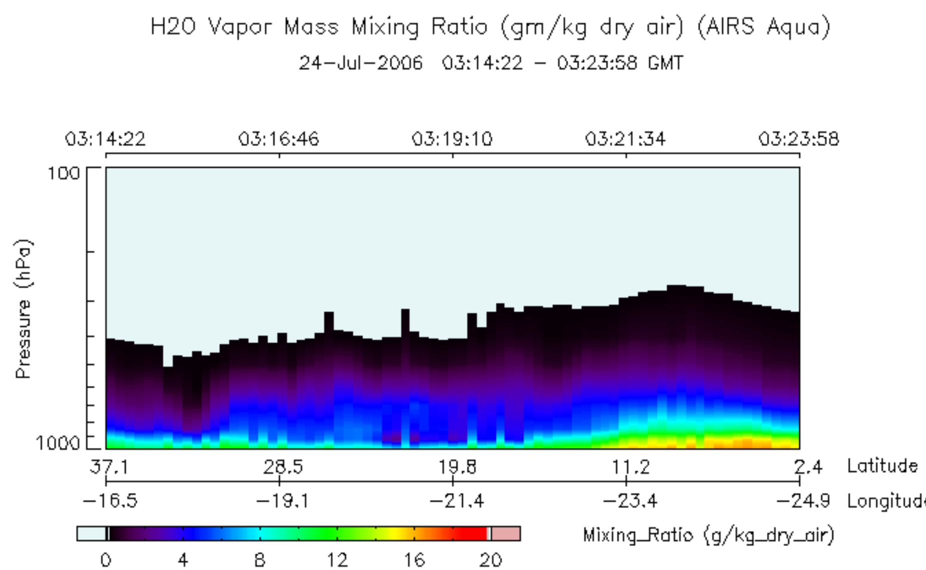
Case of July 24, 2006: cirrus over dust – very common!

AIRS cloud mask

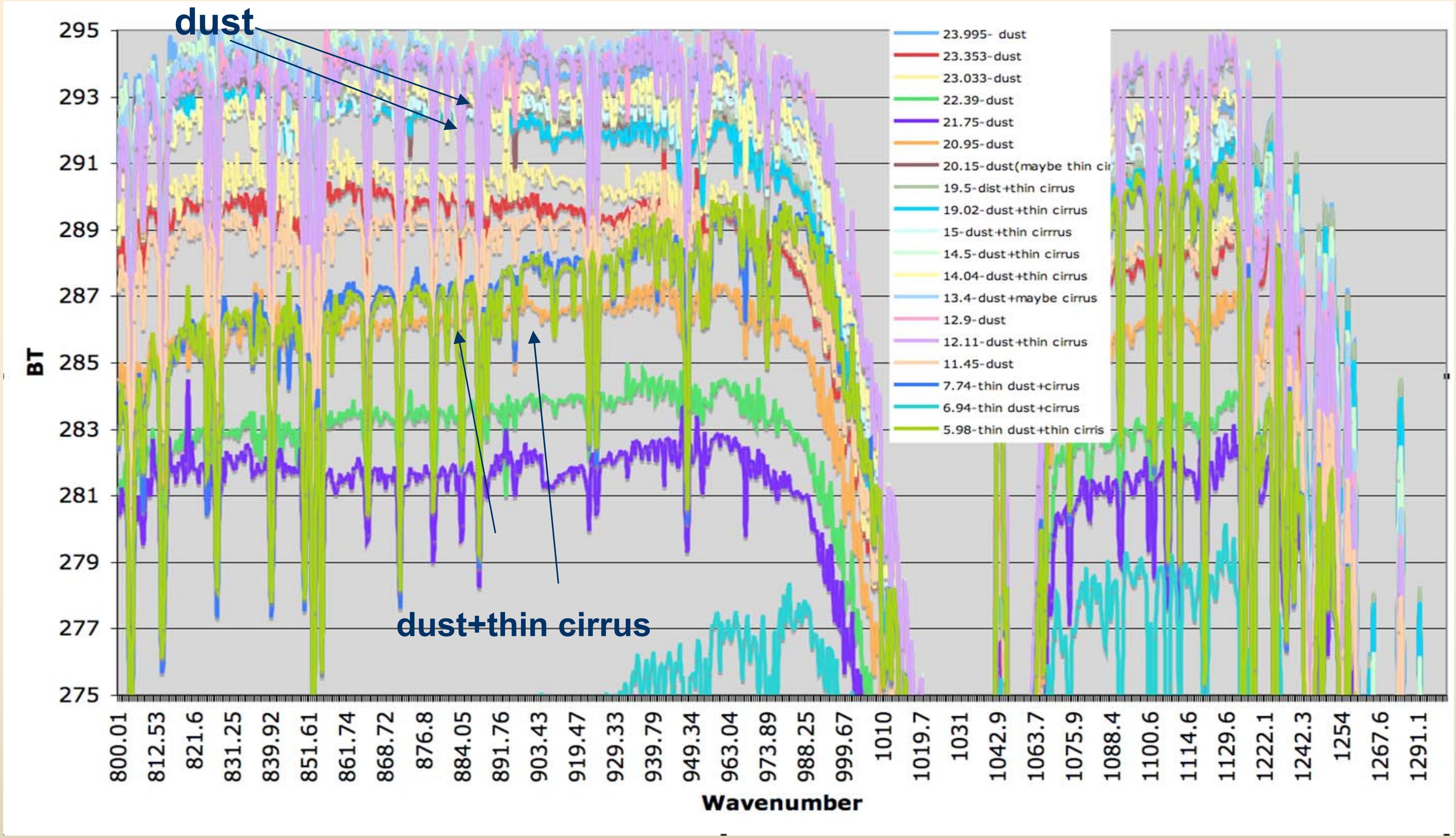








AIRS spectra along CALIPSO track



Cirrus-contaminated spectra compare to clean dust:

- Colder
- No slope or positive slope in 800-900 cm-1 region

What the CALIPSO lidar can and cannot do…

Part. IV Dust indirect forcing (via clouds)

Microphysical forcing vs. radiative forcing

(Dust as CCN, GCCN, and IN)

Impact of dust on tropical cyclones

Evan et al., Lau et al.:

Dust – TC anti-correlation (via dust radiative impact on the surface energy balance => lower SST

Zhang et al.(2008, 2009):

(Idealized TC modeled with RAMS)

Dust acting as CCN and IN can affect the intensity, structure and precipitation of storms

Zhang, Sokolik, and Curry, 2009, JAS

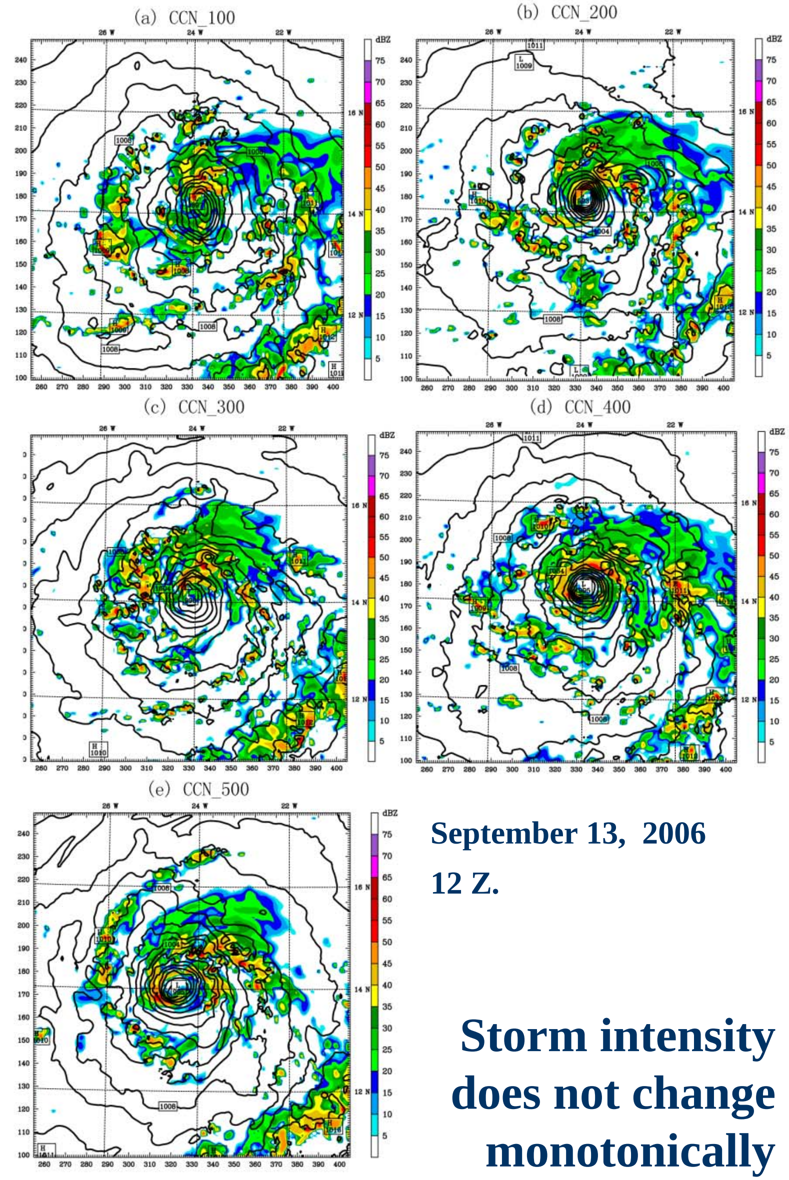
Impact of Saharan dust as nucleating aerosols on Hurricane Helene’s early development

WRF Model setup: double-moment Morrison microphysics scheme + Khvorostyanov and Curry (2005) heterogeneous freezing parameterization (soluble and insoluble aerosol)

.

