Cloud properties from Remote Sensing

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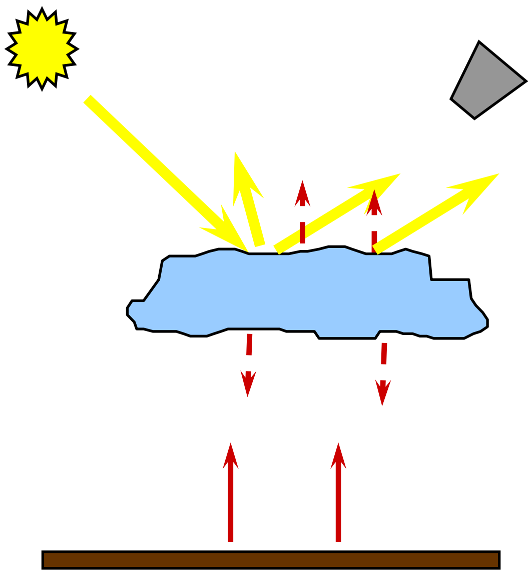
Satellite radiometers measure:



emitted, reflected, scattered

radiation

↓

INVERSION

cloud detection
inverse radiative transfer

↓

cloud properties

GEO (3hrs)*+polar*

ISCCP

IR,VIS

polar satellites (12/6 hrs)

PATMOS-x

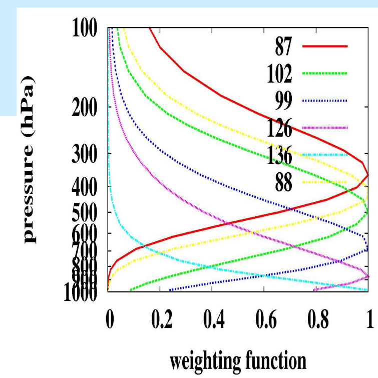
IR,NIR,VIS

HIRS-NOAA, **TOVS Path-B**

IR Vertical Sounder: CO_2-band

MODIS

AIRS



Longterm cloud climatologies:

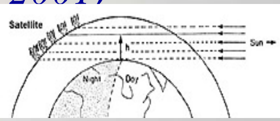
ISCCP ***GEWEX cloud dataset*** ***1983-2006*** *(Rossow et al. 1999)*

PATMOS-x ***AVHRR*** ***1981-2006*** *(NESDIS/ORA; Heidinger)*

HIRS-NOAA ***13h30/1h30*** ***1985-2001*** *(Wylie et al. 2005)*

TOVS Path-B ***7h30/19h30*** ***1987-1995*** *(Stubenrauch et al. 2006)*

SAGE ***limb solar occultation*** ***1984-1991,1993-2005*** *(Wang et al. 1996, 2001)*



SOBS (Surface Observations): ***1952-1996(sea), 1971-1996(land)*** *(Hahn & Warren 1999; 2003)*

EOS cloud climatologies *(since 2000, 2002)*:

MODIS-ST *(Ackerman et al.)* **MODIS-CE** *(Minnis et al.)*

AIRS-LMD *(Stubenrauch et al. 2008)*

+ A-Train *(since 2006)*:

CALIPSO L2 data (V2) *(Winker et al. 2007)* ***active lidar***

Global Energy and Water Cycle Experiment GEWEX WCRP

Cloud Assessment

co-chairs:
C. Stubenrauch, S. Kinne

http://climserv.ipsl.polytechnique.fr/gewexca

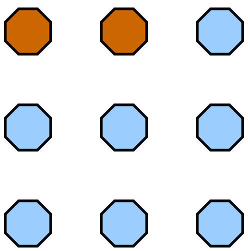
ISCCP

International Satellite Cloud Climatology Project

Cloud detection

IR spatial and temporal variability

➡ VIS, IR composite clear sky statistics



relative threshold tests

Cloud property retrieval

TOVS T profiles

R^{IR} → T_{cld}^{IR} → p_{cld}

R^{VIS} → τ → T_{cld}

radiative transfer

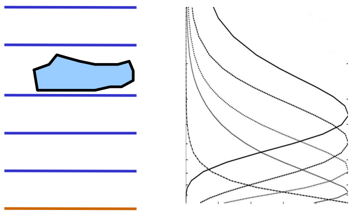
cloud microphysics

for $\tau < 11$

IR Sounders: TOVS, AIRS, IASI

>1980 NOAA,>2002 NASA,>2006 CNES

$I_m(\lambda_i)$ along H_2O, CO_2 absorption bands, ***good spectral resolution***



Inversion

(Chédin, Scott 1985; Scott et al. 1999)

- atmospheric temperature & water vapor profiles, Tsurf

$$\chi_w^2(p_k) = \sum_{i=1}^{N} \left[(I_{cld}(p_k,\lambda_i) - I_{clr}(\lambda_i)) \cdot \varepsilon_{cld}(p_k) - (I_m(\lambda_i) - I_{clr}(\lambda_i)) \right]^2 * W^2(p_k,\lambda_i)$$

min weighted $\chi_w^2(p_k)$

W: uncertainties in T profiles on I_{cld}-I_{cld}

- eff. cloud emissivity, cloud pressure *(Stubenrauch et al. 1999, 2008)*

- D_e, IWP of semi-transparent cirrus *(EU project CIRAMOSA 2001-2004)*

controlled use of a priori information: radiosondes – 4A radiative transfer

TIGR dataset: $T(p_k)$, $H_2O(p_k)$, T_s - $I_{clr}(\lambda_i)$, $I_{cld}(\lambda_i,p_k)$

Thermodynamic Initial Guess Retrieval

ISCCP *(Rossow & Schiffer BAMS, 1999)*

Evaluation

night: +75 hPa p_{cld} bias *(Stubenrauch et al. 1999)*

uncertainties depend on cloud type:

- ***Stratus (τ_{cld}>5):*** p_{cld} 25-50 hPa within radiosonde meas., ~ -65 hPa bias; err T_{cld}<1.5 K
- ***high clouds (τ_{cld}>5, with diffuse top):*** p_{cld} 150 hPa (trp)/ 50 hPa (midl) above top
- ***isolated thin Cirrus:*** difficult to detect
- ***thin Cirrus above low clouds:*** often identified as midlevel or lowlevel cloud

15% τ_{cld} decrease for doubling droplet size

TOVS Path-B *(Stubenrauch et al. J. Clim. 2006)*

p_{cld} uncertainty 25 hPa over ocean, 40 hPa over land (2nd χ^2 solution)

p_{cld} = mid-cloud p_{cld},: 600m/ 2 km below cloud-top (low/high clouds) (LITE, *Stubenrauch et al. 2005*)

Sensitivity study for D_e of Ci *(Rädel et al. 2003)*

HIRS-NOAA *(Wylie & Menzel J. Clim. 1999, Wylie et al. J. Clim. 2005)*

p_{cld} 70 hPa above top (lidar, *Wylie & Menzel 1989*)

100 hPa above for transmissive cloud overlying opaque cloud *(Menzel et al. 1992)*

ISCCP - TOVS comparison

agreement for homogeneous scenes

(collocated data)

Stubenrauch et al. J. Clim. 1999

remaining discrepancies:

- **Atmospheric temperature profiles**

  (1 operational TOVS profile per day - retrieved or TIGR)

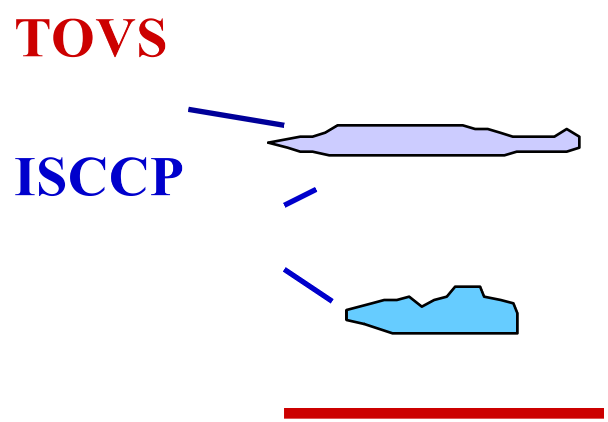
  -> mid - lowlevel misidentification

- **Small scale heterogeneities**

- **horizontal:** **vertical:**

partly cloudy **multi-layer clouds**

-> cirrus misidentification



TOVS good IR spectral resolution -> properties of uppermost cloud

High clouds not observed by radiometers

SAGE II: *1984 – 1991,* **SAGE III:** *since 2002*
Limb occultation sunrise / sunset at 1 μm, 0.5 μm, (7 / 11 λ's)
Path: 200km (x 2.5 km)

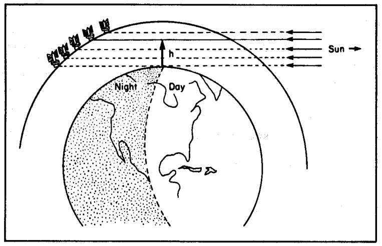


Fig. 1. ERBS/SAGE II solar occultation.

