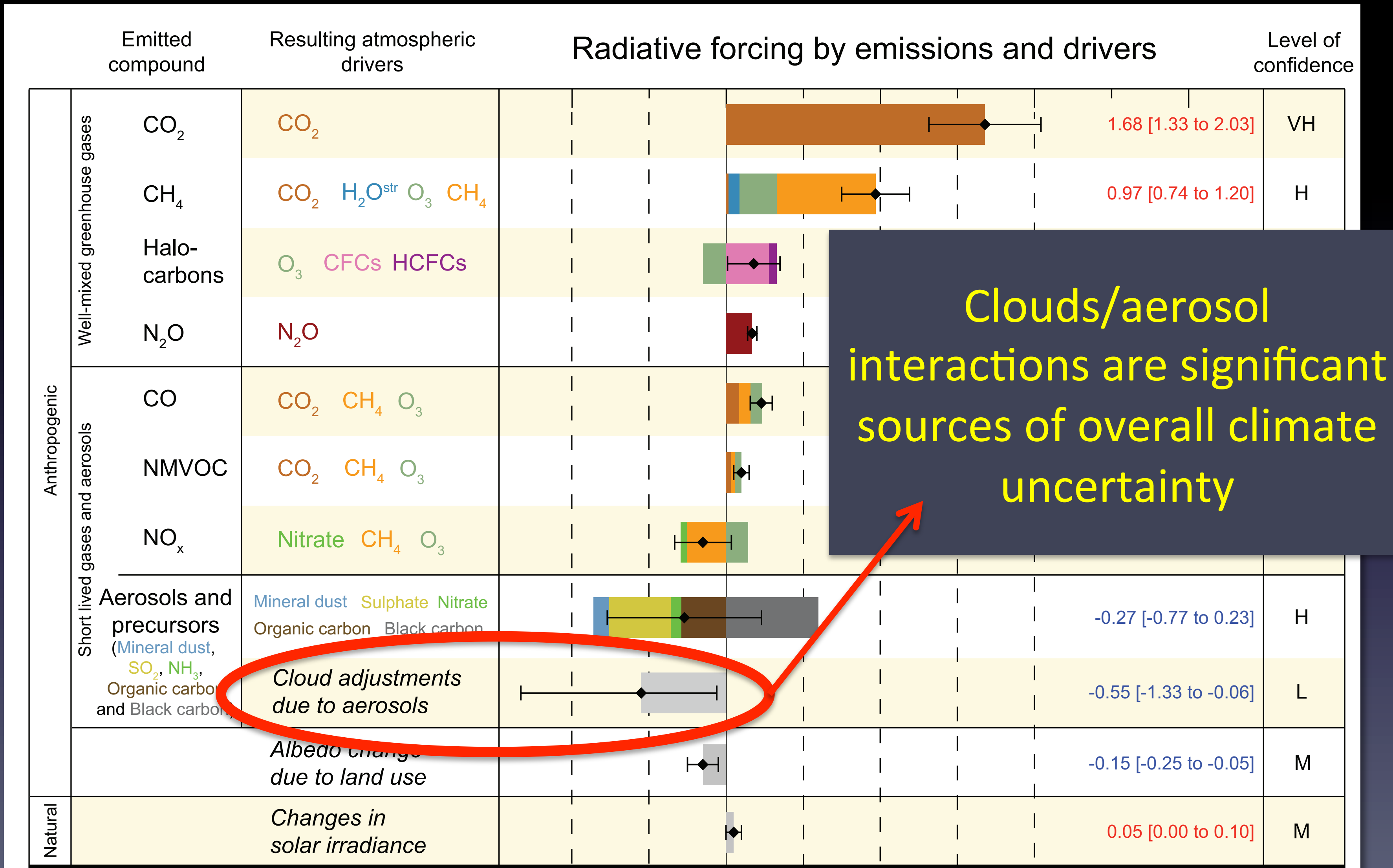
Improving our understanding of clouds in the Earth's climate using polarimetry

K. Knobelspiesse[1], S. Dunagan[1],
B. van Diedenhoven[2], A. Marshak[3] and B. Holben[3]

[1] NASA Ames Research Center, Moffett Field, CA
[2] NASA Goddard Institute for Space Studies & Columbia University, New York, NY
[3] NASA Goddard Space Flight Center, Greenbelt, MD

- Cloud relevance to earth climate
- AERONET cloud measurements
- Polarimetry as a cloud observation tool
  - Simulation results
  - Data exploration
- Next steps, instrument development

Cloud relevance to earth climate



From Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, SPM.5

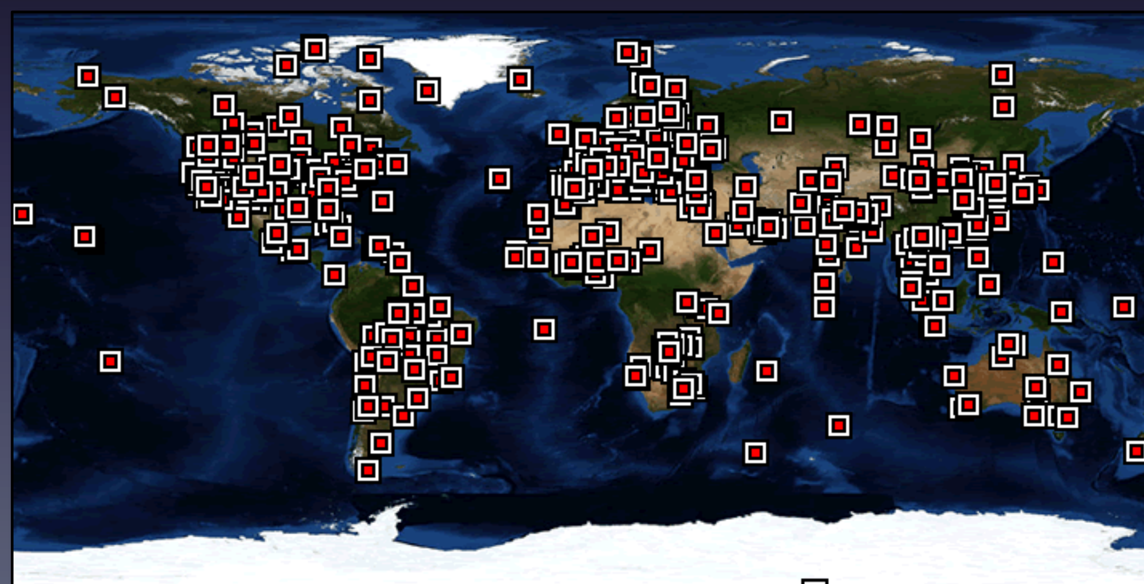
AERONET cloud measurments

AERONET (AErosol RObotic NETwork)