Dust acting as CCN has a much stronger effect compared to dust IN

Dust affects the periphery of TC (i.e, outer rainband) but not the central eyewall

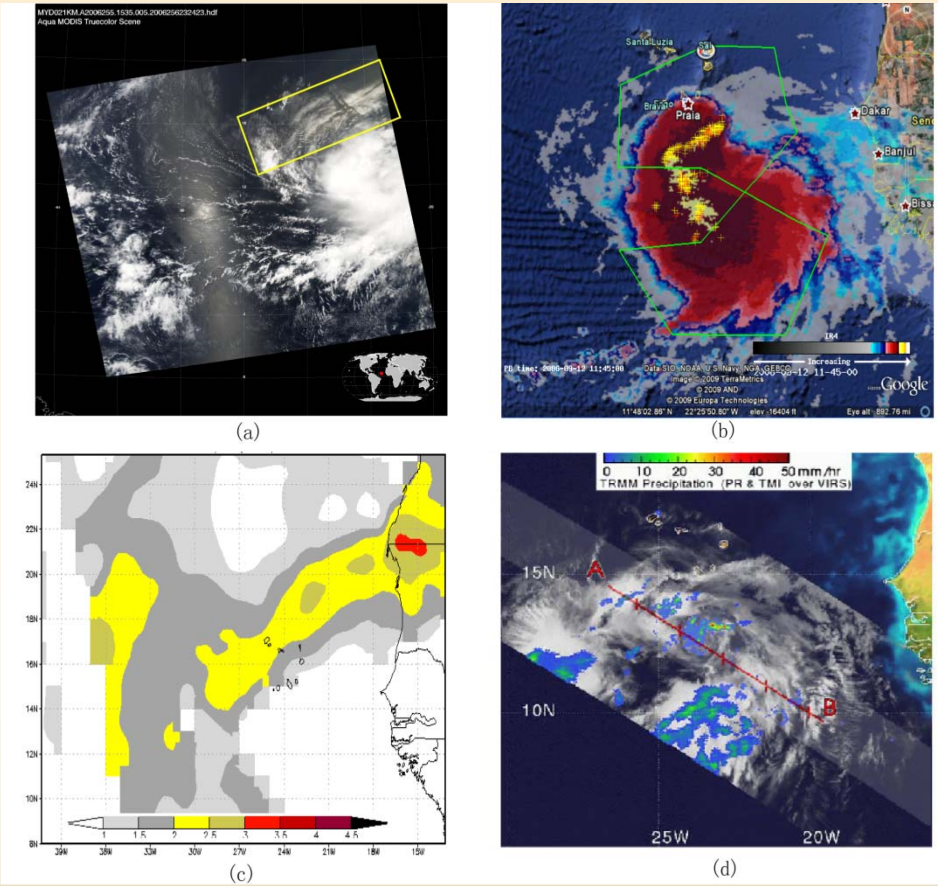


September 13, 2006

12 Z.

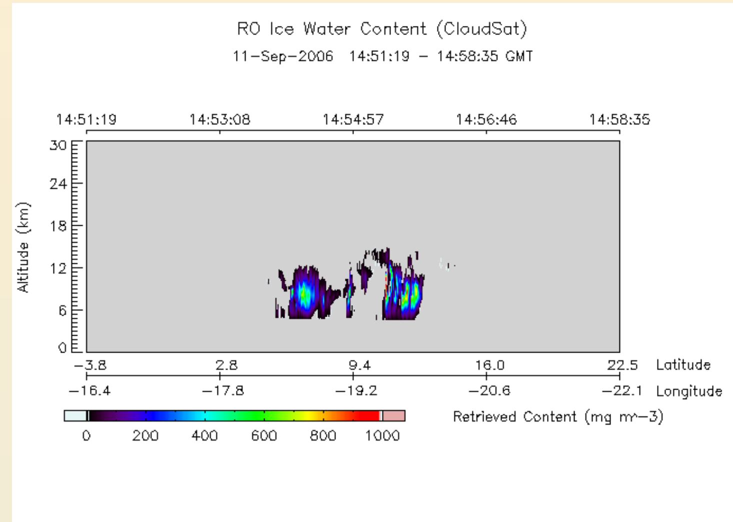
Storm intensity does not change monotonically

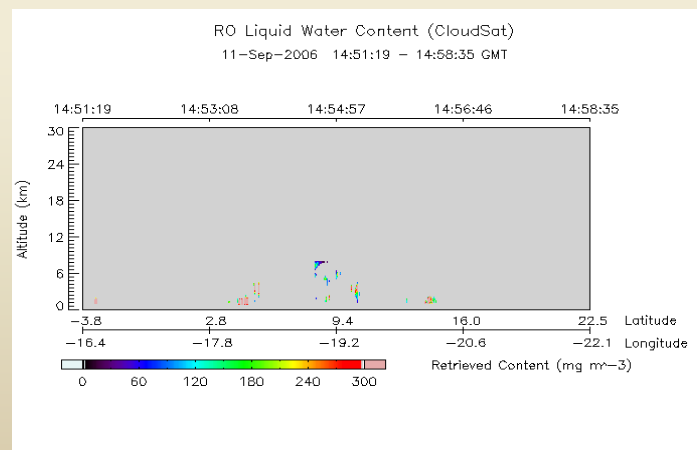
TC Helene (September, 2006)



Remote sensing images of Pre-Helene TD8 on September 12 2006: (a) MODIS true color (RGB) image (b) DC-8 flight path overlaid on Meteosat-8 IR images as seen on the Real Time Mission Monitor (RTMM) (Yellow crosses indicate the occurrences of lightning);

(c) OMI UV aerosol index; and (d) TRMM precipitation rate (retrieved from PR and TMI overlaid on VIRS image





Zhang, Sokolik, and Curry, 2009, JAS

What CALIPSO lidar can and cannot do…a few final final comments

- **CALIPSO adds in assessments of dust in sources, and during mid-range and long-range transport**
- **Profiling of dust plumes enable better assessments of radiative heating rates and LW forcing**
- **Integrated analysis of CALIPSO data with other data sets, and process-based models with horizontal resolution comparable to A-Train sensors' footprints**