L (km)	High cloud amount (%) *January / July*
200	74.6 / 69.0
75	32.1 / 29.7

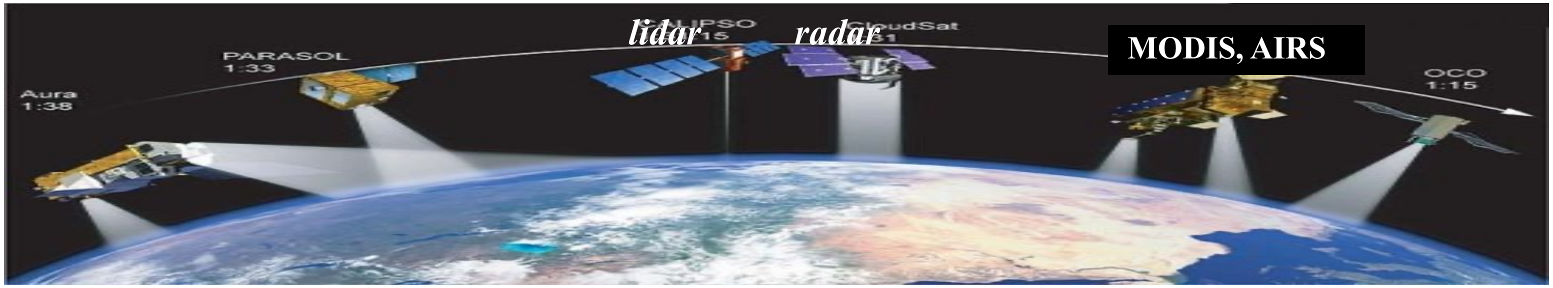
ISCCP-SAGE => L=75 km *(Liao et al.1995)*
HIRS-SAGE => L=130 km *(Wylie + Wang 1997)*

	subvisible Ci *January / July*	Cirrus *January / July*
200	24.4 / 22.5	50.2 / 46.5
75	10.5 / 9.3	21.6 / 20.4

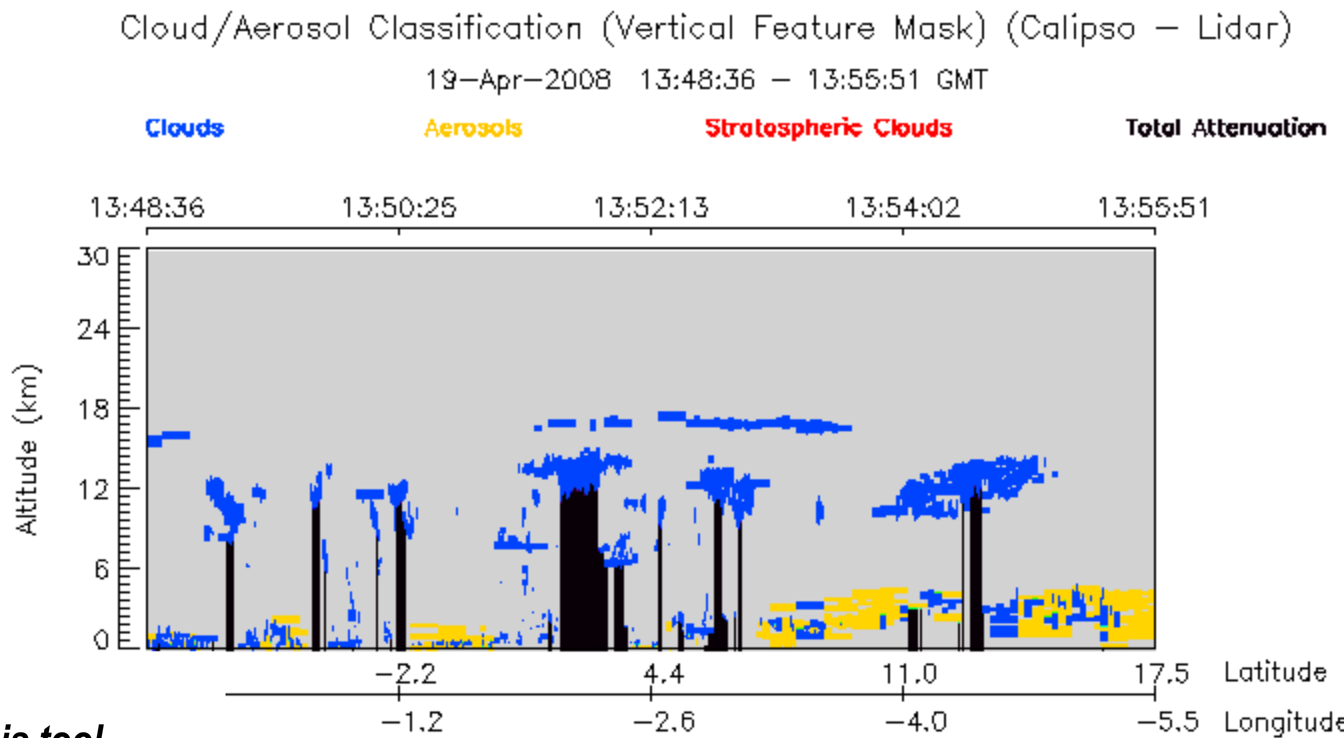
1/3 of high clouds: subvisible Ci
(not observed by radiometers)

$CA_{high}^{SAGE} > CA_{high}^{TOVS} > CA_{high}^{ISCCP}$

A-Train: synergy of passive and active instruments



active instruments -> vertical structure of clouds
lidar sensitive to very thin cirrus



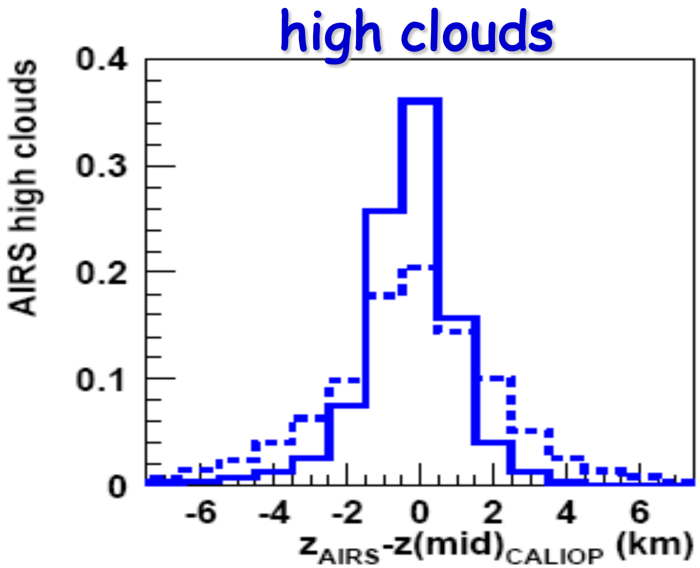
NASA Giovanni:
online data visualization & analysis tool

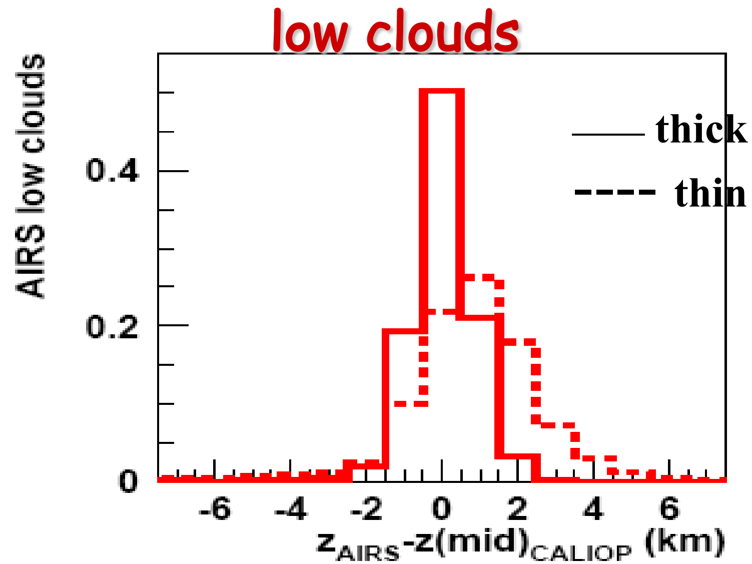
http://disc.sci.gsfc.nasa.gov/techlab/giovanni

Evaluation of AIRS-LMD cloud height with 1 year collocated CALIPSO data

retrieval based on weighted χ^2 method as in TOVS-B

Stubenrauch et al., JGR 2008





good agreement with CALIPSO midlevel of cloud *(highest with τ>0.1)*
slightly broader distributions for optically thinner clouds, but no bias
sampling: *(5 km x 0.07 km) in (13.5 km x 13.5 km)*

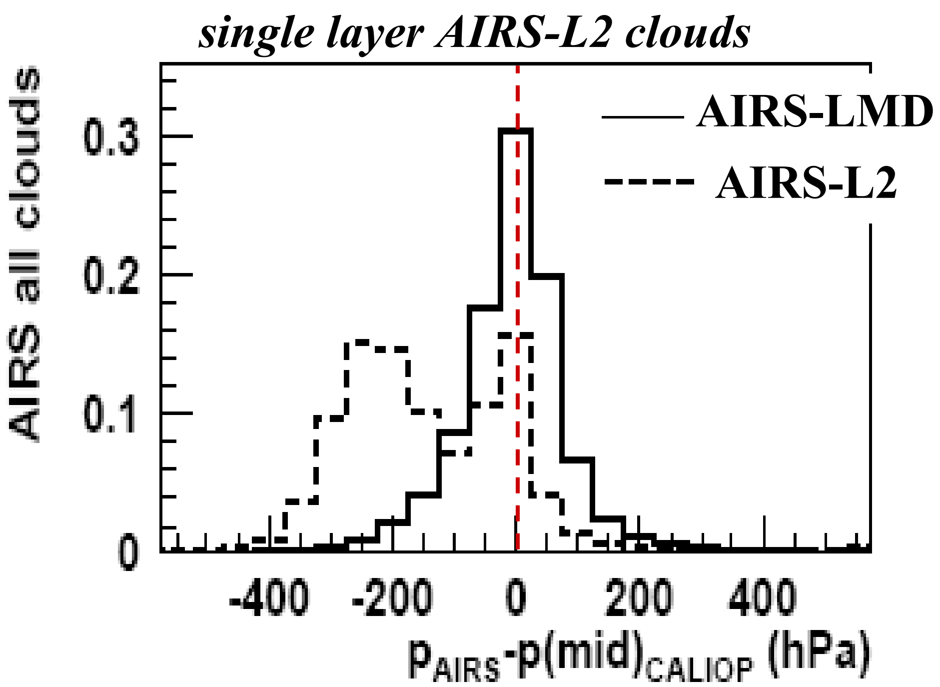
Δz_{mid}(AIRS-CALIPSO) ± 1.5 km:

