Clouds Simultaneous Retrieval of the Water Vapour and Temperature Profiles, Surface Temperature and Cloud Properties from FORUM Spectral Radiance Simulated Observations

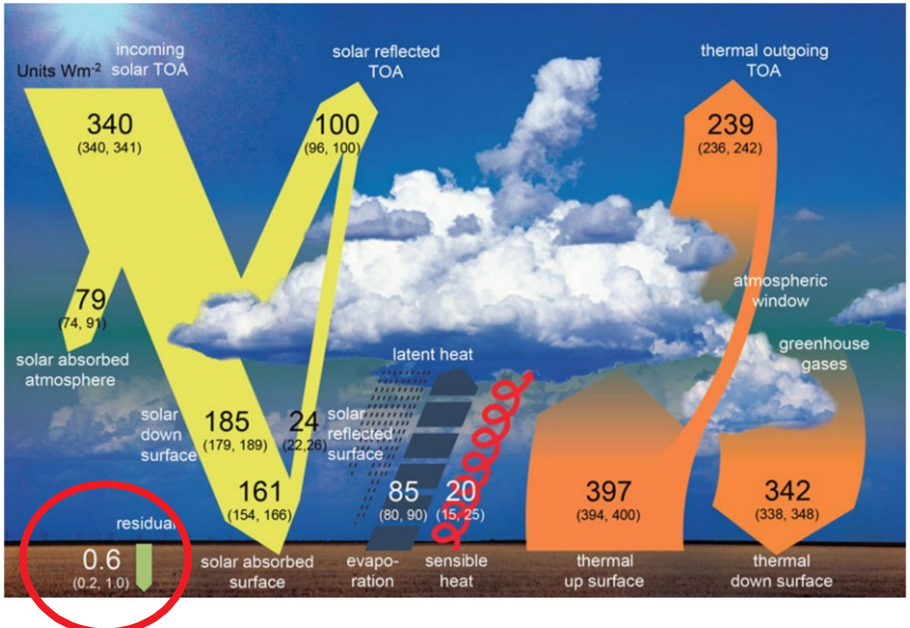
Gianluca Di Natale
INO-CNR, Florence, Italy

Luca Palchetti, INO-CNR, Florence
Giovanni Bianchini, INO-CNR, Florence
Claudio Belotti, INO-CNR, Florence
Marco Ridolfi, INO-CNR, Florence
Tiziano Maestri, Univ. of Bologna
William Cossich, Univ. of Bologna
Michele Martinazzo, Univ. of Bologna
Samuele Del Bianco, IFAC-CNR, Florence

ATMOS Conference (Virtual)
November 22-26, 2021

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Importance of Far Infrared and ice clouds

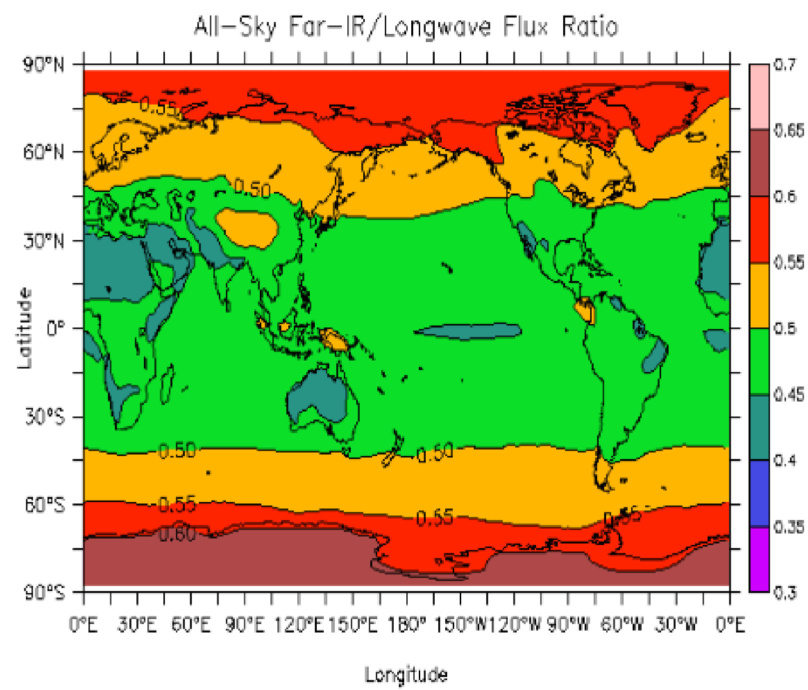


Wild et al. 2013, Clim Dyn

More than 40% of the Outgoing Longwave Radiation (OLR) and of the greenhouse effect comes from FIR where the pure rotational band of water vapour is present

