# What did we achieve from global cloud satellite observations?

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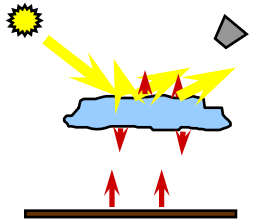
# Cloud properties from space:



**Passive remote sensing** (>1980)

info on **highest cloud layer**

good spatial coverage

- **CA** (*tot, high, midlevel, low*)
- **p/z, T, $\tau_{VIS}$ / $\varepsilon_{IR}$**
- **horizontal extension**
- **bulk microphysical properties**

**Active (A-Train**, >2002)

info on **all cloud layers**

sampling every 1000km

- **z, $\tau_{VIS}$**
- **vertical extension**
- **cloud layering**
- **microphys. prop. profiles**

➢ Intercomparisons and what we learn from them

➢ Synergy of datasets and of datasets & modelling

*(examples, see also talks of 25year ISCCP Symposium)*

# Longterm cloud climatologies:

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

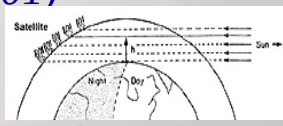
**PATMOS-x** *AVHRR* *1981-2006* *(NESDIS/ORA; Heidinger et al.)*

**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***

**CloudSat** *(Mace)* **POLDER** *(Riedi)* **MISR** *(DiGirolamo)* **ATSR2** *(Poulsen)*

Global Energy and Water Cycle Experiment GEWEX WCRP

Cloud Assessment

co-chairs:
C. Stubenrauch, S. Kinne

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

# Evaluation

## ISCCP *(Rossow & Schiffer BAMS, 1999)*

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

***uncertainties depend on cloud type:***

- ***Stratus ($\tau_{cld}$>5):*** $p_{cld}$ 25-50 hPa within radiosonde meas., ~ -65 hPa bias; err $T_{cld}$<1.5 K
- ***high clouds ($\tau_{cld}$>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

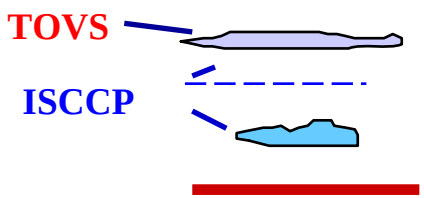
15% $\tau_{cld}$ decrease for doubling droplet size

### ISCCP – TOVS comparison

**agreement for homogeneous scenes**

remaining discrepancies: cirrus at night / partly cloudy / multi-layer clouds

IR Sounder good spectral resolution -> properties of uppermost cloud




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

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

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

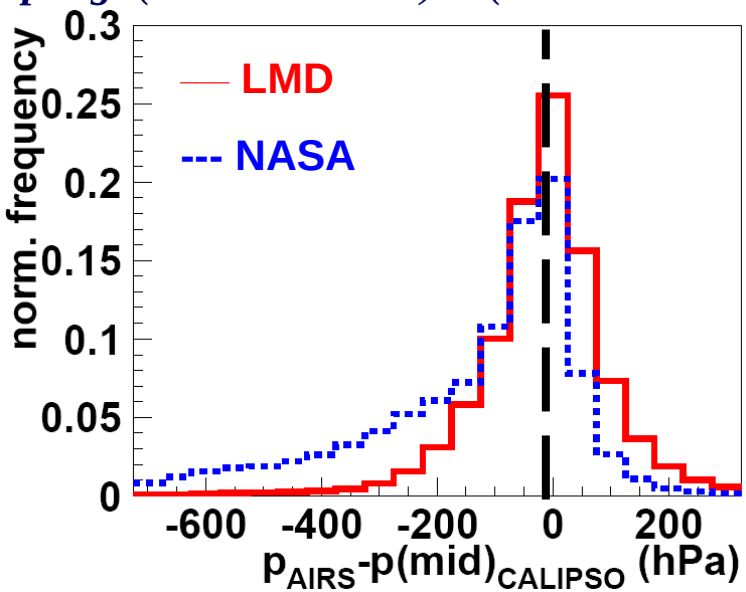
Sensitivity study for $D_e$ of Ci *(Rädel et al. 2003)*

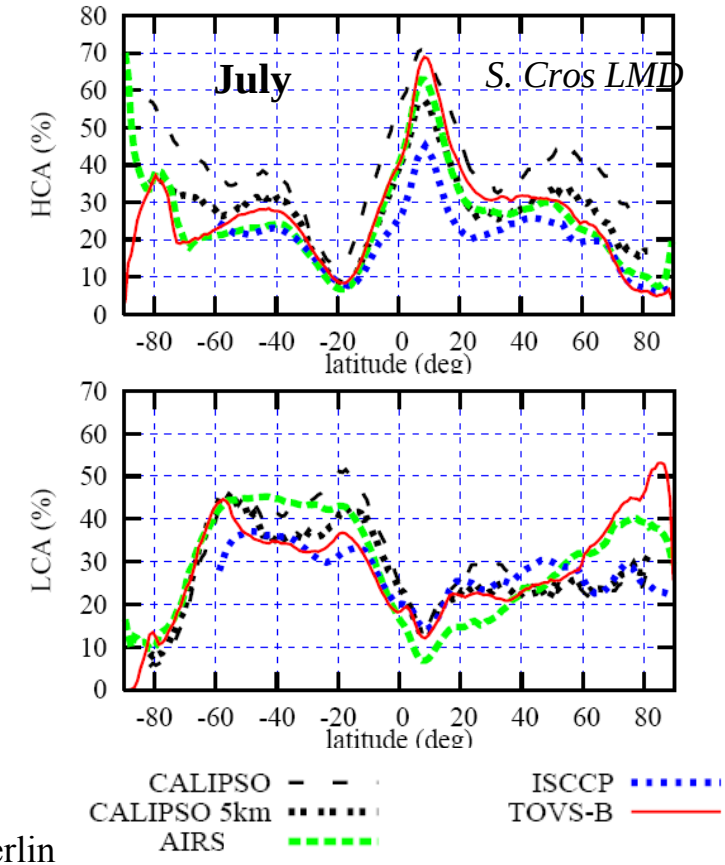
# A-Train: synergy of passive & active instruments

## Evaluation of AIRS cloud height with CALIPSO

***AIRS-LMD: retrieval based on weighted $\chi^2$ method as in TOVS-B*** *Stubenrauch et al., JGR 2008*

***sampling:*** *(5 km x 0.07 km ) in (13.5 km x 13.5 km)*




**good agreement with CALIPSO cld midlevel**

*(highest, detected at ≤5km)*

**properties also depend on retrieval method**

erlin

# Average CA

ISCCPday(84-04) TOVS-B(87-95) HIRS-NOAA(85-01) AIRS-LMD(03-08) 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 | | | | | | | | | | | oce an | | | | | | | | | | | la nd | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| all | 66 | 73 | 75 | 63 | 95 | 76 | 66 | 61 | 67 | 61 | 64 | 70 | 74 | 77 | 66 | 95 | 84 | 72 | 66 | 73 | 65 | 69 | 58 | 69 | 70 | 57 | 97 | 63 | 50 | 50 | 59 | 51 | 54 |
| Thick Ci | 3 | 2 | 2 | 4 | | | | | | | | 3 | 2 | 1 | 3 | | | | | | | | 3 | 4 | 5 | 4 | | | | | | | |
| Cirrus | 19 | 27 | 31 | 23 | | | | | | | | 18 | 27 | 33 | 23 | | | | | | | | 21 | 27 | 29 | 24 | | | | | | | |
| HCA/ CA | 33 | 41 | 44 | 43 | 44 | 50 | 38 | 42 | 30 | 21 | 23 | 30 | 39 | 44 | 39 | 44 | 46 | 35 | 37 | 27 | 18 | 17 | 41 | 45 | 49 | 50 | 45 | 61 | 47 | 56 | 37 | 29 | 43 |
| MCA / CA | 27 | 16 | 16 | 11 | 20 | 14 | 19 | 16 | 19 | 33 | 44 | 26 | 14 | 14 | 10 | 18 | 12 | 17 | 14 | 15 | 29 | 42 | 31 | 25 | 17 | 15 | 25 | 20 | 25 | 20 | 29 | 43 | 48 |
| LCA / CA | 39 | 42 | 37 | 46 | 36 | 35 | 44 | 44 | 52 | 46 | 72 | 41 | 47 | 42 | 50 | 38 | 42 | 49 | 51 | 59 | 52 | 80 | 29 | 30 | 34 | 35 | 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 $\tau$>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***