High: 51% 55% 66%
Low: 70% 74% 80%
hghst / hghst w τ>0.1 / closest layer

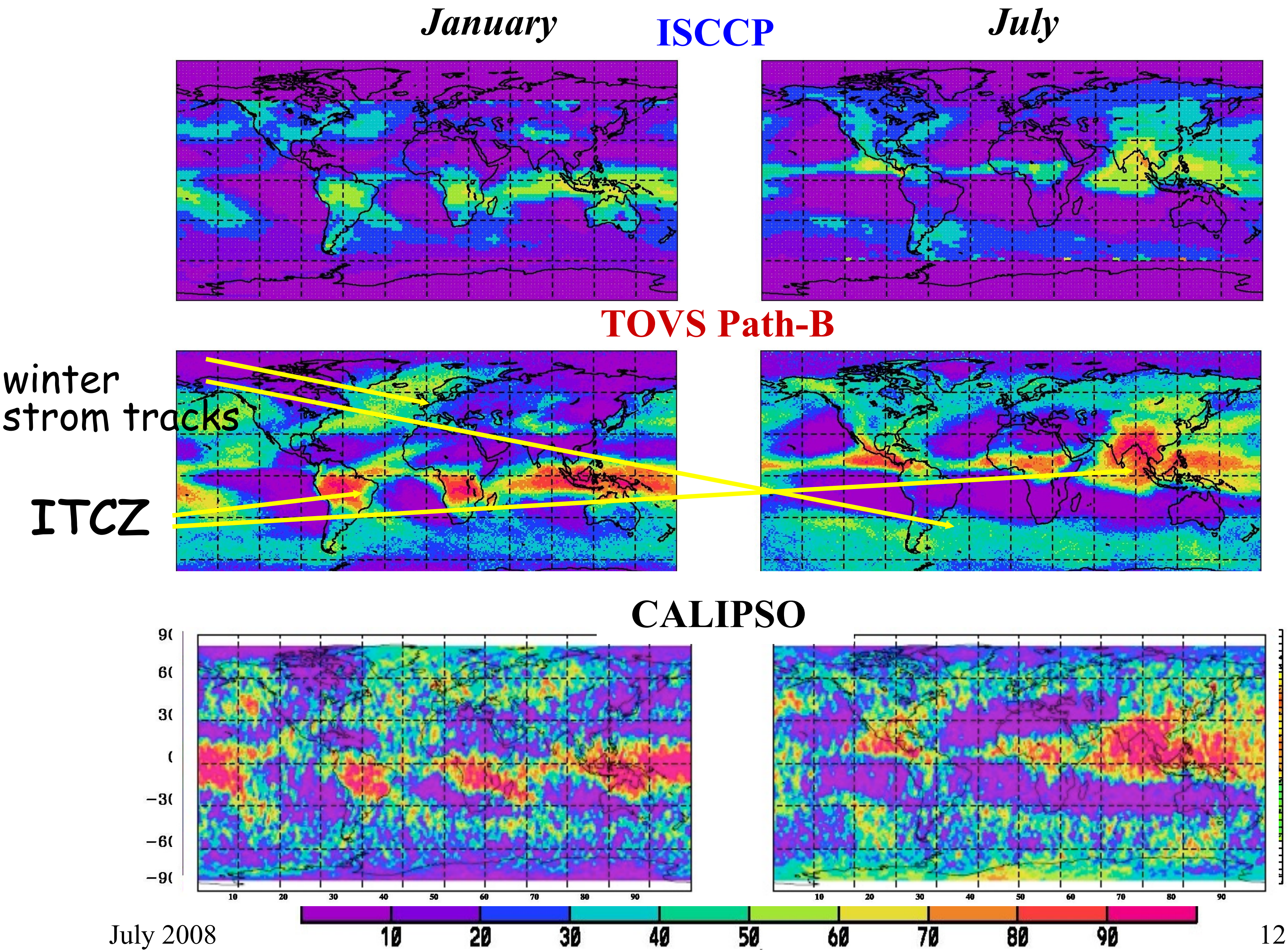
Δp_{mid}(AIRS-CALIPSO) ± 75 hPa:

High: 72% 81% (thick); 63% (thin)
Low: 59% 69% ; 38%

Cloud properties depend also on retrieval method!



HCA geographical distributions



Average CA

ISCCPday(84-04) TOVS-B, TOVS rean(87-95) HIRS-NOAA(85-01) SAGE(85-99) CALIPSO(06-07) PATMOS-x(81-06) MODIS-CE(03-05) MODIS-ST(02-06) ISCCP-IR(84-04) SOBS(84-04)

CA (%)	glo bal										
all	66	73	70	75	95	76	66	61	67	61	64
Thick Ci	3	2	1	2							
Cirrus	19	27	31	31							
HCA/ CA	33	41	45	44	44	50	38	42	30	21	23
MCA / CA	27	16	14	16	20	14	19	16	19	33	44
LCA / CA	39	42	37	37	36	35	44	44	52	46	72

CA (%)	oce an										
all	70	74	74	77	95	84	72	66	73	65	69
Thick Ci	3	2	1	1							
Cirrus	18	27	31	33							
HCA/ CA	30	39	42	44	44	46	35	37	27	18	17
MCA / CA	26	14	12	14	18	12	17	14	15	29	42
LCA / CA	41	47	42	42	38	42	49	51	59	52	80

CA (%)	la nd										
all	58	69	61	70	97	63	50	50	59	51	54
Thick Ci	3	4	2	5							
Cirrus	21	27	30	29							
HCA/ CA	41	45	53	49	45	61	47	56	37	29	43
MCA / CA	31	25	20	17	25	20	25	20	29	43	48
LCA / CA	29	30	23	34	29	19	29	26	34	27	48

diurnal sampling, time period for ISCCP / TOVS-B: 1% effect; low-level over land: 2% (Stubenrauch et al. 2006)

~ 70 % (±5%) cloud amount: 5-15% ***more over ocean than over land***

PATMOS, MODIS-CE low (land), SAGE CA (200km, clds τ>0.03) **1/3 higher**

40% single-layer low clouds: ***more over ocean than over land; SOBS***

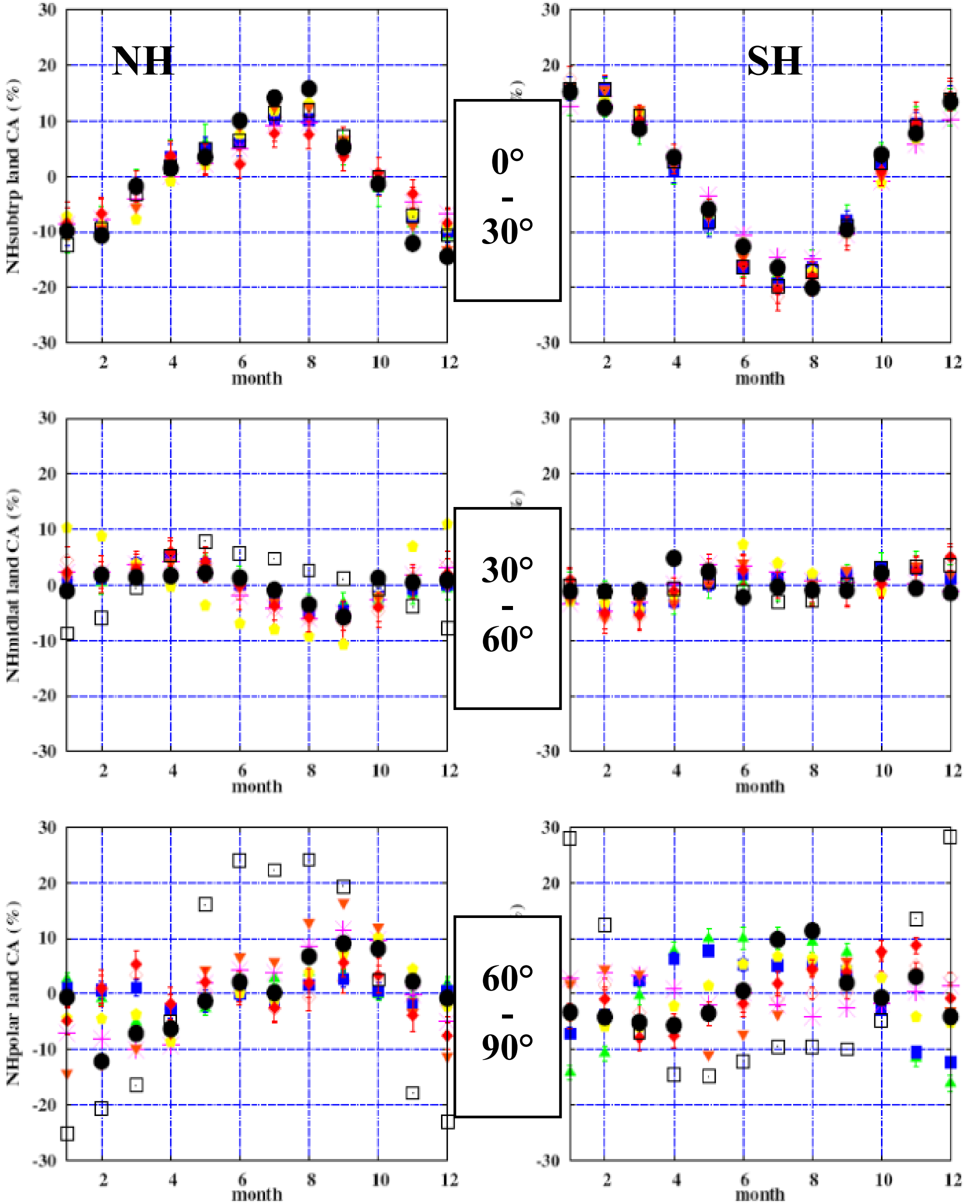
40% high clouds: ***only 3% thick Ci; more over land than over ocean***

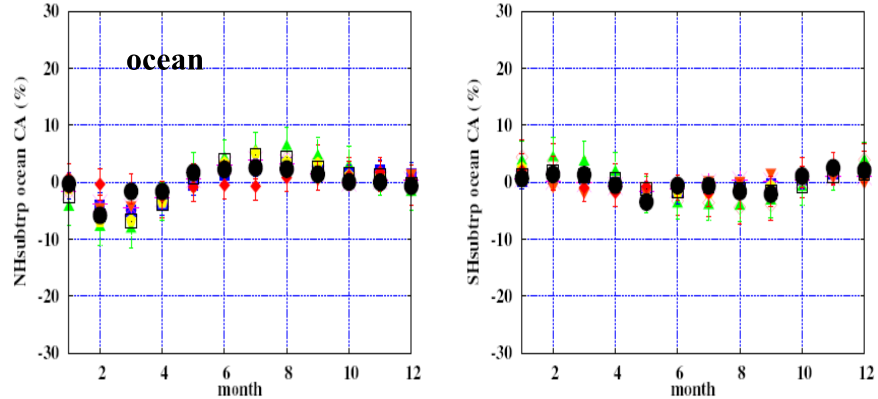
IR sounders ~ 10% more sensitive to Ci than ISCCP (15% in trps)

SAGE cloud vertical structure in good agreement with IR sounders

HCA/CA:CALIPSO>SAGE,TOVS/HIRS > MODIS-CE > PATMOS > $ISCCP_{day}$> MODIS > $ISCCP_{IR}$

CA seasonal cycle over land





Seasonal (& diurnal) cycles:

- ❑ **stronger over land than over ocean**
- ❑ **strongest in subtropics (20% - 40%)**

