Liquid cloud properties from ground-based remote sensing: Still a need for research?

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(showing the results of many other people)

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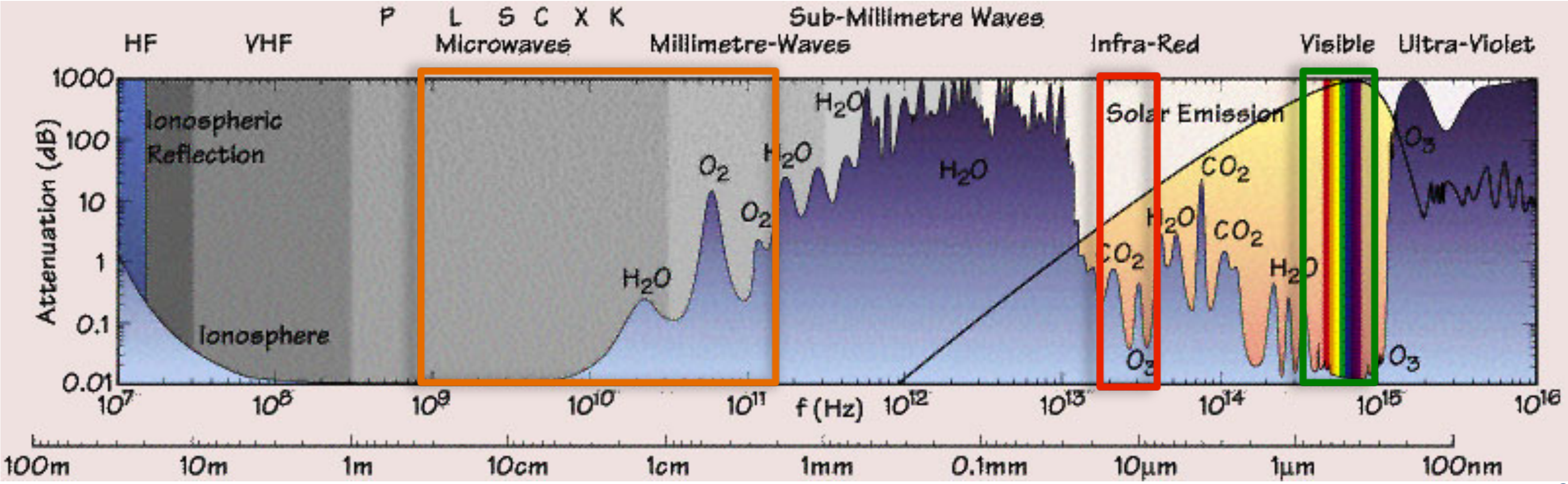
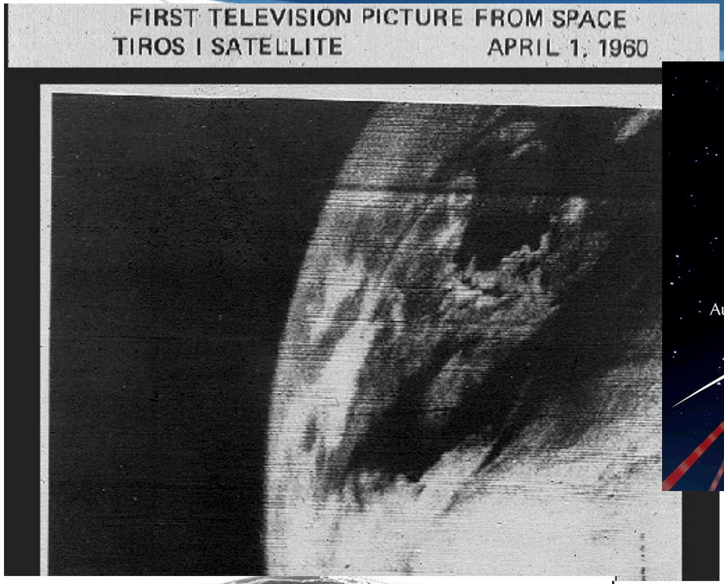
ARM Summer Training 2015

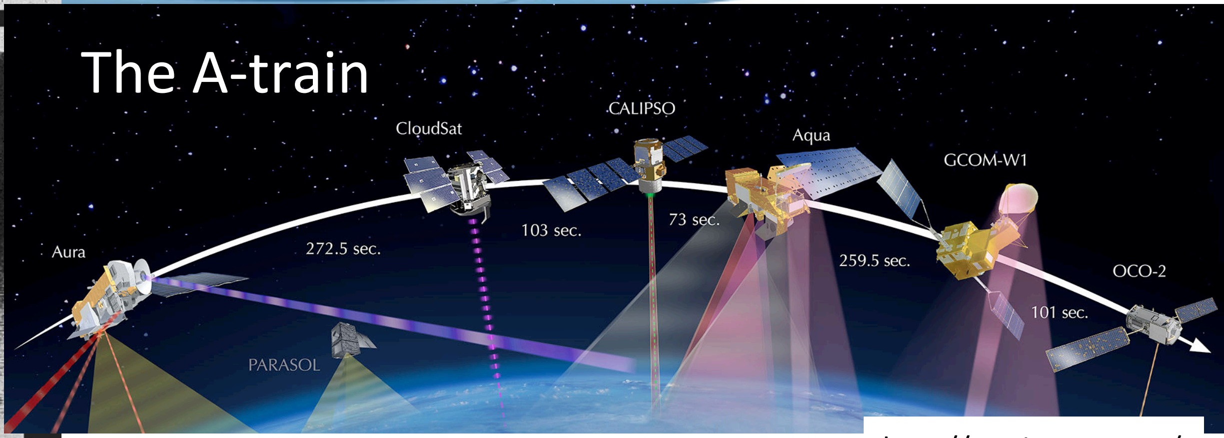
Remote-sensing

- most remote sensing methods use electromagnetic waves; important wavelengths in so-called window regions: atmosphere is especially transparent
- windows in the region of visible radiation (optical window), the maximum of terrestrial radiation (atmospheric window) and in the radio window
- Remote sensing instruments deployed on various platforms, e.g. satellites, aircraft, balloons, surface

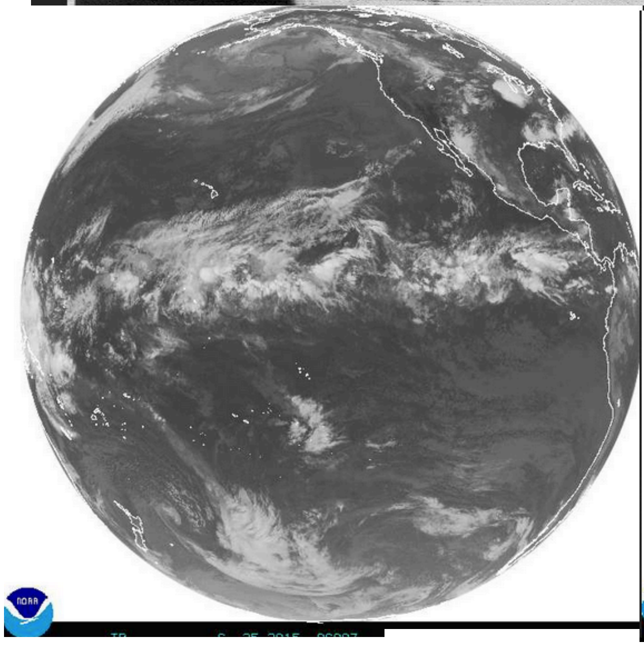


Cloud observations from satellites...

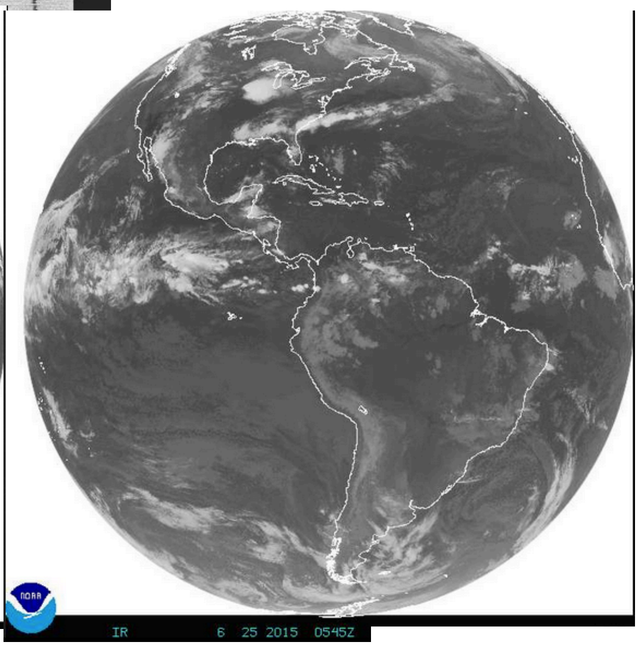




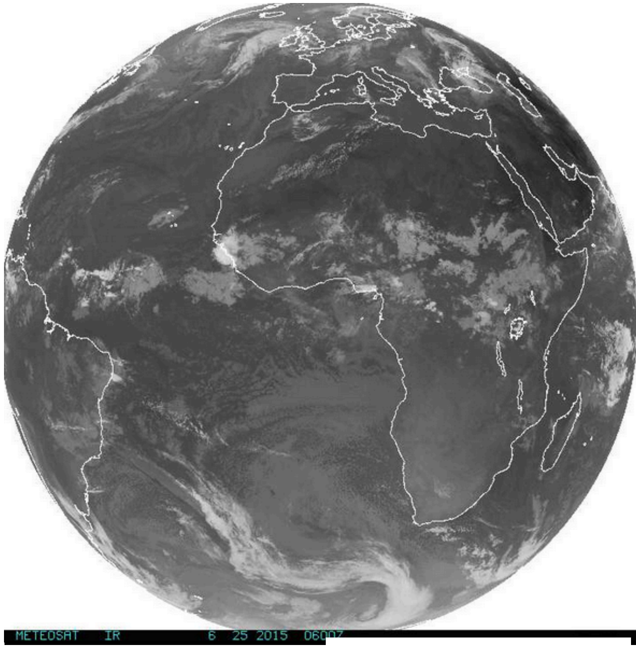
http://atrain.nasa.gov/



GOES-West, NOAA

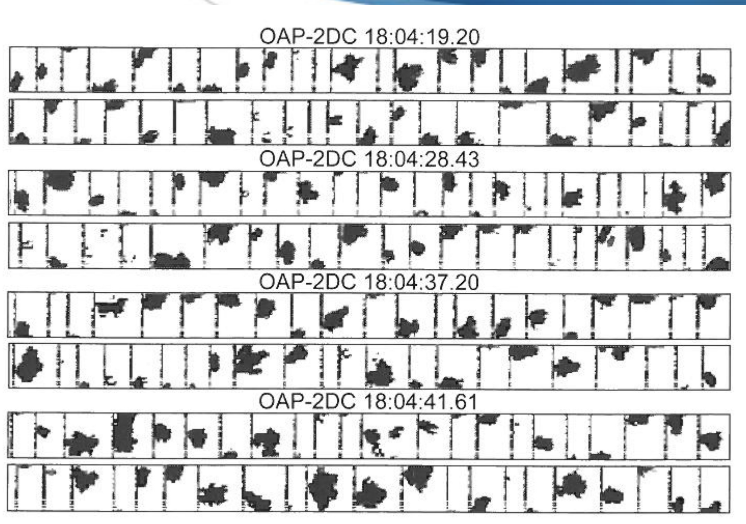


GOES-East, NOAA



Meteosat, Eumetsat

… and in-situ



Heintzenberg and Charlson (2009)

Optical Array Probes

Nevzorov Probe

Total and liquid water content → ice water content

Forward Scattering Spectrometer Probe (FSSP)

Laser beam registers every single particle. Forward scattering as measure of size (0.5 – 50 µm Ø)

Why don‘t satellites and in-situ measurements give us everything we need?