!!! Need for a dedicated CALIPSO data subset for dust studies

- **Indirect forcing: Dust radiative forcing vs. microphysical forcing:**

TOA and surface (SW and LW) forcing and radiative heating (or cooling) rates

Microphysical forcing as dust acts as CCN, GCCN, and IN

Opposing effects on clouds and precipitation

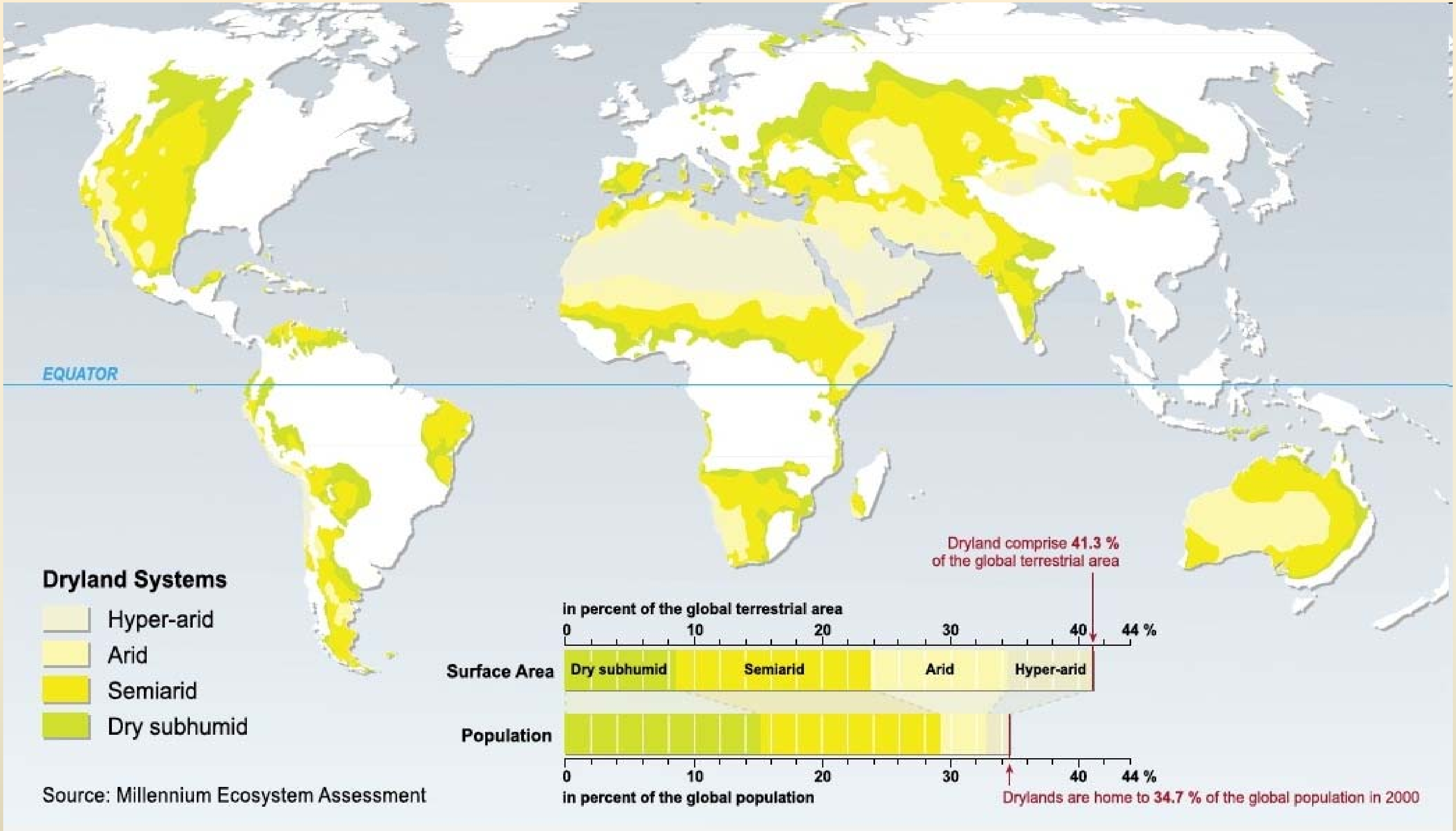
Rosenfeld et al.(2008, Science):

"optimum" aerosol properties AOD ~0.25, CCN (o.4) ~1200 cm-3, **BUT did not consider dust!**

!!!! Hard to study dust-cloud mixed scene even with A-Train capabilities

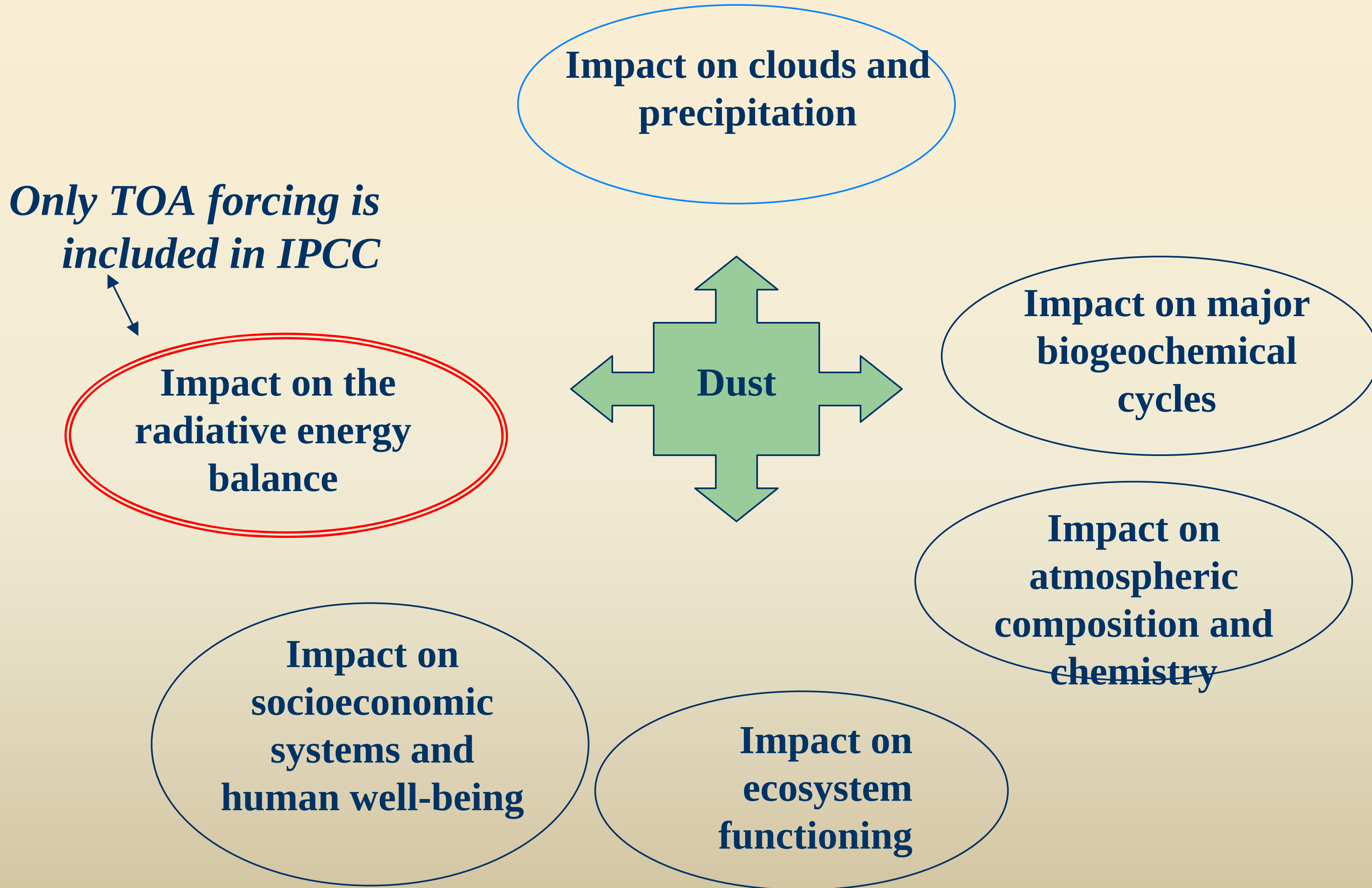
EXTRA

The global relevance of mineral dust



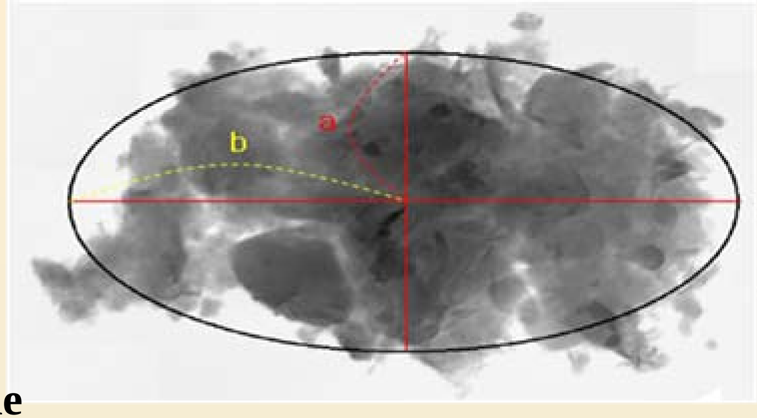
- **Dust sources are globally distributed (natural vs. anthropogenic)**
- **Mid- and long-range transport (e.g., trans-Atlantic and trans-Pacific routes)**

Importance of dust in the Earth system



Optical Modeling: T-matrix Method

- T-matrix Method: dust particle=spheroid



- Lod normal distribution

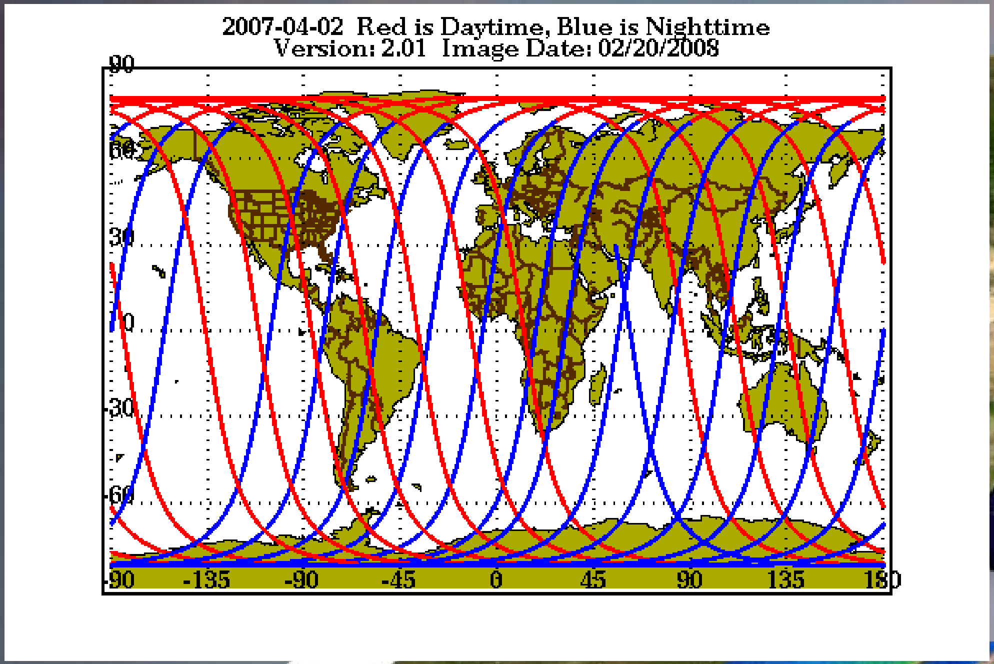
$$n(r) = \sum_{i=1}^{2} \frac{1}{\sqrt{2\pi}\ln\sigma_i r} \exp\left[-\frac{(\ln r - \ln r_{gi})^2}{2\ln^2\sigma_i}\right]$$