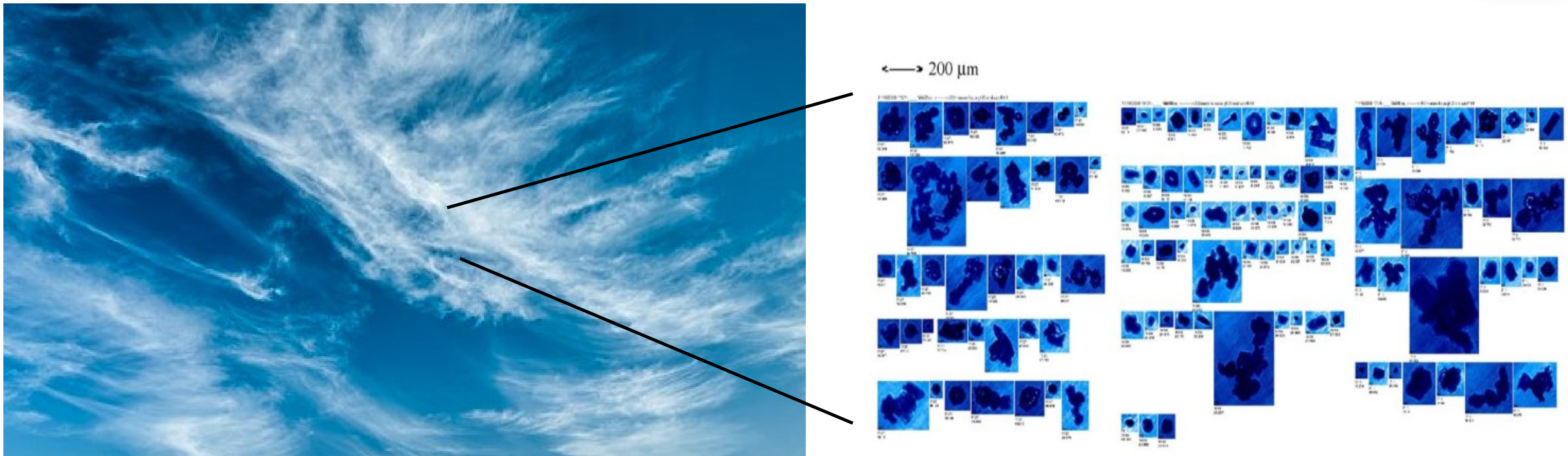
WHY CIRRUS CLOUDS ARE SO IMPORTANT?

Cirrus clouds play a key role in the Earth radiation budget since they modulate the solar incoming radiation and the outogoing thermal emission