long term network of sun photometers

Observes Aerosol Optical Depth (AOD) + aerosol microphysical properties

AERONET comprises hundreds of Cimel sun photometers and many locations globally

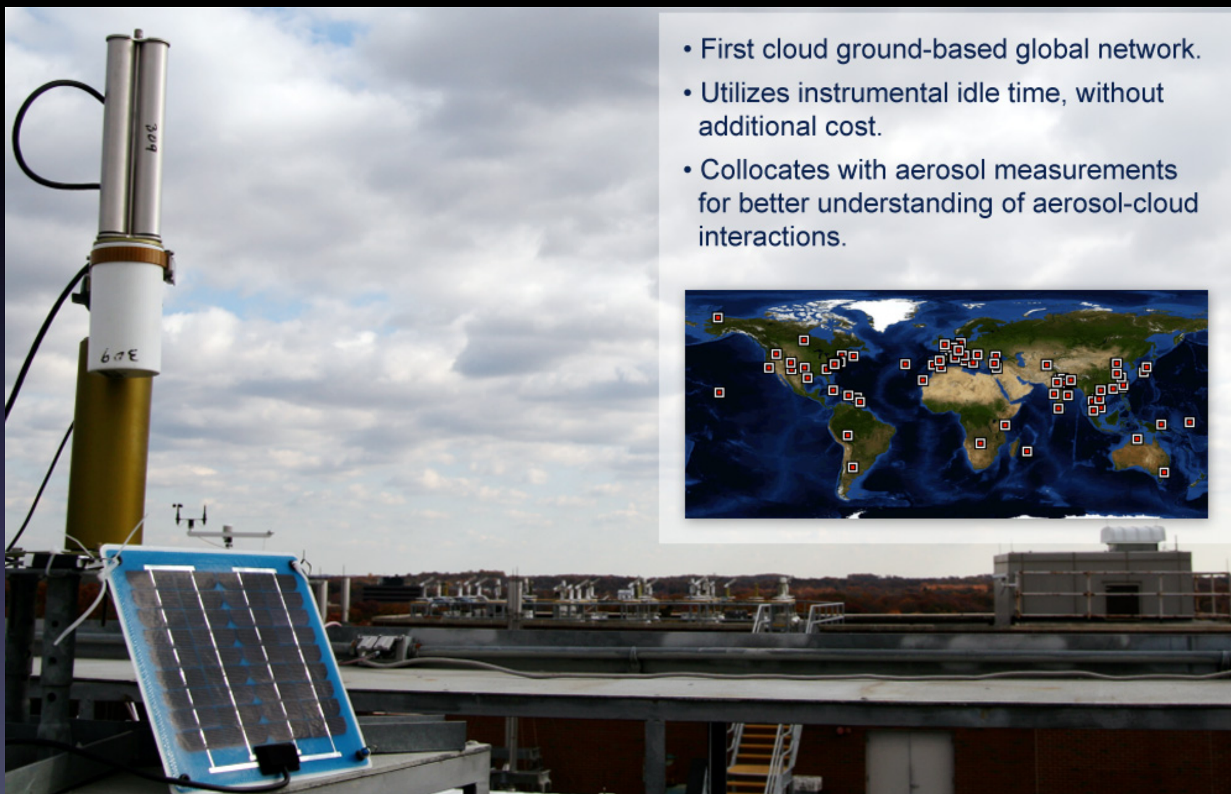


Typically AERONET instruments “sleep” when clouds cover the sun

Data available: aeronet.gsfc.nasa.gov

AERONET cloud measurments

Chiu, J. C., Huang, C.-H., Marshak, A., Slutsker, I., Giles, D. M., Holben, B. N., Knyazikhin, Y., and Wiscombe, W. J., 2010: Cloud optical depth retrievals from the Aerosol Robotic Network (AERONET) cloud mode observations. *J. Geophys. Res.*, 115 (D14202), .



From NASA Climate & Radiaiton Science Research portal January 1, 2012 monthly highlight: atmospheres.gsfc.nasa.gov/climate/index.php?section=172

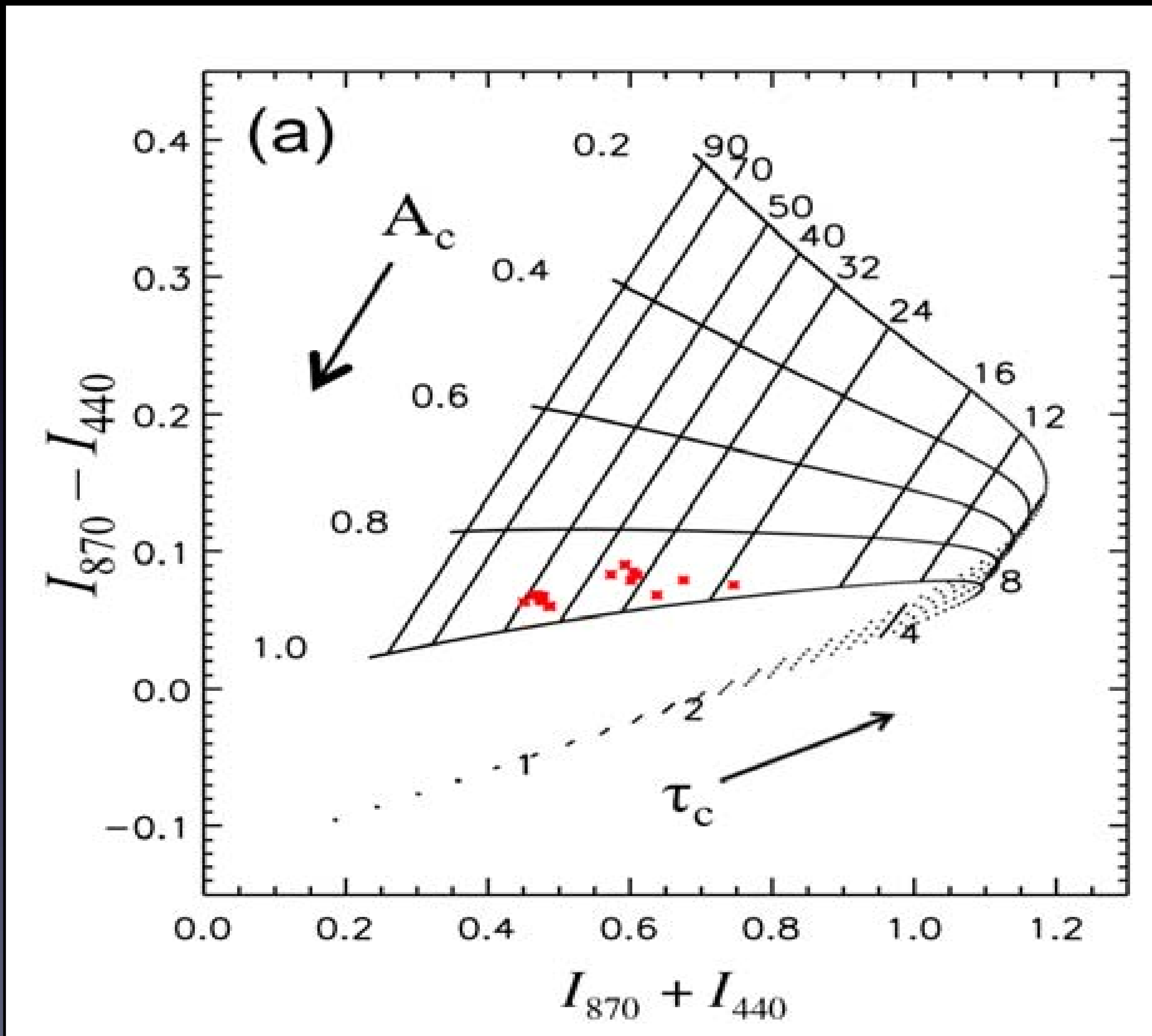
Instead of "sleep" for clouds, instruments make a zenith measurement

Radiances at 870nm and 440nm used to determine Cloud Optical Depth (COD) and Cloud Fraction (A_c)

Basis: spectral contrast of vegetation reflection vs. 'white' clouds

AERONET cloud measurments

From Chiu et al. (2010)



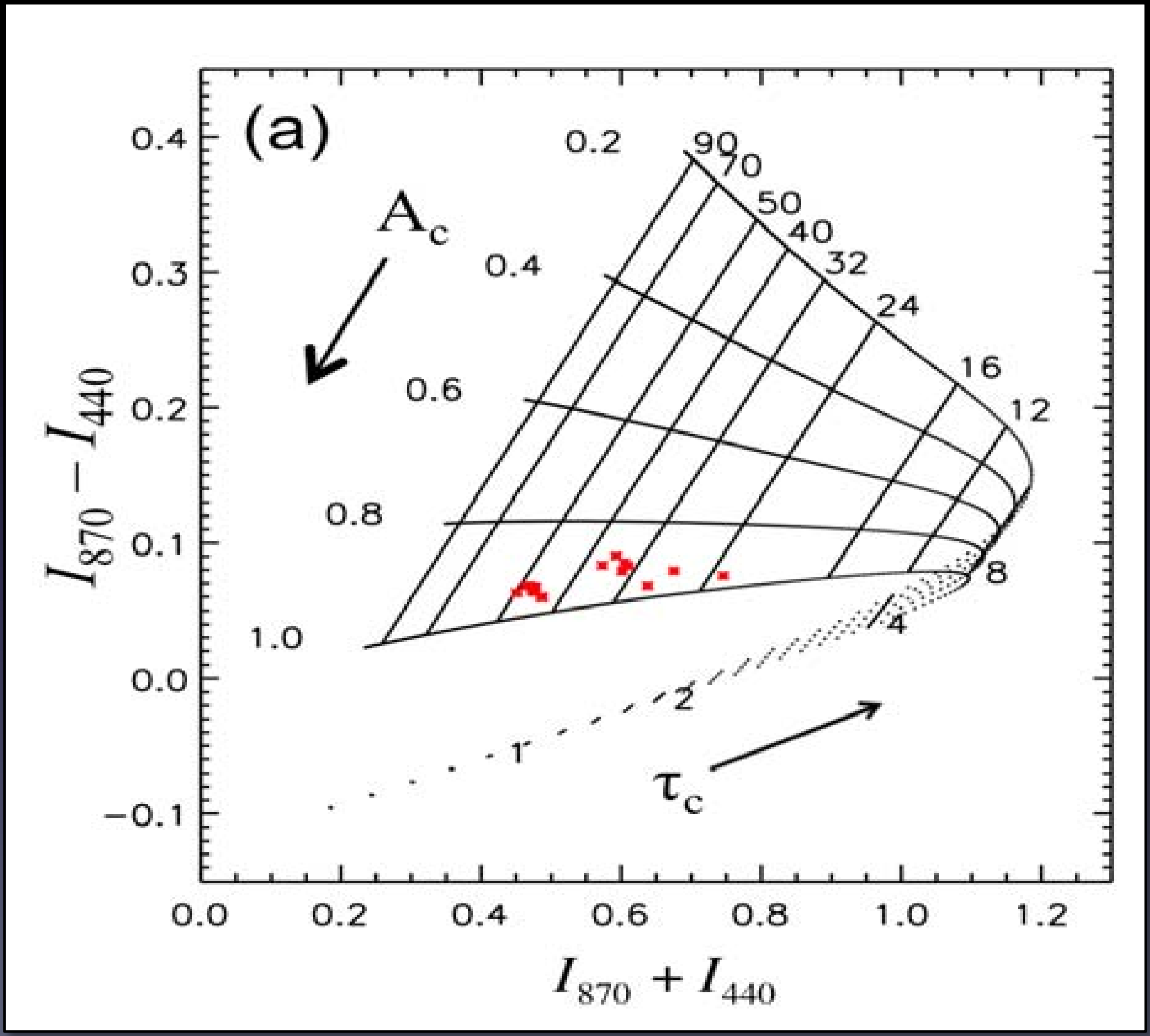
Instead of "sleep" for clouds, instruments make a zenith measurement

Radiances at 870nm and 440nm used to determine Cloud Optical Depth (COD) and Cloud Fraction (A_c)

Basis: spectral contrast of vegetation reflection vs. 'white' clouds

AERONET cloud measurments

From Chiu et al. (2010)



LUT at left is appropriate for liquid clouds, there is another ice clouds

Which to use?