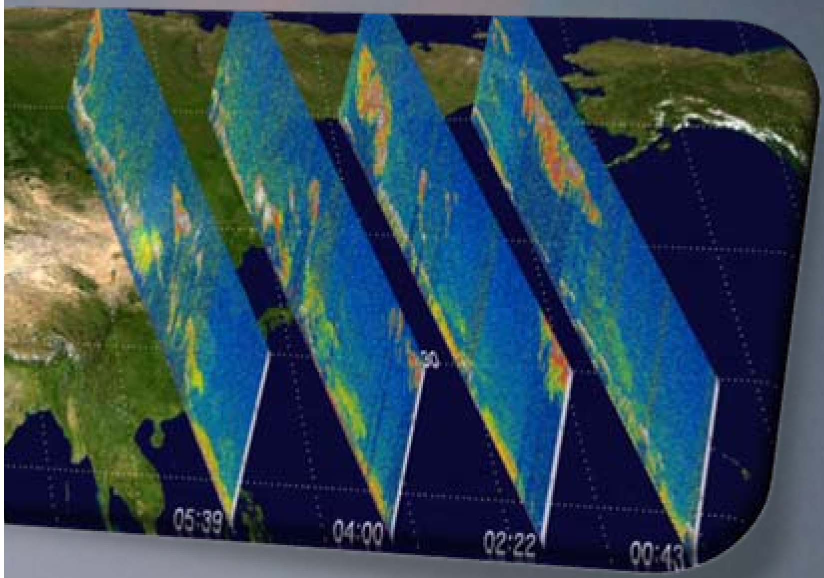
  - Refractive index: 1.56 + 0.003*i* at 532 nm
  - 0.1< r < 1 μm, r_{g1} = 0.5 μm for the fine mode
    0.1< r < 3 μm, r_{g2} = 1.0 μm for the coarse mode, and $\ln\sigma_2$ = 0.5

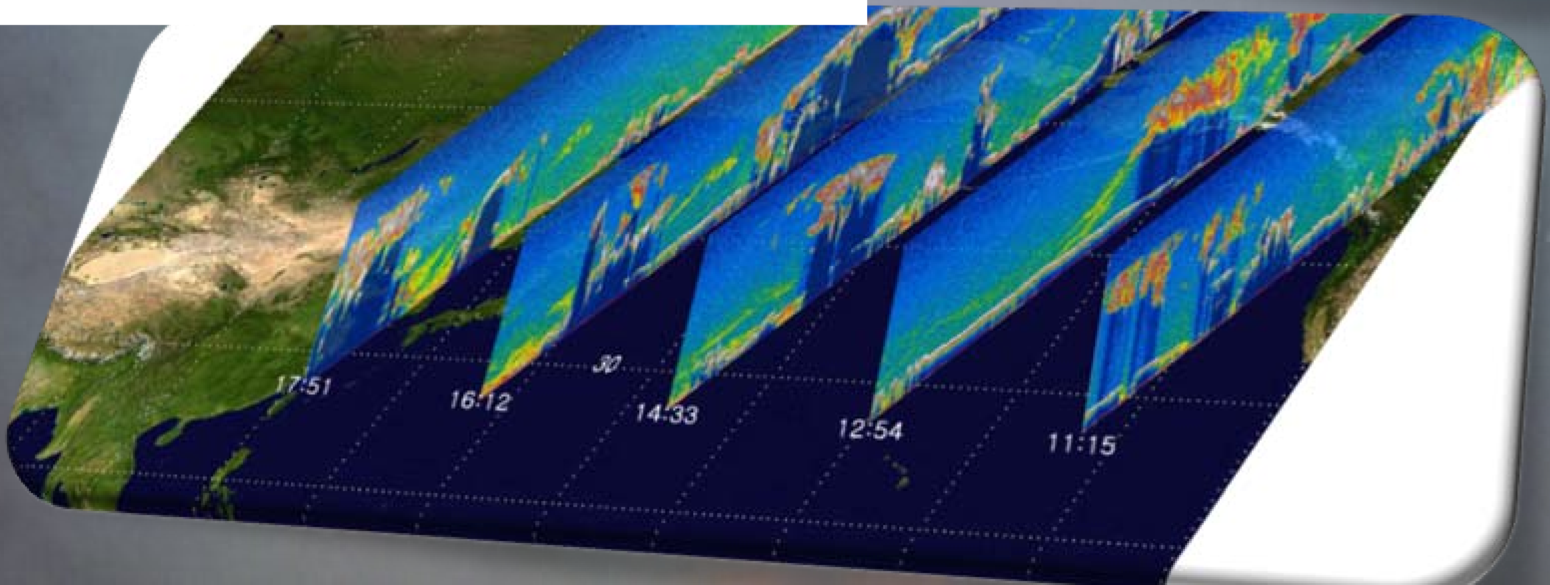
- The aspect ratio(ε'): the ratio of the largest to the smallest particle dimensions
  - Axial ratio(ε) = a/b, ε'=ε is for prolate spheroids and ε'=1/ε for oblate spheroids
  - Mixtures 1 & 2: Dubovik et al.(2006)
  - Mixture 3: Wiegner et al. (2008) for Saharan dust
  - Mixtures 4 & 5: Okada et al. (2001) for Asian dust

Aspect ratio(ε ')		1.05	1.1	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
Mixture1[a]				0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Mixture2[a]		0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Mix-ture3 [b]	Fine			0.535	0.289	0.108	0.040	0.015	0.007	0.003	0.001	0.001	0.001
	Coarse			0.103	0.234	0.218	0.157	0.101	0.065	0.041	0.027	0.018	0.026
Mixture4[c]				0.335	0.319	0.179	0.087	0.042	0.020	0.009	0.005	0.002	0.001
Mixture5[c]		0.141	0.173	0.230	0.219	0.123	0.060	0.029	0.014	0.006	0.003	0.001	0.001