Why ground-based?

detailed **physical process studies** through

- more direct signals
- less surface disturbances
- high temporal resolution
- interchangeable configurations

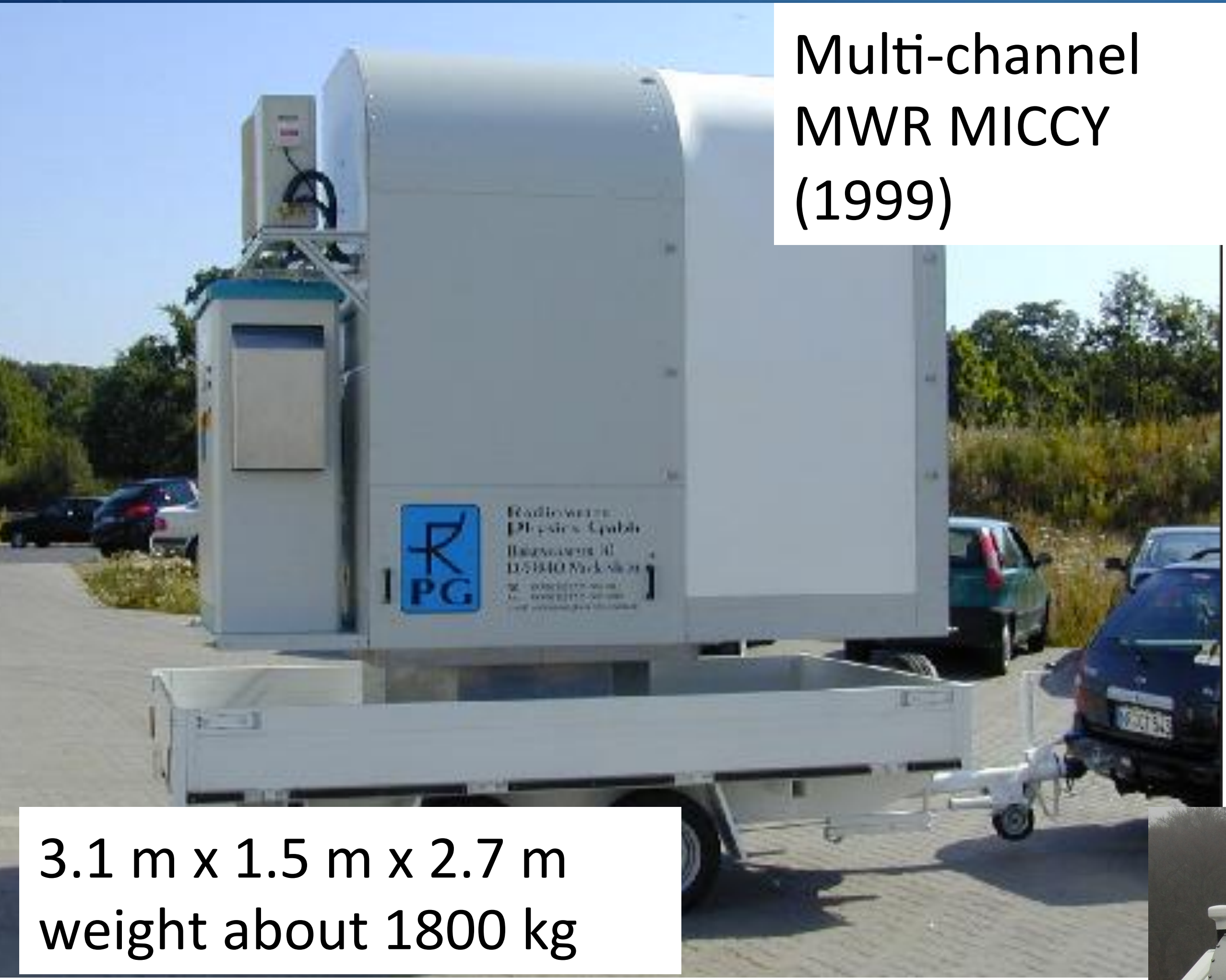
→ develop **prototypes** for future satellite missions

- **boundary layer** observations → complementary to satellites
- **continuous observations**: diurnal cycle, mesoscale meteorology

- atmospheric ground-based remote sensing **technology** developing fast (24/7, unmanned, affordable …)

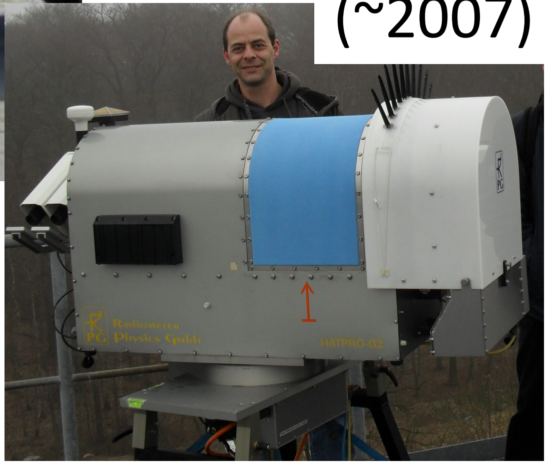
→ last decade: leaps in technological development

Multi-channel
MWR MICCY
(1999)



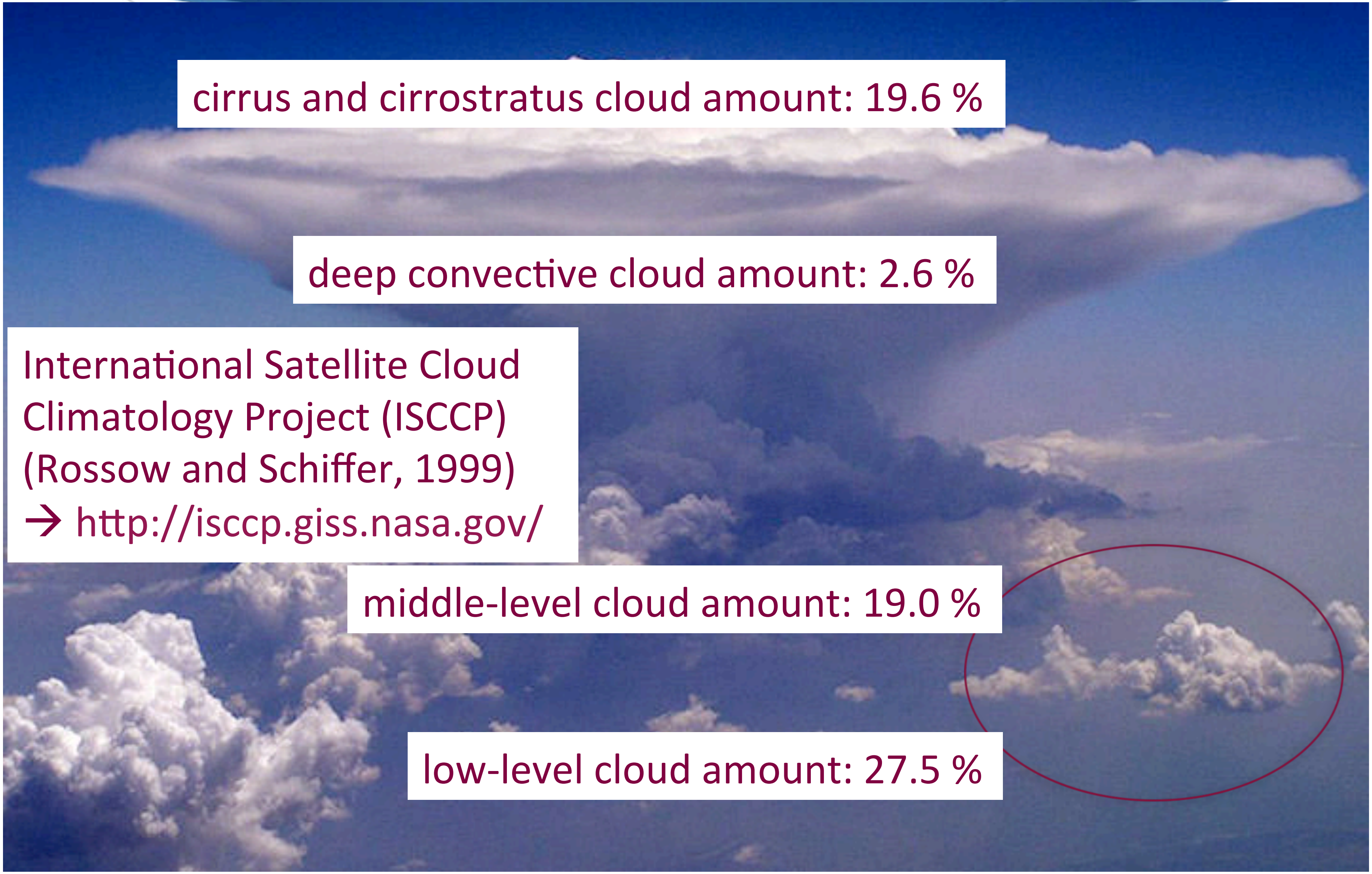
3.1 m x 1.5 m x 2.7 m
weight about 1800 kg

Multi-channel
MWR HATPRO
(~2007)



0.63 × 0.36 × 0.9 m
weight about 60 kg

Why do I care about water clouds?



tpevolavoile.e-monsite.com

Radiative impact of low-level clouds

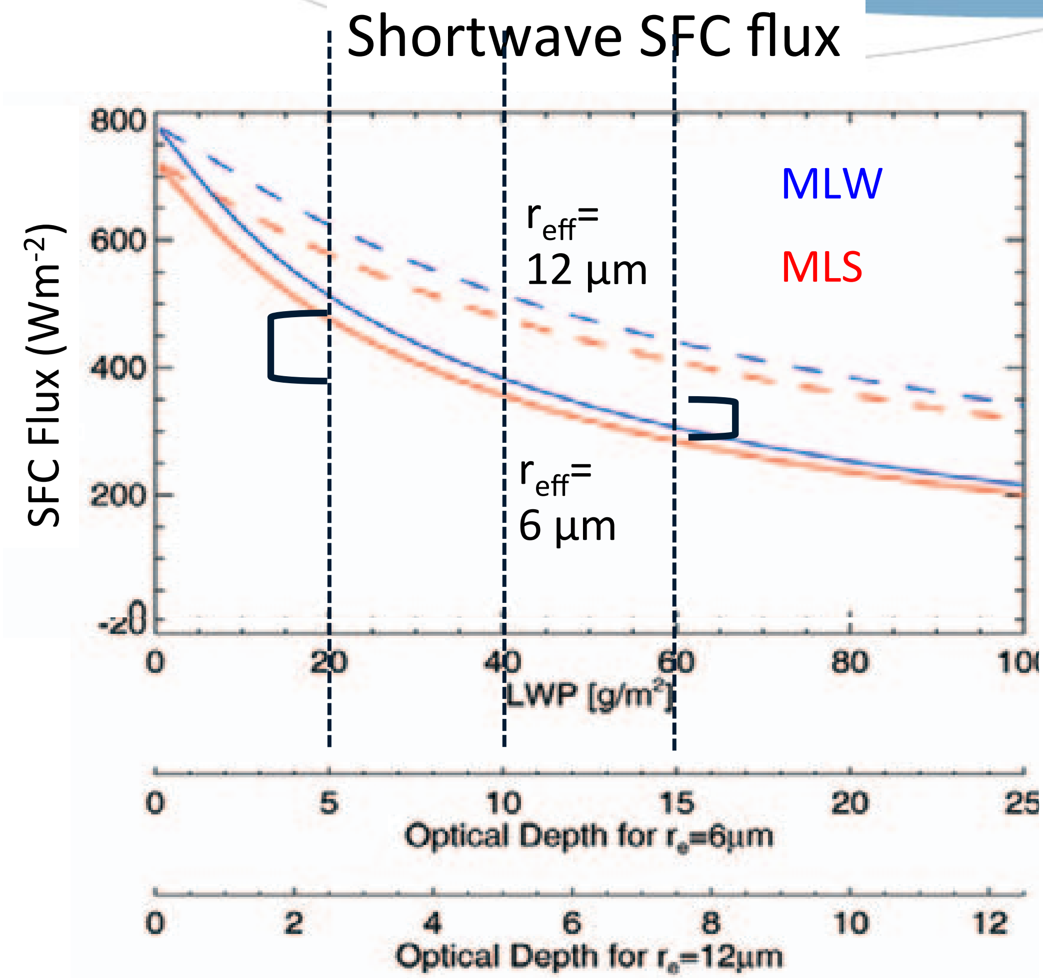
Global annual mean full sky cloud-induced radiative flux changes (W m^2) at TOA

Cloud type	TL =TOTAL
Cirrus	1.3
Cirrostratus	−2.4
Deep convective	−3.3
Altocumulus	−1.7
Altostratus	−6.3
Nimbostratus	−2.7
Cumulus	−4.6
Stratocumulus	−11.5
Stratus	−2.2
Sum (true)	−33.4

from Chen et al. (2000)

- ← based on ISCPP data and radiative transfer model calculations
- low clouds provide 55 % to 60 % to the annually averaged net cloud effect at the TOA

Radiative flux sensitivity to LWP



LWP: 40 gm^{-2}

-20 gm^{-2}
→ ΔSW_{SFC} +150 Wm^{-2}

+20 gm^{-2}
→ ΔSW_{SFC} -70 Wm^{-2}

- small errors in LWP → large errors in radiative impact of these clouds
- radiative fluxes are very sensitive to changes in LWP, if LWP is low

from Turner et al. (2007)

What do we want to know?