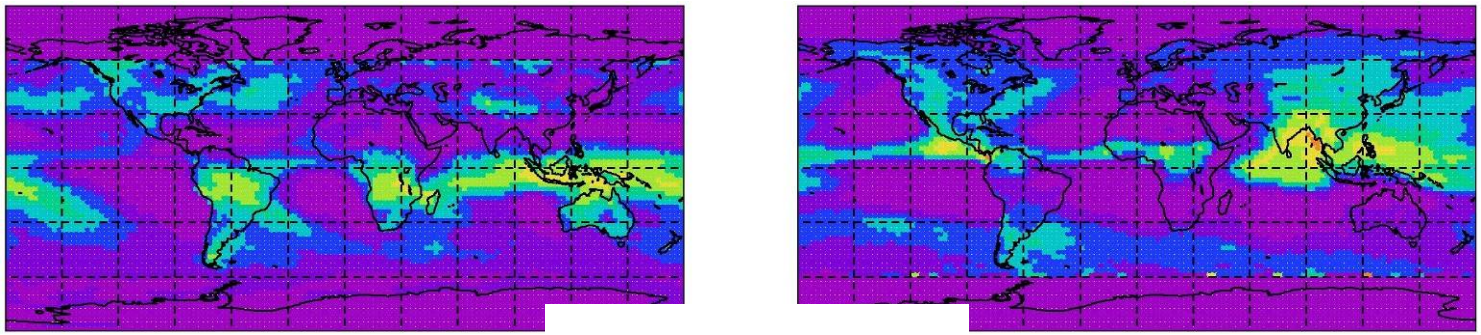
**IR sounders ~ 10% more sensitive to Ci than ISCCP (15% in trps)**