Standard measurements do not indicate thermodynamic phase, incorrect selection is a large source of error

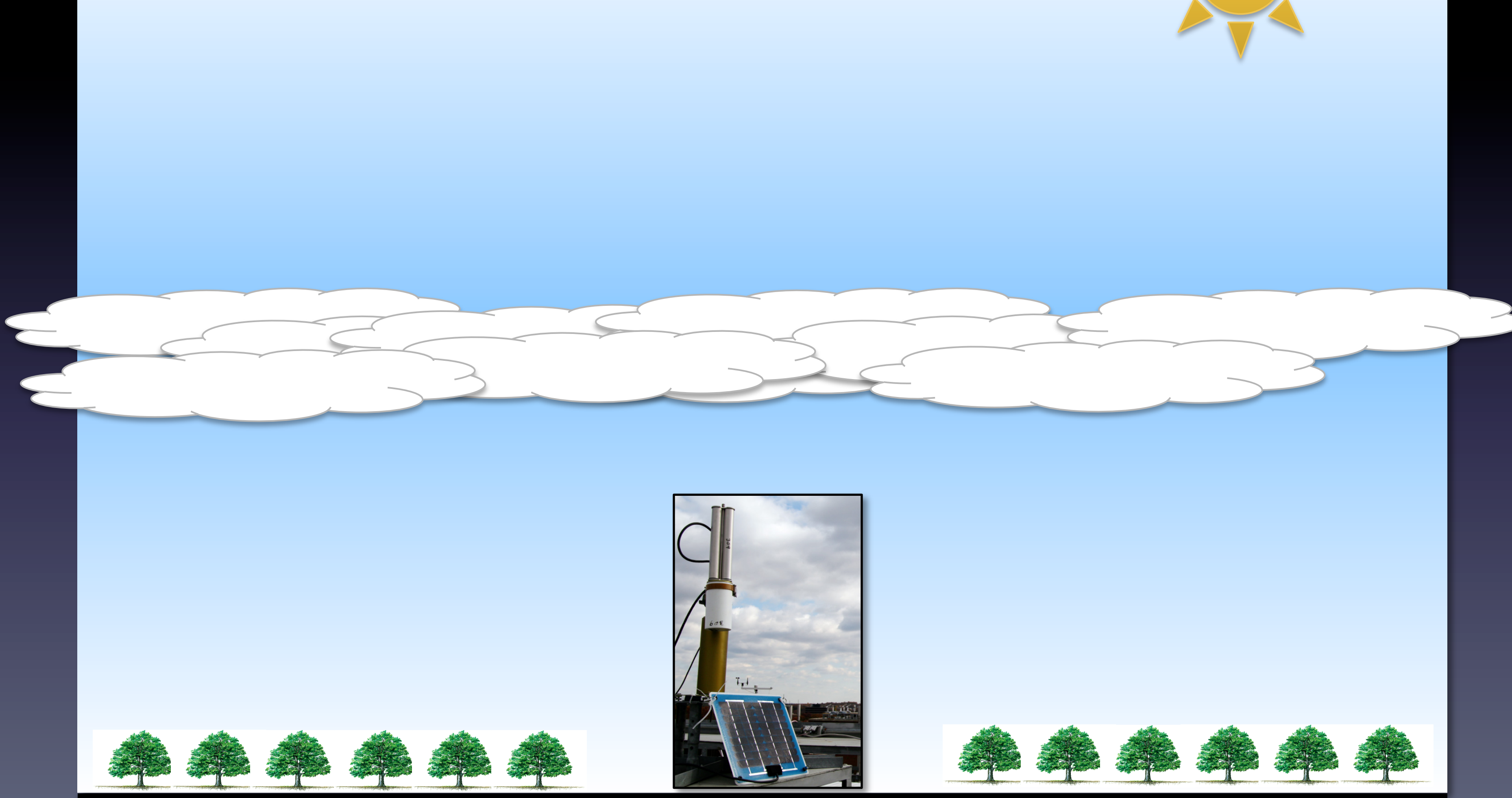
Polarimetry as a cloud observation tool

Some AERONET Cimel sun photometer/ radiometers have polarization sensitivity…

can it be used to determine cloud phase?

Polarimetry as a cloud observation tool

We simulate the polarization from this scene (using a doubling and adding vector radiative transfer code)



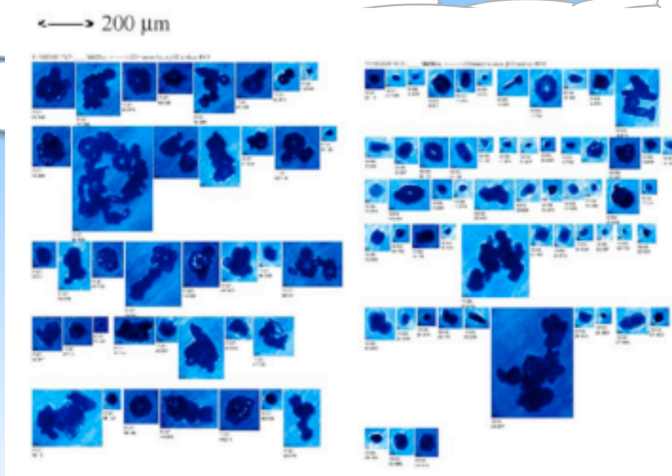
Polarimetry as a cloud observation tool

We simulate the polarization from this scene

Ice phase clouds
- Shape: plates and hexagonal columns
- "roughened" ice
- (size not relevant for polarization)
- (more complex shapes also less relevant)

vs.

Water phase clouds
- Large droplets, effective radius = 10µm
- Small droplets, effective radius = 5µm



ex. from Cloud Particle Imager (CPI) from Baran, JQSRT (2009)

Polarimetry as a cloud observation tool

$$\bar{I} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \frac{2}{3}\left(\hat{I}(0°)+\hat{I}(120°)+\hat{I}(240°)\right) \\ \frac{2}{3}\left(\hat{I}(0°)-\hat{I}(120°)-\hat{I}(240°)\right) \\ \frac{2}{\sqrt{3}}\left(\hat{I}(240°)+\hat{I}(120°)\right) \\ \ldots \end{bmatrix}$$

- Stokes polarization vector
  - I: total
  - Q, U: linear polarization
  - V: circular polarization (minimal for earth science)

$\hat{I}(x°)$ radiance observed with linear polarizer oriented at angle ***x*** from the reference frame

Degree of Linear Polarization (DoLP)

$$DoLP = \frac{\sqrt{Q^2+U^2}}{I}$$

Portion of reflectance due to polarization, always positive
Often less sensitive to calibration, but…
…expresses both total and polarized interactions