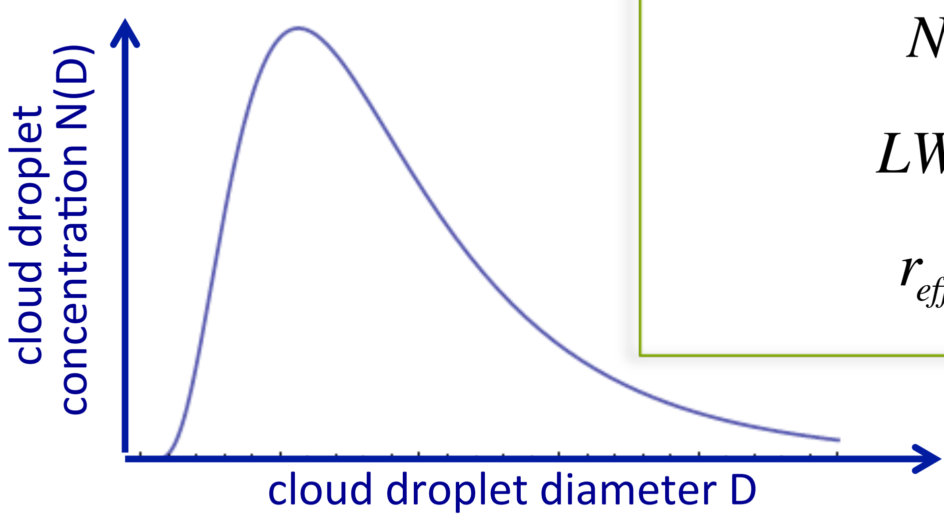
- **macrophysics**: cloud yes/no, location in atmospheric column, vertical and horizontal extension, cloud fraction, overlap
- **microphysics**:
  - phase: liquid, ice, liquid+ice, melting ice,..
  - column intergrated water amount (liquid water path LWP), vertical distribution of water, size of droplets → information on drop size distribution N(D)

*k*th moment of DSD: $M_k = \int_0^\infty D^k N(D)\,dD$

$$N_t = M_0$$

$$LWC = \frac{\pi\rho_l}{6}\int_0^\infty D^3 N(D)\,dD = \frac{\pi\rho_l}{6}M_3$$

$$r_{eff} = \frac{M_3}{M_2}$$



→radiative properties can be paramterized by moments, e.g.:

if $\lambda << r$

$$\tau_C = \frac{3LWP}{2\rho_l r_{eff}}$$

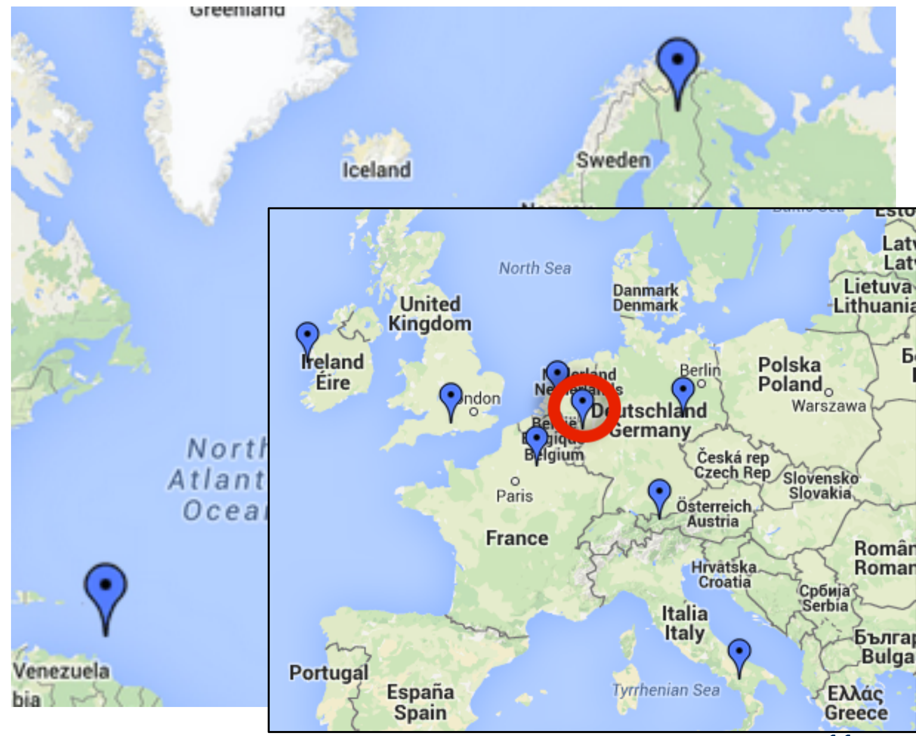
The rise of the „supersites“

supersite = atmospheric profiling observatory that has instruments to derive vertical (line of sight) profiles of temperature, wind, humidity, aerosol, clouds and precipitation

→ long-term, continuous cloud observations

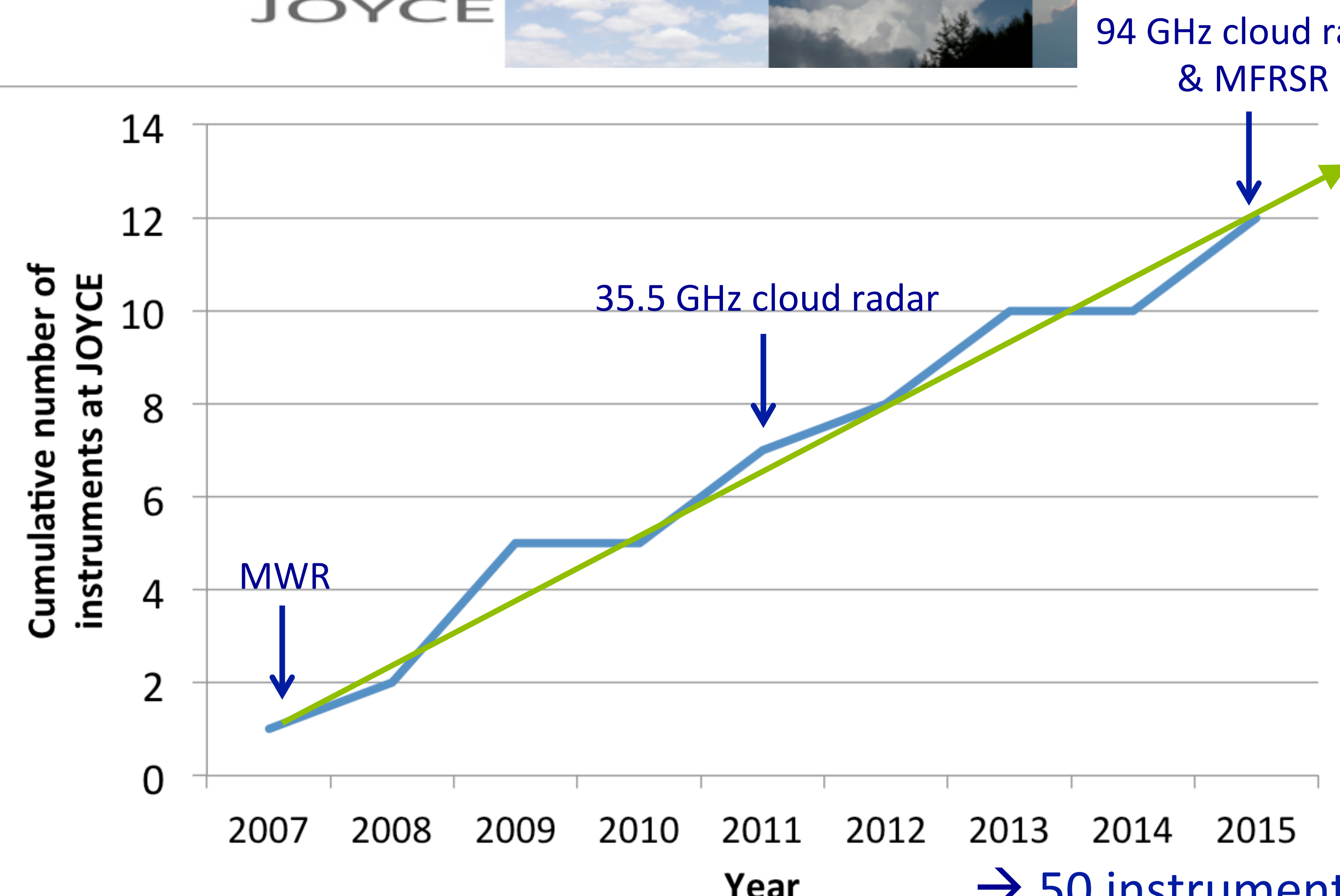
ARM Climate resarch facilities

European sites/initiatives



Jülich Observatory for Cloud Evolution

JOYCE



→ 50 instruments in 2043!

JOYCE instruments

- Scanning 35 GHz cloud radar MIRA[1]
- Scanning 14 channel microwave radiometer[2] with IR pyrometer[3]
- Scanning Doppler wind lidar[4]
- Atm. emitted radiance interferometer[5]
- Total Sky Imager TSI[6]
- Laser ceilometer CT25K and CHM15k[7]
- Micro Rain Radar[8], sodar[9]
- Cimel sun photometer
- Radiation sensors[10]
- 120 m meteorological mast[11] including eddy covariance station

\+ multifilter rotating shadowband radiometer and FM-CW 94 GHz cloud radar in 2015!

Liquid cloud property check list

- vertically resolved cloud mask?
- phase identification?
- liquid water path?
- vertical distribution of liquid water?
- effective radius of cloud droplets?