**SAGE cloud vertical structure in good agreement with IR sounders**

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

# HCA geographical distributions

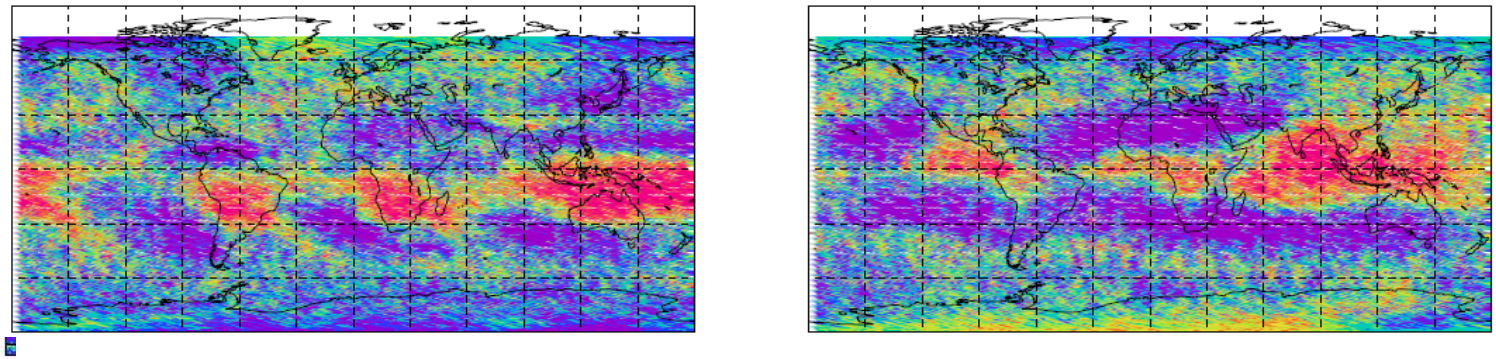
*January* **ISCCP** *July*



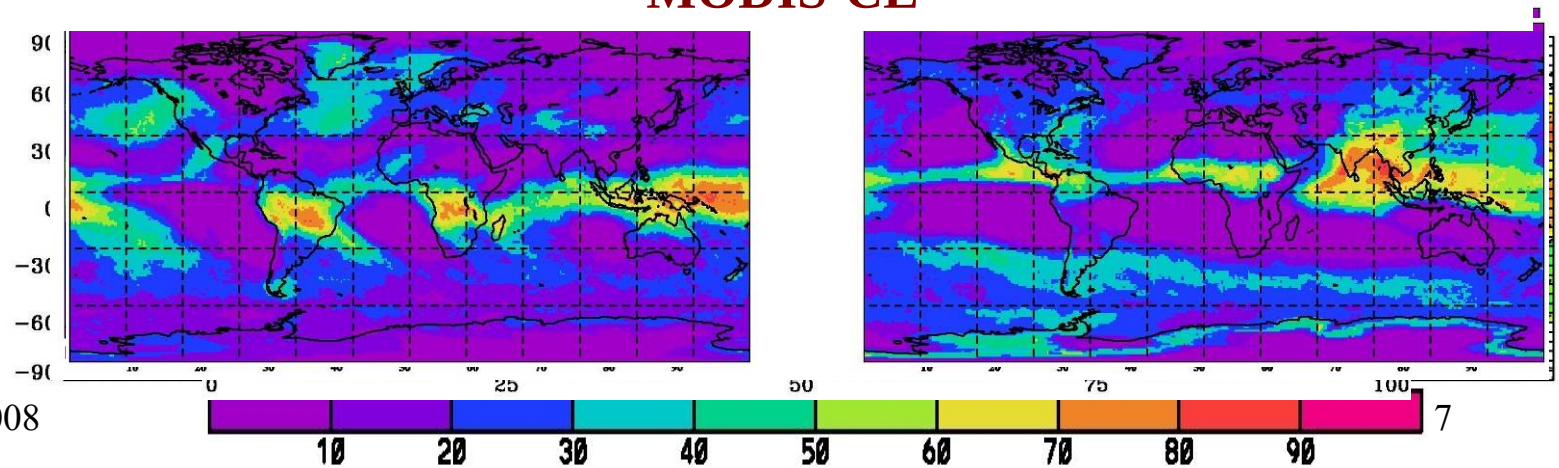
**CALIPSO**

winter
strom tracks

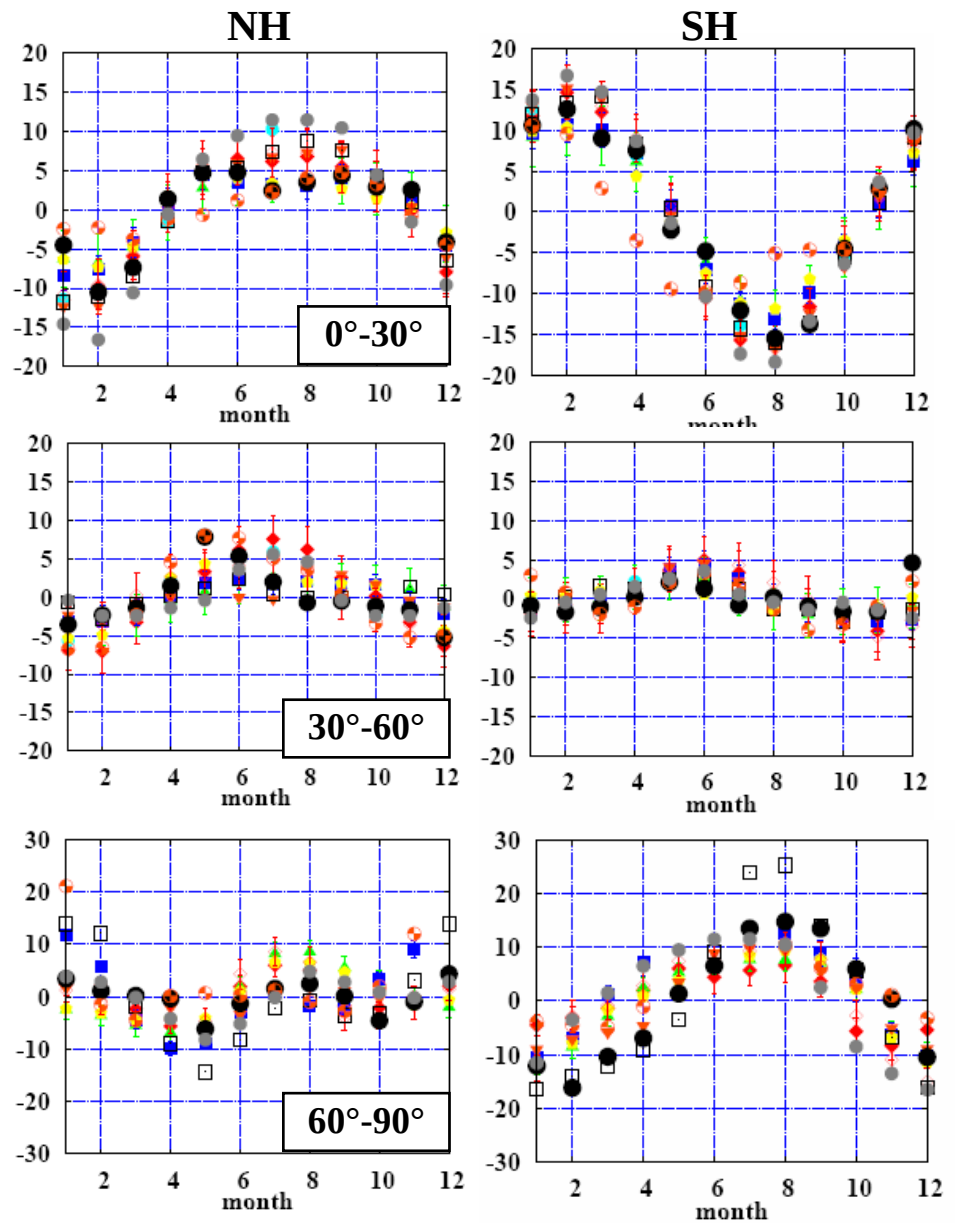
**ITCZ**



**MODIS-CE**



# HCA/CA seasonal cycle

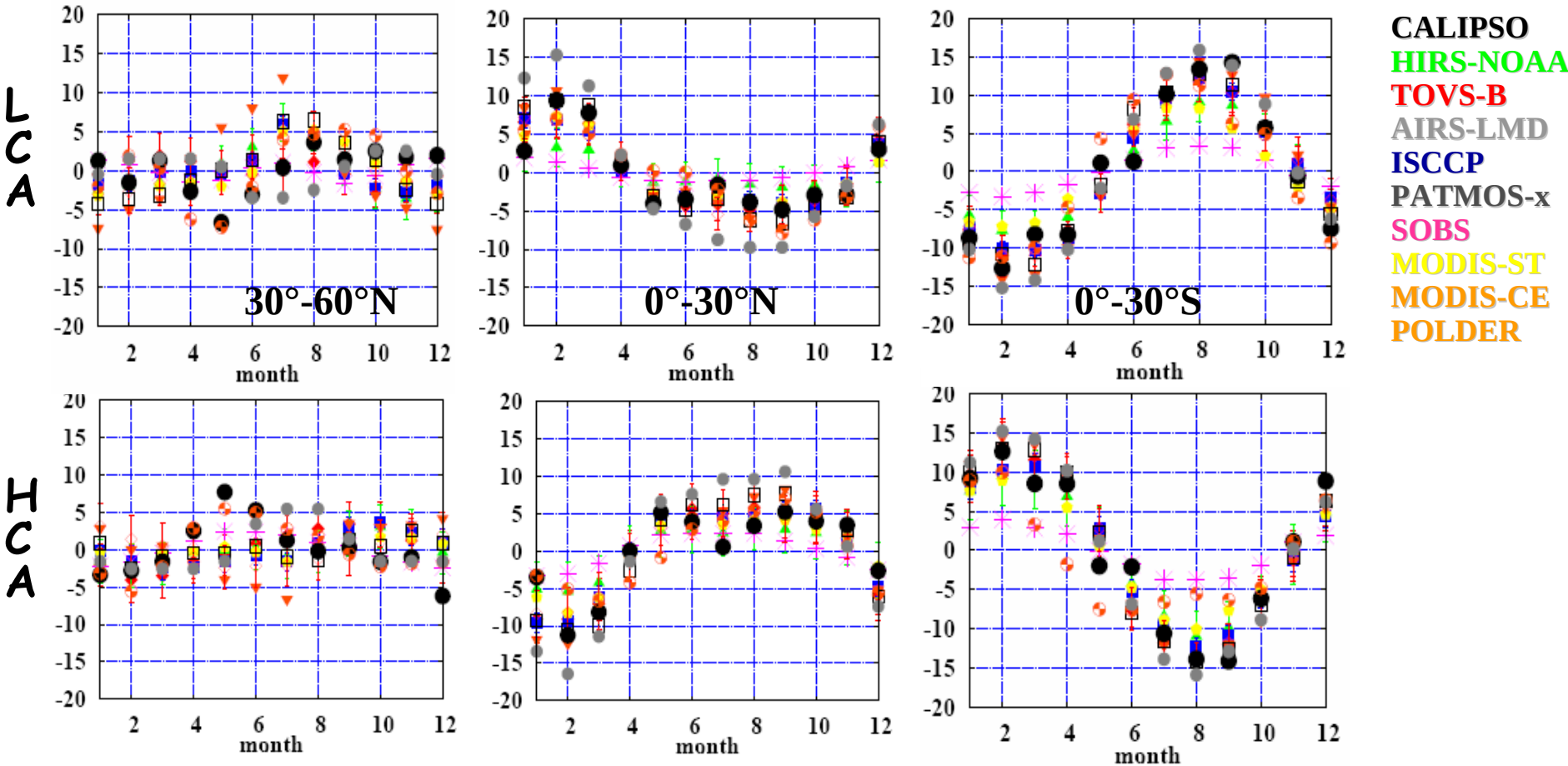



ISCCP
HIRS-NOAA
TOVS-B
PATMOSX
MODIS-ST
MODIS-CE
POLDER
AIRS-LMD
CALIPSO-V2
SAGE

**Seasonal cycles similar:**

**30% in SH tropics to 5% in SH midlatitudes**

# LCA/CA seasonal cycle over ocean

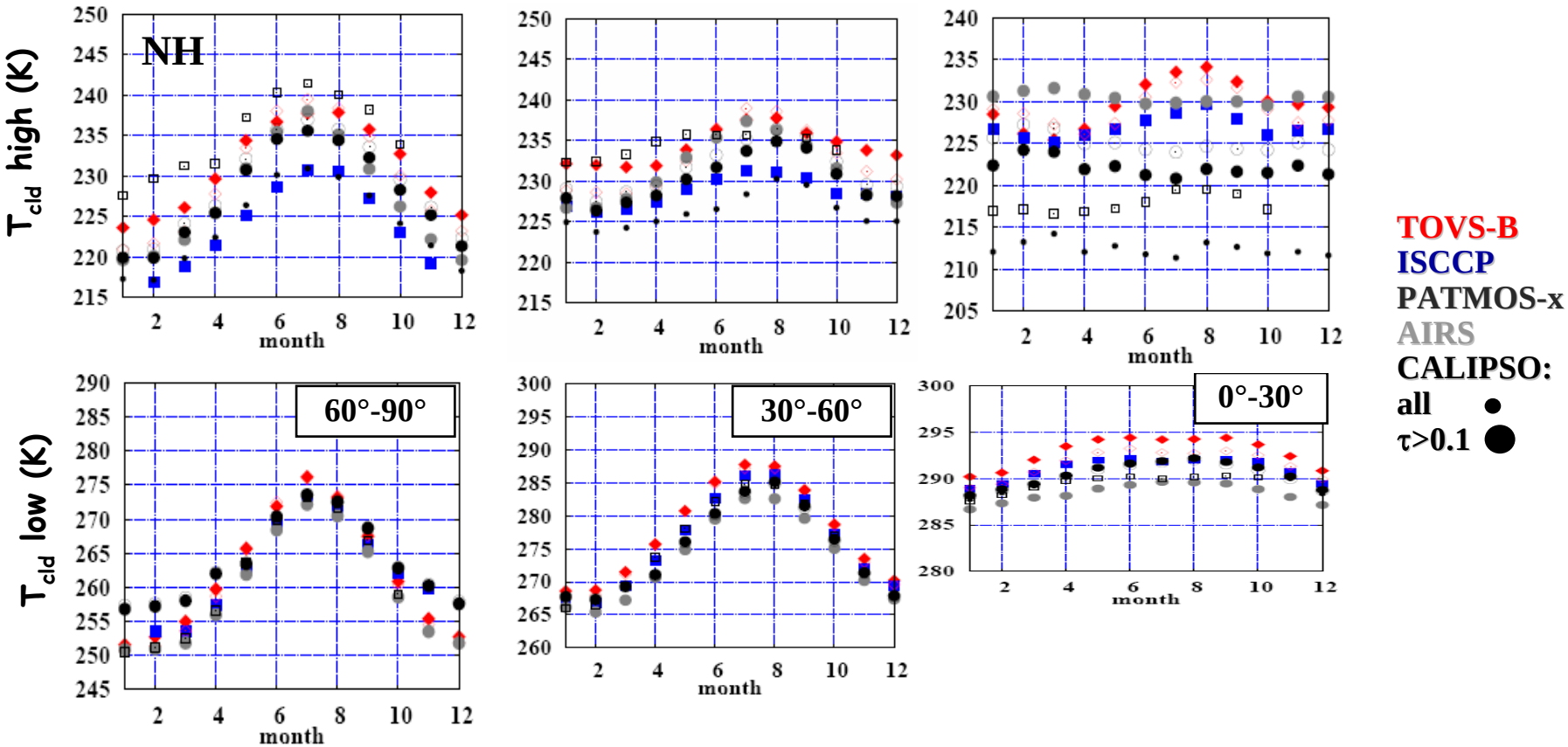