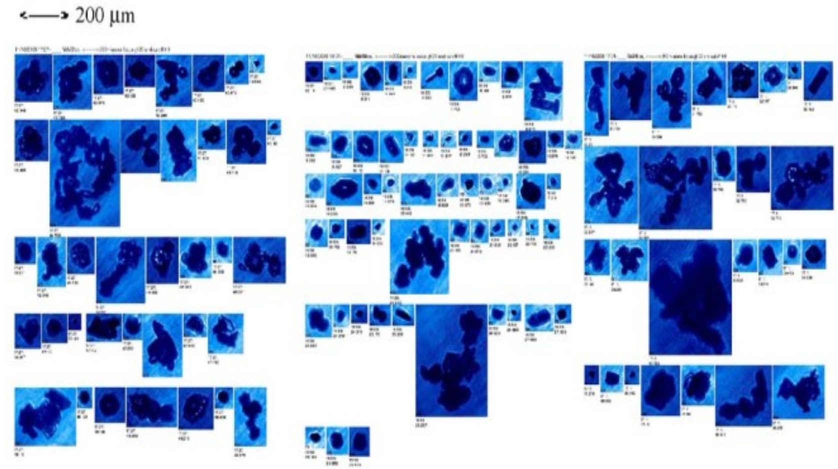
Cirrus clouds: a very complex system

Cirrus clouds: a very complex system

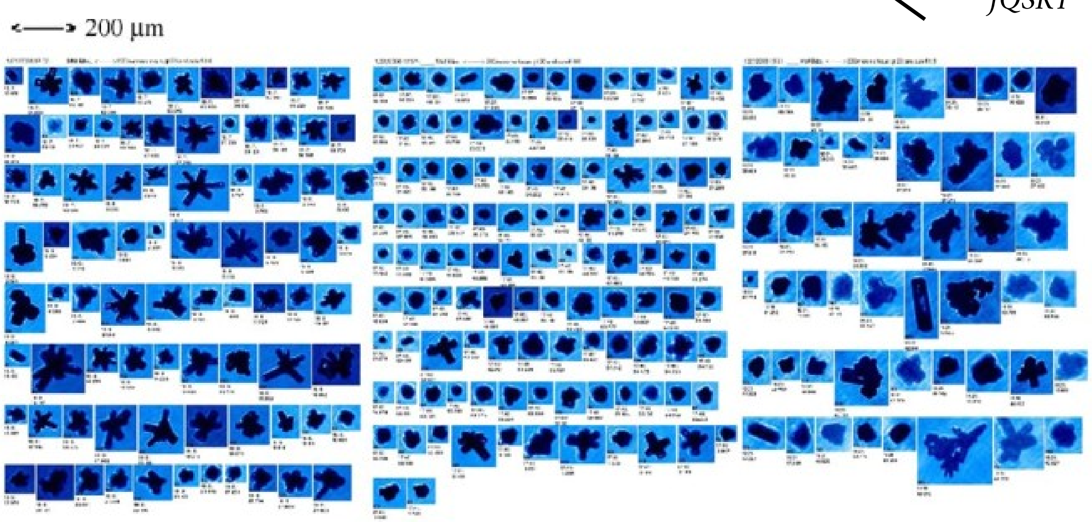


From “A review of the light scattering properties of cirrus”, Baran 2009

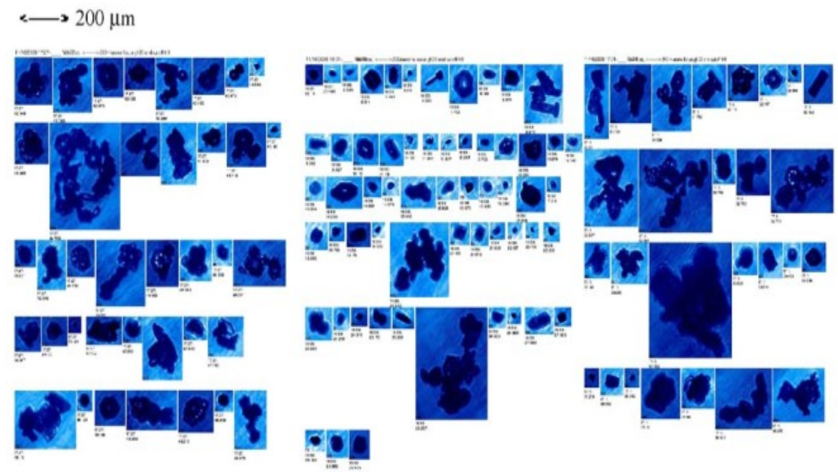
Cirrus clouds: a very complex system



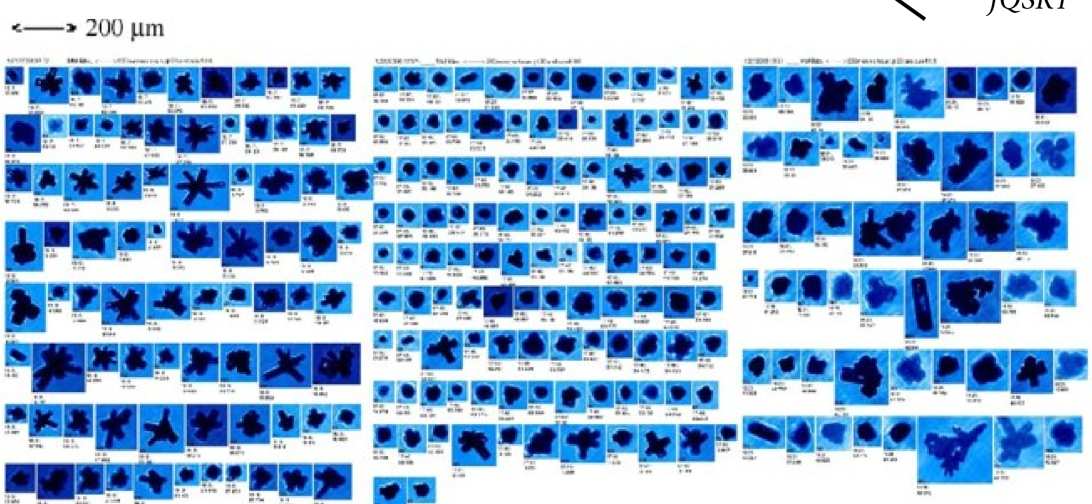
From "A review of the light scattering properties of cirrus", Baran 2009, JQSRT