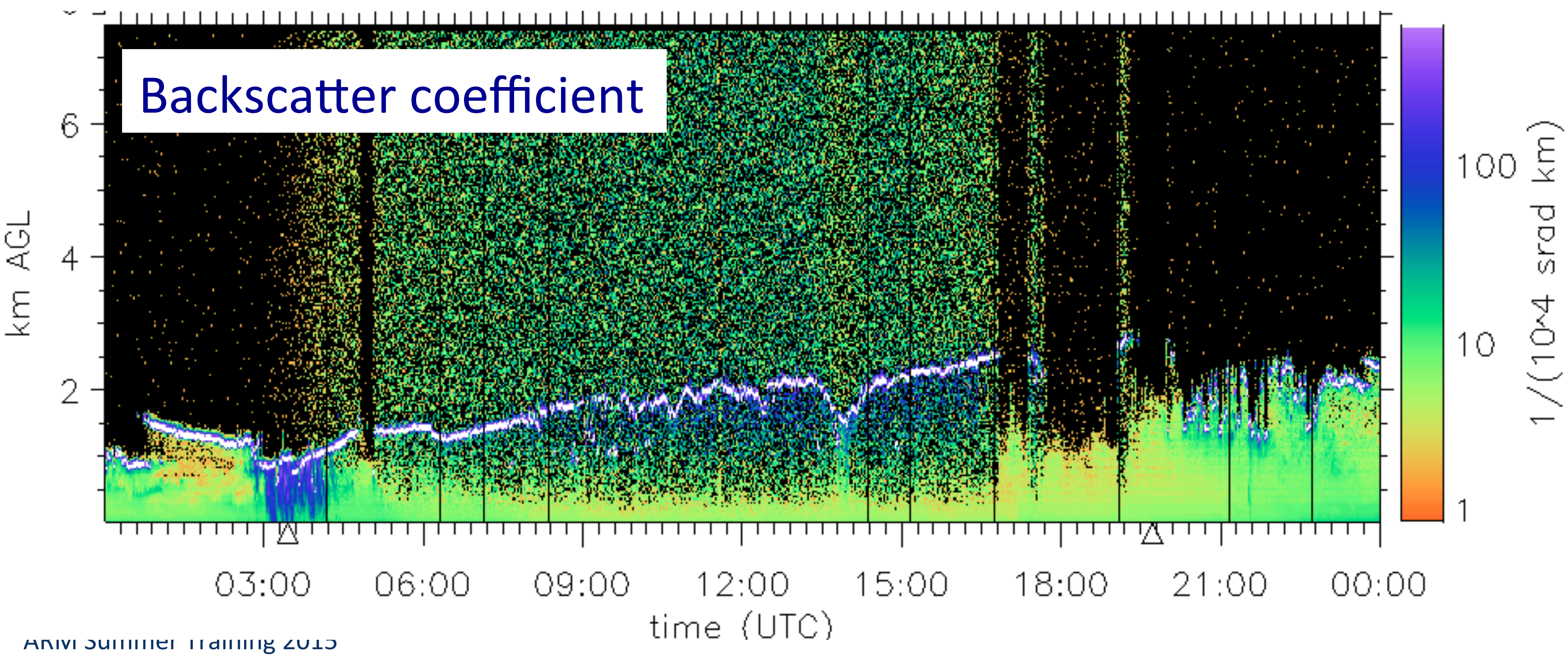
Ceilometer/Micropulse lidar

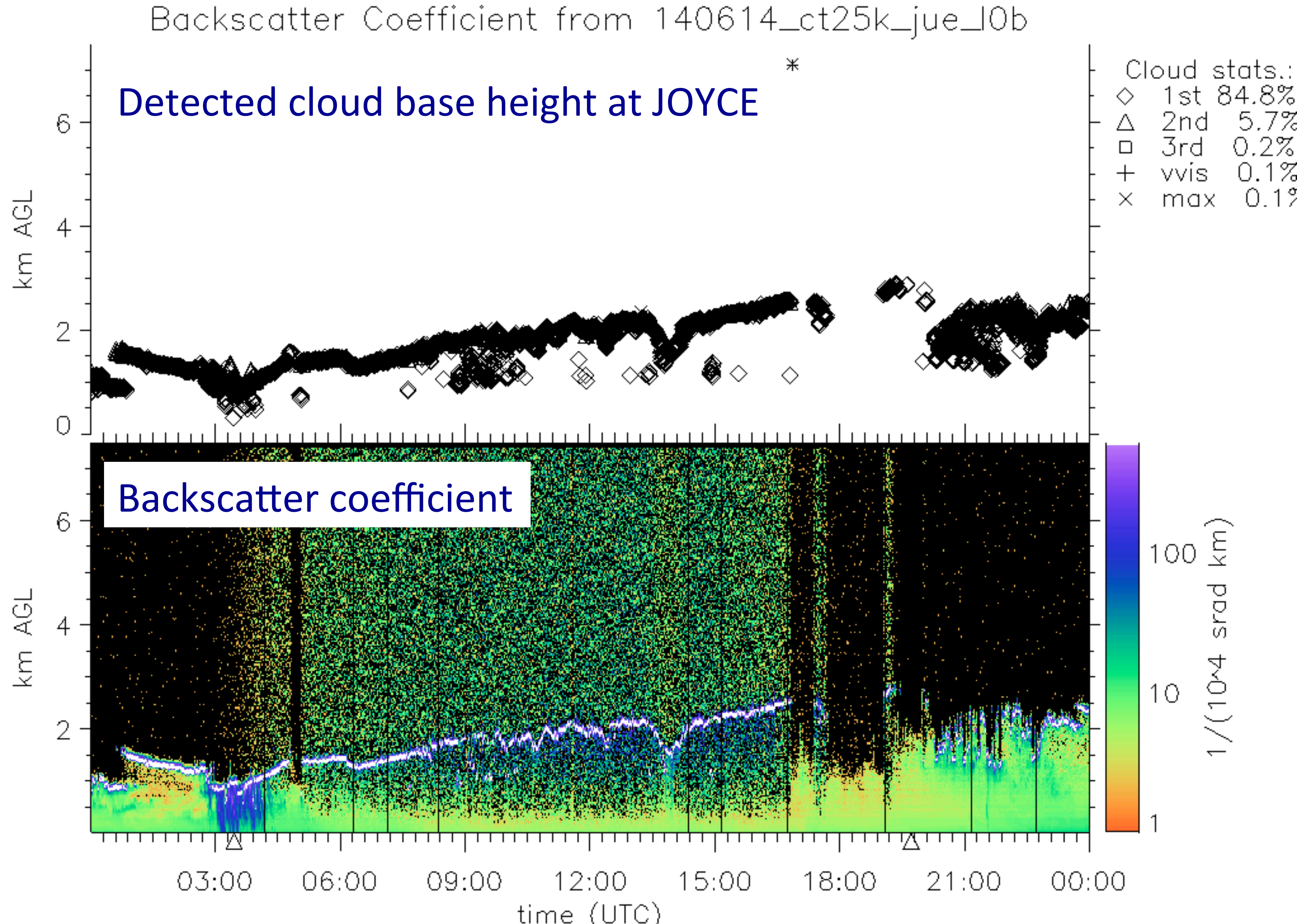
- active instrument: sends laser pulses (optical spectrum, e.g. 905 nm or 532 nm) and measures backscattered light → profiles of backscatter coefficient
- backscatter proportional to D^2
- very sensitive to small particles → cloud base height = ceiling (aviat.)

www.arm.gov

www.arm.gov

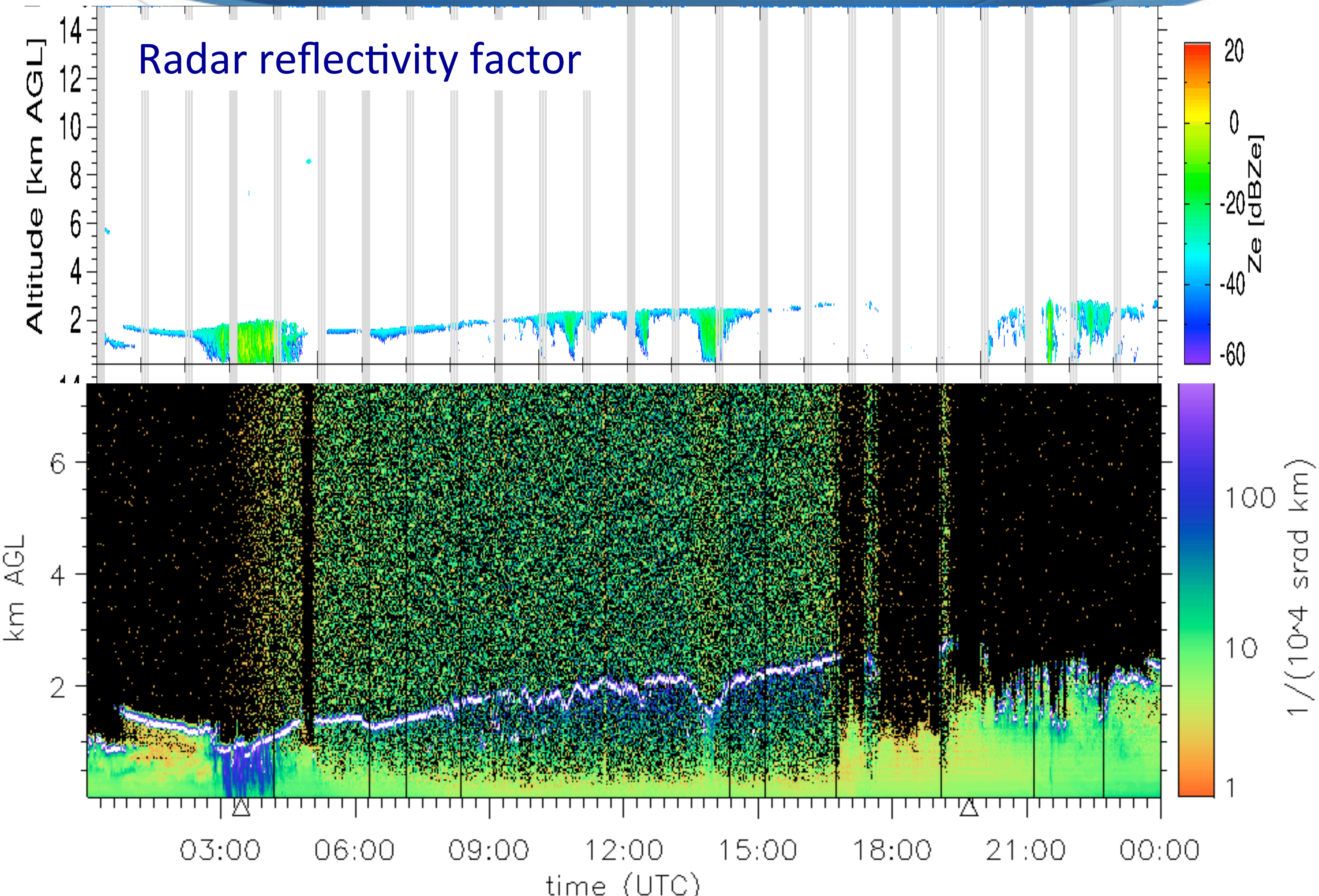
Cloud detection/cloud base height





Backscatter Coefficient from 140614_ct25k_jue_l0b
Detected cloud base height at JOYCE
Backscatter coefficient
Cloud stats.:
1st 84.8%
2nd 5.7%
3rd 0.2%
vvis 0.1%
max 0.1%
km AGL
1/(10^4 srad km)
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
time (UTC)

Cloud radar vs. ceilometer



Cloud radar

- active instrument: sends laser pulses (microwave spectrum, e.g. ~35 GHz, ~94 GHz)
  → sensitive towards cloud droplets

- backscatter proportional to D^6
  → few drizzle/rain drops dominate radar signal

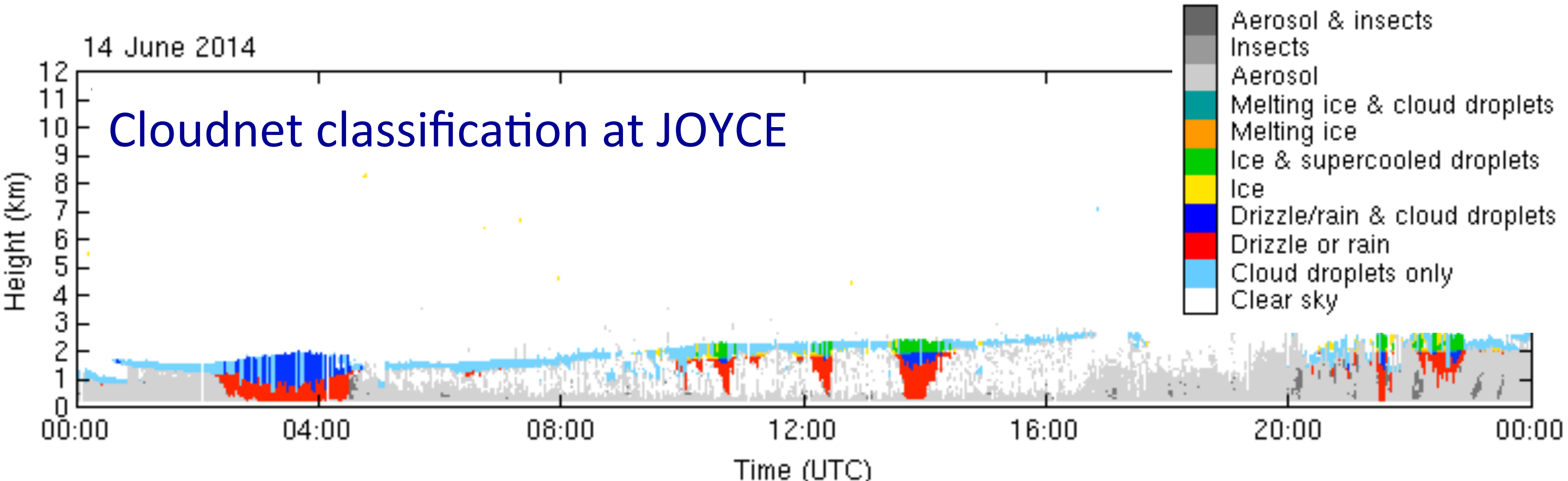
- measures backscattered signal
  →Doppler spectrum and moments: profiles of radar reflectivity, mean Doppler velocity, Doppler spectral width, linear depolarization ratio

www.arm.gov

Cloudnet cloud classification

- synergistic product based on measurements from **radar and ceilometer/lidar + additional information: MWR, radiosondes/NWP model data**

→ lidar backscatter, radar reflectivity, change of radar reflectivity with height, LDR, (change in) Doppler velocity, temperature profile



→ more on Clodnet and products **www.cloud-net.org** or ask Ewan!
also other, e.g. Shupe (2007), Active Remote Sensing of Clouds (ARSCL) VAP → $Z_{hydrom.}$

Liquid cloud property check list

- vertically resolved cloud mask ✔
- phase identification ✔
- liquid water path?
- vertical distribution of liquid water?
- effective radius of cloud droplets?

Microwave radiometer

- passive instrument measuring at different fequencies:
  - channels along the water vapor abs line (22 GHz) + 1 window channel at 31.4 GHz for cloud information
  - channels along oxygen abs. complex at 60 GHz provide vertical temperature information

Products & accuracies

→ Integrated Water Vapor (IWV): 0.6 kg m^{-2}

→ Liquid Water Path (LWP): 20 g m^{-2}

→ Hum. Profiles: 0.4-0.8 g m^{-3}
(2 degrees of freedom for signal)

→ Temp. profiles 0.5-1.0 K
(4 degrees of freedom for signal)