small seasonal cycle; exception: SH subtropics stratocumulus regions (20%)

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

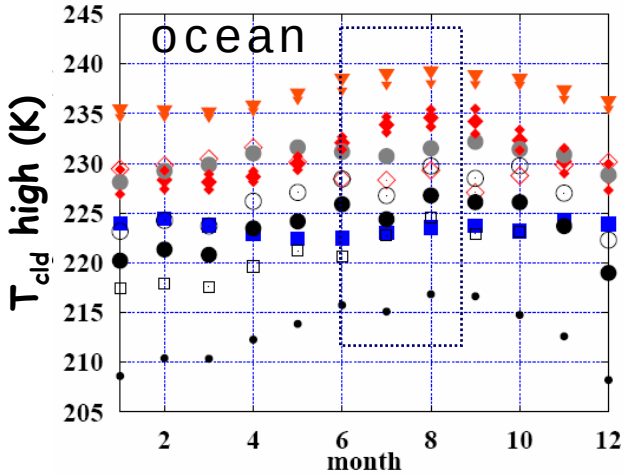
uncertainties in cloud height determination (esp. thin cirrus), T profiles

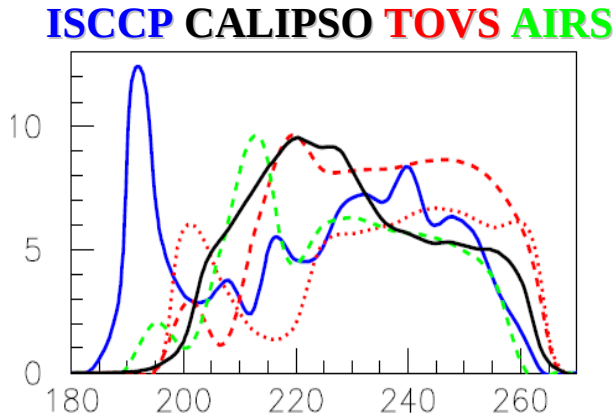
# Tropical high clouds: $T_{cld}$ distributions

SH

0°-30°

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




## Clouds in tropics have diffuse cloud tops:

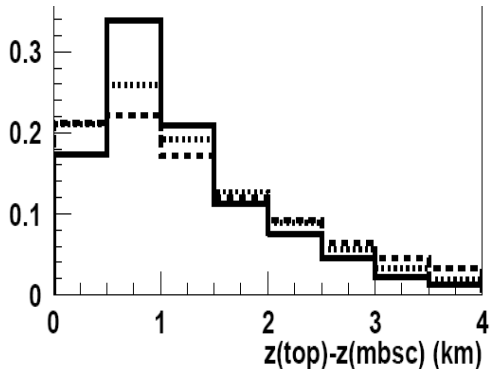
CALIPSO max backscatter ≥ 1km below cloud top