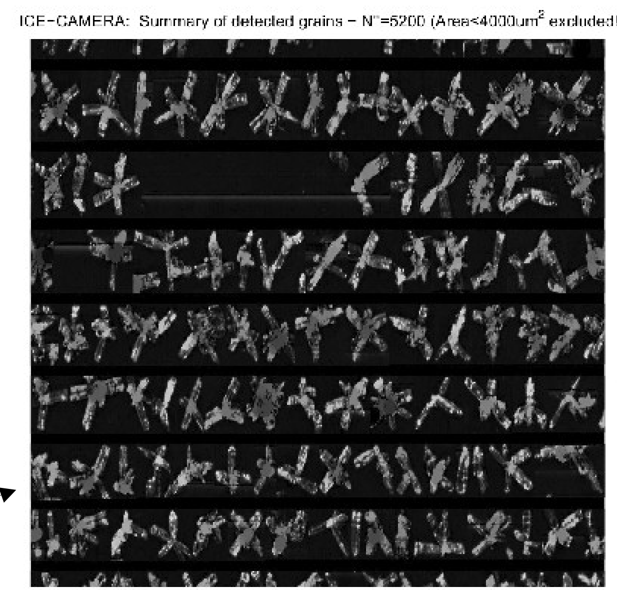


Cirrus clouds: a very complex system



From "A review of the light scattering properties of cirrus", Baran 2009, JQSRT

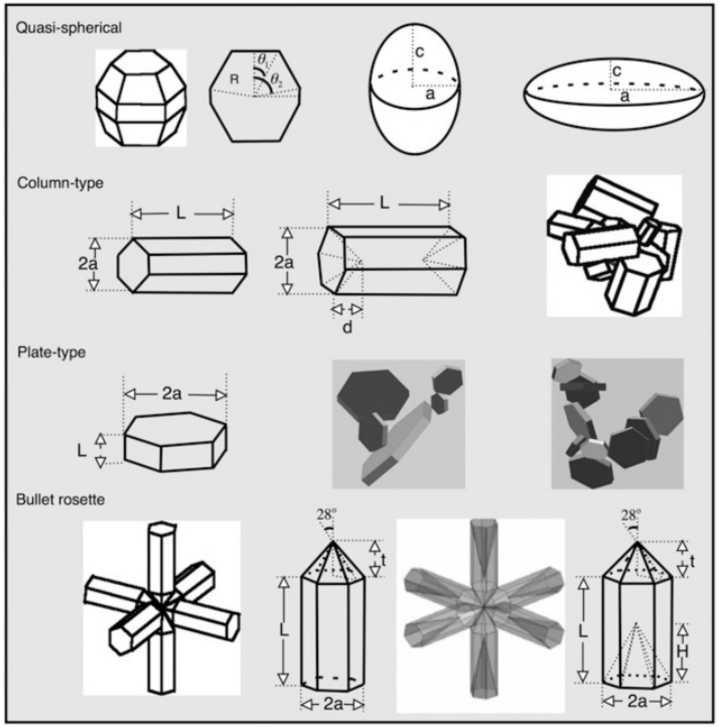




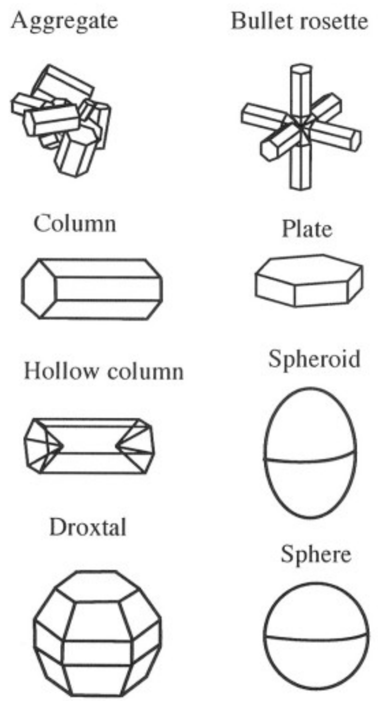
Photograph from ICE-CAMERA installed in Antarctica (Dome-C) by Dr. Massimo Del Guasta

How can we simplify?

From complex to simple habits



Ping Yang et al. 2013, Jour. Atm. Sci.



Ping Yang et al. 2005, Applied Optics

$$D_e = \frac{3}{2} \frac{\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) V_i(L)\right] n(L) \mathrm{d}L}{\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) A_i(L)\right] n(L) \mathrm{d}L}.$$

$$n(L) = N_0 L^{\mu} e^{-\Lambda L} = N_0 L^{\frac{1-3\sigma}{\sigma}} e^{\frac{-L}{\sigma L_m}}$$