Seasonal cycles very similar

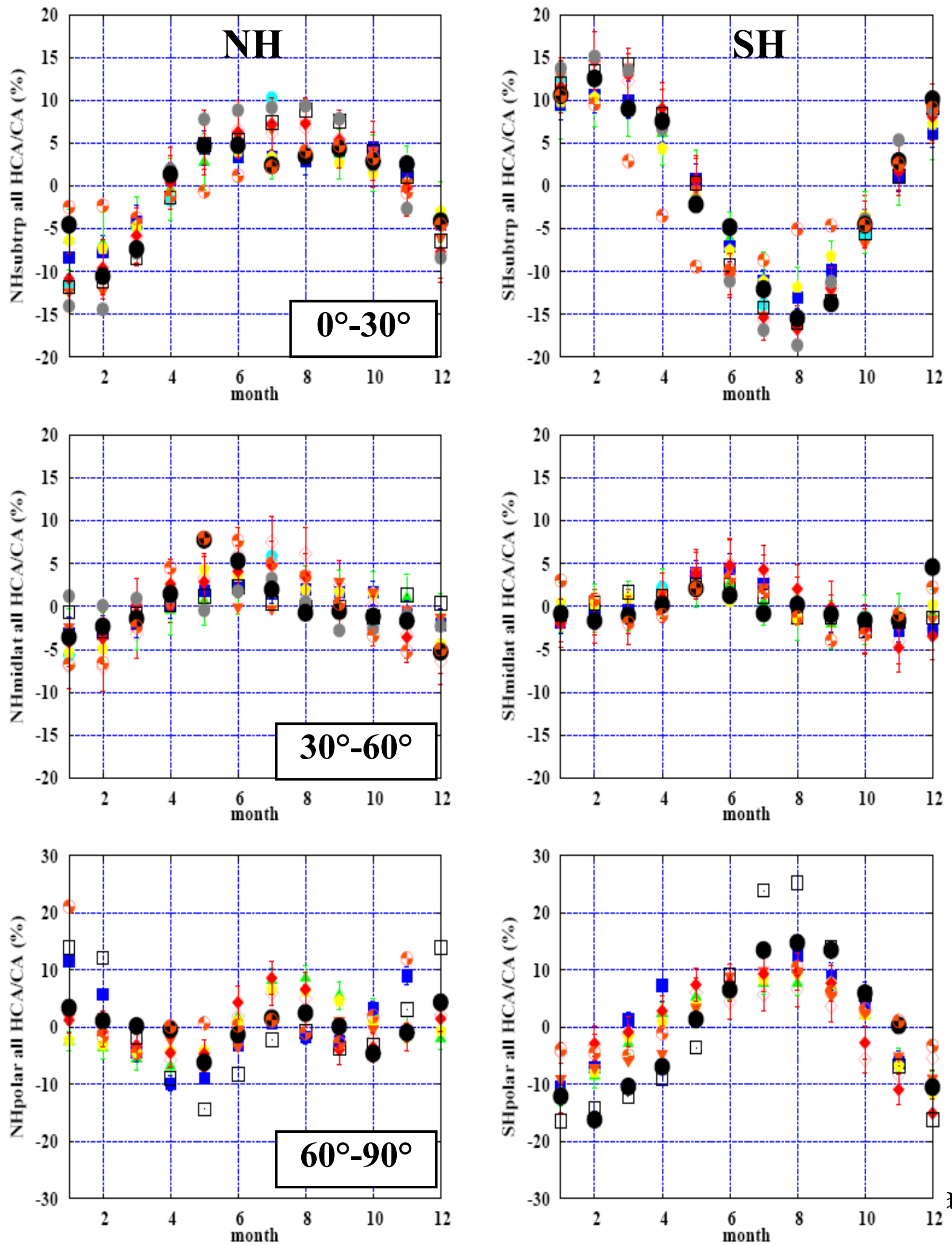
exception: *SH polar land*

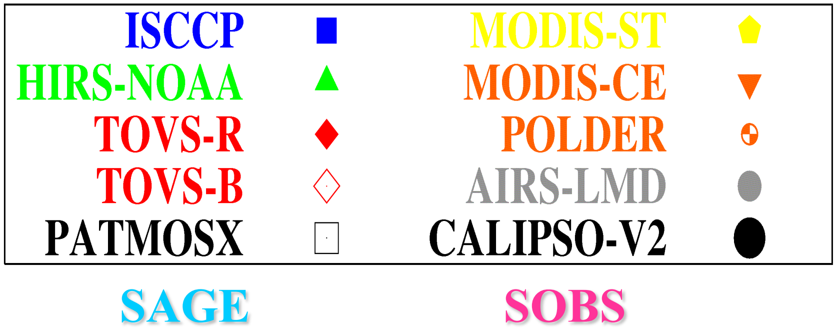
& newer datasets (PATMOS, MODIS-ST)

ISCCP	■	MODIS-ST	⬟
HIRS-NOAA	▲	MODIS-CE	▼
TOVS-R	◆	POLDER	⊕
TOVS-B	◇	AIRS-LMD	●
PATMOSX	□	CALIPSO-V2	●

SAGE SOBS

HCA/CA seasonal cycle



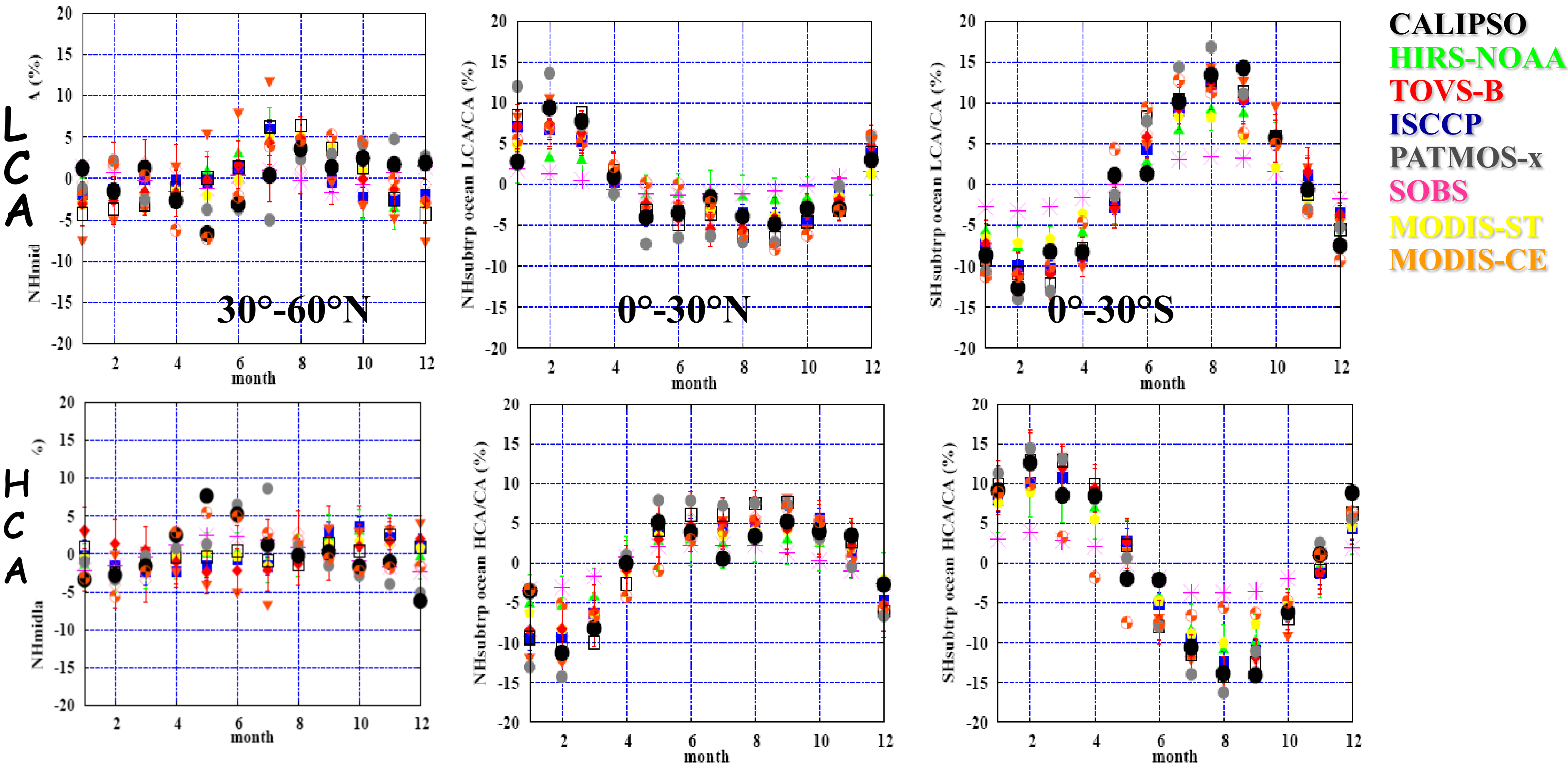


Seasonal cycles similar:

25% in SH tropics to 5% in SH midlatitudes

again stronger over land than over ocean

LCA/CA seasonal cycle over ocean

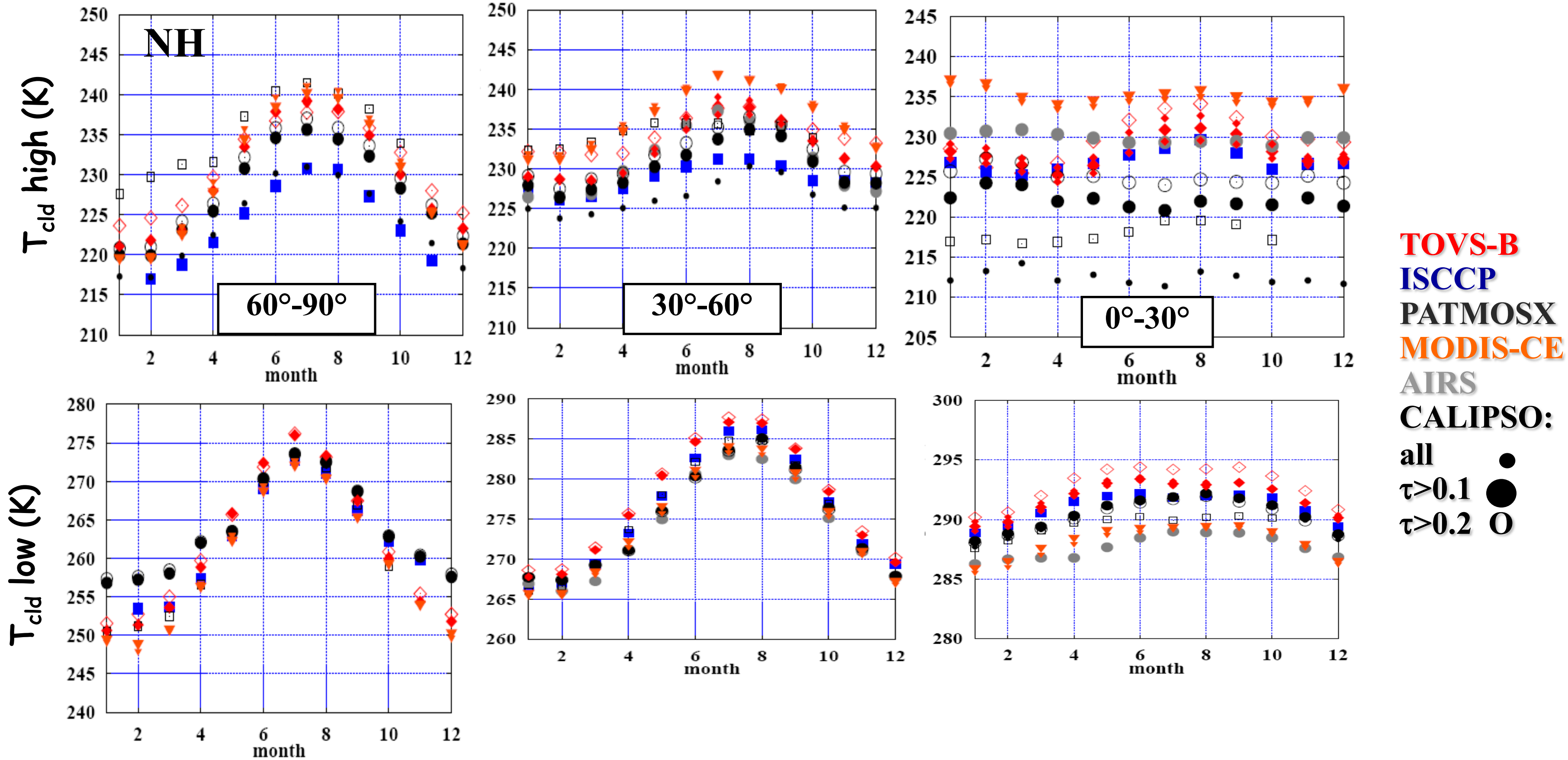


small seasonal cycle; exception: SH subtropics stratocumulus regions (20%)

SOBS: 18% more LCA and smaller seas. cycle over ocean

=> LCA seas. cycle from satellite modulated by HCA & MCA seas. cycle

cloud temperature of high and low clouds



Seasonal cycle of high T_{cld} decreases from polar (15°), midlat (10°) to tropics (5°)
low T_{cld} (20°) (20°) (5°)

CALIPSO: thin high clouds colder than thicker high clouds (τ>0.1), esp. in tropics

differences : largest for high clouds in tropics, very good agreement for low clouds

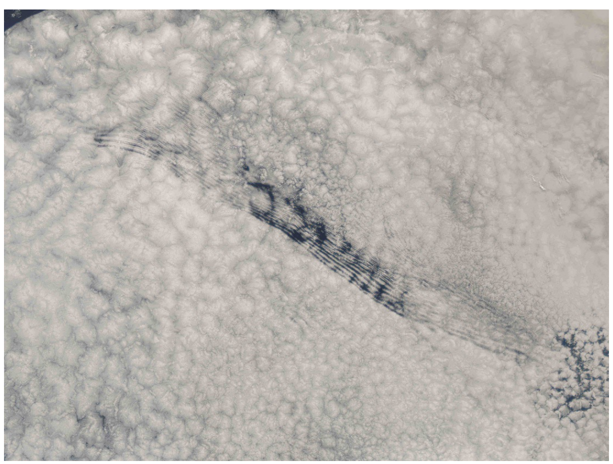
uncertainties in cloud height determination (esp. thin cirrus), T profiles

Solar heating & cloud formation

warm air rises, expands, cools ➡ ***condensation***

cumulus:

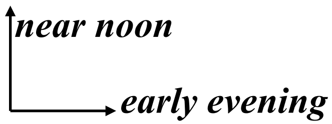
form in unstable atmosphere [large lapse rate (~11°C/km)]
(warming of the Earth's surface or cooling of air aloft)
summer afternoon*, tropics*



Source: NASA Visible Earth

stratus:

form in stable atmosphere [small lapse rate (~4°C/km)]
(cooling of the Earth's surface or warming of air aloft)
early morning*, subsidence*



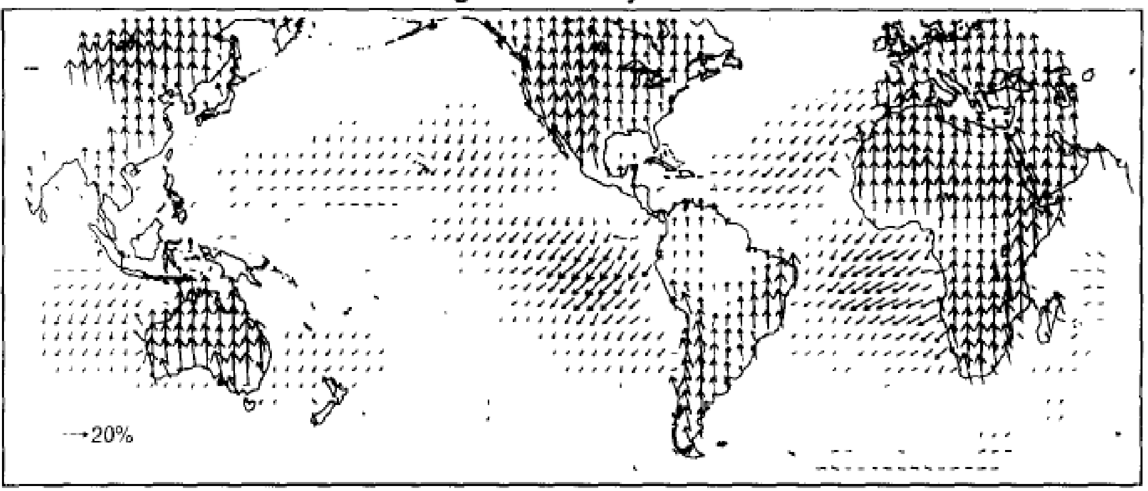
diurnal cycle of clouds

Cairns, Atm. Res. 1995

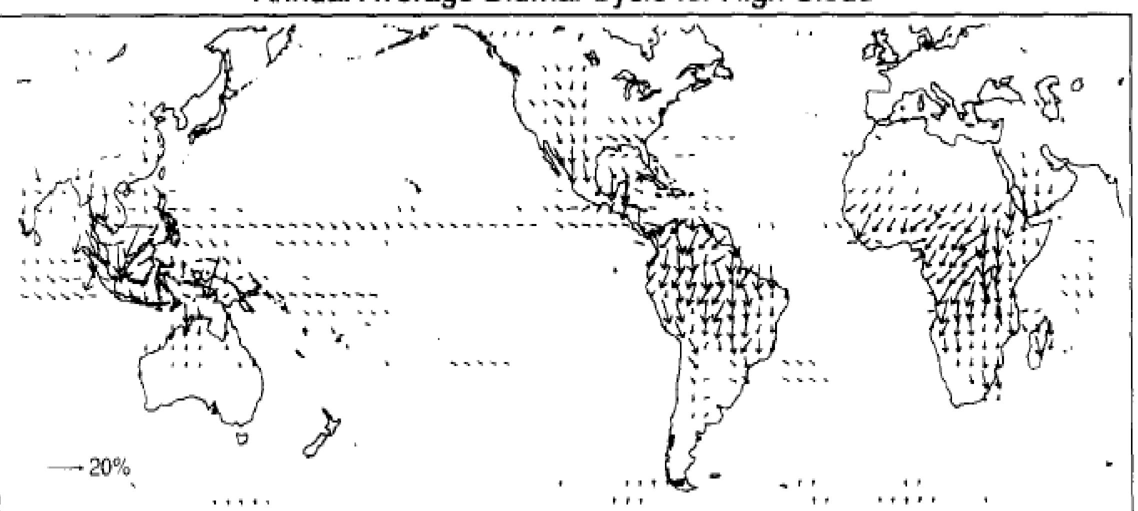
ISCCP C2, Complex Empirical Orthogonal Functions,

project. on distorted diurnal harmonics

Annual Average Diurnal Cycle for Low Cloud



Annual Average Diurnal Cycle for High Cloud



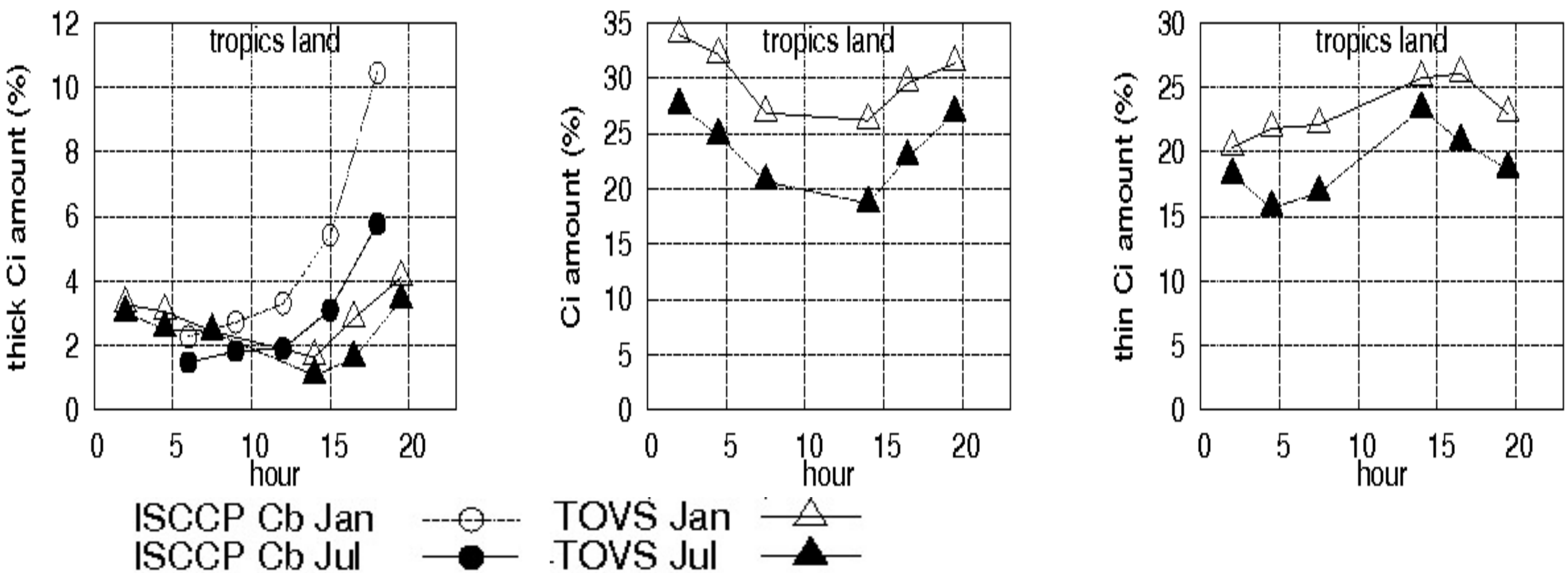
- **Low clouds over land:** significant diurnal cycle, *max early afternoon*
- **Low clouds over ocean:** *max in early morning*
- **High clouds:** *max in evening*
- **Mid clouds:** *max in early morning or late at night (cirrus -> TOVS)*