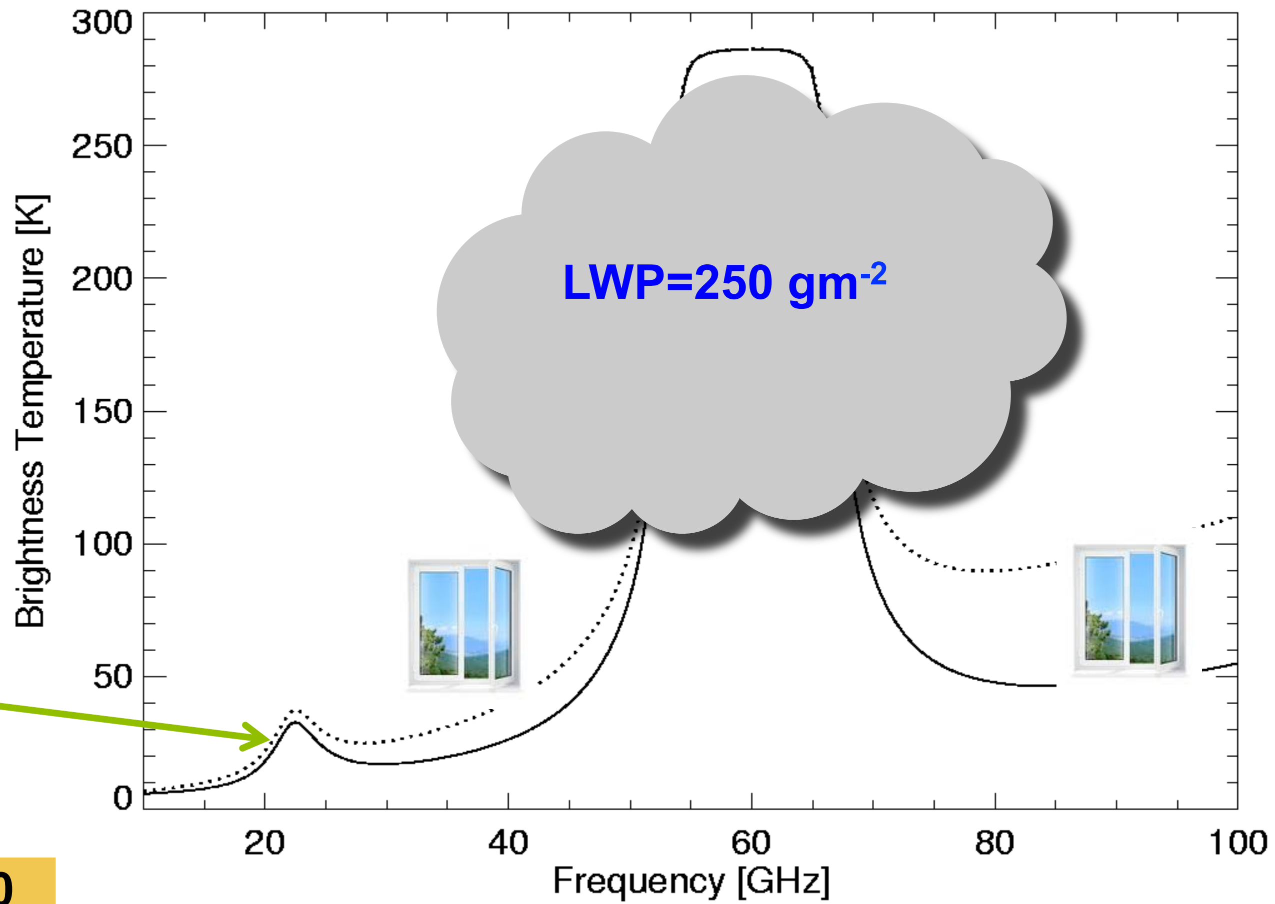
Retrieval of LWP and IWV from MWR

- Integrated Water Vapour (IWV)
- Liquid Water Path (LWP)

→ both integrated column amounts

10 kg m^{-2} correspond to a liquid column of 1cm

Amplitude of H_2O line is proportional to IWV

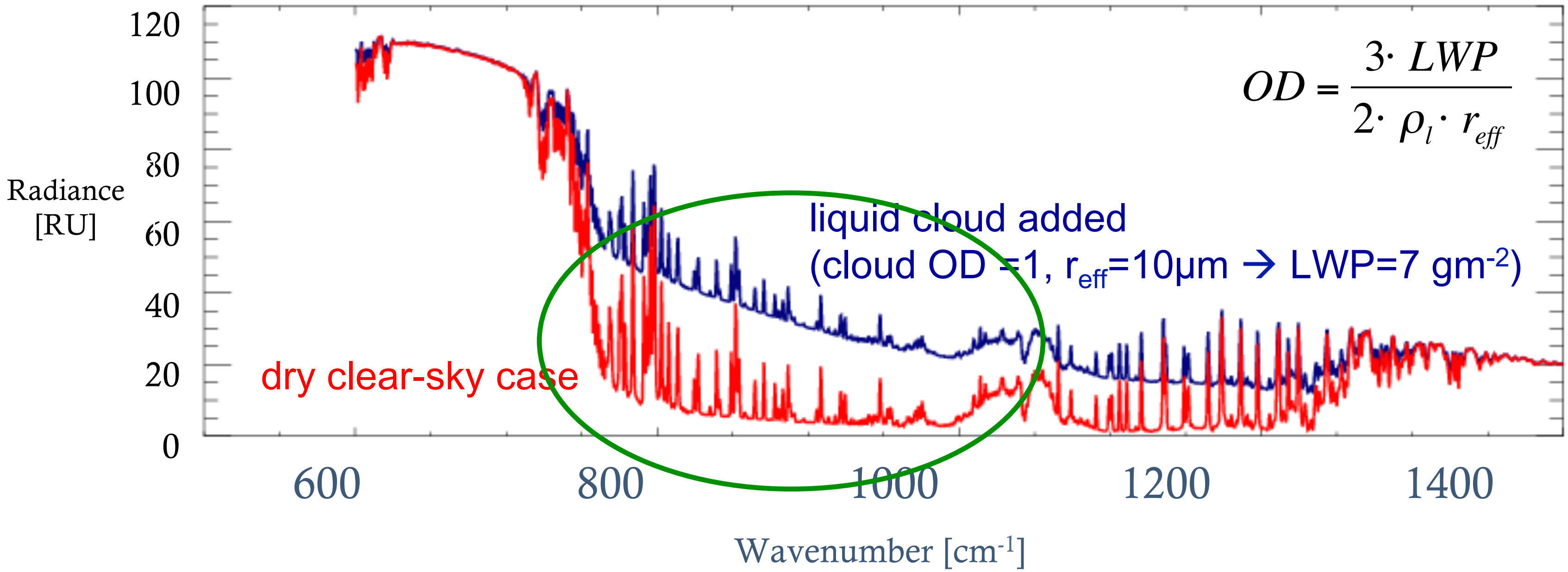


ν / GHz	31	36	90
ΔTB / K	9	12	50

$$LWP = a_1 + b_1 * TB_{31} - c_1 * TB_{24}$$

$$IWV = a_2 - b_2 * TB_{31} + c_2 * TB_{24}$$

Liquid clouds in the IR



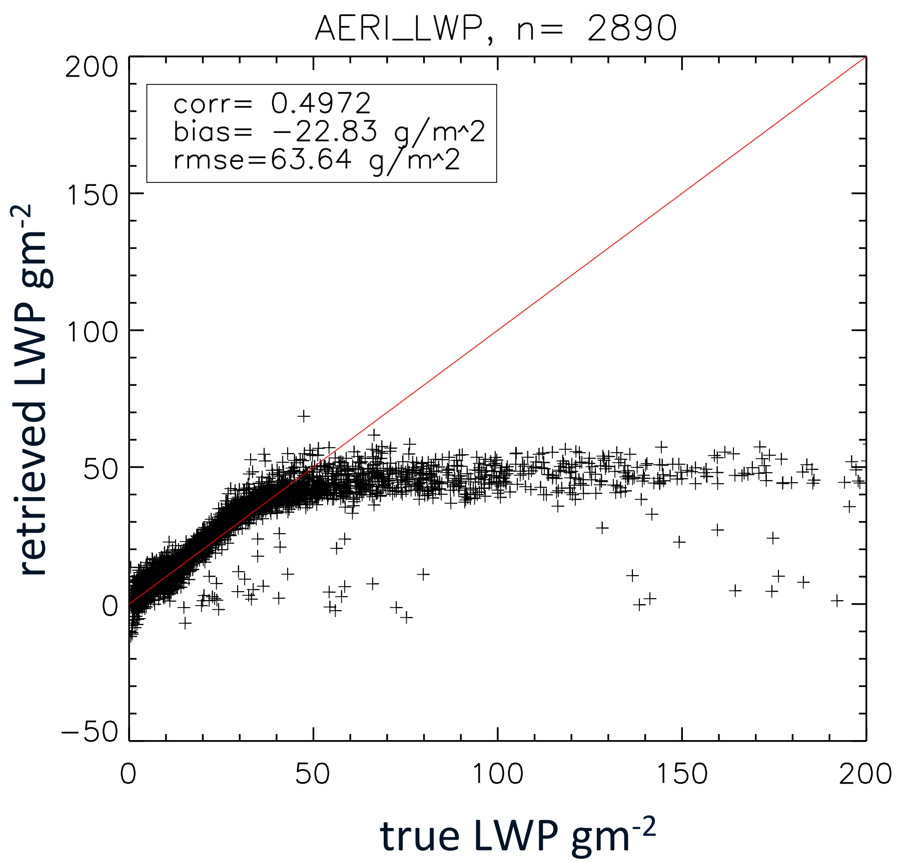
- **Offset** is sensitive to cloud optical depth (OD), **slope** to effective radius (r_{eff})

IR spectrometer

- multivariate regression based retrieval using AERI radiances

$$LWP = c_0 + \mathbf{c}_1 \mathbf{I}_{AERI} + \mathbf{c}_2 \mathbf{I}_{AERI}^2$$

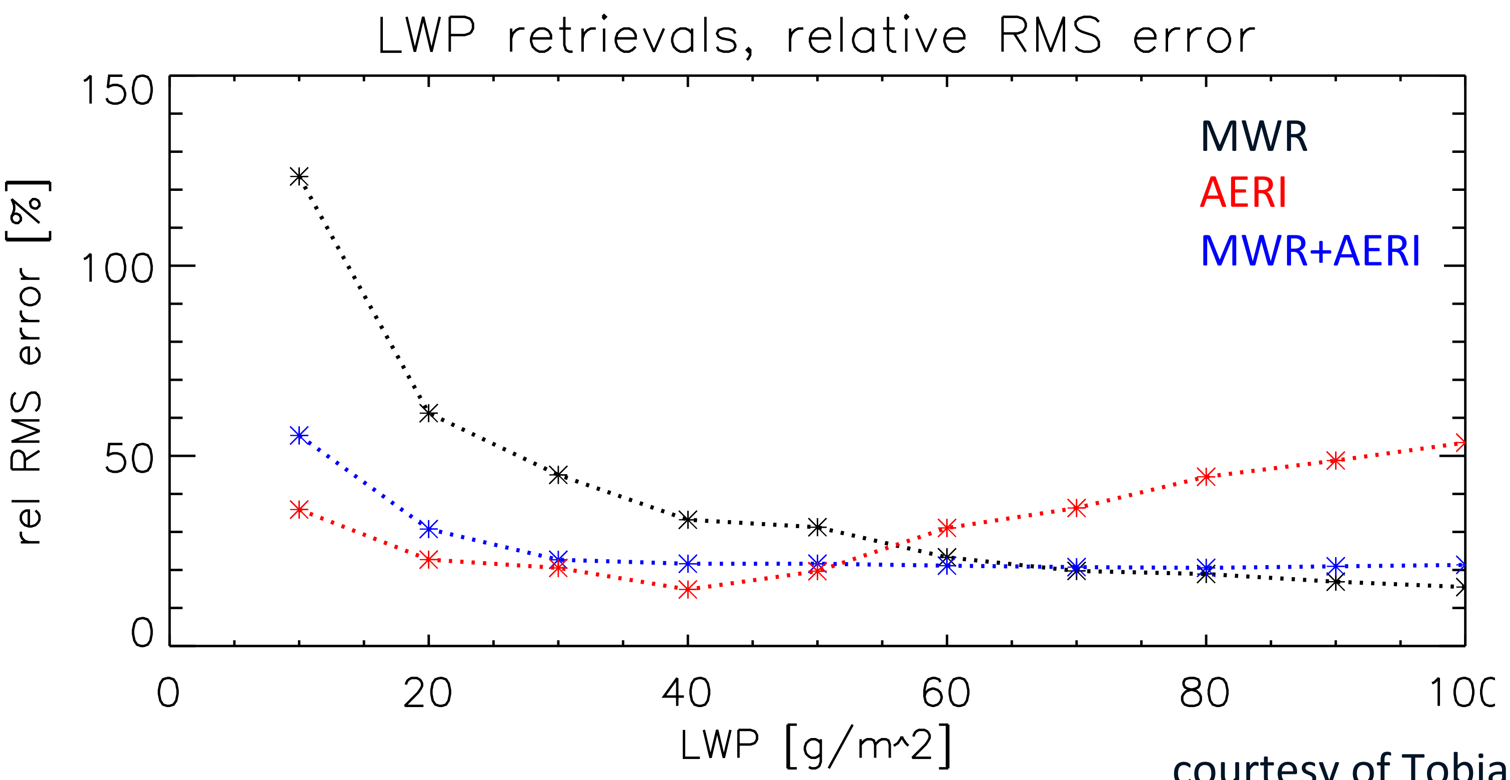
- Liquid clouds saturate the signal at LWP ≅ 60 gm^{-2}
- MWR needed for thicker clouds



courtesy of Tobias Marke

Combination of MWR + AERI

- results of a regression-based approach by T. Marke



courtesy of Tobias Marke

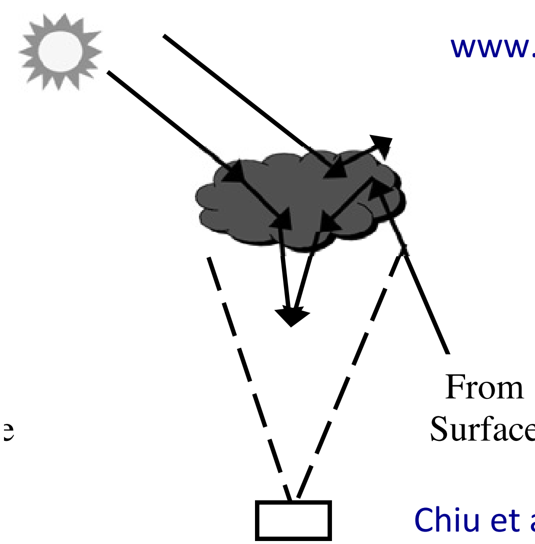
for variational-based approach see Turner (2007)