$$Q_v^{e,a} = Q_v^{e,a}(D_e)$$

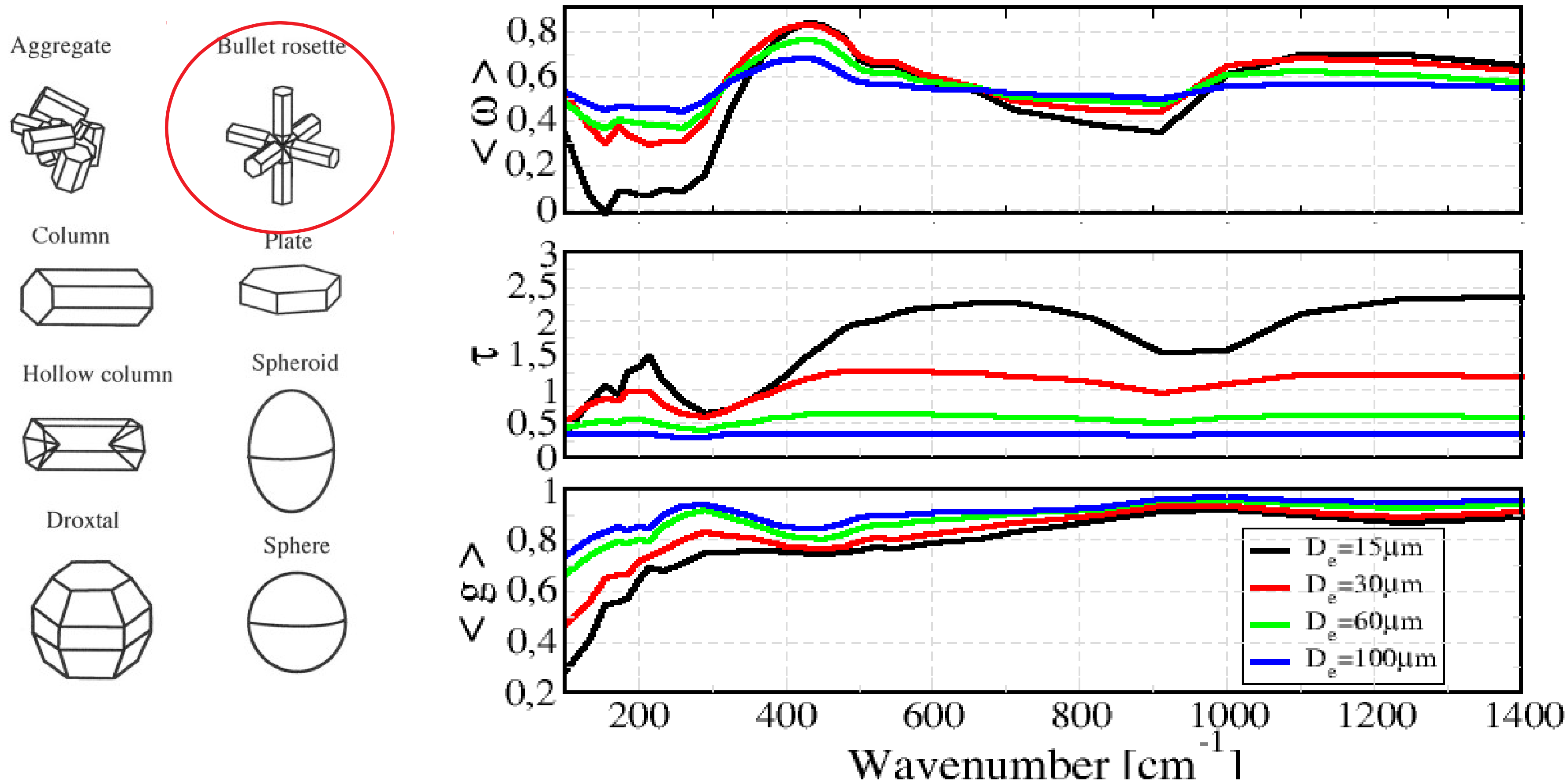
$$\omega_v = \omega_v(D_e)$$

$$g_v = g_v(D_e)$$

OPTICAL COEFFICIENTS

$$\tau = \frac{\langle Q_e \rangle}{2} \tau_{\text{vis}}$$

From complex to simple habits



Simultaneous Atmospheric and Clouds Retrieval code

$$\langle Q_e \rangle = \frac{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{ei}(L) A_i(L) \right] n(L) \mathrm{d}L}{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) A_i(L) \right] n(L) \mathrm{d}L}$$

$$\langle g \rangle = \frac{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) g_i(L) Q_{si}(L) A_i(L) \right] n(L) \mathrm{d}L}{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{si}(L) A_i(L) \right] n(L) \mathrm{d}L}$$

$$\langle \omega \rangle = \frac{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{si}(L) A_i(L) \right] n(L) \mathrm{d}L}{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{ei}(L) A_i(L) \right] n(L) \mathrm{d}L}$$

Averaged optical properties

Simultaneous Atmospheric and Clouds Retrieval code

$$\langle Q_e \rangle = \frac{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{ei}(L) A_i(L)\right] n(L)\,\mathrm{d}L}{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) A_i(L)\right] n(L)\,\mathrm{d}L}$$

$$\langle g \rangle = \frac{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) g_i(L) Q_{si}(L) A_i(L)\right] n(L)\,\mathrm{d}L}{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{si}(L) A_i(L)\right] n(L)\,\mathrm{d}L}$$

$$\langle \omega \rangle = \frac{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{si}(L) A_i(L)\right] n(L)\,\mathrm{d}L}{\displaystyle\int_{L_{\min}}^{L_{\max}} \left[\sum_{i=1}^{N} f_i(L) Q_{ei}(L) A_i(L)\right] n(L)\,\mathrm{d}L}$$

Averaged optical properties

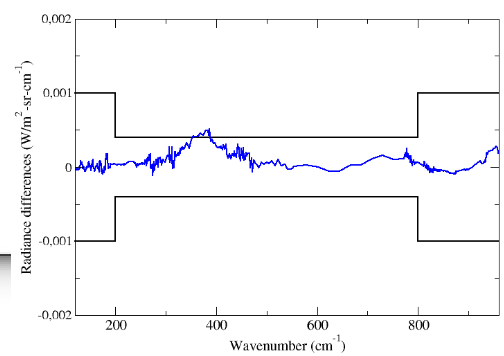
SACR is composed of a forward model which takes account of multiple scattering effect by clouds and aerosols + retrieval code (Levenberg-Marquardt/Optimal estimation)

δ-Eddington analytical solution of RTE

$$\mathcal{P}_{\delta-Edd}(\mu,\mu') = 2f\delta(\mu-\mu') + (1-f)(1+3g'\mu\mu')$$

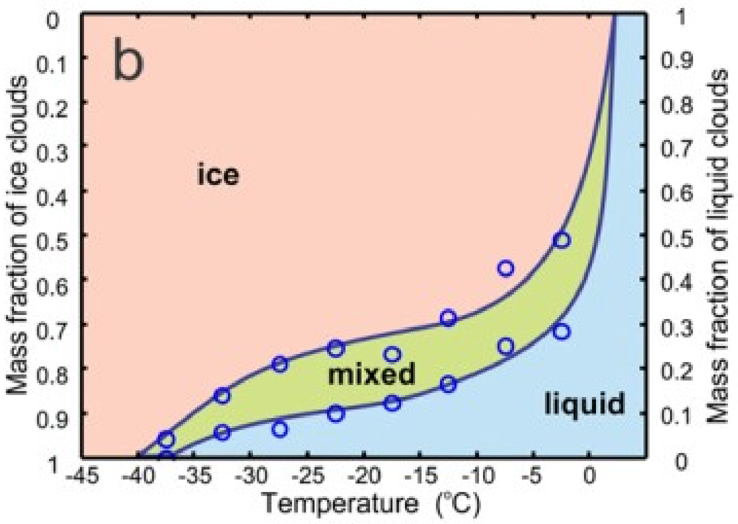
$$\boxed{\begin{aligned} g' &= \frac{g}{1+g} \\ f &= g^2 \\ \tau' &= (1-\omega g^2)\tau \\ \omega' &= \frac{(1-g^2)\omega}{1-\omega g^2} \end{aligned}}$$