Transport of Asian dust: CALIPSO



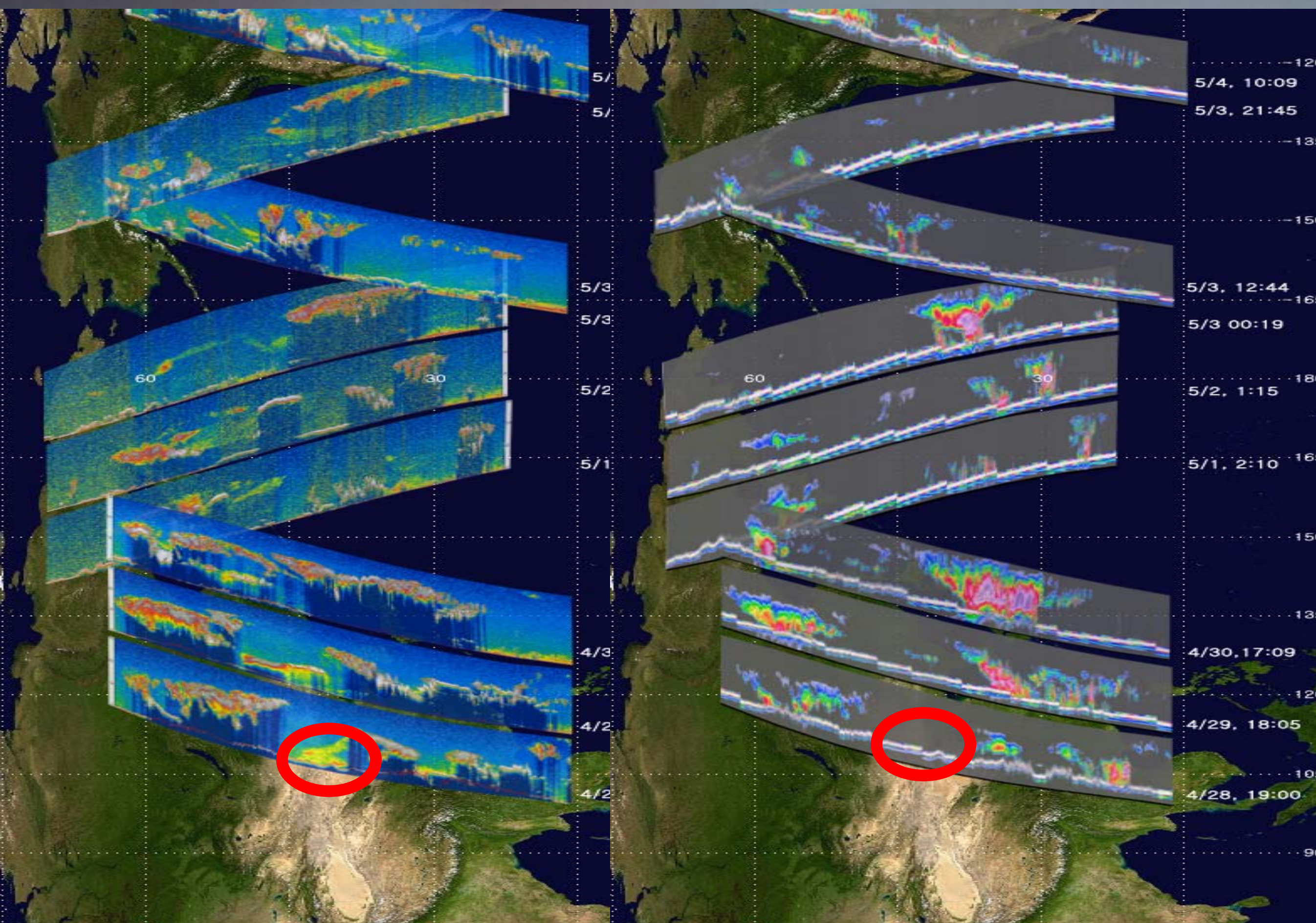




Transport of Asian dust: vertical distribution of aerosols and clouds from CALIPSO and CloudSat

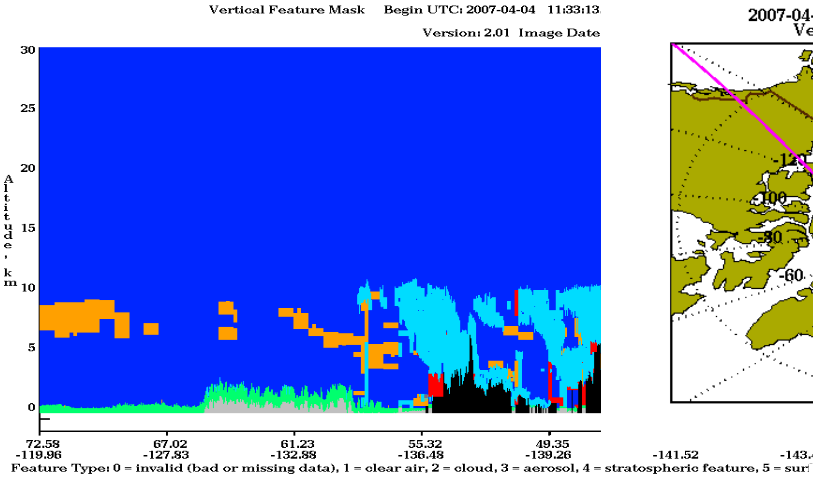
CALIPSO

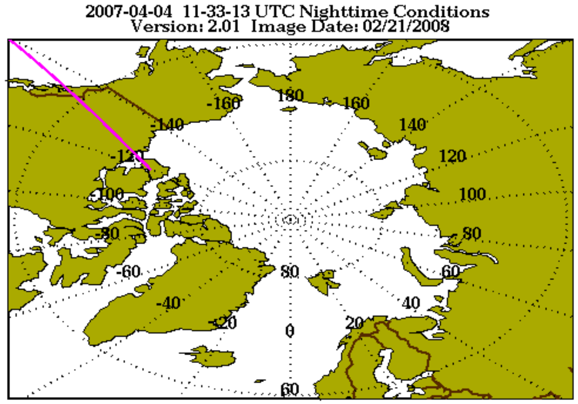
CloudSat

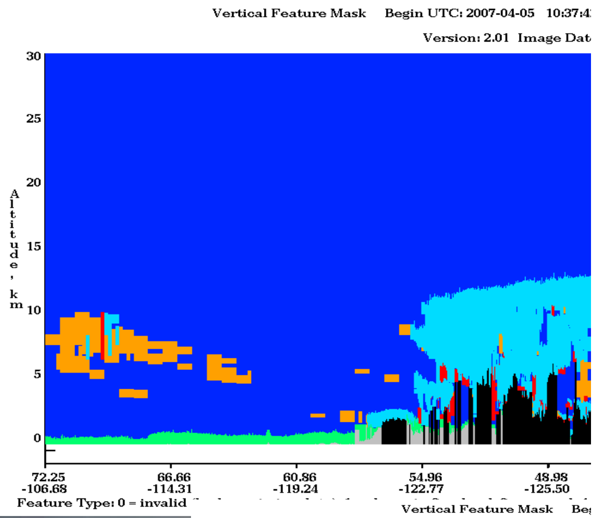


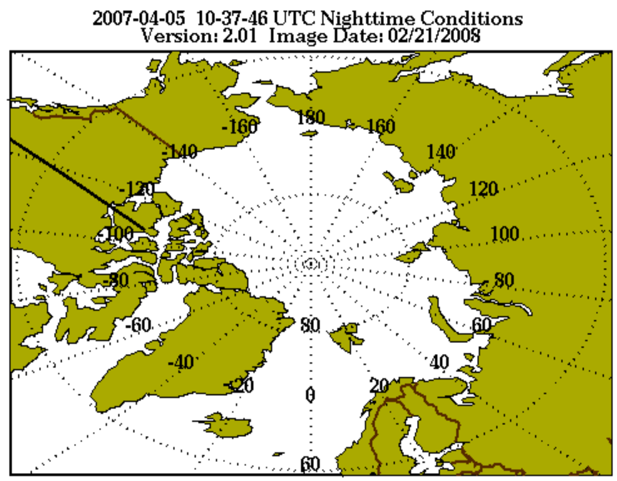
Vertical distribution is a key factor in controlling radiative impacts of aerosols, aerosol-cloud-precipitation interactions and aerosol removal/depositio

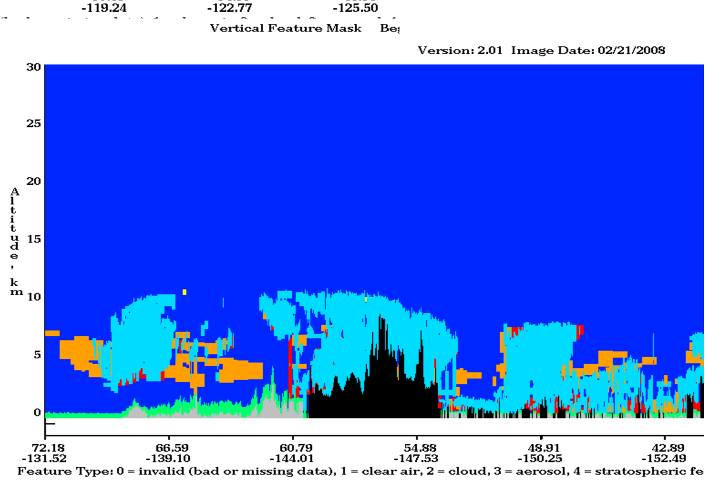
Examples of aerosol vertical distribution from CALIPSO (April 2-5)