Sunphotometer

- sun/sky radiometers with a 1.2° field-of-view (FOV) that measure radiance at wavelengths of 440, (500), 675, 870, 1020, (1640) nm
  → clear-sky: microphysical and optical properties of aerosol
  Aerosol Robotic Network (AERONET)
  http://aeronet.gsfc.nasa.gov/

- cloudy sky: „cloud mode“: zenith radiance measurements 440, 870, 1640 → COT, r_{eff}

www.cimel.fr



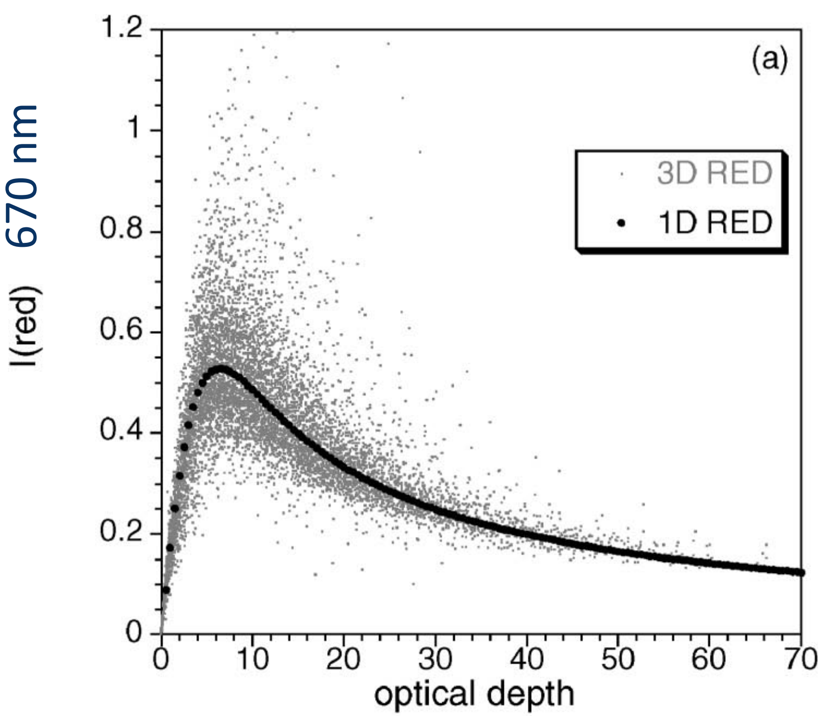
Chiu et al. (2006)

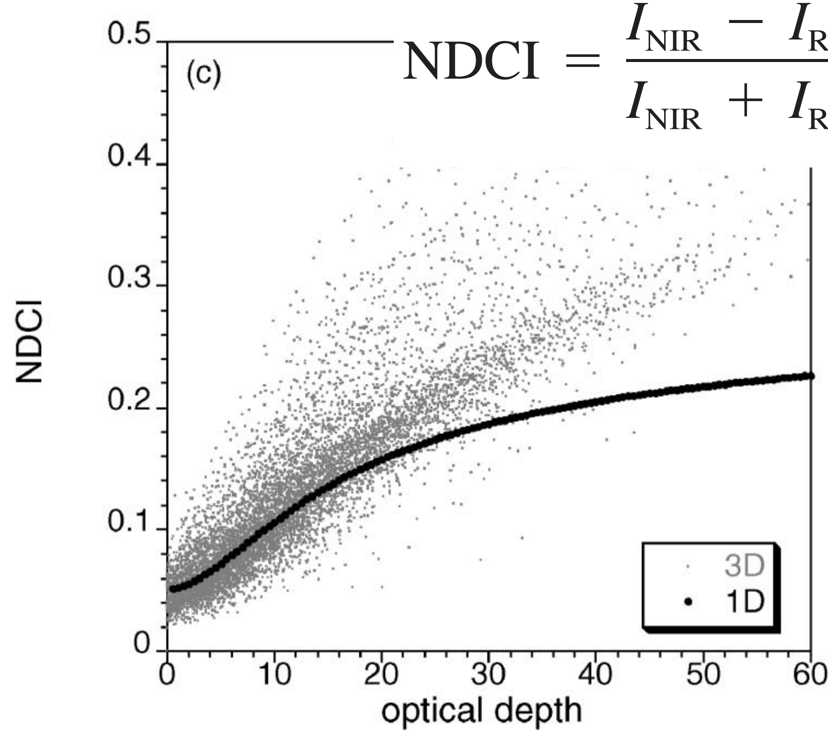
Sunphotometer

- principle: spectral contrast in surface reflectance
→ most vegetated surfaces are dark at red wavelengths and bright at NIR wavelengths → different surface-cloud interactions

870 nm 670 nm

$$\mathrm{NDCI} = \frac{I_{\mathrm{NIR}} - I_{\mathrm{RED}}}{I_{\mathrm{NIR}} + I_{\mathrm{RED}}}$$





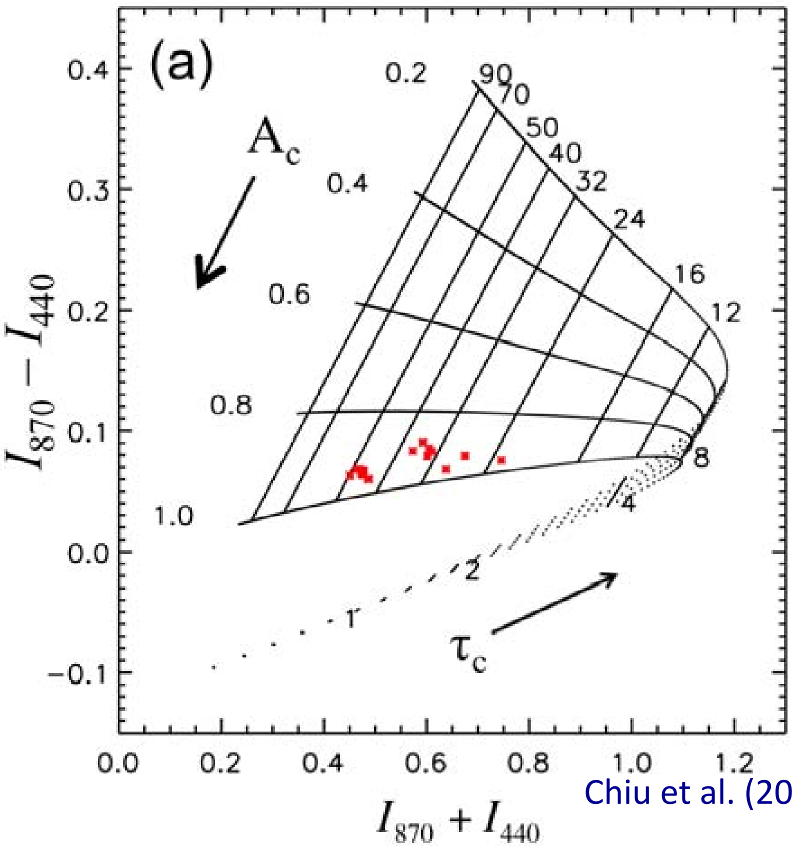
Marshak et al. (2004)

→ need to take into account for 3D-effects via a „radiatively effective“ cloud fraction A_c

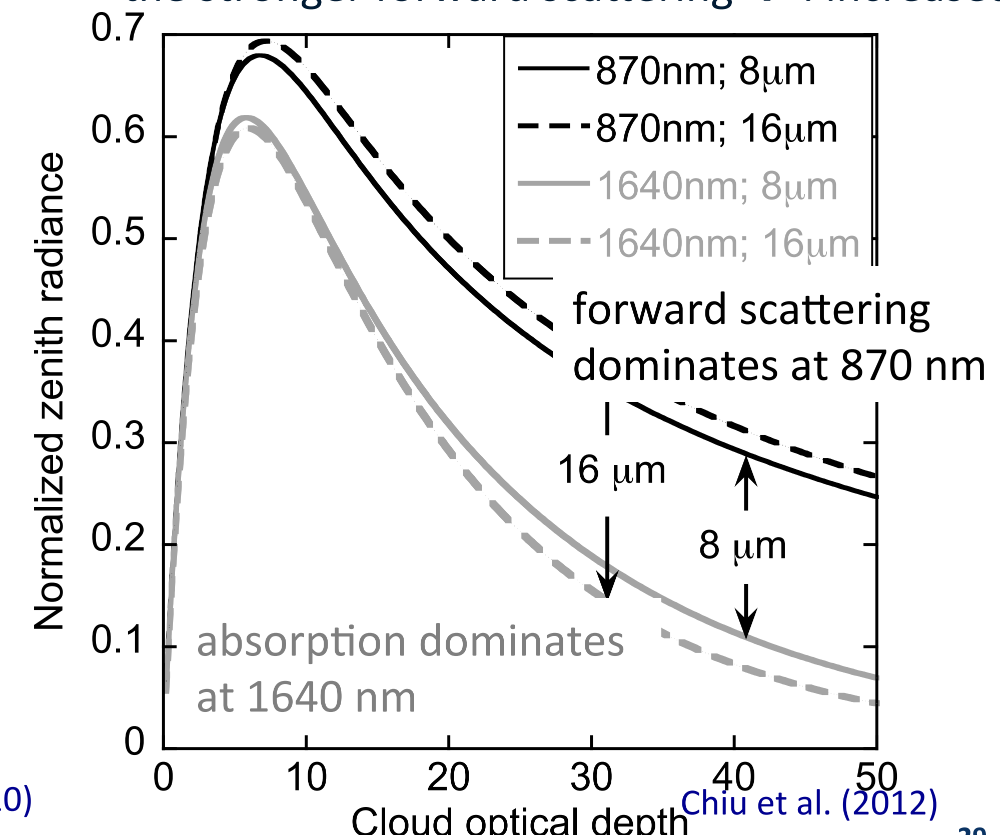
Sunphotometer

- look-up table approach: for differente COT and„effective“ cloud fraction A_c, precalculate zenith radiance measurements at 440 and 870
- inclusion of 1640 nm → r_{eff}

the larger r_{eff}
- the stronger absorption → I reduced
- the stronger forward scattering → I increased



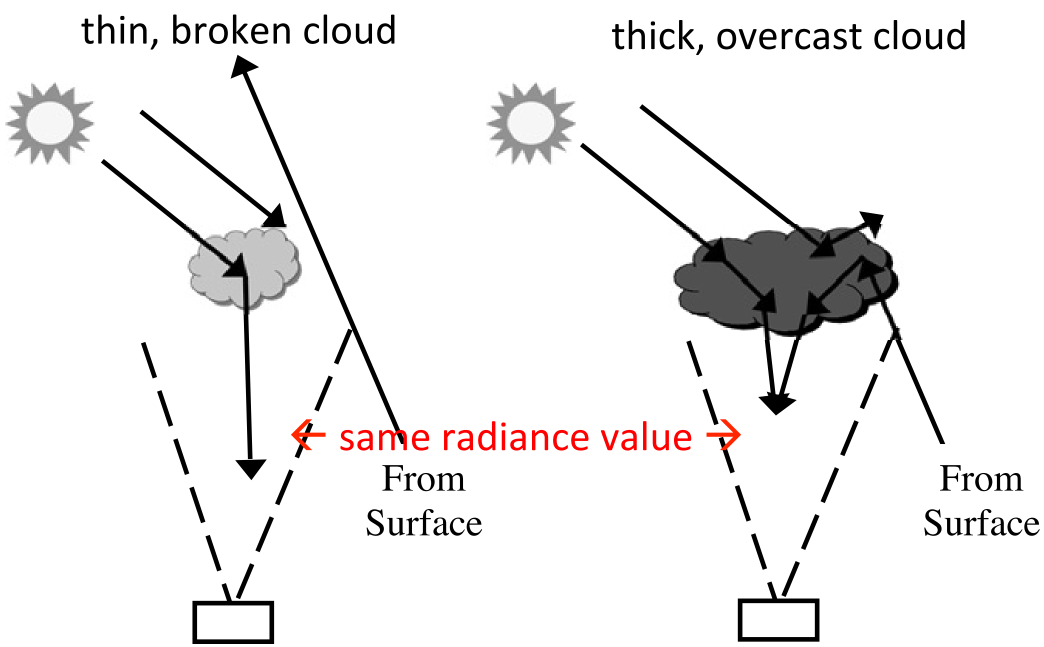
Chiu et al. (2010)



Chiu et al. (2012)

Sunphotometer

- clear-sky contamination



Chiu et al. (2006)

→ method works best for overcast cloud scenes

→ COT error 15-25 %, r_{eff} error 11-22 %

→ ice clouds above ok, as long as liquid fraction > 0.2 (25% error in COT)

Liquid cloud property check list

- vertically resolved cloud mask ✔
- phase identification ✔
- liquid water path ✔ cloud optical thickness, layer-averaged r_{eff} ✔
- vertical distribution of liquid water?
- effective radius of cloud droplets?