TOVS-B diurnal cycle of high clouds

Stubenrauch et al. J. Climate 2006

NOAA10/12 7h30 AM&PM, NOAA11 2h00 AM&PM(1989-90) NOAA11 4h30 AM&PM(1994-95)

strongest diurnal cycles over land, in tropics (& in midlat summer)



- max Cb (ISCCP) in early evening
- max. thick (large-scale) cirrus & cirrus in evening
- cirrus occurrence continues during night & decreases during day
- max. thin cirrus in early afternoon

Longterm dataset

-> explore rare events

Rossow & Pearl GRL 2007

tropical convection penetrating into the lower stratosphere

cluster analysis if ISCCP DX data

occurrence predominantly
in larger, organized mesoscale convective systems

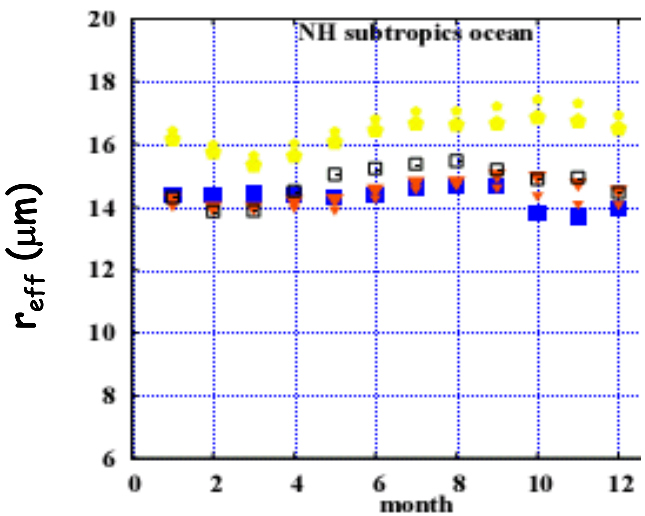
water cloud effective droplet radius

ISCCP: AVHRR NIR-VIS

Han, Rossow & Lacis J. Clim. 1994, Han et al. 1998

cloud properties	global	ocean	land
r_e [μm]	11.4	11.8	8.5
τ	7.0	6.9	8.1
LWP [gm^{-2}]	87.1	87.4	85.4

r_e slightly larger over land than over ocean



ISCCP
PATMOSX
MODIS-CE
MODIS-ST

preliminary

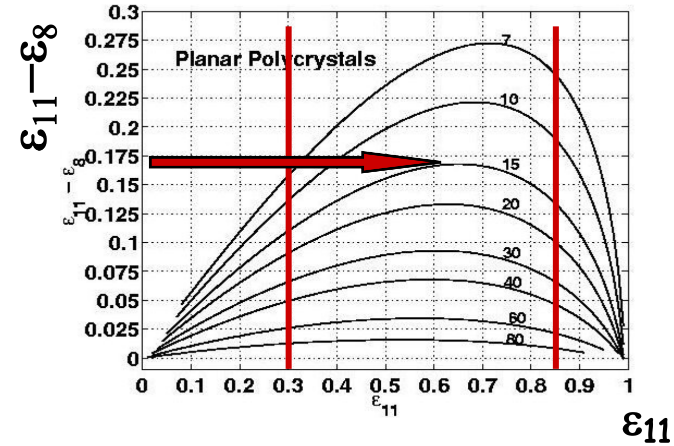
good agreement between ISCCP, PATMOSX, MODIS-CE

MODIS-ST:
2.1 μm instead of 3.7 μm

effective ice crystal diameter

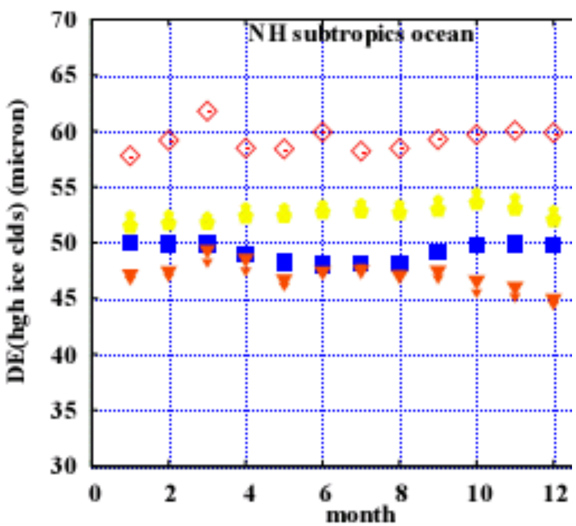
semi-transparent cirrus **TOVS Path-B, 87-91**

cloud properties	60N-60S	ocean	land
D_e [µm]	55.3	54.7	56.8
ε	0.59	0.58	0.60
IWP [gm^{-2}]	30	30	31



Rädel et al. JGR 2003

D_e similar over land & ocean



ISCCP
TOVS-B
MODIS-CE
MODIS-ST

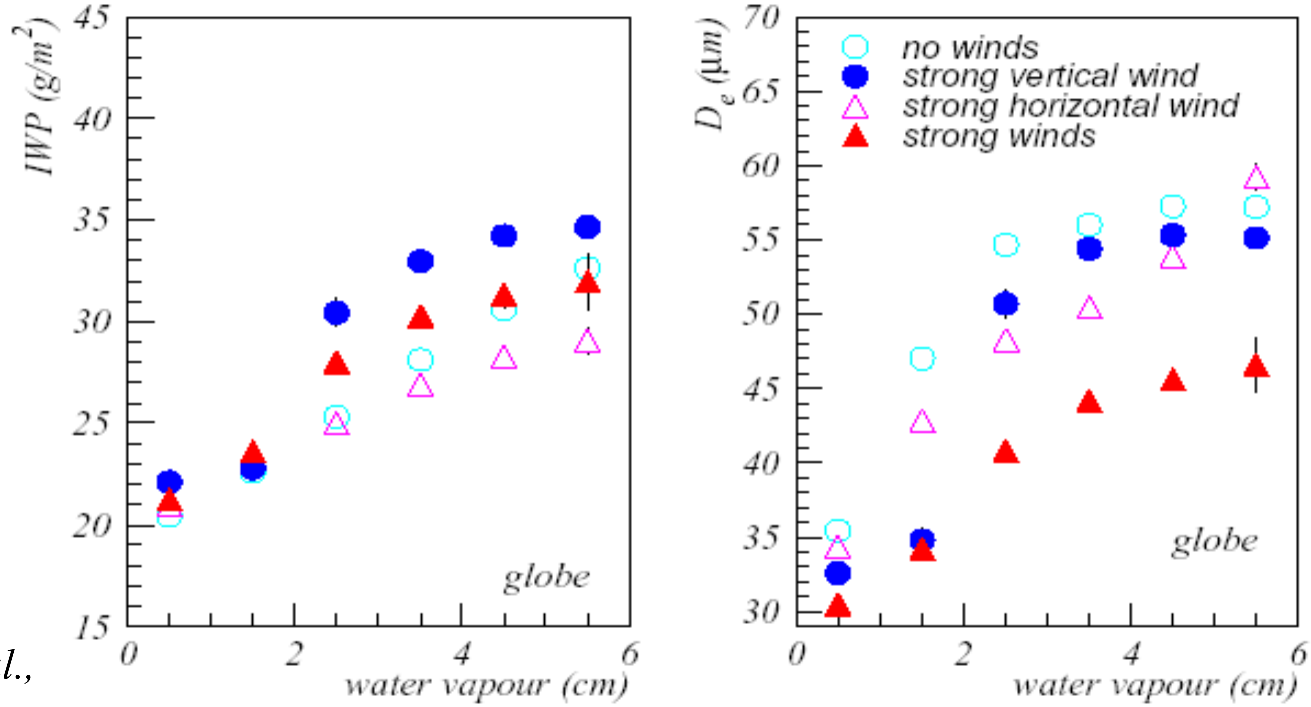
preliminary

NIR-VIS:
D_e near cloud top

IR:
D_e averaged over cloud depth

D_e & IWP as function of humidity & wind

Large-scale semi-transparent cirrus 60°N – 60°S, 4 year averages



Stubenrauch et al., Atm. Res.2004

TOVS -ERA40

IWP and D_e increase with atmospheric water vapour

IWP largest in case of strong large-scale vertical updraft

D_e smallest in case of strong large-scale hor. & vert. winds

Synergy of retrieved cloud properties & model :

Cirrus radiative flux analysis

eliminate
multi-layer
clouds

TOVS
atmospheric profiles
cirrus properties

D_e=10-90 μm; D_e=f(IWP),= f(T)

radiative transfer model:

♦ p_{cld} = p(mid-cloud) Δp = 100 hPa(≈ 2 km)

♦ *Single scattering properties (SSPs) = f(λ, D_e)*
for hex. columns, aggregates

♦ choose IWP with $\varepsilon(IWP,D_e) \approx \varepsilon_{cld}^{IR}$
look-up tables $\varepsilon_{cld}^{IR}(IWP,D_e)$*,depending on* θ_v, Δz, *SSPs*