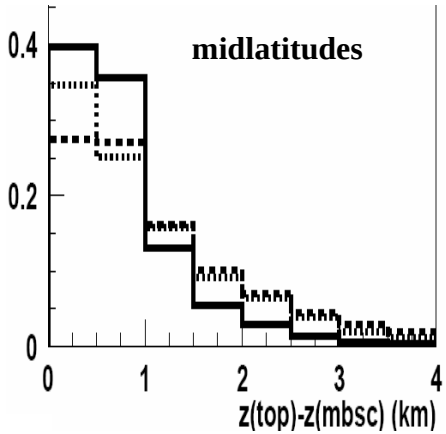
**AIRS-LMD:**

— $\varepsilon_{cld} > 0.95$

--- $0.95 > \varepsilon_{cld} > 0.50$

···· $0.50 > \varepsilon_{cld} > 0.05$



*near noon*

*early evening*

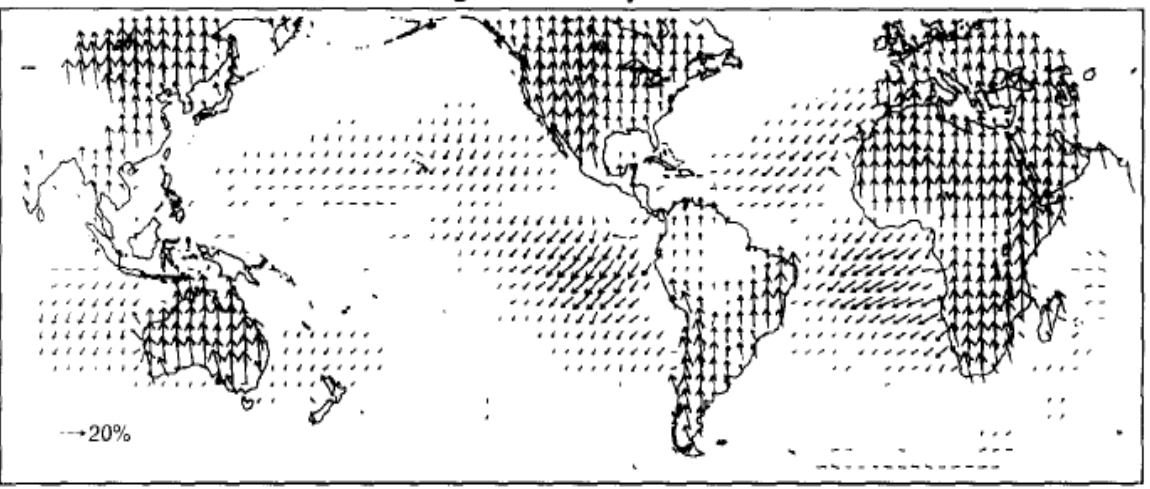
# diurnal cycle of clouds

*Cairns, Atm. Res. 1995*

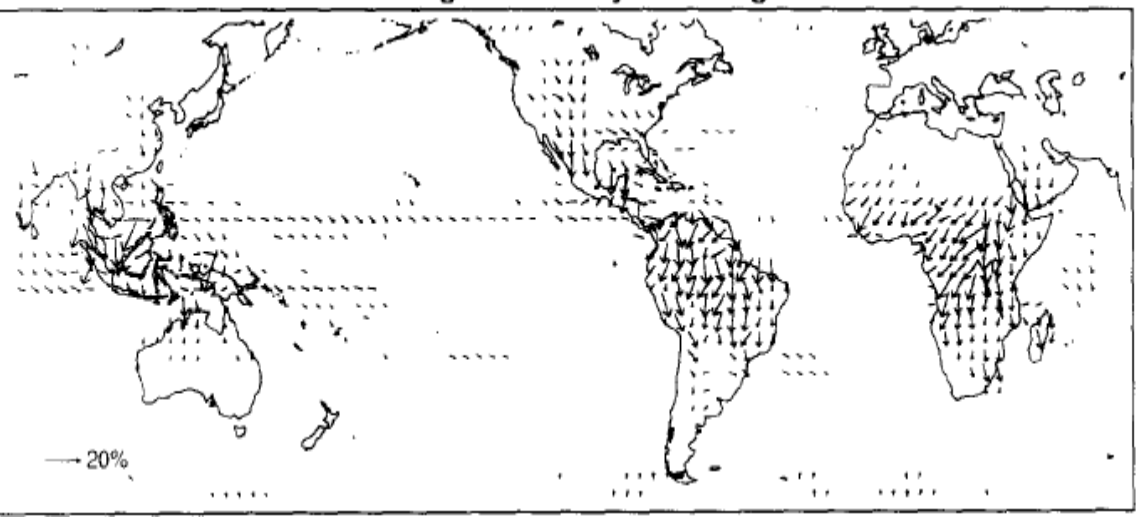
**ISCCP C2, Complex Empirical Orthogonal Functions,**

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*

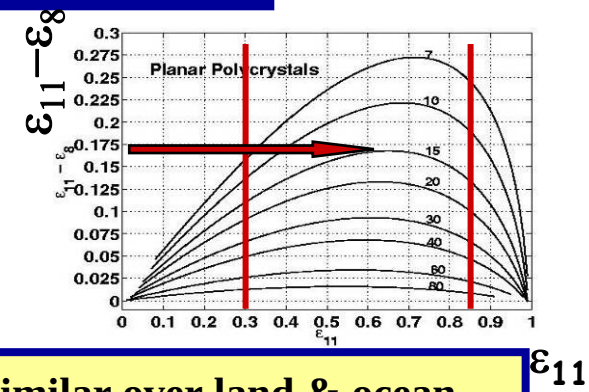
- **Mid clouds:**
  *max in early morning*
  *or late at night*
  *(-> cirrus : TOVS analysis)*

*Stubenrauch et al. 2006*

# effective ice crystal diameter

semi-transparent cirrus **TOVS Path-B, 87-91** *(Rädel et al. JGR 2003)*

| 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 |

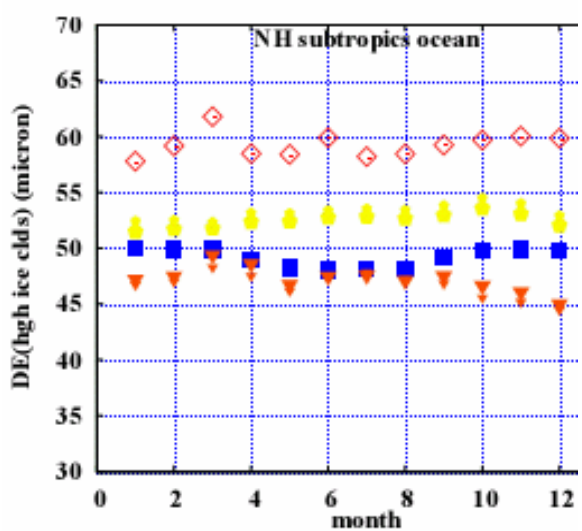



**$D_e$ similar over land & ocean**

high clouds **MODIS-ST, 02-05** *(Hong et al. J. Appl. Met. 2007)*

| cloud properties | 30N-30S | ocean | land |
|---|---|---|---|
| $D_e$ [μm] | 53.0 | 55.6 | 47.0 |
| ε | 0.69 | 0.70 | 0.66 |

**$D_e$ slightly larger over ocean**




**ISCCP**
**TOVS-B**
**MODIS-CE**
**MODIS-ST**

*preliminary*

**NIR-VIS:**
**$D_e$ near cloud top**

**IR:**
**$D_e$ averaged over cloud depth**

# Uncertainties on ice crystal size retrieval

*Rädel et al., JGR 2003*

**Overestimation of $D_e$:**

**up to 25%**

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

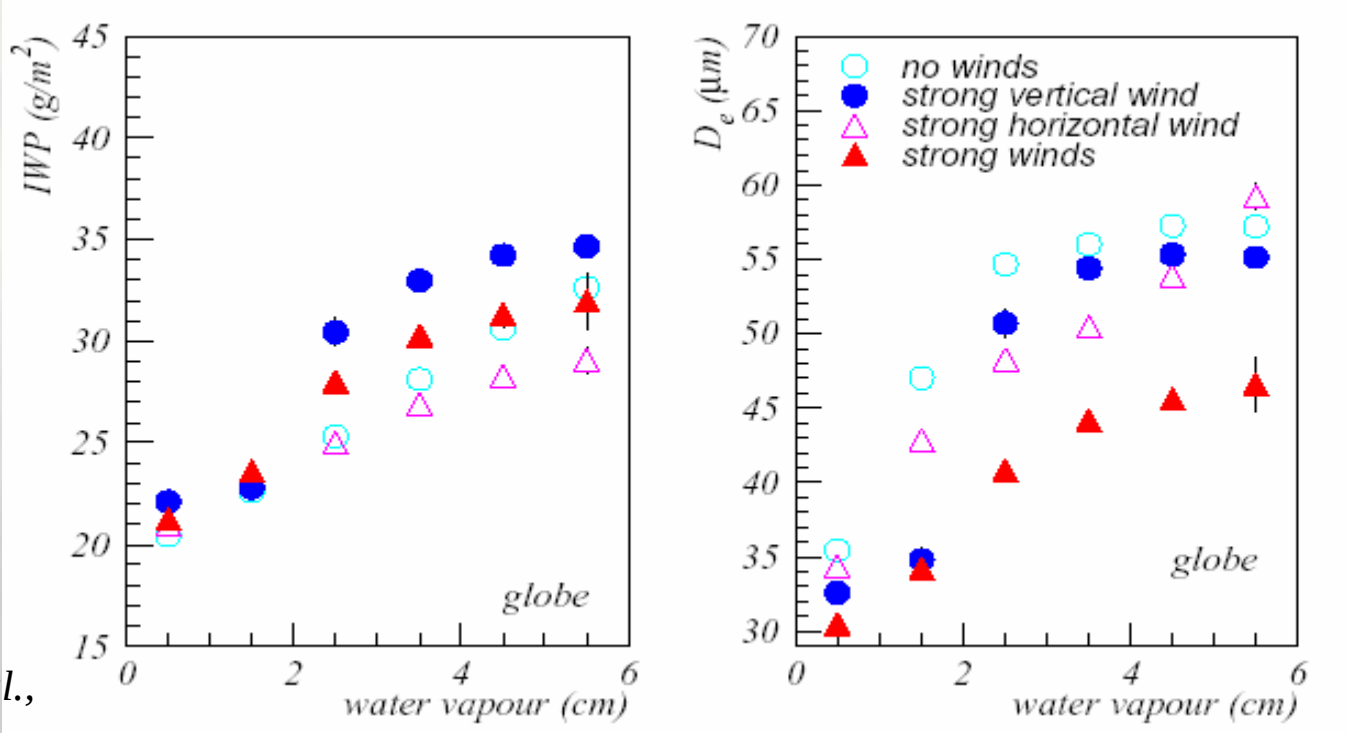
**Underestimation of $D_e$:**

**up to 25%**

- **increasing $D_e$ with cloud depth**
- **broader size distribution**

# $D_e$ & 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***

# Longterm datasets

- **trend analysis :**
- ***be very careful of artificial satellite features***
- ***use synergy of different variables***