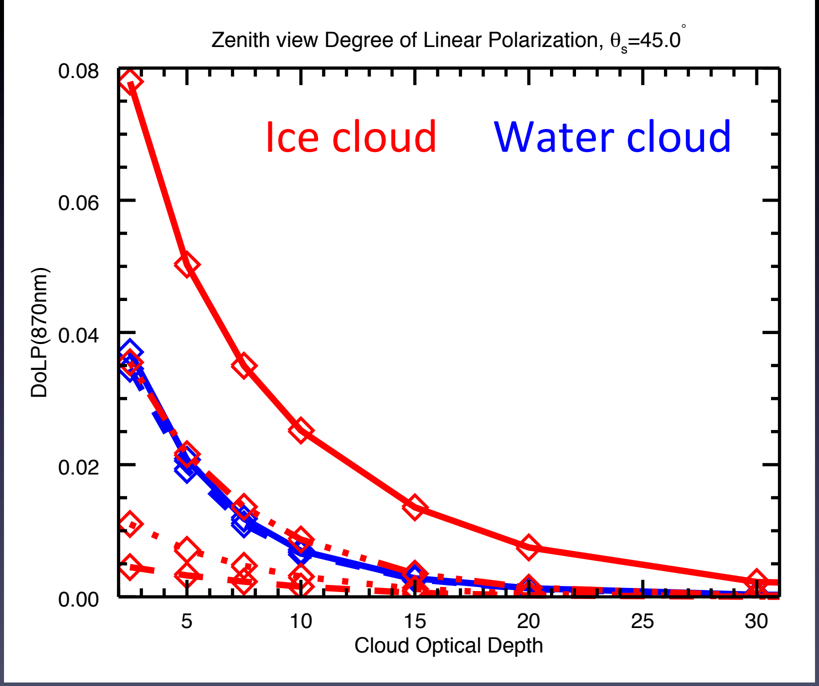
Reflectance R_I, R_Q, R_U

$$R_I = \frac{I\pi r_o^2}{F_o\cos(\theta_s)}$$

Similar for Q, U & V radiances [w/m^2 sr]
r_o – solar distance [AU]
F_o – Exo-atmospheric irradiance [w/m^2]

Simulation results

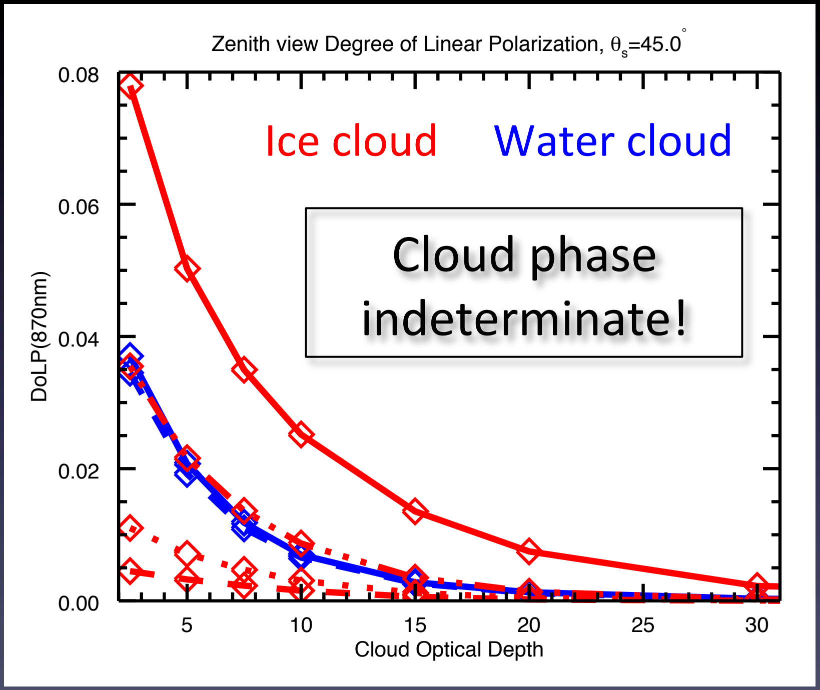
Cloud Optical Depth (COD) vs.
Degree of Linear Polarization



$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I}$$

Simulation results

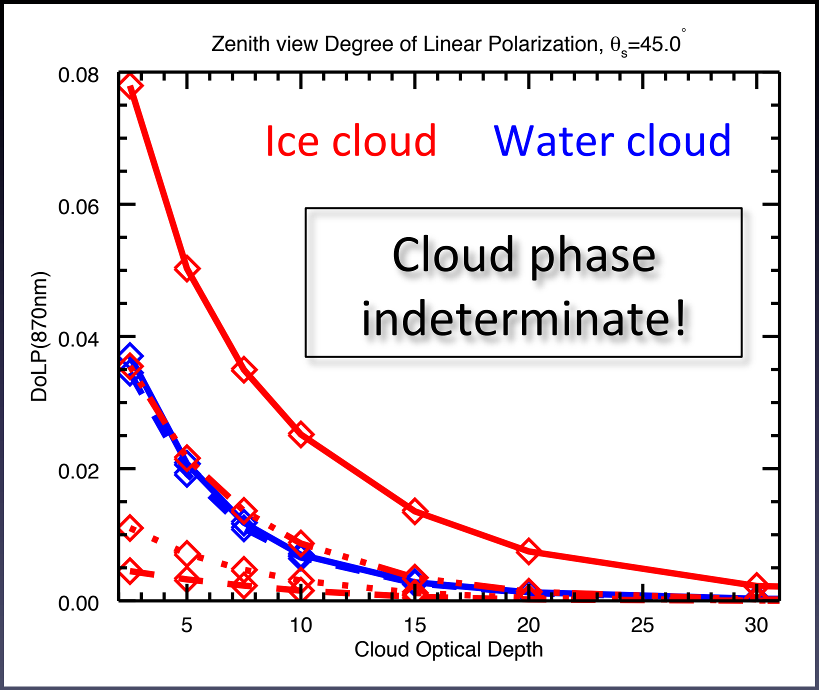
Cloud Optical Depth (COD) vs.
Degree of Linear Polarization



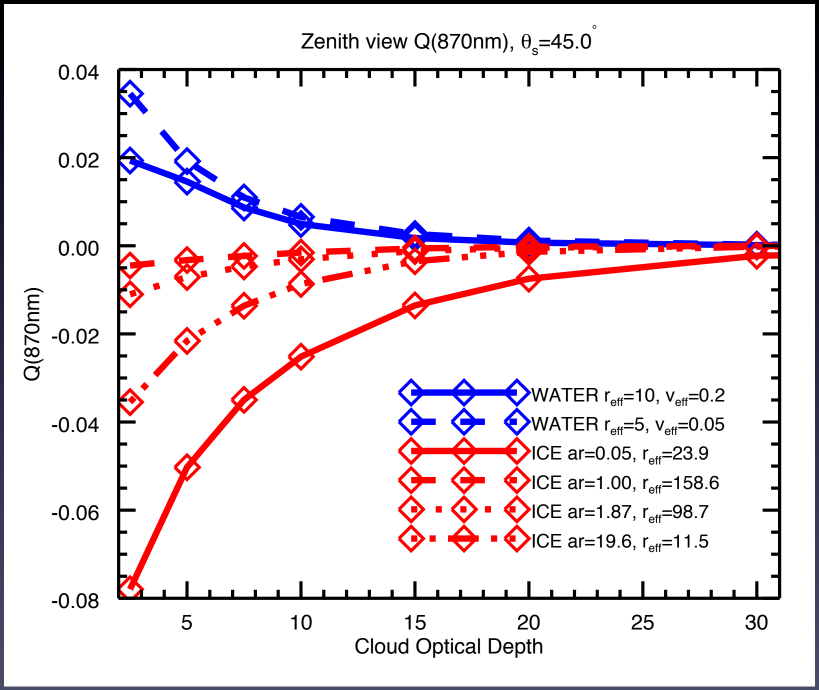
$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I}$$

Simulation results

Cloud Optical Depth (COD) vs. Degree of Linear Polarization



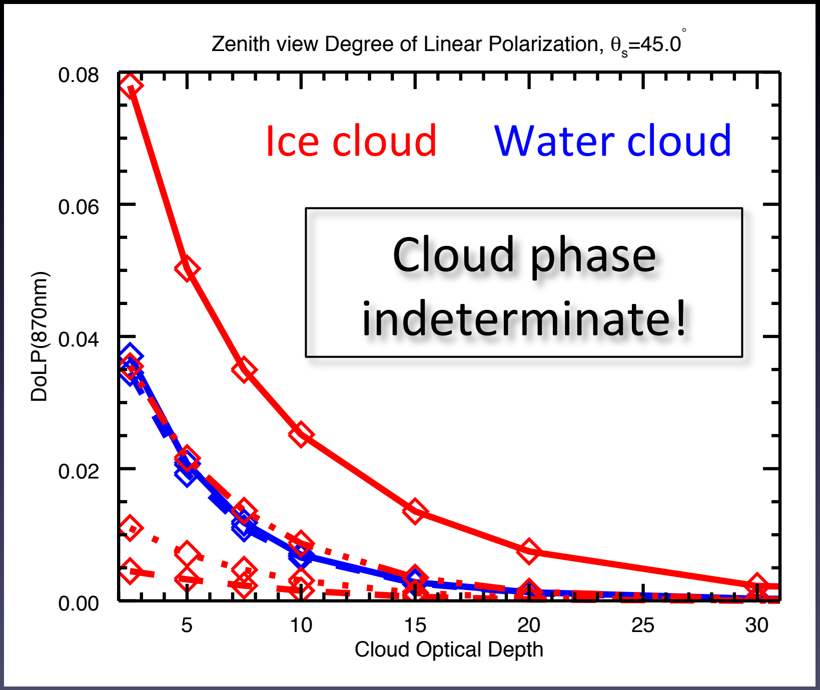
Cloud Optical Depth (COD) vs. Q reflectance (in scattering plane, U≈0)