Strong forward peak represented by means a δ-Dirac

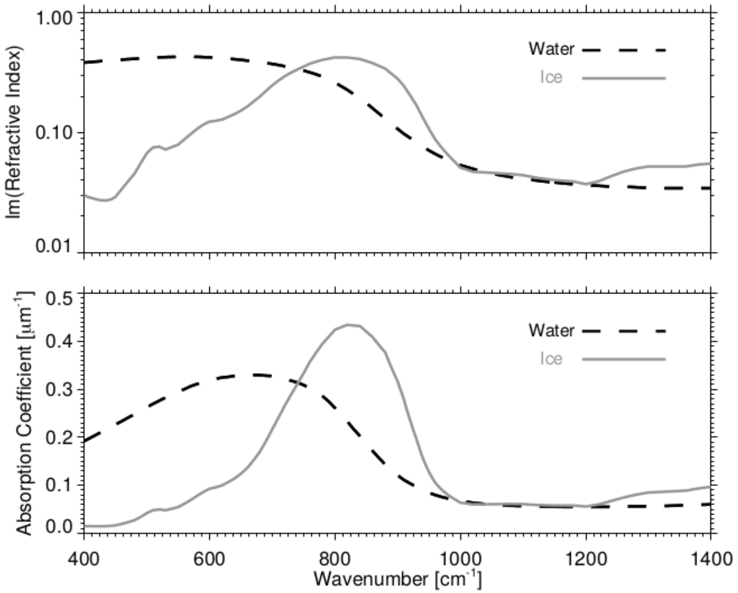


Radiance differences simulated with realistic Mie phase function with 125 Legendre polynomials and with 32 streams minus δ-Eddington with Henyey-Greenstein

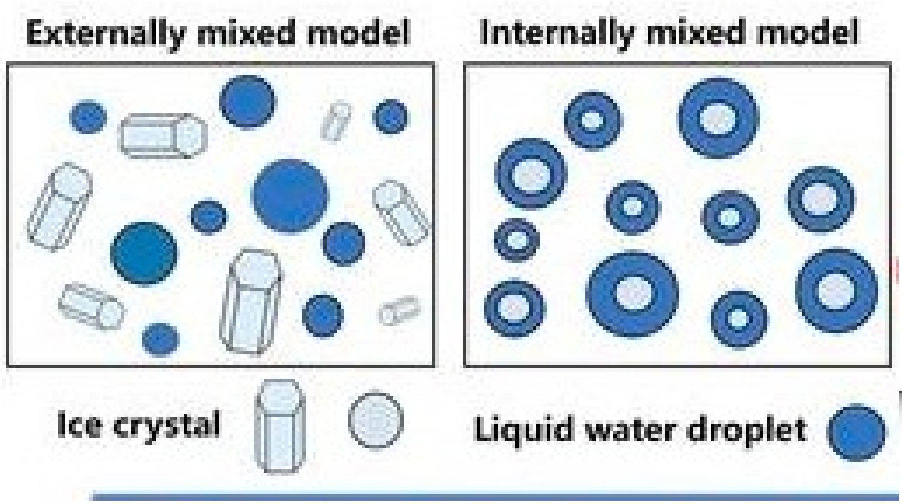
Mixed-phase clouds



Korolev et al. 2017, Meterol. Monogr.

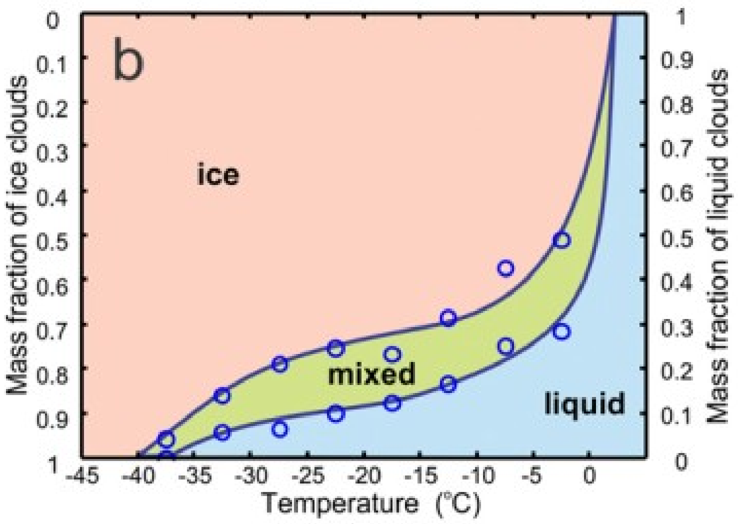


Turner et al. 2003, Journ. Appl. Meteorl.