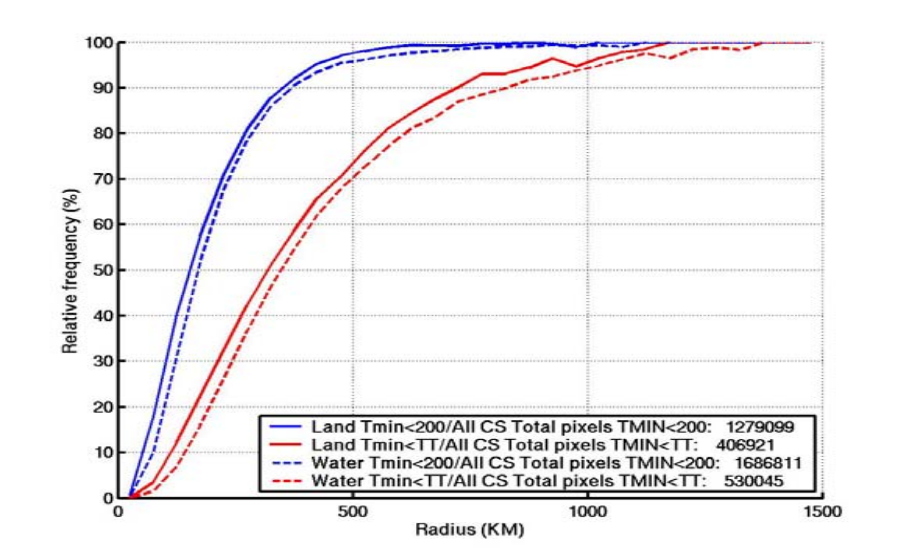
- **explore rare events :**

**tropical convection penetrating into the lower stratosphere**

**cluster analysis of ISCCP DX data** (***Rossow & Pearl GRL 2007***)

⬇

occurrence predominantly
in larger, organized mesoscale
convective systems



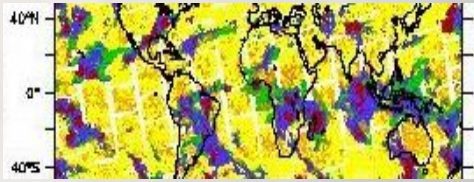
# Instantaneous global coverage

➢**explore horizontal extension of cloud systems**

**& relation with thermodynamic and dynamic properties:**

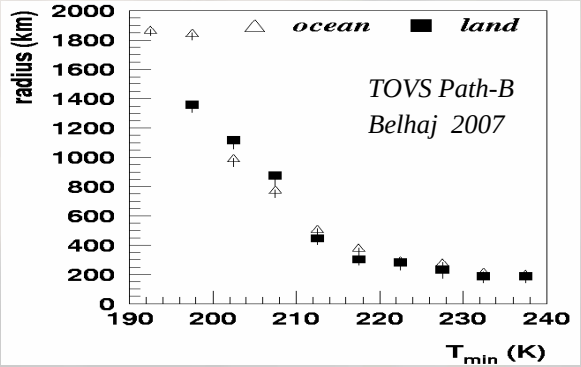
cluster analyses (ISCCP: *Rossow & Jakobs, GRL 2005*; TOVS Path-B: *Rädel 2004*)

**30/12/1989 7:30 PM**




## Tropical systems

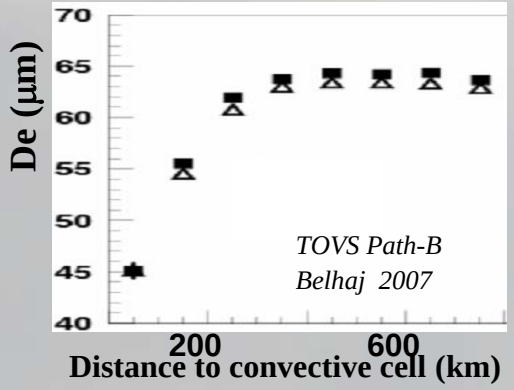
~50% of Ci originate from convection *(Luo & Rossow, J. Climate 2004)*




**anvil size increases** continuously **with decreasing $T_{min}$**

*ISCCP* *Machado & Rossow 1993*

but also depends on dynamics; *Chen et al. JGR 1997* *Belhaj et al. 2007*



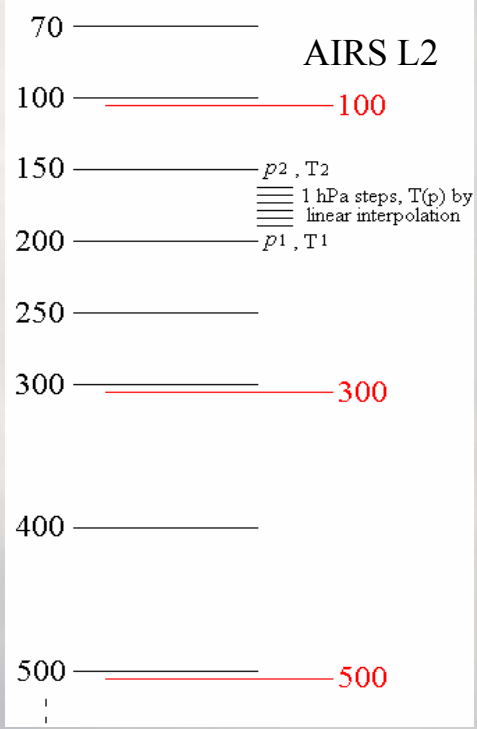

***Evolution of $D_e$ during life cycle of convective system***

➢$D_e$ increases with distance from convective cell

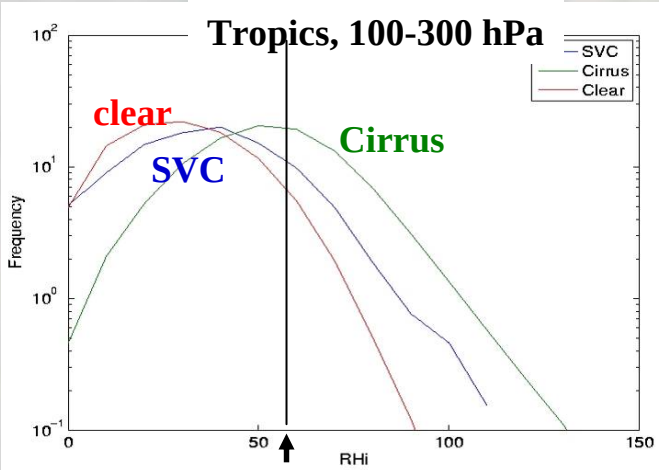
➢$D_e$ increases during life cycle of system