$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I}$$

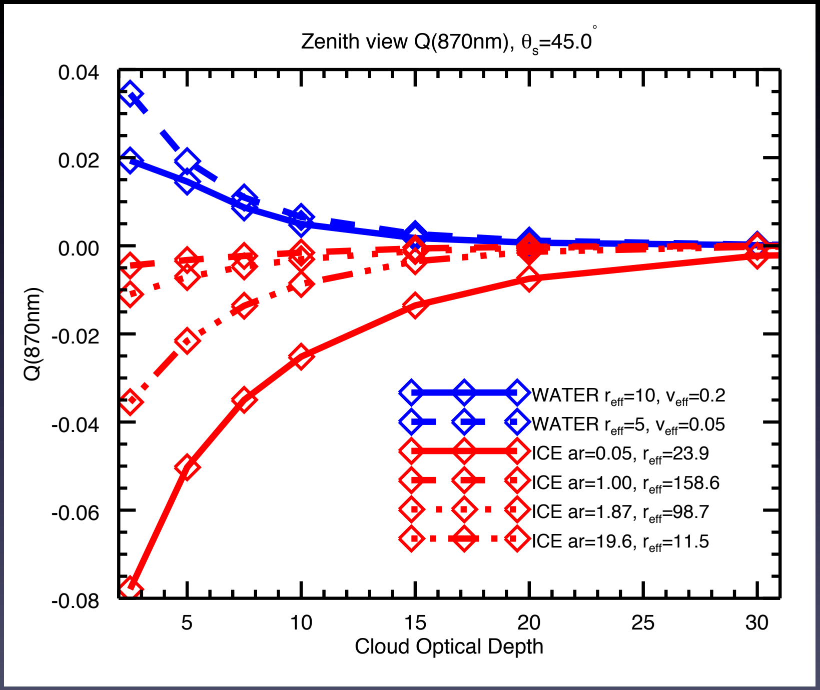
Simulation results

Cloud Optical Depth (COD) vs.
Degree of Linear Polarization



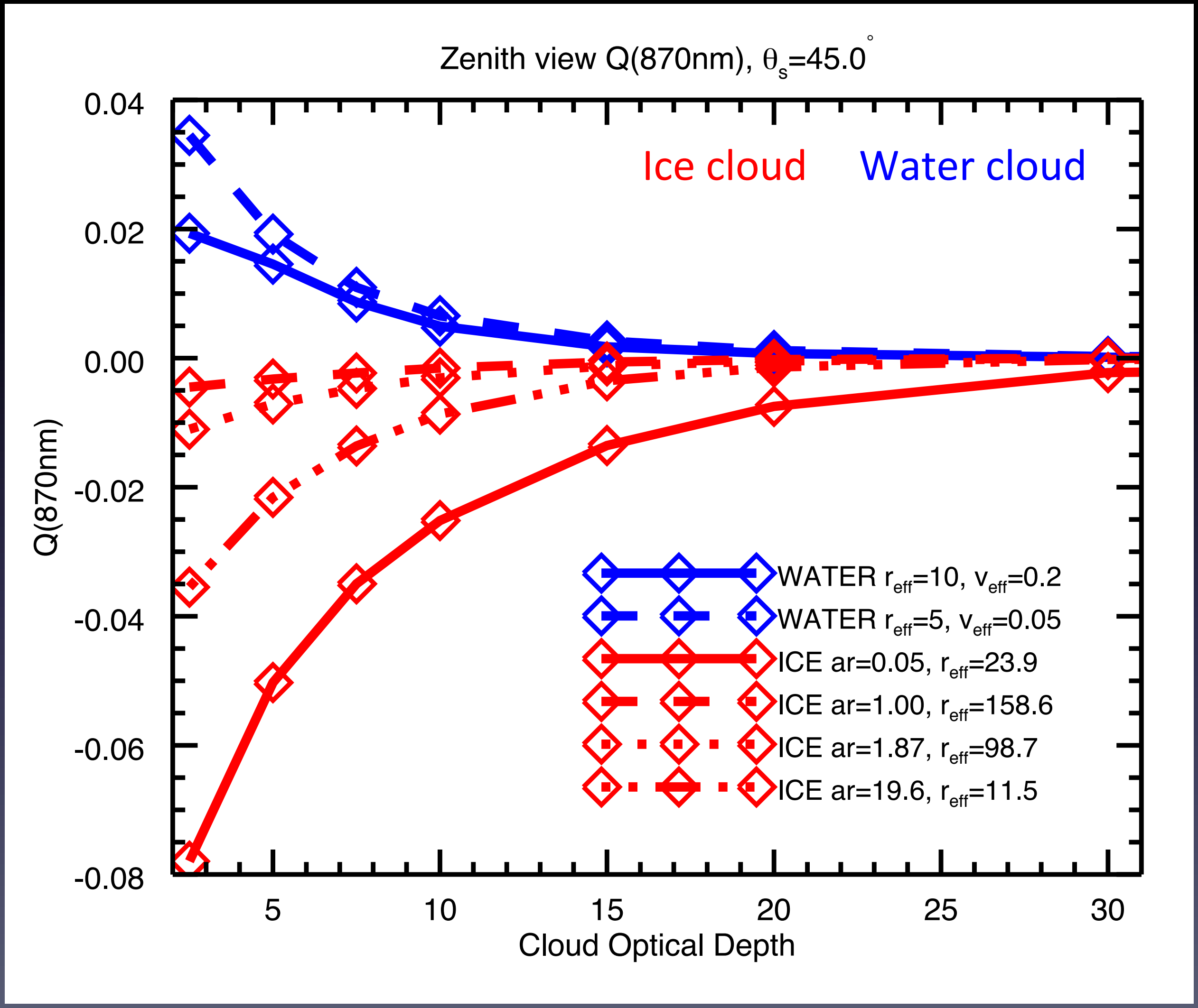
$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I}$$

Cloud Optical Depth (COD) vs.
Q reflectance
(in scattering plane, U≈0)



A clear distinction! But Cimels are designed to measure DoLP, not Q… are they accurate enough?

Simulation results



Cloud phase determination depends on

- Q measurement accuracy
- Cloud Optical Depth
- Solar Geometry

Can it be done with AERONET Cimels?

Data exploration

Research site: a polarization sensitive Cimel operating at the Cabauw Experimental Site for Atmospheric Research (CESAR) in the Netherlands

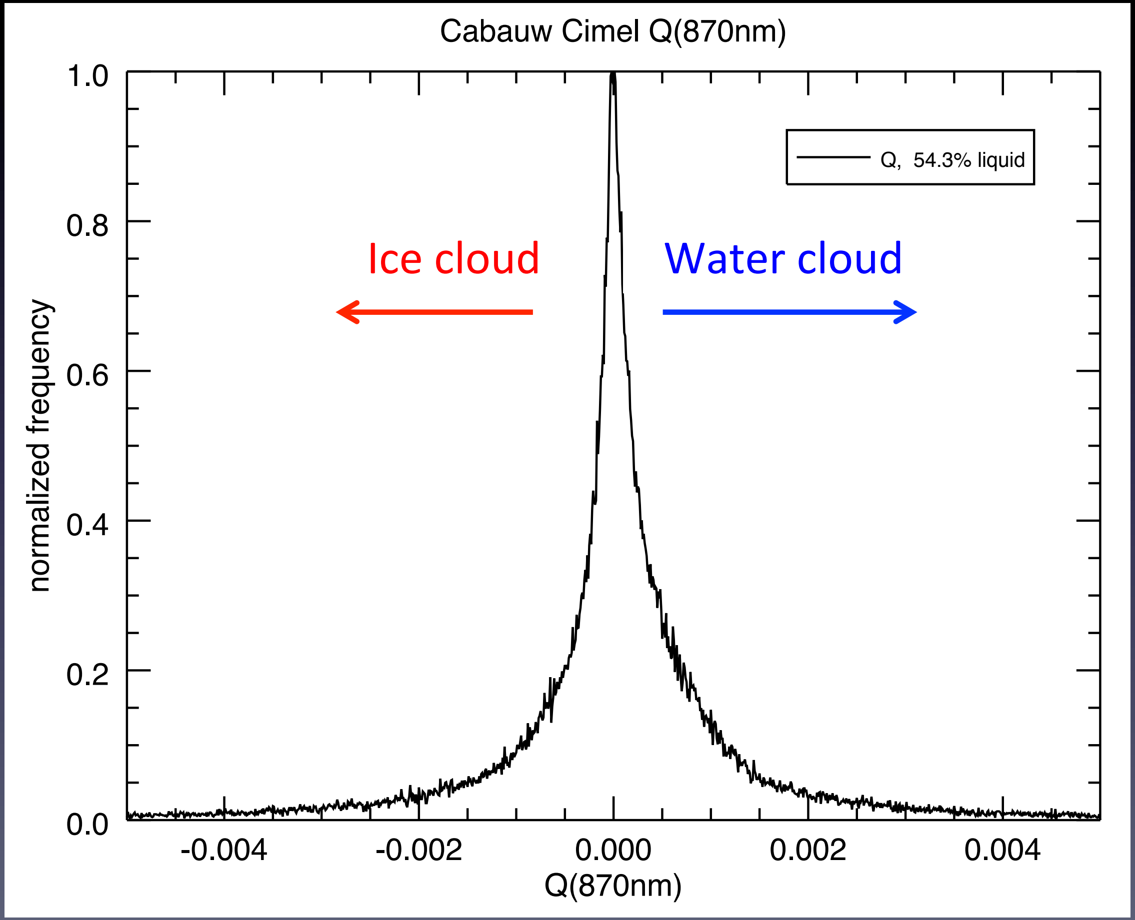
In addition to AERONET Cimel, Cabauw has for cloud phase verification:

- Vaisala LD-40 Ceilometer
  (cloud base height)

- Pyrometer NubiScope
  (cloud base temperature)

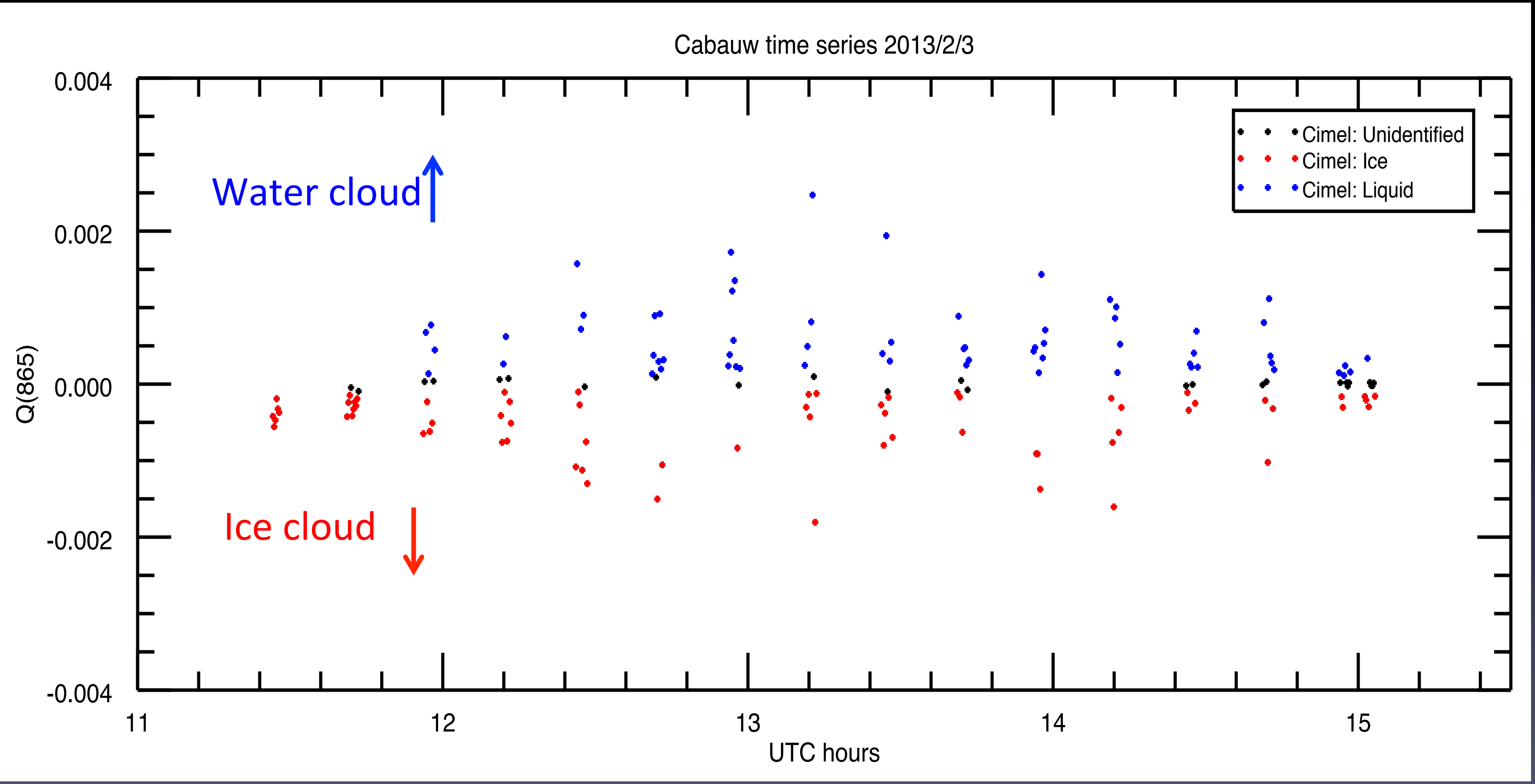
Data exploration

Histogram of Q observations – we expect majority of values to be positive, indicating the more common case of liquid clouds – not so in the data