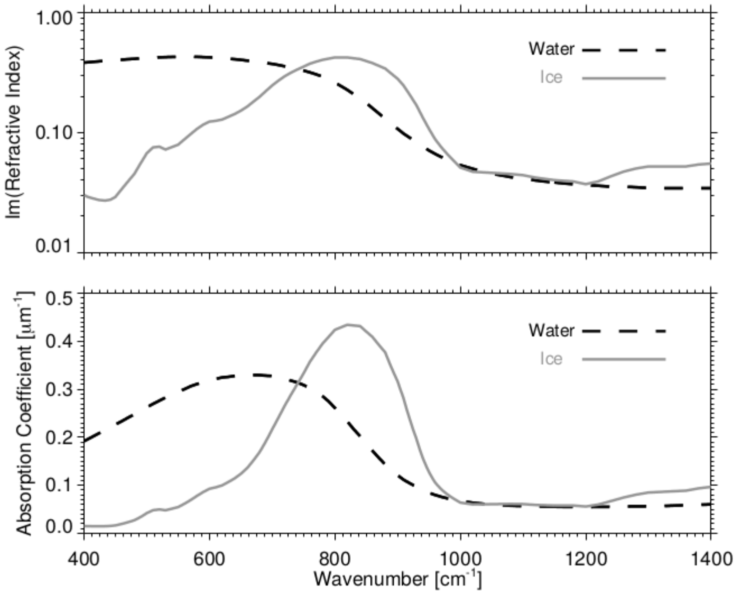


Luo et al. 2021, Rem. Sens.

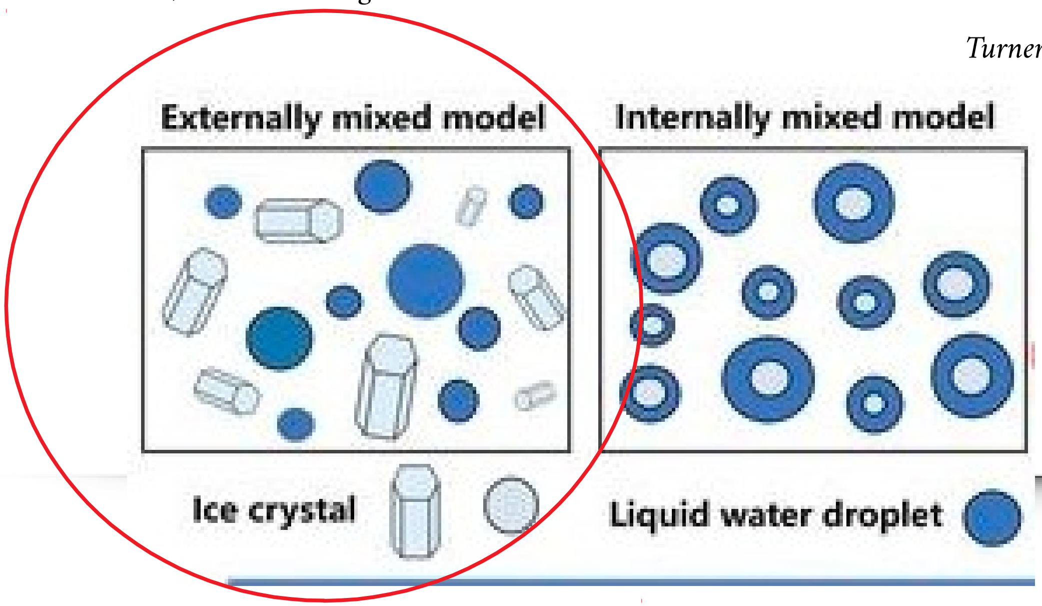
Mixed-phase clouds



Korolev et al. 2017, Meterol. Monogr.



Turner et al. 2003, Journ. Appl. Meteorl.

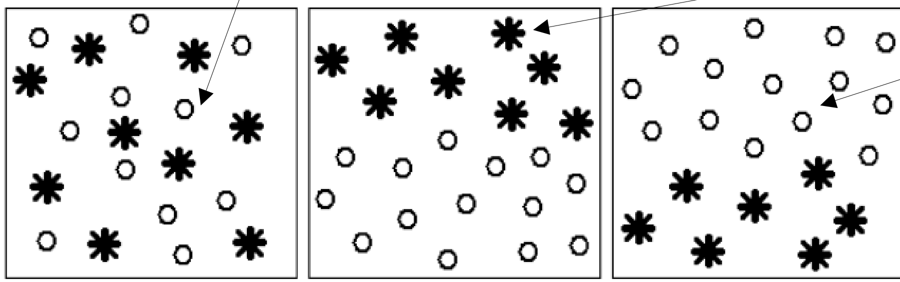


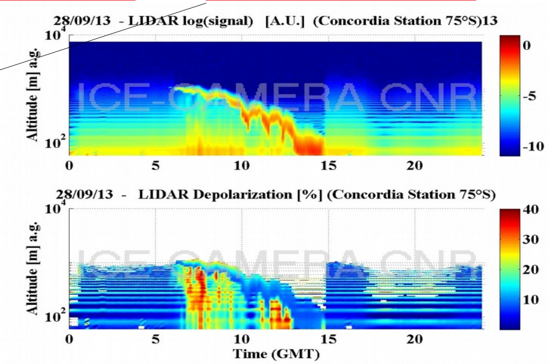
Luo et al. 2021, Rem. Sens.