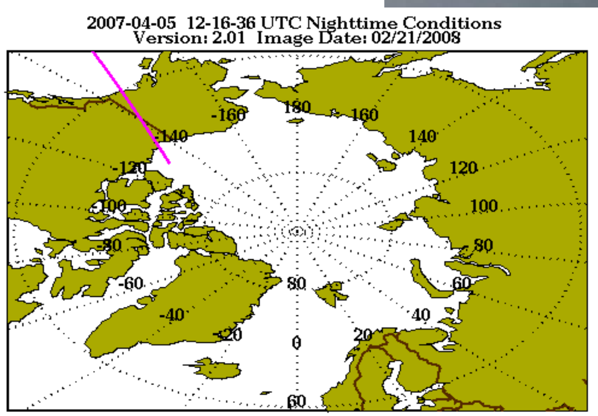






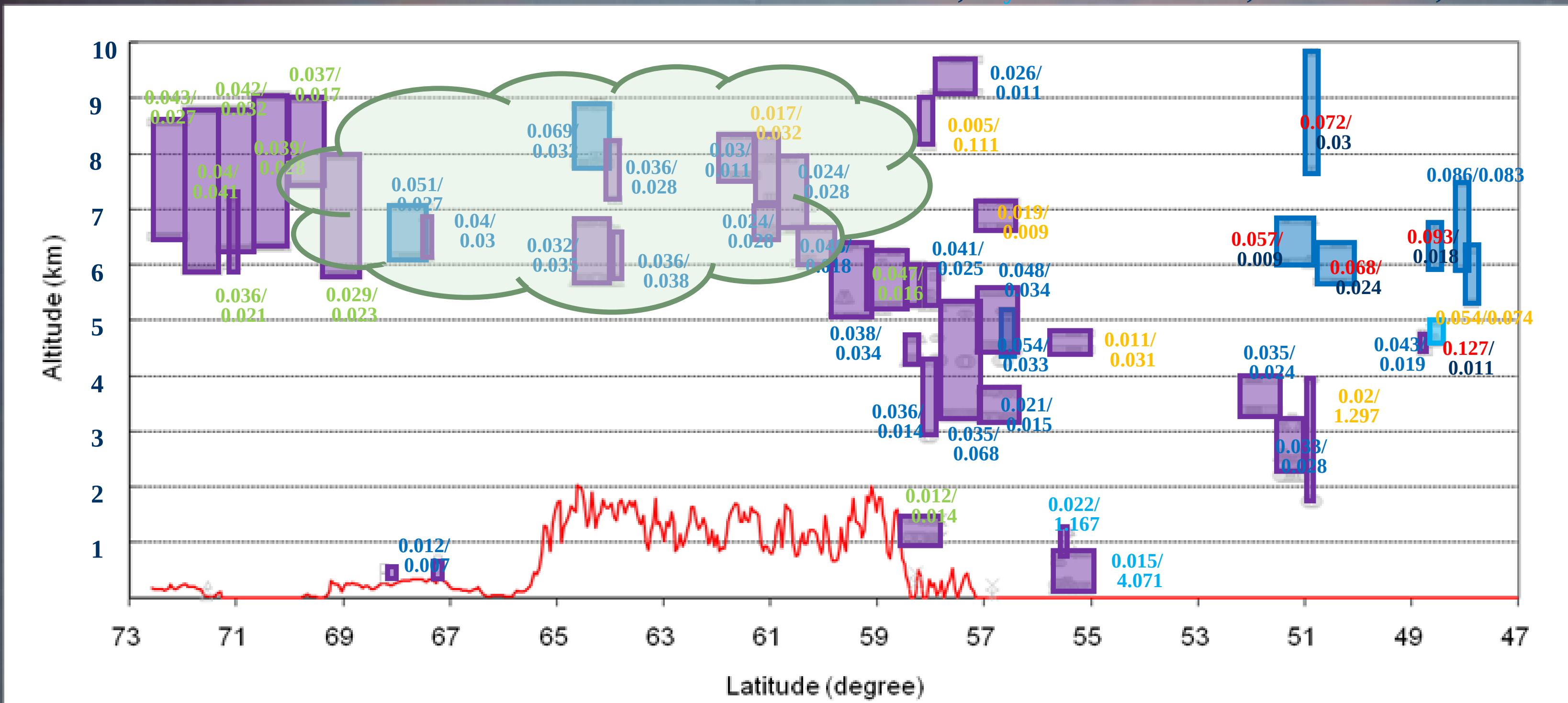


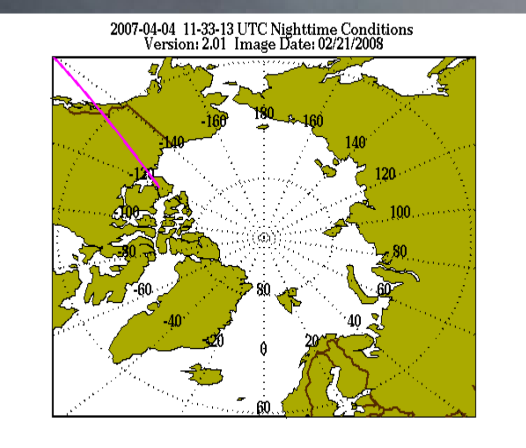


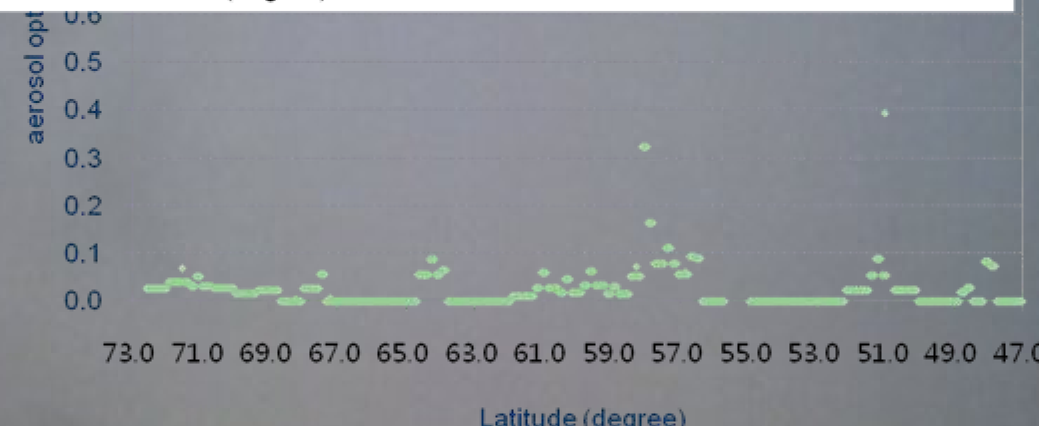


CALIPSO pass: UTC 11:33 April 4, 2007

Red/ Black : Depolarization ratio/Aerosol Optical Depth, Green: Clean Continental Aerosol
Blue: Polluted dust, Sky blue: clean marine, Yellow: smoke,







Dust-induced perturbations in radiative energy

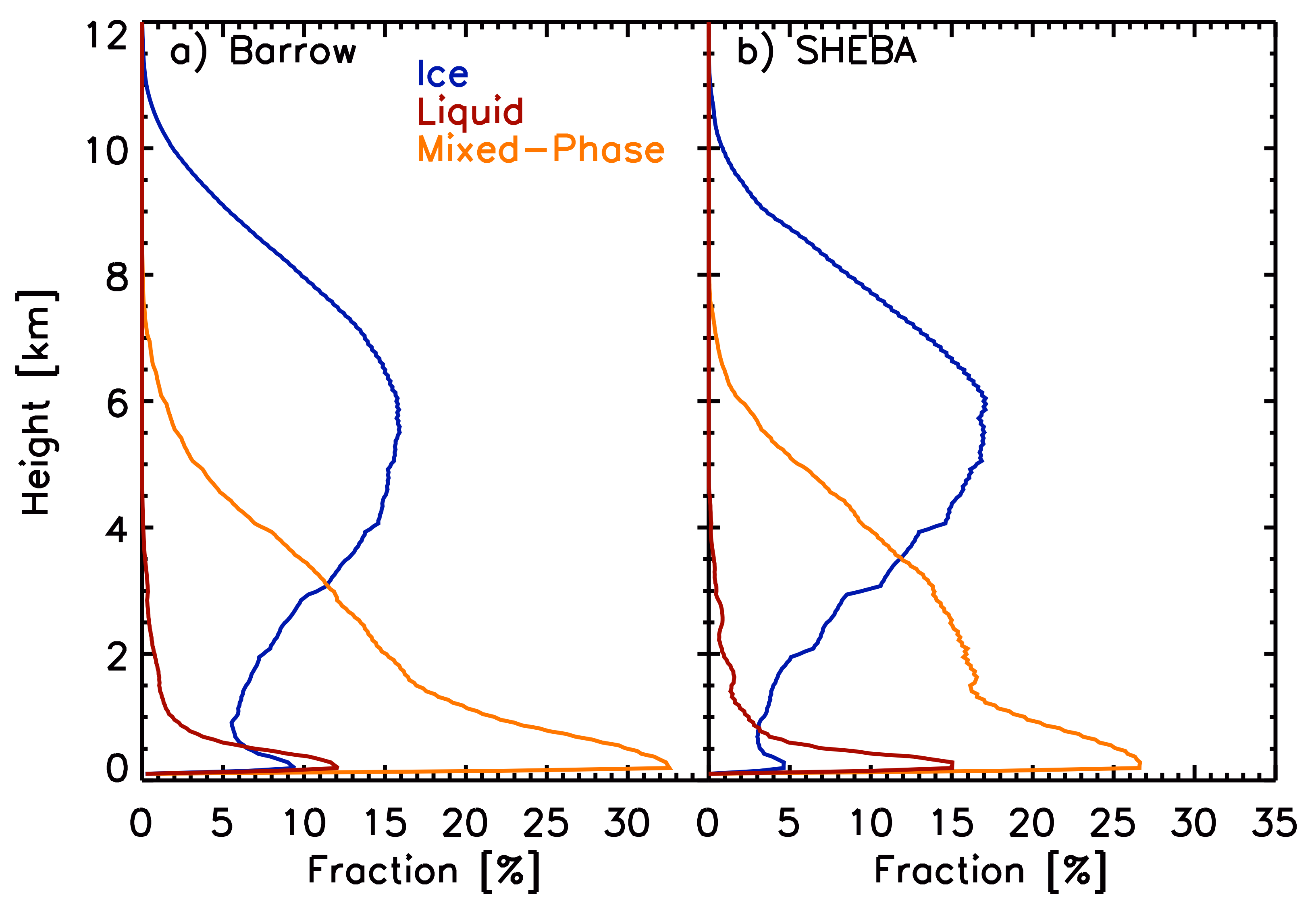
Considered conditions:

AOD (500) ~ 0.05-0.1

Cosine of solar zenith angle =0.25

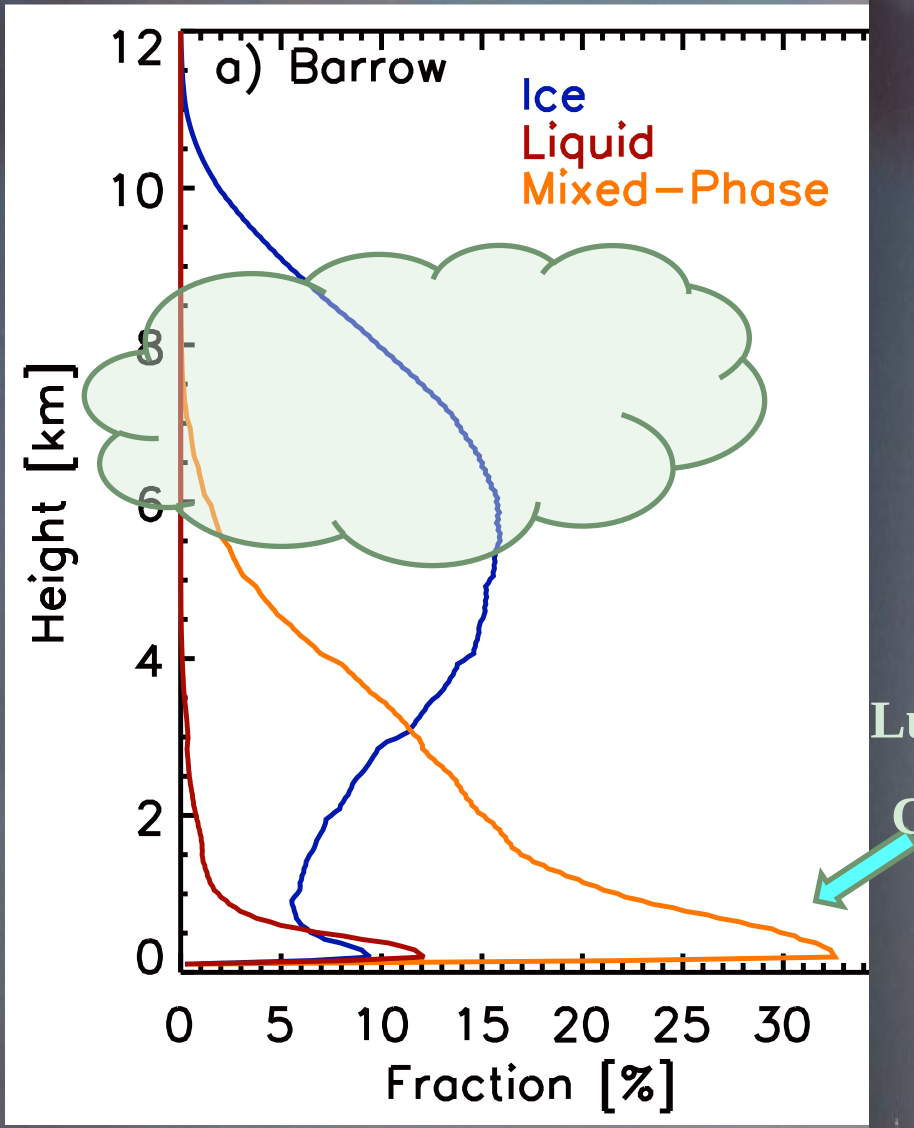
Varying surface albedo (ocean, tundra, snow/ice)

Vertical Distributions of Cloud Type



- Remarkable similarities
- Slightly different balance at surface. *Shupe et al.*

Asian dust impact on ice and mixed-phase clouds



Dust/aged dust as IN/CCN?

Dust IN ↑ => ice crystal size ↓
Longer cloud lifetime/coverage => warming tendency

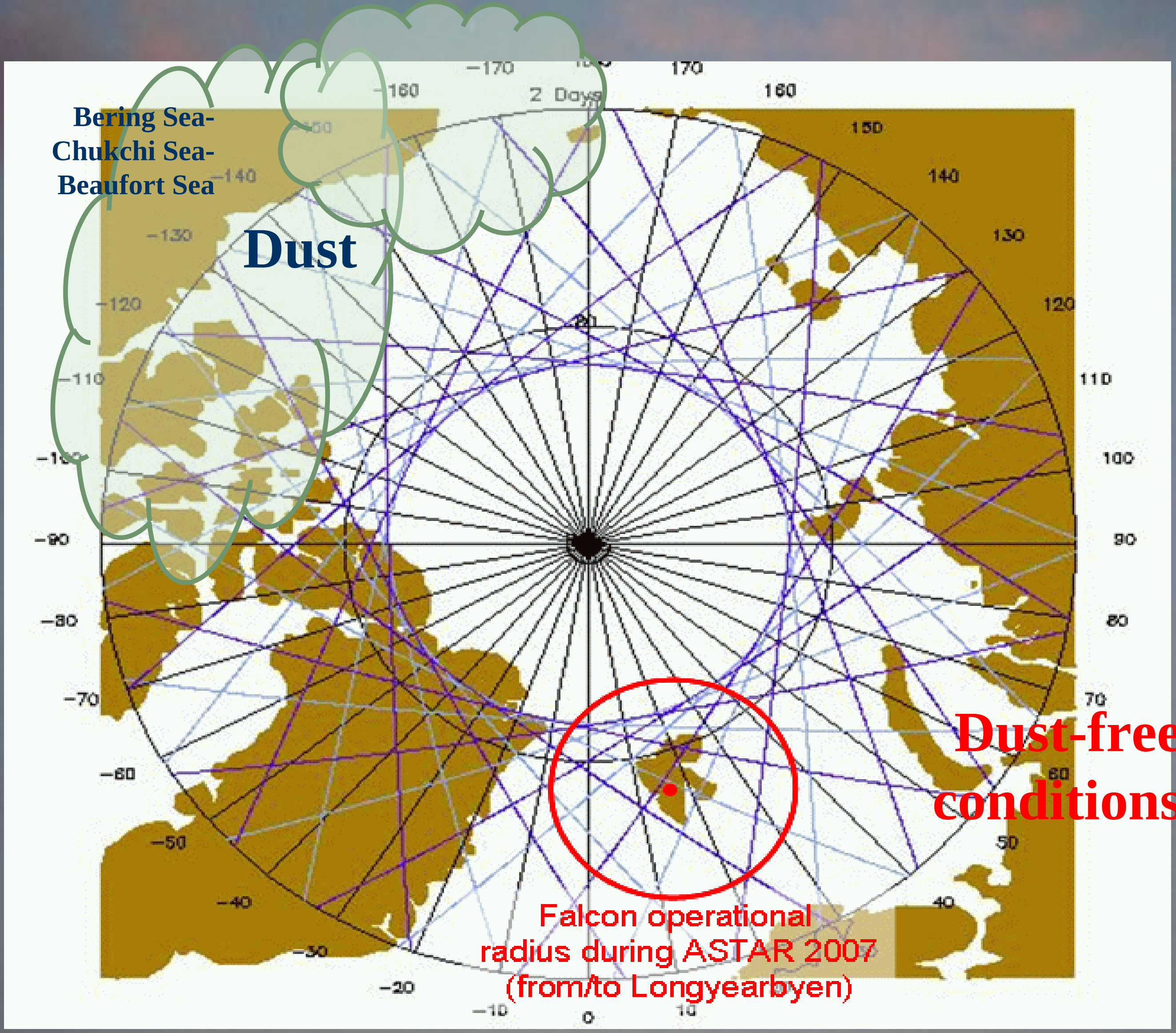
Aged dust IN ↓ => ice crystal size ↑
=> precip/dehydration => cooling tendency (Blanchet et al.)