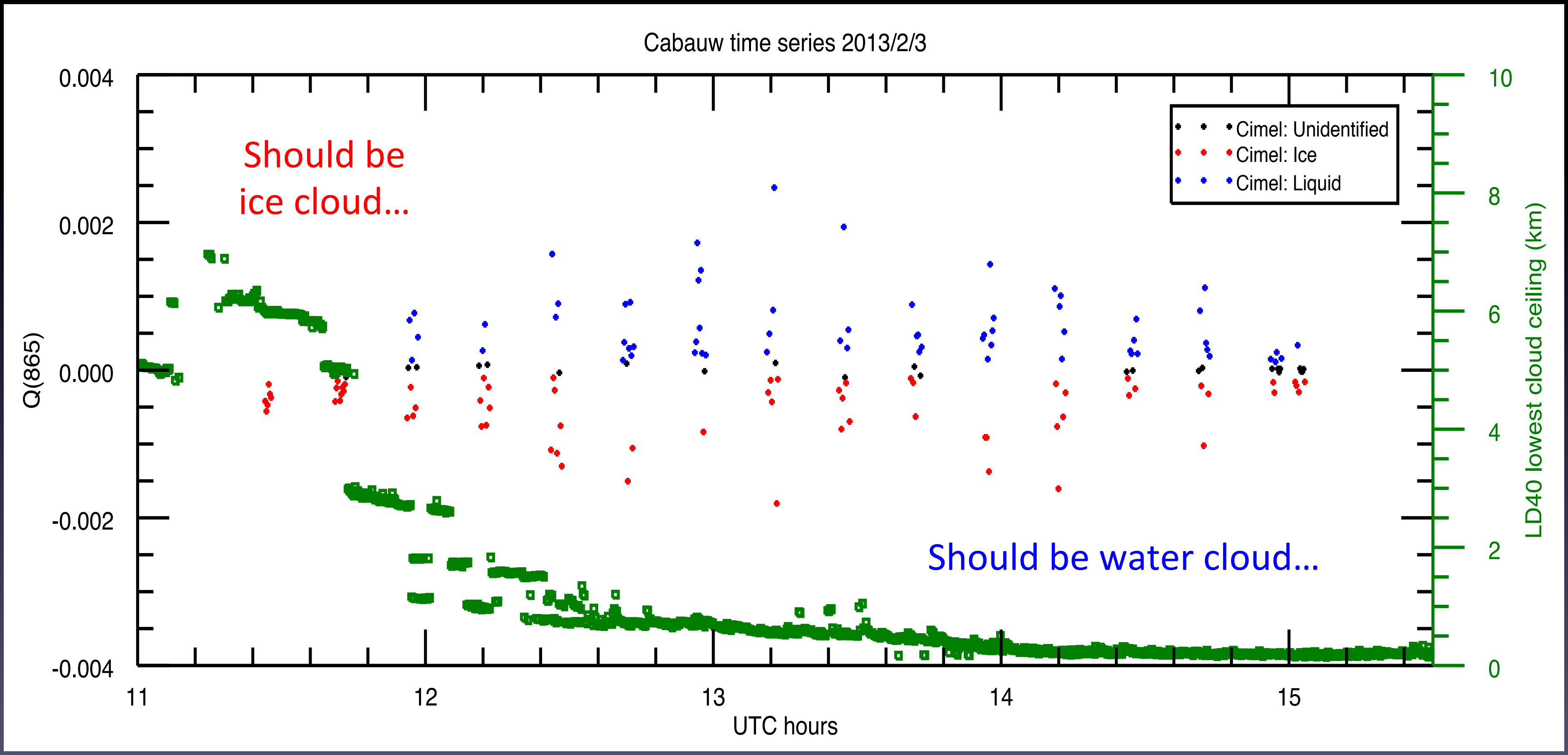
Data exploration

One revealing day – lots of scatter



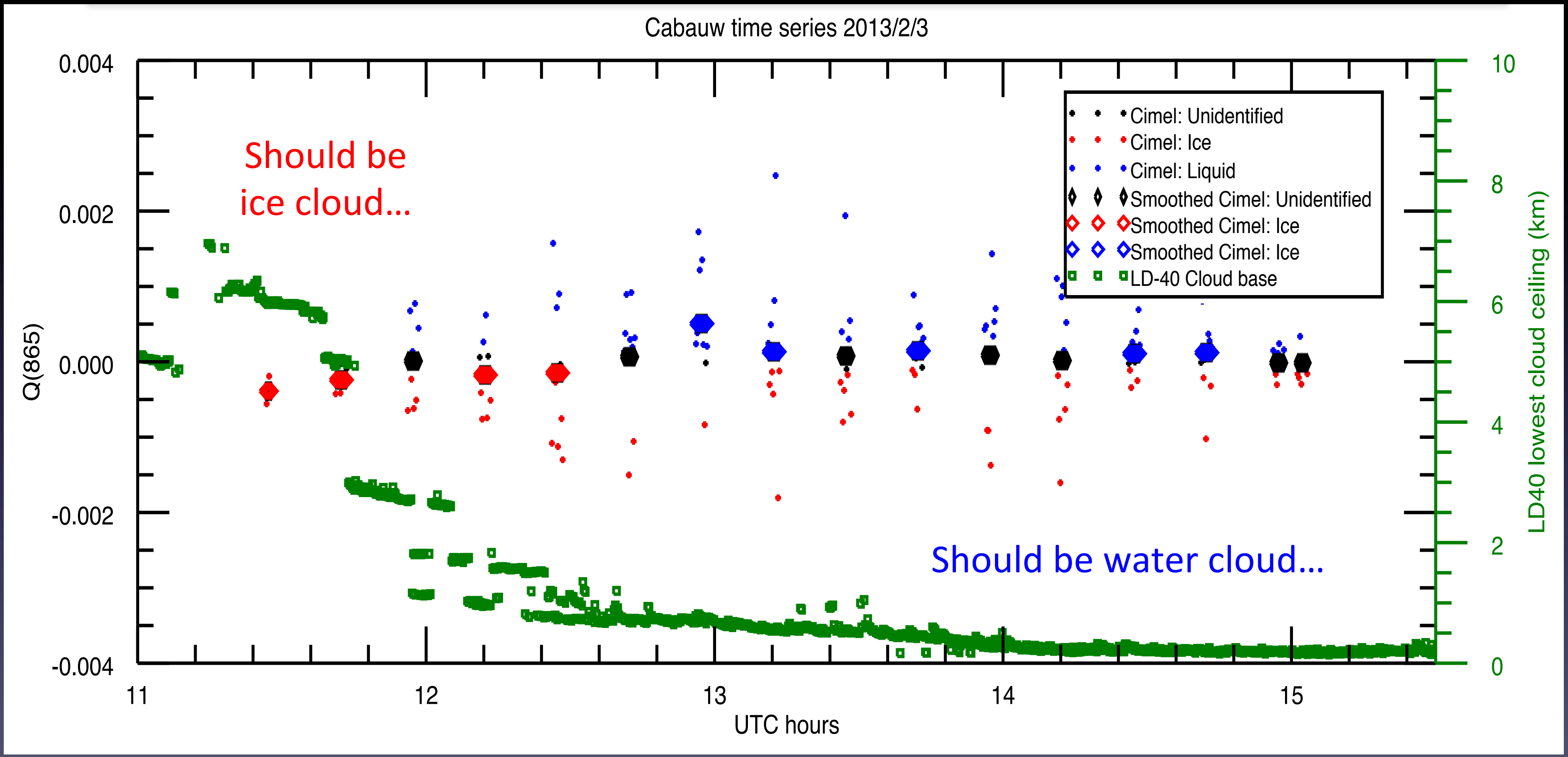
Data exploration

One revealing day – Cimel Q doesn't seem to correspond to cloud type



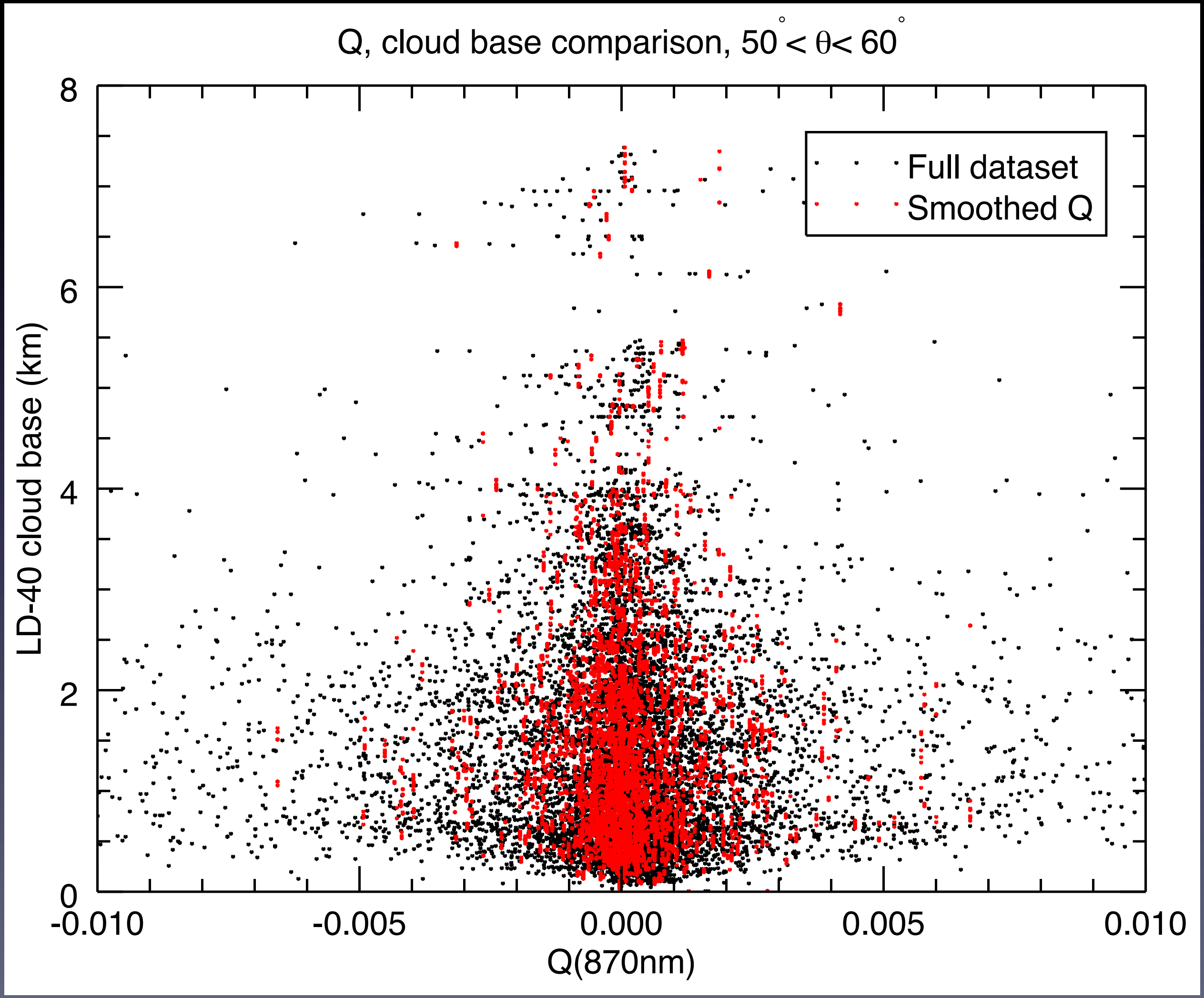
Data exploration

One revealing day – averaging helps somewhat…



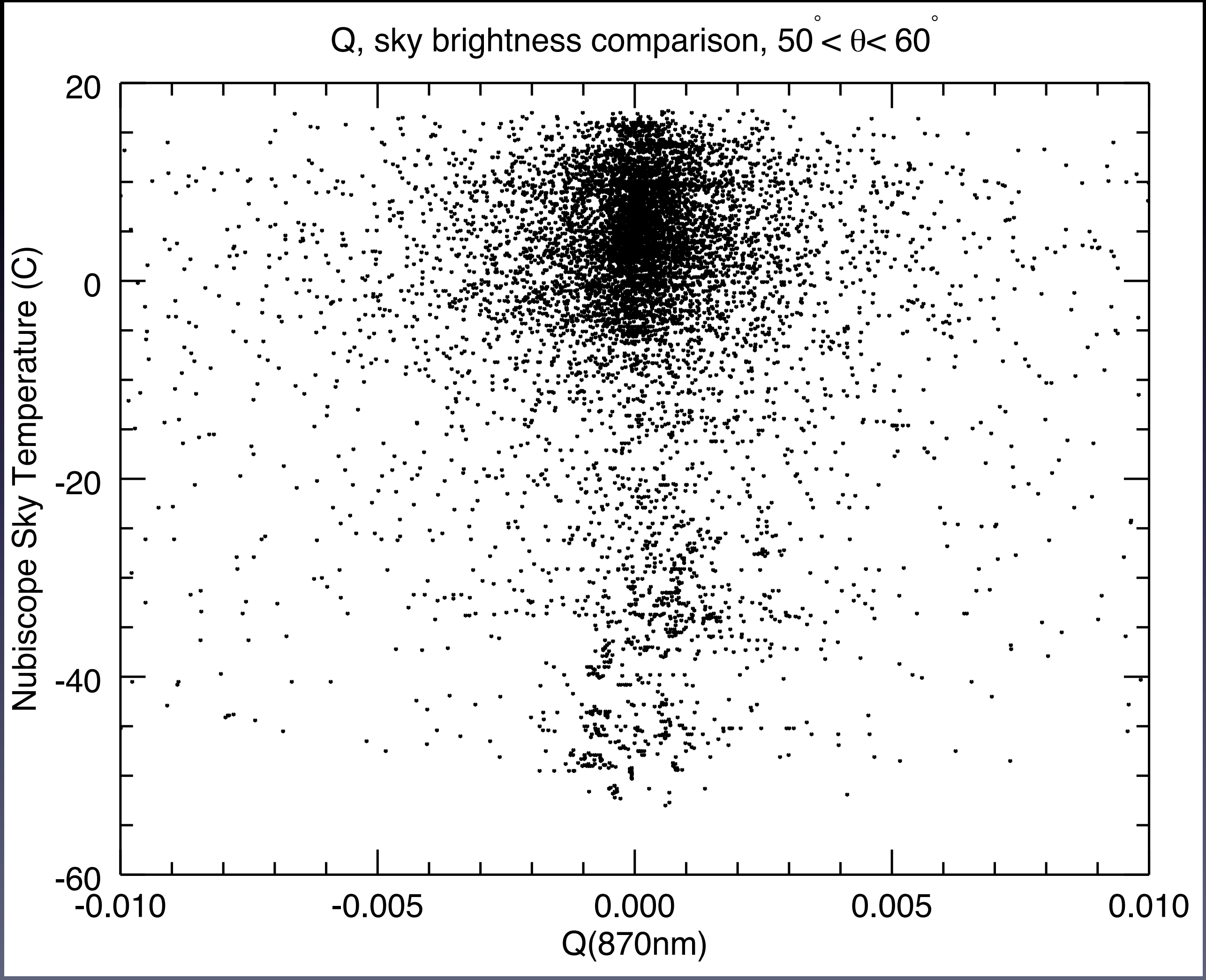
Data exploration

Noise appears to overwhelm any cloud phase signal



Data exploration

Similar results for Nubiscope



Conclusions, next steps, instrument development

AERONET polarized cimel cloud measurments at CESAR site are too noisy to show the expected cloud phase polarization predicted by theory

- Polarized Cimel instruments at CESAR site were designed to measure DoLP, not Q reflectance, which we need. Uncertainty assessment doesn't exist.

- Newer polarized Cimels have been deployed at NASA GSFC in Maryland. These instrument have multiple polarized channels and possibly better uncertainty. Initial analysis is promising, but ongoing.

- Efforts are underway at NASA Ames to develop a prototype instrument, with high polarimetric accuracy, intended for cloud phase measurements (Steve Dunagan).

Conclusions, next steps, instrument development

We are developing a high polarimetric accuracy instrument as a test of these concepts

Utilizes Biospherical Instruments Microradiometers (24 bit) + Wollaston prisms to detect polarization

Modular system can support up to 18 channels/polarization components

Goal: to determine if cloud phase detection using polarization is a reasonable measurement objective

www.biospherical.com

Thank you!

Henk Klein Baltink, KNMI, The Netherlands
- for CESAR site data