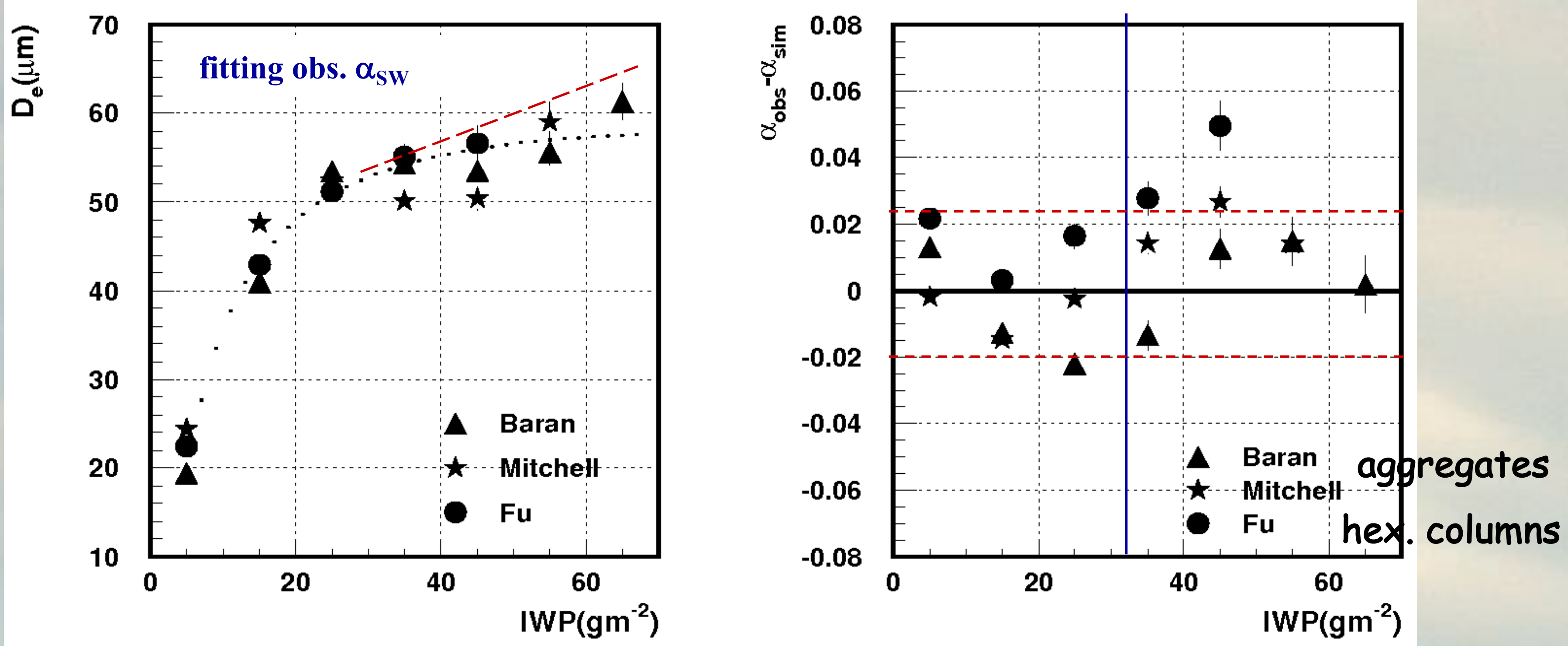
ADMs

1500 ScaRaB fluxes ⟷ **simulated fluxes**

$$\alpha^{SW}(\theta_0) = \frac{\pi L^{SW}}{R(\theta_0,\theta_v,\phi,\tau,phase,het)\,E_0\cos\theta_0}$$

Coherence between IR IWP and SW albedo

Stubenrauch et al. J. Clim. 2007



best fit to data:
increase of D_e with IWP

columns only fit data at small IWP,
aggregates at larger IWP

effect on TOA SW flux : ~2 Wm^{-2}

Satellite observations:

❖ unique possibility to study cloud properties over long period
-> climatological values of CA, HCA, MCA & LCA
(also variabilities, T_{cld}, ε, τ, D_{eff}, WP) to help evaluate climate models

❖70% (±5%) clouds: ~ 40% high clouds & ~40% single-layer low clouds

❖**in general geographical cloud structures agree quite well:**
max of high clouds in ITCZ (up to 60%),
few single-layer midlevel clouds in tropics (5%), most in NH midlat winter (15%)
low clouds over ocean: seasonal cycle in Stratocum regions in good agreement
❖Seasonal cycle of LCA from SOBS smaller and abs value 20% higher
-> multilevel clouds

❖**CALIPSO L2 analysis confirms:**
IR sounders are the passive instruments most sensitive to cirrus
They only miss 10%/5% subvisible cirrus in tropics/midlat
(These are caught by limbsounding SAGE & active CALIPSO)

ISCCP miss 15%/10% in tropics/midlat compared to IR sounder, (included in MCA)

PATMOS, MODIS still in validation process, but will miss more thin Ci than TOVS/HIRS, AIRS, IASI

- ISCCP only dataset which resolves diurnal cycle

  (drift of NOAA afternoon satellites -> TOVS)

- advantage of longterm dataset: exploration of rare events

- droplet size smaller over land than over ocean

- ice crystal size slightly larger from IR than from NIR-VIS

- synergy of different variables & data sets important

- CALIPSO-CLOUDSAT to determine vertical structure of clouds & help to evaluate other cloud properties

- evaluation continues & WMO report in preparation

  (lastt meeting 21-23 July in New York)

Sensitivity study

Rädel et al. JGR 2003

Overestimation of D_e:

- thin Ci with underlying water cloud
- partial cover of thick Ci
- hexagonal columns instead of polycrystals

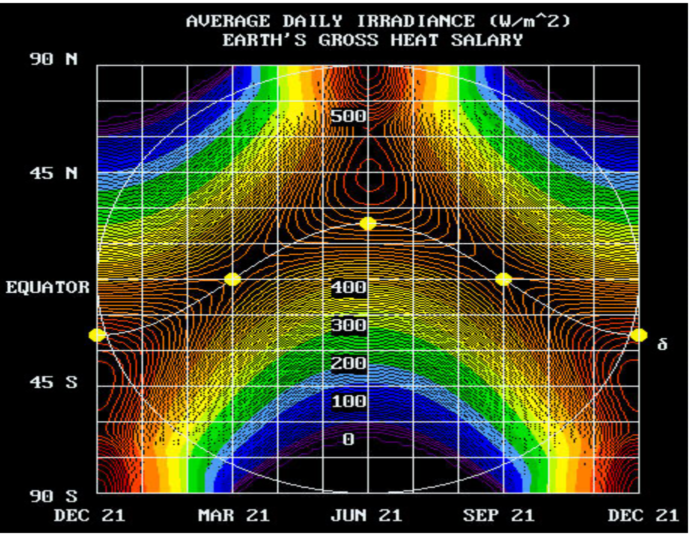
Underestimation of D_e:

- increasing D_e with cloud depth
- broader size distribution

sun / atmospheric circulation

geographical cloud distributions

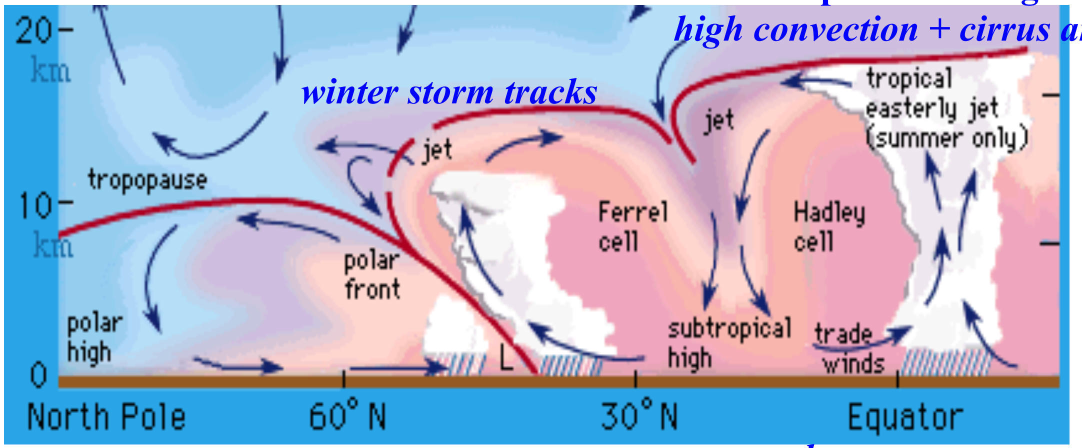
av. daily irradiance (Wm^{-2})



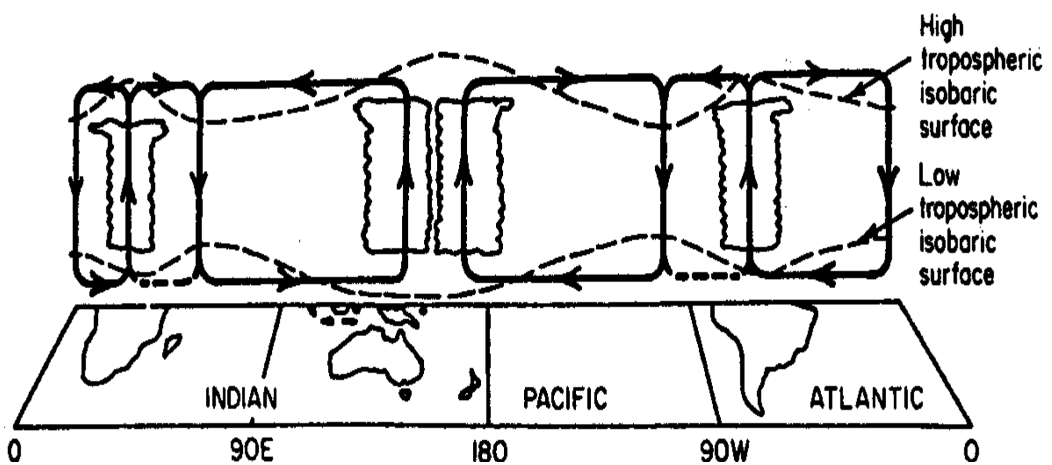
www.sci.ccny.cuny.edu/~stan/e31_sunl.ppt#10