# How can we detect ice supersaturation from satellite observations ?

**TOVS/AIRS humidity: per layer**

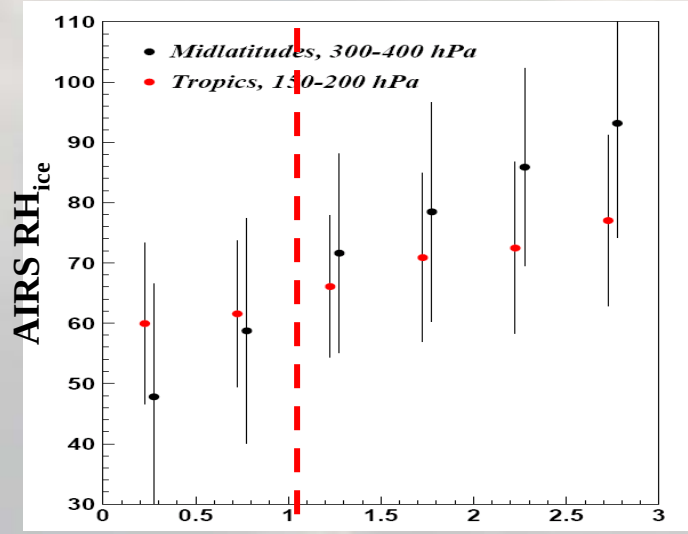



**$RH_{ice}$ distributions**




*Stubenrauch & Schumann GRL 2005*
*Kahn et al. Atmos. Chem. Phys. 2007*

**ice supersaturation : $RH_{ice}$ > 60% (peak for Ci)**




*Lamquin et al. JGR 2008*

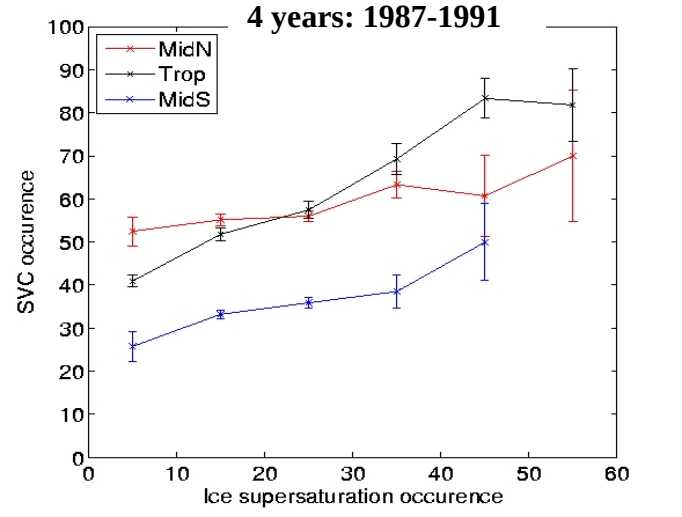
**$RH_{ice}$ increases with $\Delta z_{cld}$**
**but: $\langle RH_{ice} \rangle \approx 65\%$**
**even if whole layer is filled**

# Influence of ice supersaturation on cirrus occurrence

**$RH_{ice}$ :** TOVS Path-B

**subvis. Ci (SVC) :** SAGE II

*(P.-H. Wang)*

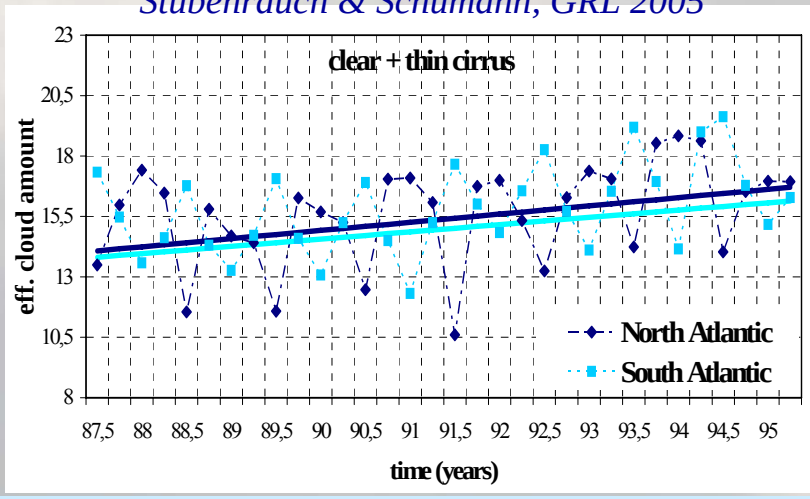



*Lamquin et al.* EGU 2007

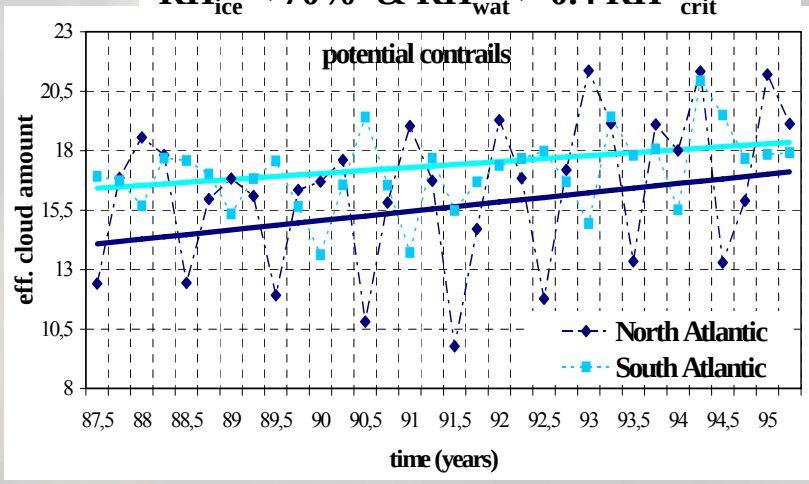
extending results of *Gierens (2000)* *(using MOZAIC data in NH midlat)*

# Contrail occurrence

*Stubenrauch & Schumann, GRL 2005*




**$RH_{ice}$ < 70% & $RH_{wat}$ > 0.4 $RH^*_{crit}$**




**increase of thin Ci in <u>both</u> hemispheres**

**stronger increase related to contrails in NH**

# Synergy of retrieved cloud properties & model :

## Cirrus radiative flux analysis

eliminate multi-layer clouds

*TOVS*
*atmospheric profiles*
*cirrus properties*

*$D_e$=10-90$\mu$m; $D_e$=f(IWP),= f(T)*

### radiative transfer model:

- *$p_{cld}$ = p(mid-cloud)* *$\Delta p$ = 100 hPa( $\approx$2 km)*
- *Single scattering properties (SSPs) = f($\lambda$, $D_e$)*
  *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 $\theta_v$, $\Delta z$, SSPs*

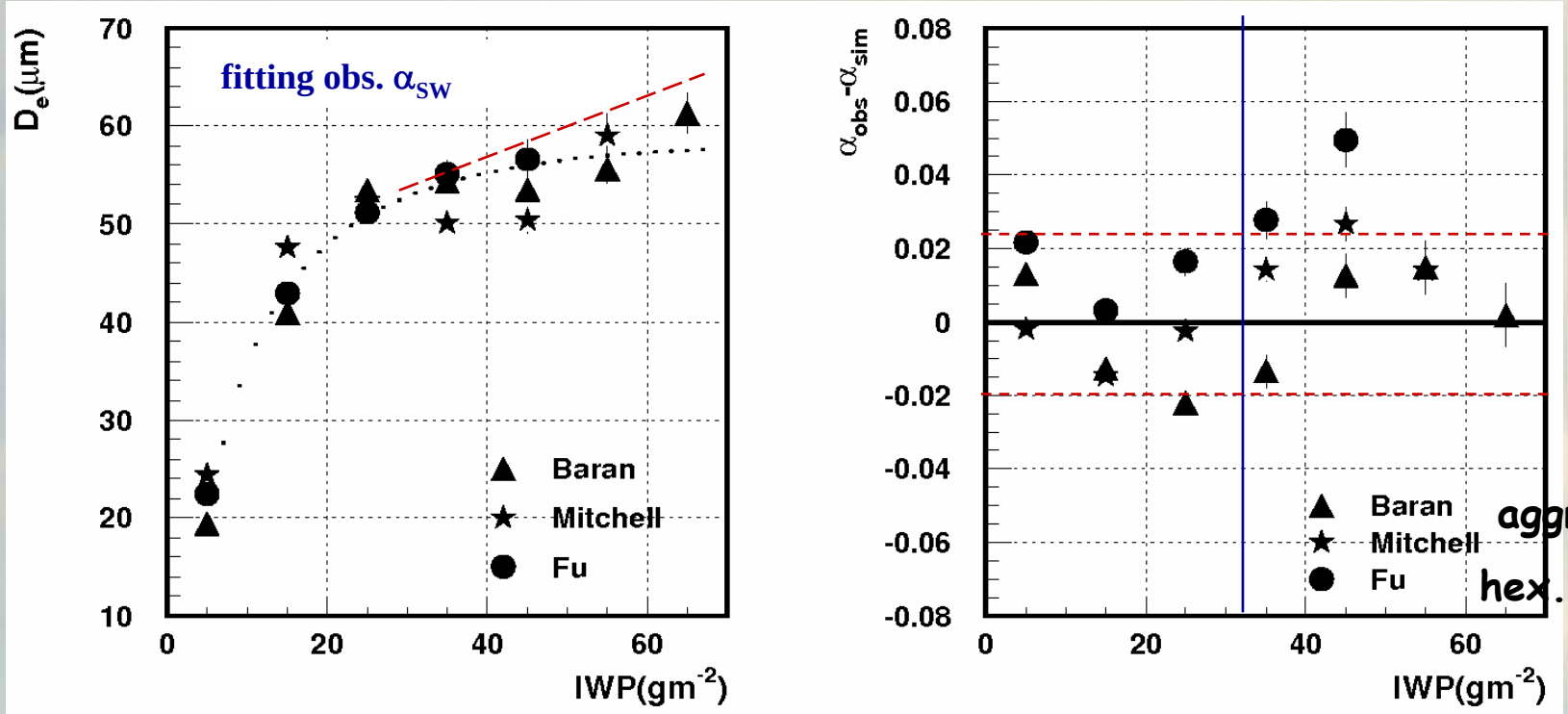
ADMs

*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

❖ Satellite instruments:
unique possibility to study cloud properties over long period

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

❖geographical cloud structures and seasonal cycles agree quite well

❖absolute values depend on instrument sensitivity (& retrieval method)

❖GEWEX Cloud Assessment: WMO report in preparation *(end 2009)*

❖ monthly mean cloud parameters (CA,HCA,MCA,LCA,$T_{cld}$,$\varepsilon$,$\tau$, $D_{eff}$,WP), variabilities, uncertainties will be available in netcdf at:

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

❖ Synergy of different data sets & variables very important:
Evaluation of climate models by comparing correlations!