Lubin and Vogelmann (2006, *Nature*)

CCN ↑ => Rclouds ↓ => Emissivity ↑

Enhanced aerosol amounts can make clouds emit more thermal energy to the surface…
BUT they considered only low-level , optically thin clouds and CCNs are under clouds

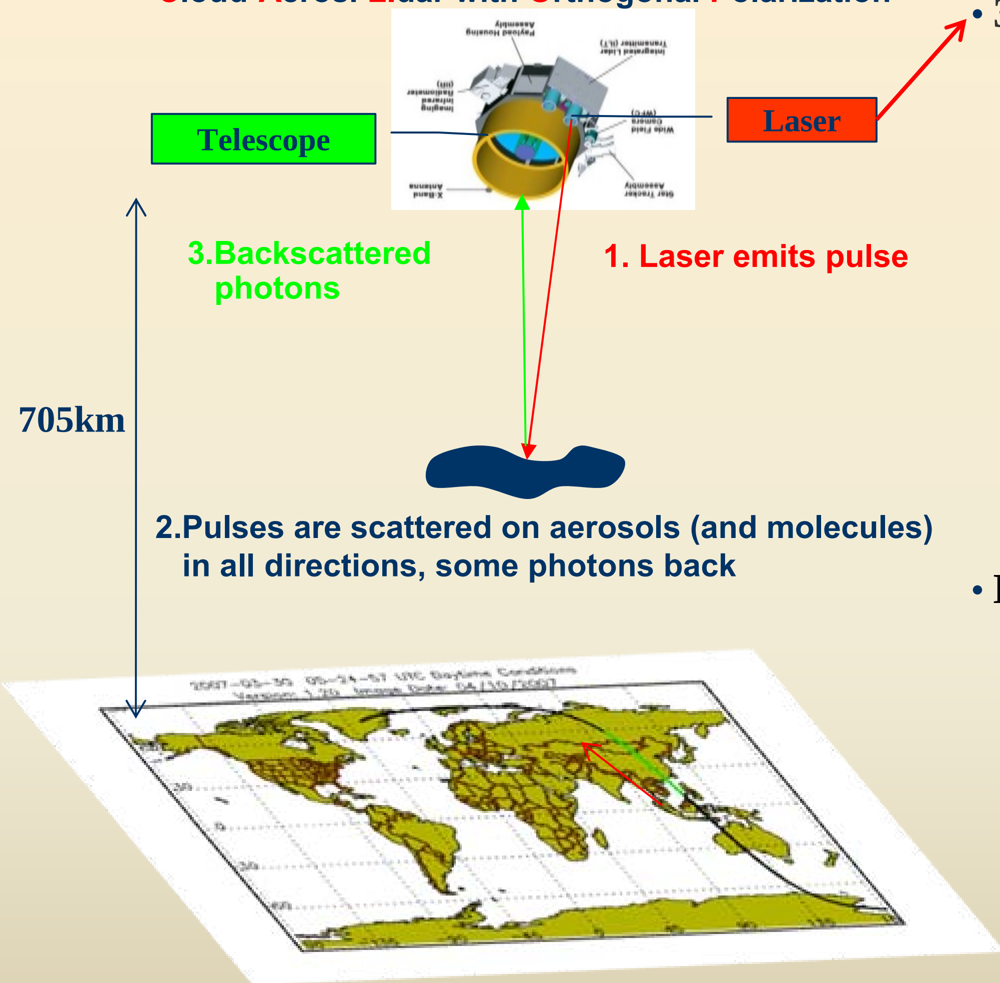
Asian dust in the Arctic (Spring 2007)



CALIOP Data Description

CALIOP(CALIPSO)

Cloud-Aerosl LIdar with Orthogonal Polarization



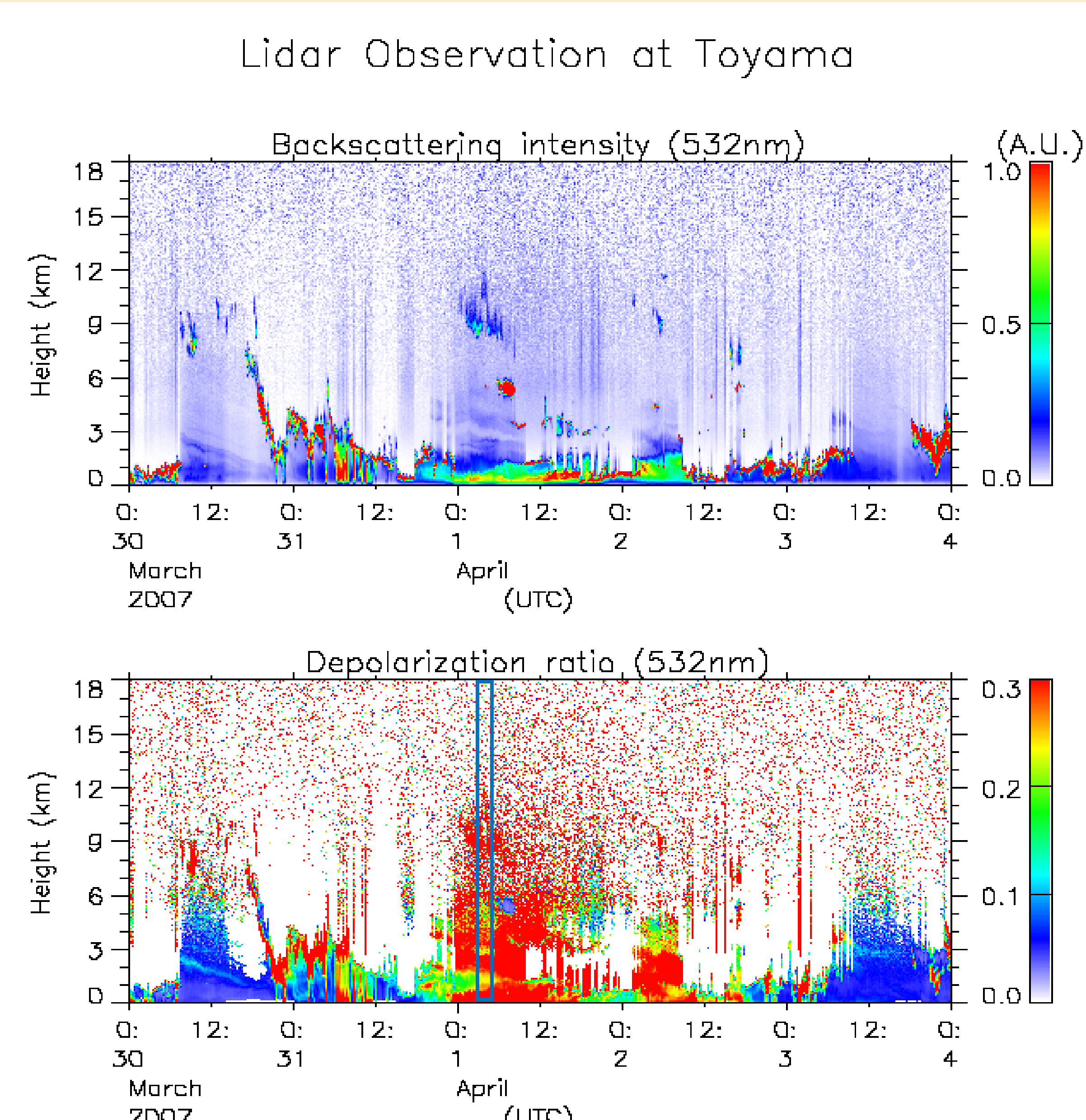
Orbit of CALIPSO

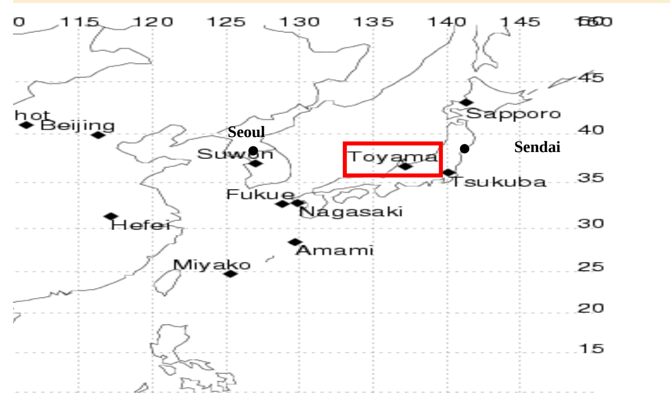
CALIOP data products used in this study

- 3-channel lidar (CALIOP)
  - 532 nm (I): $\beta_{532, I}$
    Perpendicular attenuated backscatter coefficient
  - 532 nm (II): $\beta_{532, II}$
    Parallel attenuated backscatter coefficient

  => 532 nm: $\beta_{532} = \beta_{532, I} + \beta_{532, II}$
  Total attenuated backscatter coefficient
  - 1064 nm: β_{1064}
    Attenuated backscatter coefficient
- Level 2 (Version 2 as of 1/25/2008)
  - Integrated attenuated backscatter
    $\gamma' = \int \beta(z)T^2(z)dz$
  - Vertical feature mask
  - Layer-integrated lidar volume depolarization ratio
    $\delta_v = \gamma'_{532, I} / \gamma'_{532, II}$
  - Layer-integrated attenuated backscatter coefficient
    $\chi_{layer} = \beta_{1064} / \beta_{532}$
  - Aerosol optical depth of a layer at 532 nm
    $\gamma' = 1-\exp(-2\eta\tau) / 2\eta\tau$

The ground based Lidar data in Japan at the same day





- The CALIPSO data were compared against ground-based lidar located in Japan.
- Left figures show ground-data lidar backscatter and depolarization ratio at selected locations as a function of time.
- Time corresponding to the CALIPSO overpasses is shown with blue vertical lines.
- Depolarization ratio of Ground lidar is as high as that of CALIPSO data.