→ active remote sensing methods

Cloud radar: Z-LWC relations

*k*th moment of DSD:

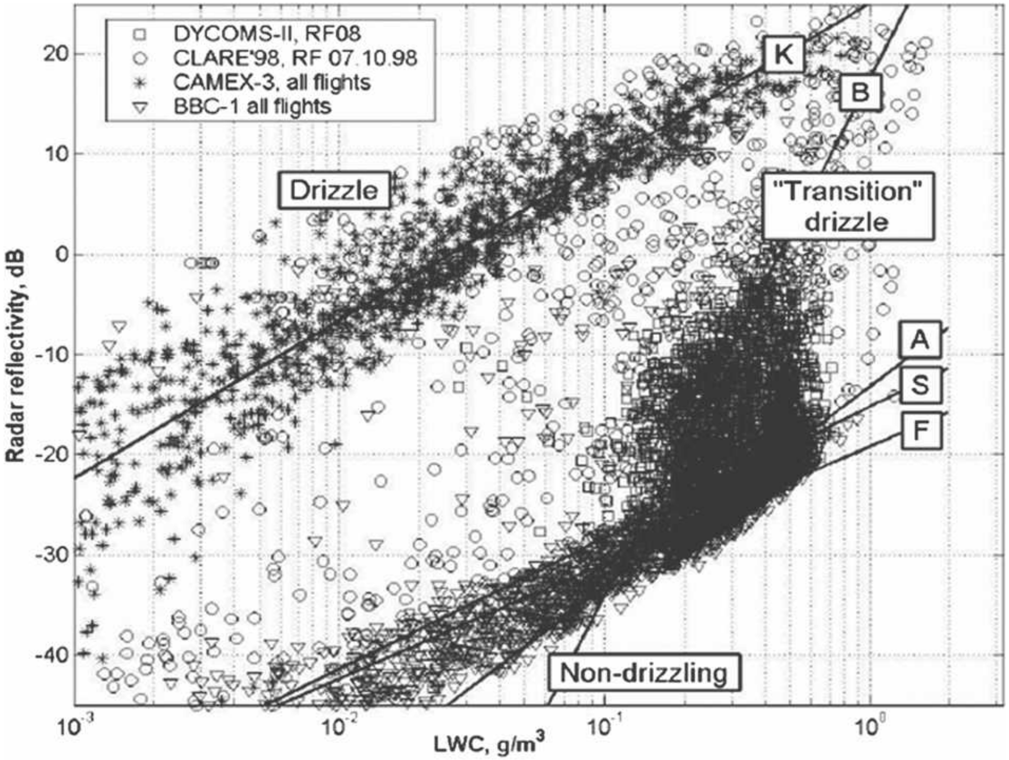
$$M_k = \int_0^\infty D^k N(D)\,dD$$

$$LWC = \frac{\pi\rho_l}{6} M_3$$

$$Z = \int_0^\infty D^6 N(D)\,dD = M_6$$

→ Z=a LWC^b

- problem: N(D) results from a number of complex processes and is therefore highly variable even within a cloud!



Khain et al. (2008)

→ many Z-LWC relations : Atlas (1954); Sauvageot and Omar (1987); Fox and Illingworth (1997); Khain et al. (2008),...

→ large uncertainty, particularly if drizzle drops are present

LWC from dual-frequency radar

- in Rayleigh regime (r <<λ), attenuation of MW radiation is proportional to LWC and increases with frequency → use rate of change with height of DWR=Z_{35}-Z_{94} to deduce LWC

adjustment to account for change in dieletric constants with temperature

$$\overline{\mathrm{LWC}} = \frac{1}{\kappa_{94} - \kappa_{35}} \left(\frac{\mathrm{DWR}_2 - \mathrm{DWR}_1 - \beta}{2(h_2 - h_1)} - \alpha_{94} + \alpha_{35} \right)$$

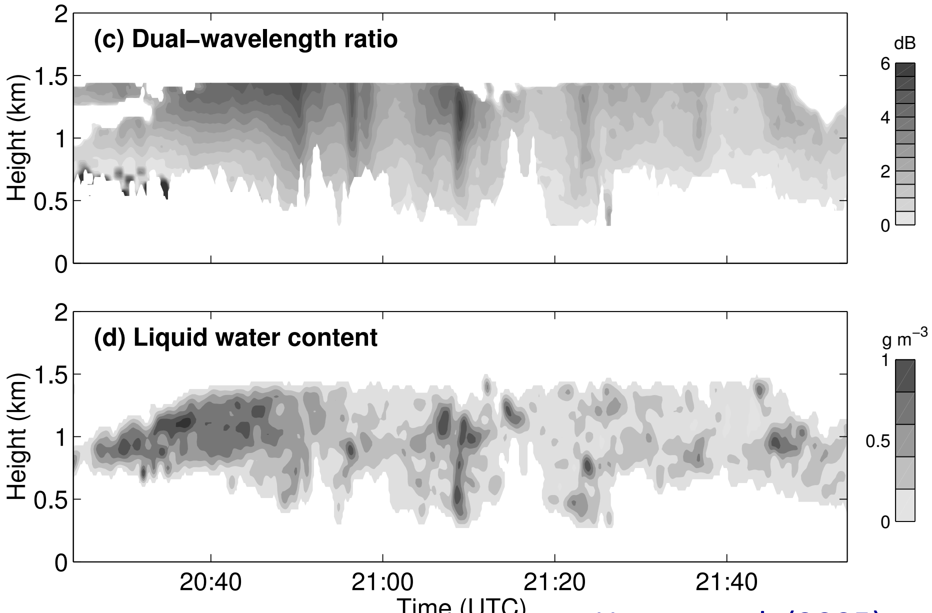
liquid absorption coeff.

atm. absorption coeff.

- each 1 dB difference corresponds to a LWP of ~120 gm^{-2}

advantage: no assumptions on DSD, insensitive to absolute calibration, presence of drizzle drops does not effect the retrieval

LWC accuracy depends on SNR, limited by number of independent measurements



Hogan et al. (2005)

Radar + MWR

- **LWC profile**: MWR LWP is used to scale LWC profile from Z measurements

$$LWC(h) = \frac{Z^{1/2}(h)}{\sum_{i=cb}^{ct} Z_i^{1/2} \Delta h} LWP_{MWR}$$

Frisch et al. (1998)

Δh: radar range gate thickness

- **r_{eff} profile**:
  e.g Frisch et al. (2002):
  assuming lognormal DSD → $n(r) = \frac{N_{tot}}{\sqrt{2\pi}\sigma_x} \exp\left(-\frac{(\ln r - \ln r_0)^2}{2\sigma_x}\right)$
  N(h)=const
  assuming σ_x

$$r_{eff}(h) = \frac{Z^{1/6}(h)}{2LWP_{MWR}} \left(\frac{\pi\rho}{6}\right)^{1/3} \left(\sum_{i=cb}^{ct} Z^{1/2}(h_i)\Delta h\right)^{1/3} \exp(-2\sigma_x^2)$$

Variational-based retrieval methods

observations **y:**
TB Z ...
+ error estimates

forward model
$F(T,q,LWC,r_{eff})=y$
+ error estimates

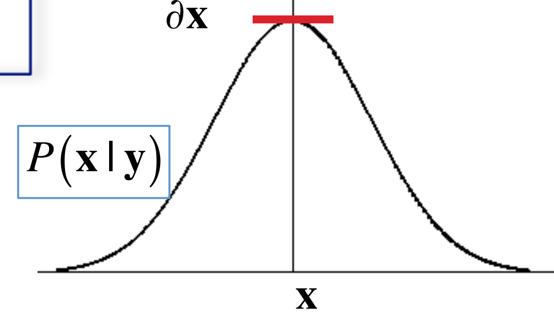
atmospheric state **x:**
T q LWC r_{eff} ...
+ error estimates

- prior information, observations and forward model have uncertainties
  → represent probability distributions

prior information on atmospheric state **x:**
T q LWC r_{eff} ...
+ error estimates

Bayes Theorem $$P(\mathbf{x}\,|\,\mathbf{y}) = \frac{P(\mathbf{y}\,|\,\mathbf{x})P(\mathbf{x})}{P(\mathbf{y})}$$

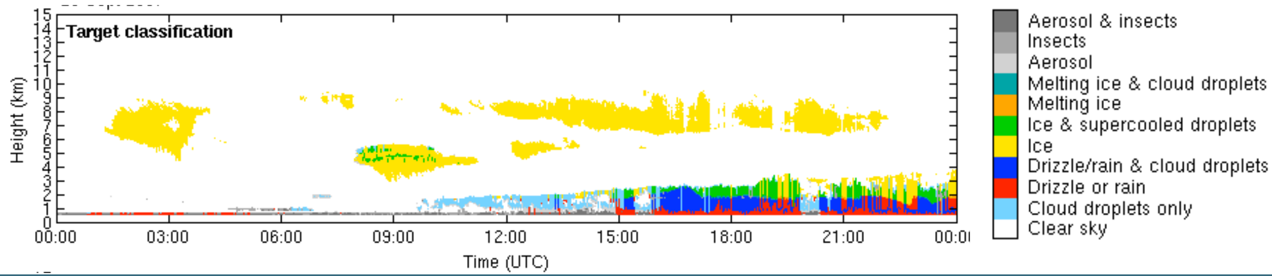
$$\frac{\partial P(\mathbf{x}\,|\,\mathbf{y})}{\partial \mathbf{x}} = 0$$



- does provide a class of solutions and assignes a probability density to each

Integrated profiling technique IPT

Cloudnet Target Categorization product (Illingworth et al., 2007)



prior information
$\mathbf{x}_a$= [T, q, LWC, reff]
with error covariance matrix **$\mathbf{S}_a$**

forward model F(x)=y
with error covariance matrix **$\mathbf{S}_e$**

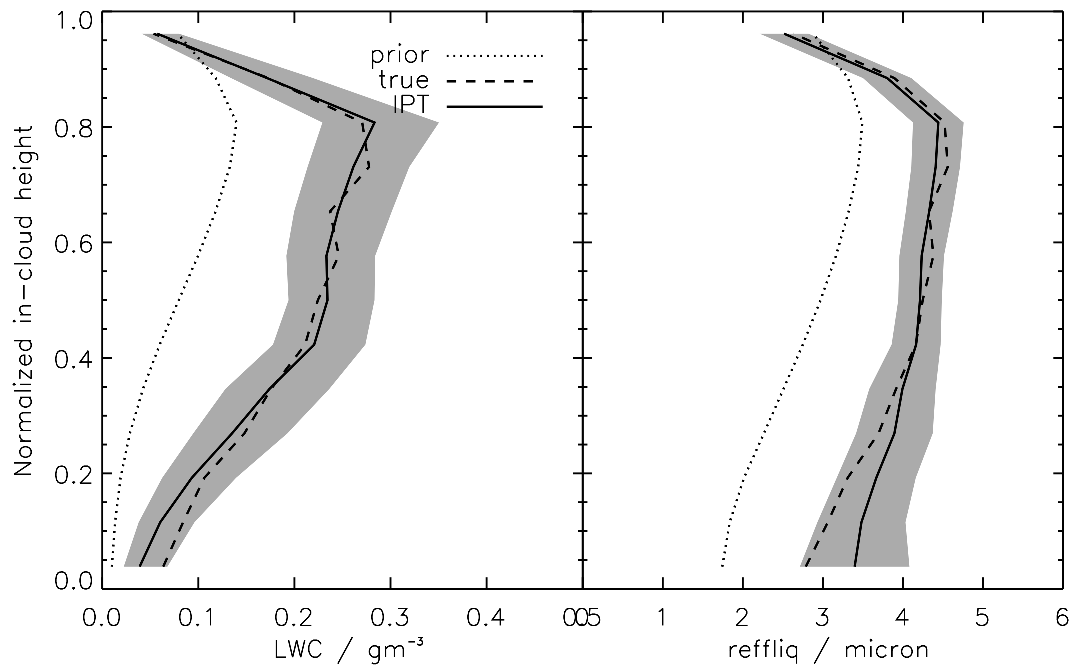
measurements y=[TB,Z]
with error covariance matrix **$\mathbf{S}_e$**

1 D variational retrieval algorithm (optimal estimation equation, e.g. Rodgers, 2000)

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \left(\frac{\partial \mathbf{F}(\mathbf{x}_i)}{\partial \mathbf{x}_i}^T \mathbf{S}_e^{-1} \frac{\partial \mathbf{F}(\mathbf{x}_i)}{\partial \mathbf{x}_i} + \mathbf{S}_a^{-1} \right)^{-1} \times \left[\frac{\partial \mathbf{F}(\mathbf{x}_i)}{\partial \mathbf{x}_i}^T \mathbf{S}_e^{-1} \left(\mathbf{y} - \mathbf{F}(\mathbf{x}_i) \right) + \mathbf{S}_a^{-1} \left(\mathbf{x}_a - \mathbf{x}_i \right) \right]$$

minimizing cost function → $\mathbf{x}_{op}$=[**T, q, LWC, reff**] with **$\mathbf{S}_{op}$**

IPT: synthetic data study



- know the „truth“: liquid cloud with Δz=370 m (13 levels), LWP=65 gm^{-2}

→ simulate **TB, Z** → IPT

- IPT can very well reproduce the truth **σ_{reff}≈10%, σ_{LWC}≈30%**
- „Degrees of freedom for signal“: How much information in the retrieved profile comes from the Z and TB measurements? **LWC: 38% , r_{eff}: 34%**
- weight of measurements/prior information in the solution determined by their error covariance matrices

y error	1x	2x	3x
LWC			
rel. DOF / %	**38**	**31**	**27**
rel. err. / %	**31**	**38**	**45**
r_{eff}			
rel. DOF / %	**34**	**29**	**26**
rel. err. / %	**10**	**13**	**16**

Variational-based methods

- provide **physically consistent** solution
(and if not, something is wrong with your measurements, assumptions,...)
- directly provide **retrieval uncertainties** based on assumed measurement, forward model and prior uncertainties

Be aware that

- **prior information is crucial**: constrains solution space
- **error covariance matrices**, i.e. uncertainties of prior information, forward model, and measurements, need to be **carefully defined**
- **prior information** and its error often **difficult to determine**
(e.g. cloud profile, correlation of cloud layers?)
- variables and errors are **Gaussian distributed**
→ bias / offset errors can not be handled and need to be removed before

Liquid clouds: Still a need for research?