⇒ important to synchronize satellite missions (A-Train)

EarthCARE (1:30AM/PM) – IASI Metop (10AM/PM) synergy ?

# ISCCP

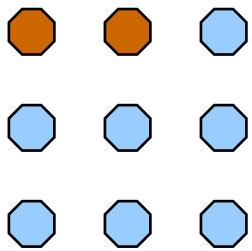
International Satellite Cloud Climatology Project

## ♦ Cloud detection

**IR spatial and temporal variability**

➡ VIS, IR composite clear sky statistics

*relative threshold tests*



## ♦ Cloud property retrieval

$R^{IR} \longrightarrow T_{cld}^{IR} \xrightarrow{\text{TOVS T profiles}} p_{cld}$

$R^{VIS} \longrightarrow \tau \longrightarrow T_{cld} \longrightarrow p_{cld}$

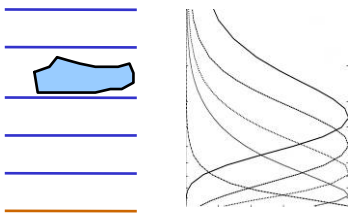
**radiative transfer** — **for $\tau < 11$**

*cloud microphysics*

# 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**

**TOVS**

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

**AIRS-L2**

*(Susskind et al. 2003)*

- 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 $\chi_w^2(p_k)$**

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

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

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

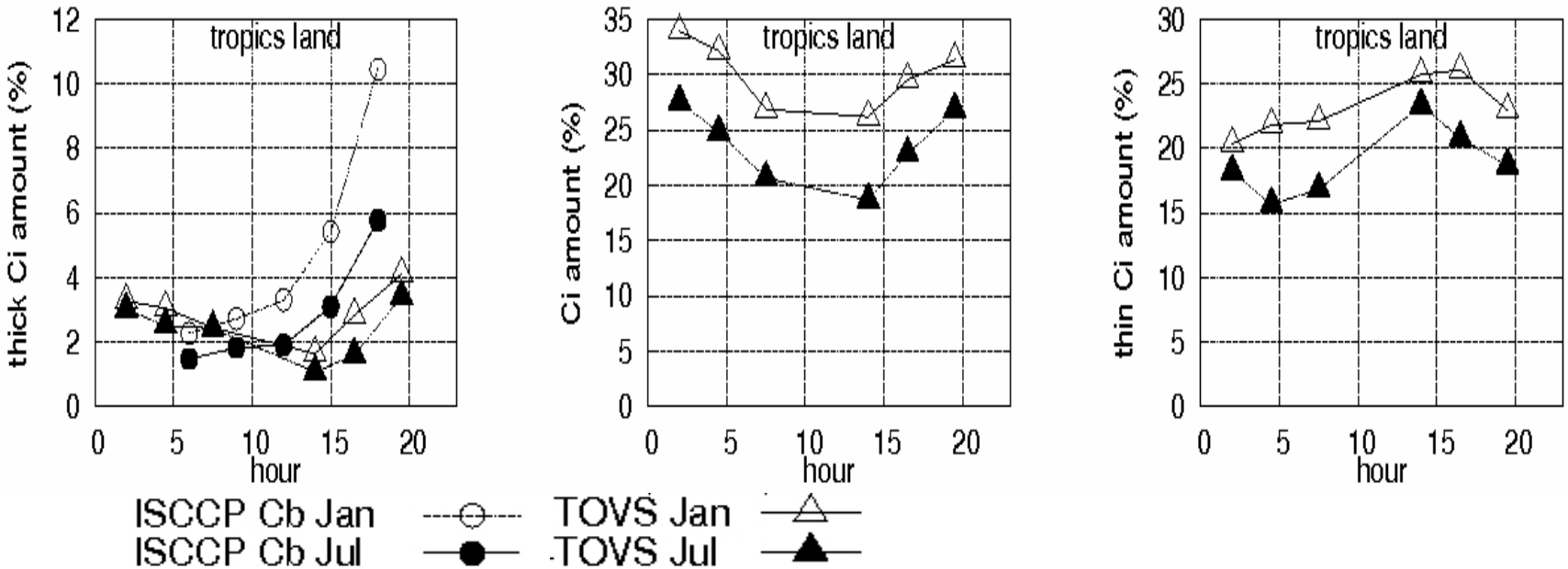
***Thermodynamic Initial Guess Retrieval***

# 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

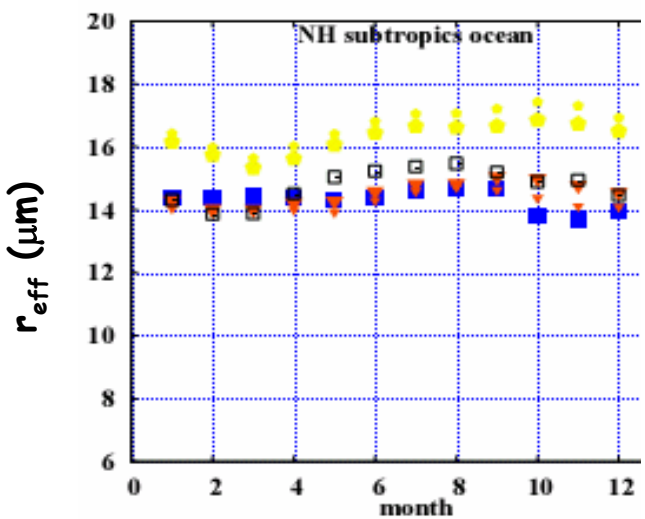
# water cloud effective droplet radius

## 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 ocean than over land**




ISCCP
PATMOSX
MODIS-CE
MODIS-ST

*preliminary*

**good agreement between ISCCP, PATMOSX, MODIS-CE**

**MODIS-ST:**
**2.1 μm instead of 3.7 μm**
**Cirrus contamination ?**

# Uncertainties on ice crystal size retrieval

**Reference:** homogeneous cloud, $T_{cld}$=237K, z=1km, $T_{surf}$=300K, polycrystals, bimodal-Γ size distribution

| parameter | changed to/by | $(D_e^{standard}-D_e')/D_e^{standard}$ 15μm | 60μm | | |
|---|---|---|---|---|---|
| crystal shape | spheres | +15% | | +30% | |
| | hexagonal columns | +15% | | +25% | |
| size distribution | tropical | -20% | | -28% | |
| | | thin cirrus 15μm | 60μm | thick cirrus 15μm | 60μm |
| horiz.heterogeneity | 90% cloud cover | +7% | +2% | +25% | +12% |
| vert. heterogeneity | $D_e^{low}=2\ D_e^{high}$ | -15% | –20% | -15% | –20% |
| + water cloud | $r_e$=7μm;LWC=0.2g/m$^3$ | +25% | +25% | +15% | +15% |
| lapse rate | 6.5 -> 11°/km | +3% | +3% | +5% | +5% |
| $\Delta h_{cld}$, $\Delta T_{surf}$, $\Delta z$ | +4km, -15K, +1km | -6% to +10% | | | |