Ilya Slutsker, NASA GSFC, USA
- for help with AERONET data

Stephane Victori, Cimel Advanced Monitoring, France and **Fabien Waquet**, Laboratoire d'Optique Atmospherique, France
- for help understanding the Cimel instrument

Funding provided by the center Science Innovation Funds at NASA Ames Research Center (Knobelspiesse) and NASA Goddard Space Flight Center (Marshak)

Physical reason for cloud phase expression?

…difference in single scattering properties

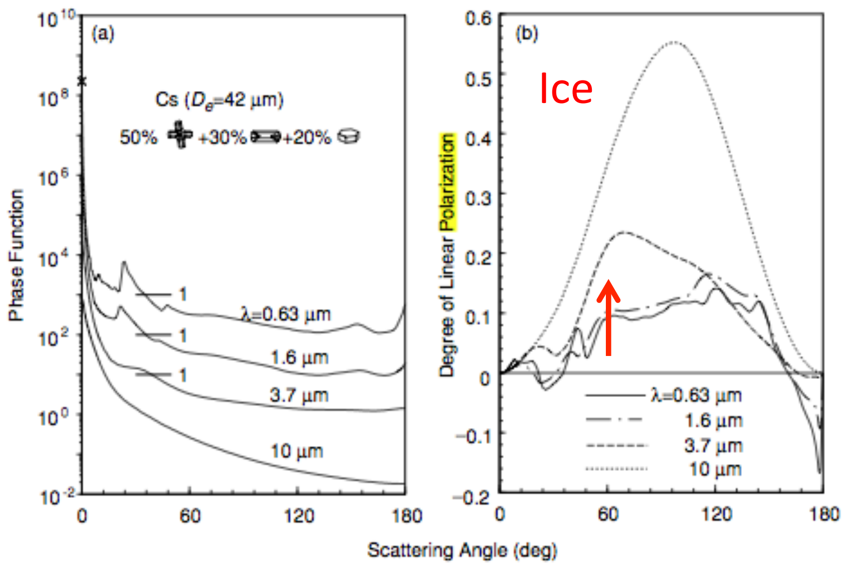


Figure 5.23 (a) Phase function and (b) degree of linear polarization for a typical cirrostratus with a mean effective ice crystal size of 42 μm composed of 50% bullet rosettes/aggregates, 30% hollow columns, and 20% plates, a shape model based on replicator and optical probe measurements. Four remote sensing wavelengths are displayed. For size parameters less than 15, the finite-difference time domain method is employed in the calculations. In the phase function, the vertical scale is applied to the lowest curve, while the upper curves are displayed upward by a factor of 10. The symbol × denotes the diffraction peak for the 0.63 μm wavelength.

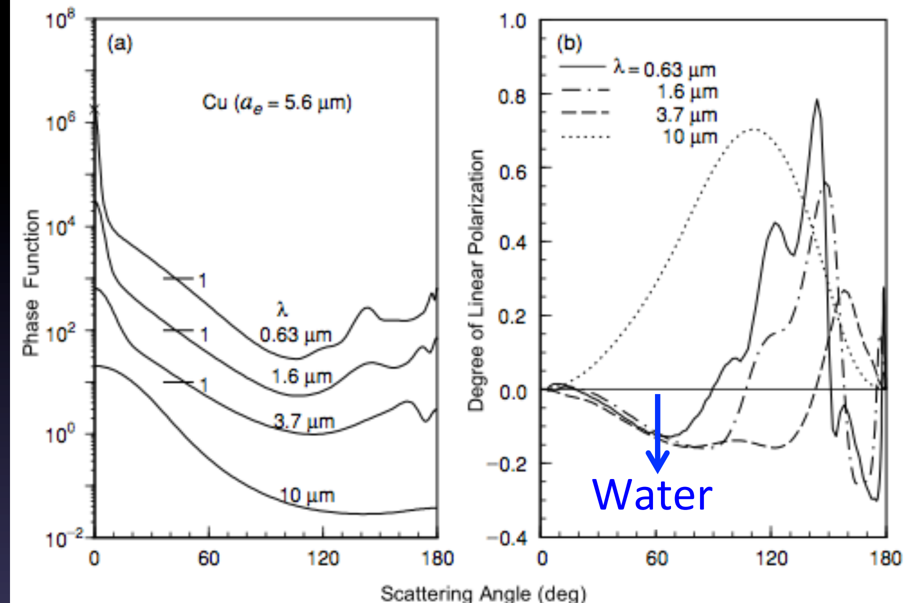


Figure 5.15 Phase function (a) and degree of linear polarization (b) for incident wavelengths of 0.63, 1.6, 3.7, and 10 μm involving the droplet size distribution representative of cumulus and stratus clouds. For the phase function, the vertical scale applies to the lowest curve, while the upper curves are displayed upward by a factor of 10. The symbol × denotes the diffraction peak for the 0.63 μm wavelength.

From K.N. Liou *An Introduction to Atmospheric Radiation* 2002