YES!

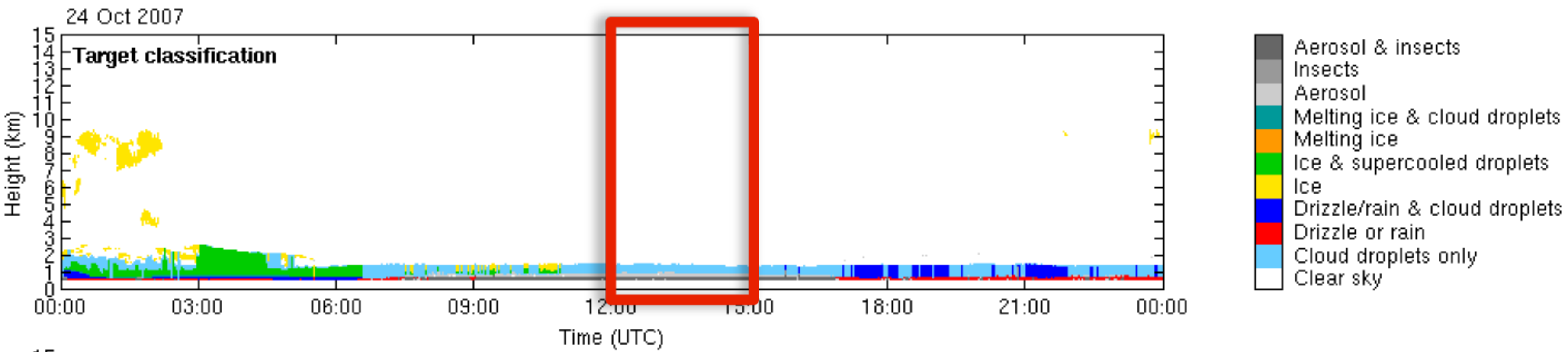
- many cloud retrievals only applicable in certain atmospheric/cloudy conditions
- liquid cloud as a result of complex processes
  → difficult to develop robust „universal" methods
- „perfect" liquid water clouds rarely exist: e.g. drizzle, droplets+ice,...
  → Doppler spectra analysis
  → improved phase detection
- maximize information by integrating as many as observations as possible, e.g. radar, lidar, MWR, IR and solar radiances,...
  → high demands on measurements: data quality (e.g. bias-free measurements), spatial+temporal matching,...

Liquid clouds: Still a need for research?

Thanks for listening!

Now, it's up to you...

Let's have a look at this stratus cloud observed by AMF instruments on 24 October 2007 in the Murg Valley, Black Forest (Germany)



I want you to answer a simple (?) question:

What is the **mean liquid water path** of the cloud observed between 12-15 UTC?

→ use data in file: lwp_exercise.nc
(data are already sampled for this time window)

What is the **mean liquid water path** of the cloud observed between 12-15 UTC?

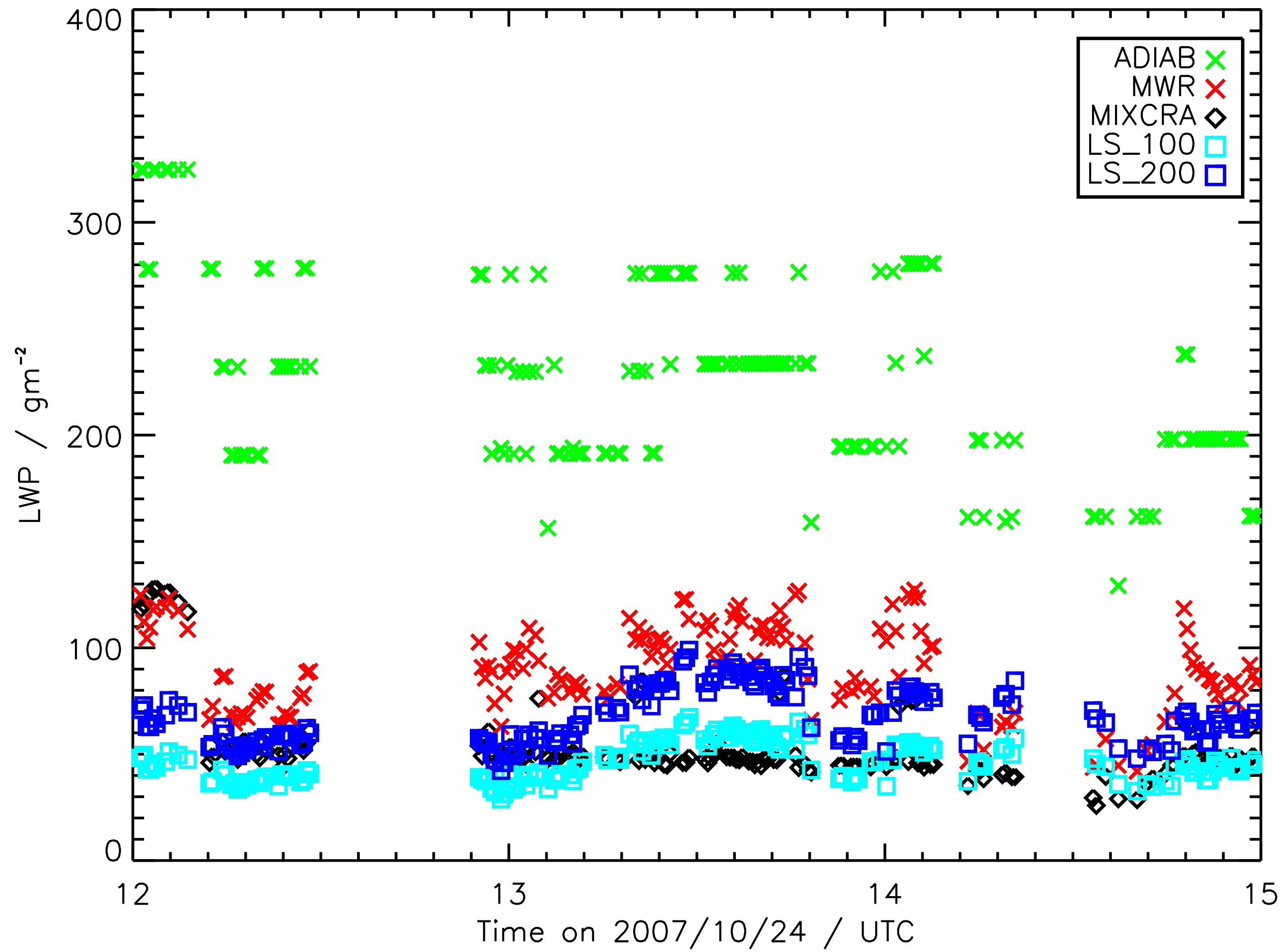
data in file: lwp_exercise.nc

- **time** [time]
- **lwp_ad** [time] (gm^{-2}): adiabatic LWP
- **lwp_mixcra** [time] (gm^{-2}): LWP from MIXCRA (variational-based retrieval using MWR and AERI)
- **lwp_mwr** [time] (gm^{-2}): LWP from MWR (a two-channel, regression-based retrieval)
- **Z** [time, cloudlayer] (mm^6/m^3): radar reflectivity factor (fill values -9999. !)
- **rg**: radar range gate length (m)
  → to calculate lwc profile for each time step from Z use the relationship from *Liao and Sassen* (1994)

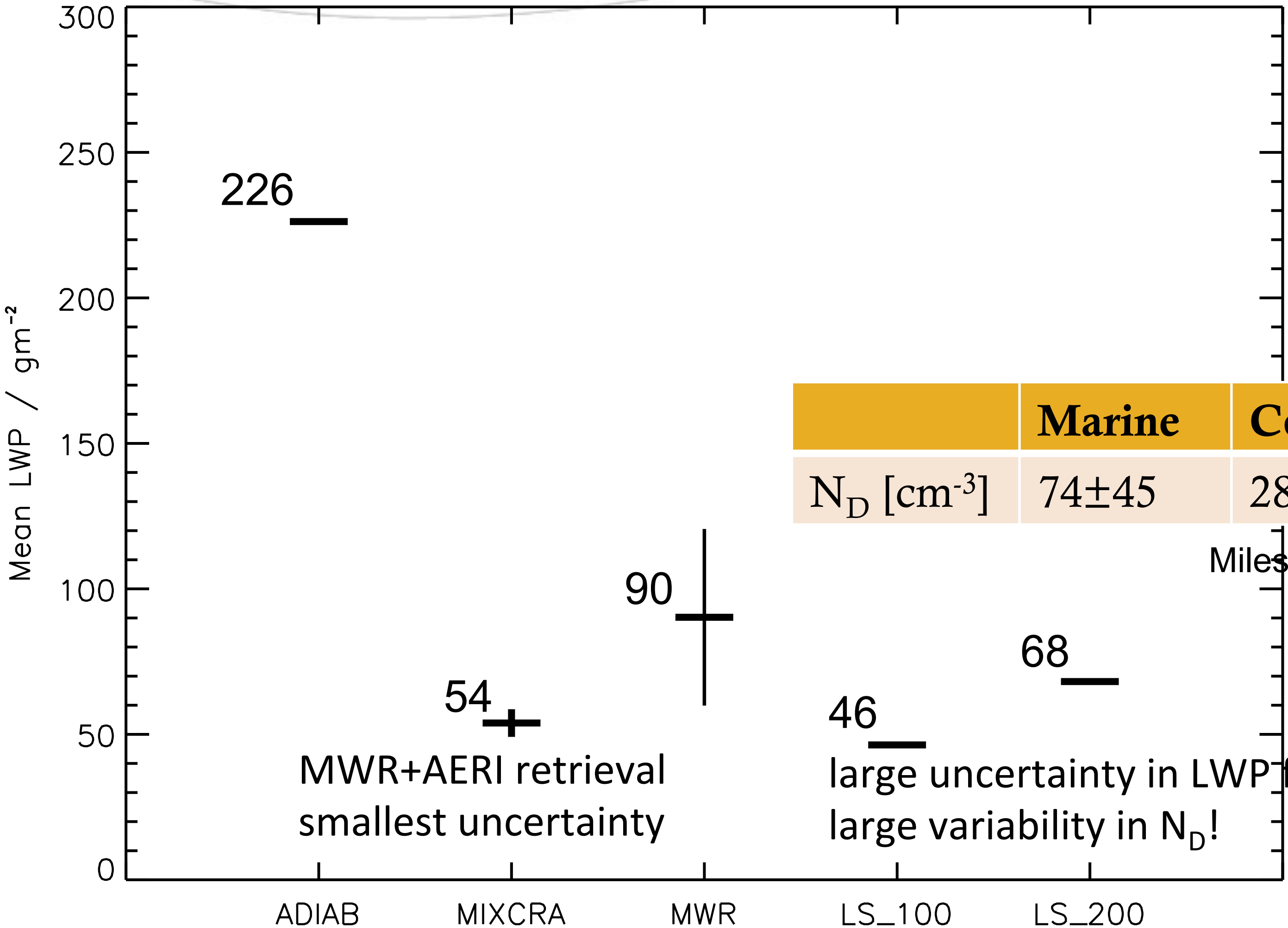
$$LWC = \left(\frac{Z N_d}{3.6} \right)^{1/1.8}$$

with LWC in gm^{-3}, Z in mm^6/m^3, N_d droplet number concentration in cm^{-3}
set N_d=100 cm^{-3} ? 200 cm^{-3} ?
→ **lwp_radar** for each time step is then **TOTAL(lwc_radar*rg)**

LWP on 24 October 2007



Mean LWP on 24 October 2007, 12-15 UTC



	Marine	Continental
N_D [cm^{-3}]	74±45	288±159

Miles et al. (2000)

MWR+AERI retrieval
smallest uncertainty

large uncertainty in LWP from radar
large variability in N_D!

all methods reveal subadiabtic clouds

ARM → could perform radiative closure study (SW/LW) to further check with method is best