Earth axial tilt (obliquity) -> seasons

InterTropical Convergence Zone:
high convection + cirrus anvils

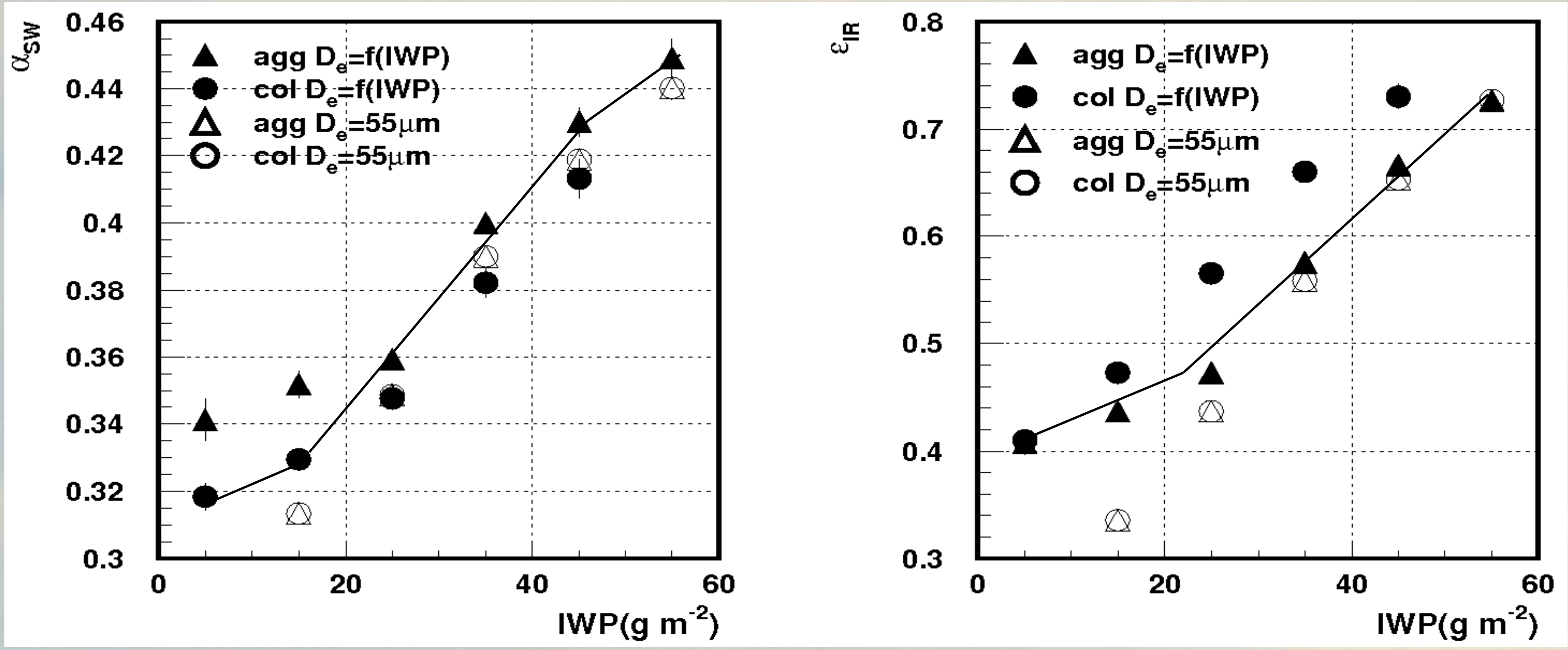


stratocumulus



Schematic view of the east-west Walker circulation along the equator *(from Webster 1987)*

Cirrus SW albedo & IR emissivity as fct of IWP



Aggregates reflect more solar & keep less therm. rad. than pristine crystals!

best fit to data (●▲):

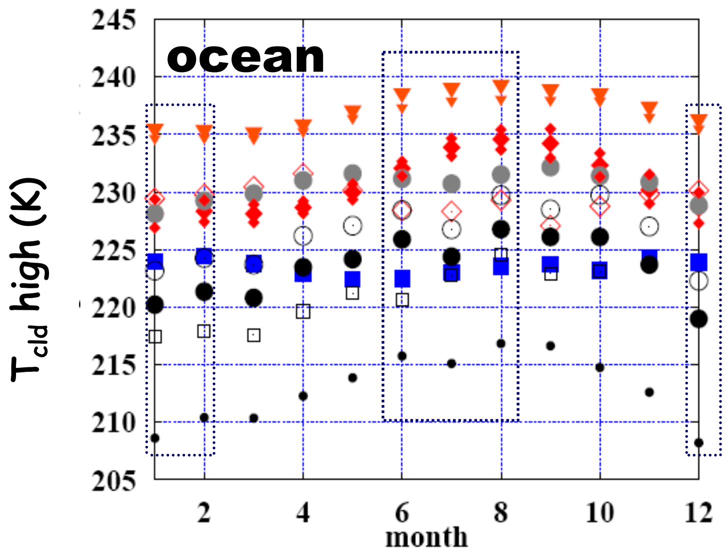
α_{SW}= 32% – 45% & ε_{IR}= 0.4 – 0.75 for IWP = 5 gm^{-2}– 55 gm^{-2}

D_e = 55 μm (Δ): underestimation of α_{SW} & ε_{IR}

aggregates in all cirrus (▲): 2% overestimation of α_{SW} at small IWP

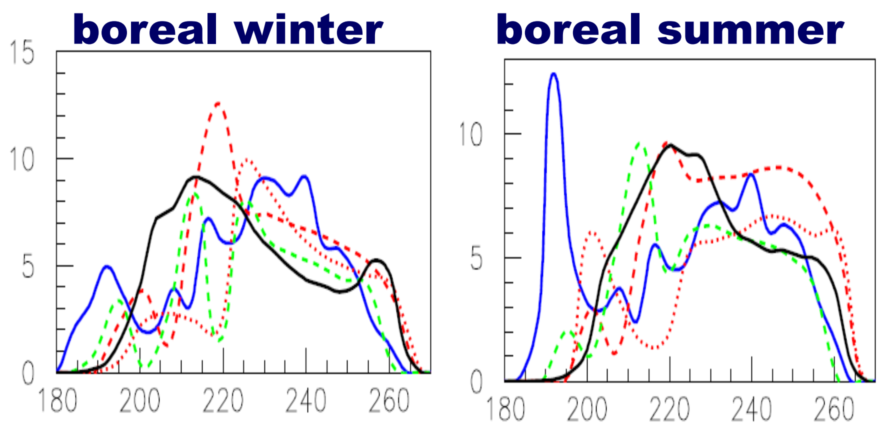
Tropical high clouds: T_{cld} distributions

TOVS-B
ISCCP
PATMOSX
MODIS-CE
AIRS
CALIPSO:
all ●
τ>0.1 ⬤
τ>0.2 O



SH

0°-30°



T_{cld} distribution shape differences

ISCCP CALIPSO TOVS AIRS

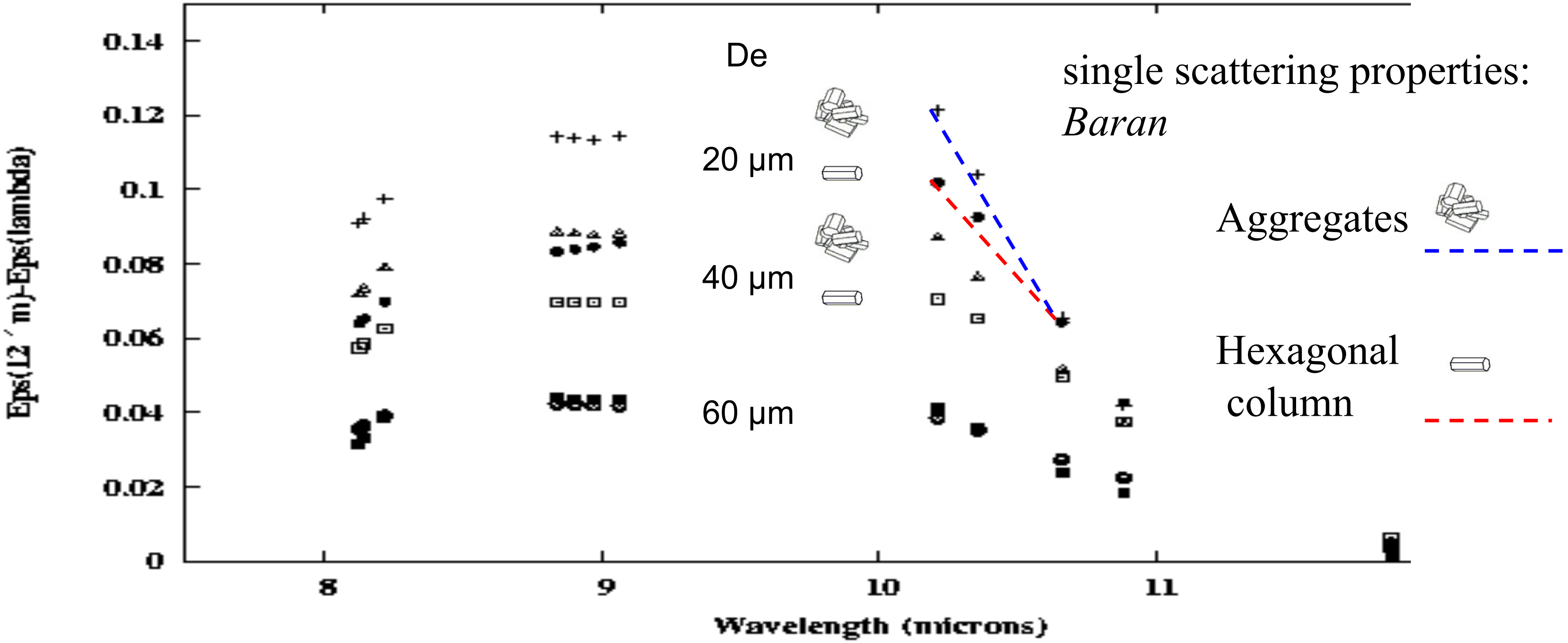
D_e, IWP & crystal shape retrieval with AIRS

based on spectral emissivity difference

for $0.3 < \varepsilon_{11\mu m} < 0.85$ ***sensitivity up to*** $D_e \leq 80 \mu m$

$0.7 < \tau_{VIS} < 3.8$

4A-DISORT simulation of radiances: I_{clr}, I_{cld}, I_{meas} $7 < D_e < 90$ µm, $1 < IWP < 130$ g.m^{-2}



CALIPSO: distinguish single layer clouds