Two possible representations

Uniformely mixed in volume

Adjacent layers of ice over water or water over ice





Ping Yang et al., 2003, JQSRT

Sun and Shine, 1994, Journ. Of Clim.

$$\tau_m = \tau_i + \tau_w$$

$$\omega_{0,m} = \left(\tau_i \omega_{0,i} + \tau_w \omega_{0,w}\right) / \tau_m$$

$$g_m = \left(\tau_i \omega_{0,i} g_i + \tau_w \omega_{0,w} g_w\right) / \left(\tau_m \omega_{0,m}\right)$$

$$p_m = \left(\tau_i \omega_{0,i} p_i + \tau_w \omega_{0,w} p_w\right) / \left(\tau_m \omega_{0,m}\right)$$

$$TWP = IWP + LWP \qquad \frac{1}{\rho_e} = \frac{\gamma}{\rho_i} + \frac{1-\gamma}{\rho_w}$$

$$\gamma = \frac{IWP}{TWP} \qquad \frac{1}{D_e \rho_e} = \frac{\gamma}{D_{ei}\rho_i} + \frac{1-\gamma}{D_{ew}\rho_w}$$

$$\langle Q_e \rangle = \left[\frac{\langle Q_{ei}\rangle \gamma}{D_{ei}\rho_i} + \frac{\langle Q_{ew}\rangle (1-\gamma)}{D_{ew}\rho_w}\right] D_e \rho_e$$

$$\langle Q_a \rangle = \left[\frac{\langle Q_{ai}\rangle \gamma}{D_{ei}\rho_i} + \frac{\langle Q_{aw}\rangle (1-\gamma)}{D_{ew}\rho_w}\right] D_e \rho_e$$

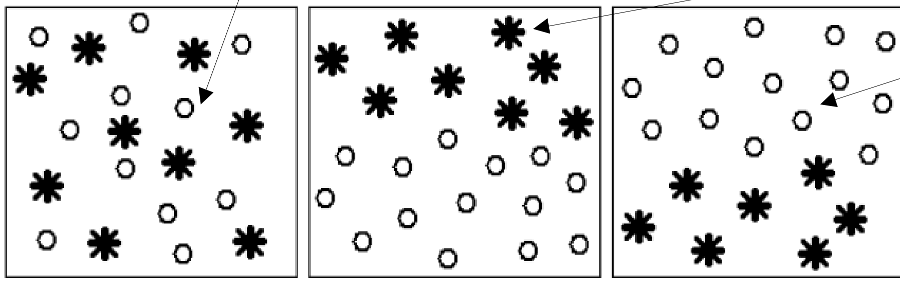
$$\langle g_e \rangle = \left[\frac{g_i \langle Q_{si}\rangle \gamma}{D_{ei}\rho_i \langle Q_s\rangle} + \frac{g_w \langle Q_{sw}\rangle (1-\gamma)}{D_{ew}\rho_w \langle Q_s\rangle}\right] D_e \rho_e$$

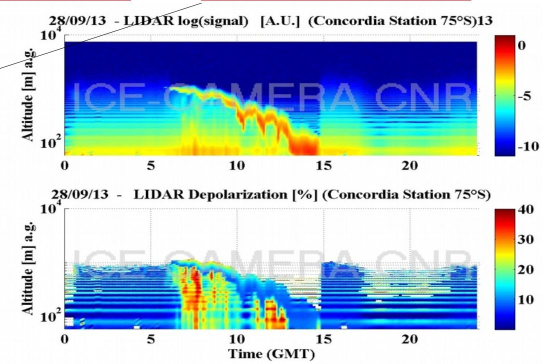
$$\omega = 1 - \frac{\langle Q_a \rangle}{\langle Q_e \rangle}$$

Two possible representations

Uniformely mixed in volume

Adjacent layers of ice over water or water over ice





Ping Yang et al., 2003, JQSRT

Sun and Shine, 1994, Journ. Of Clim.

$$\tau_m = \tau_i + \tau_w$$

$$\omega_{0,m} = \left(\tau_i \omega_{0,i} + \tau_w \omega_{0,w}\right) / \tau_m$$

$$g_m = \left(\tau_i \omega_{0,i} g_i + \tau_w \omega_{0,w} g_w\right) / \left(\tau_m \omega_{0,m}\right)$$

$$p_m = \left(\tau_i \omega_{0,i} p_i + \tau_w \omega_{0,w} p_w\right) / \left(\tau_m \omega_{0,m}\right)$$

$$TWP = IWP + LWP \qquad \frac{1}{\rho_e} = \frac{\gamma}{\rho_i} + \frac{1-\gamma}{\rho_w}$$

$$\gamma = \frac{IWP}{TWP} \qquad \frac{1}{D_e \rho_e} = \frac{\gamma}{D_{ei} \rho_i} + \frac{1-\gamma}{D_{ew} \rho_w}$$

$$\langle Q_e \rangle = \left[\frac{\langle Q_{ei} \rangle \gamma}{D_{ei} \rho_i} + \frac{\langle Q_{ew} \rangle (1-\gamma)}{D_{ew} \rho_w} \right] D_e \rho_e$$

$$\langle Q_a \rangle = \left[\frac{\langle Q_{ai} \rangle \gamma}{D_{ei} \rho_i} + \frac{\langle Q_{aw} \rangle (1-\gamma)}{D_{ew} \rho_w} \right] D_e \rho_e$$

$$\langle g_e \rangle = \left[\frac{g_i \langle Q_{si} \rangle \gamma}{D_{ei} \rho_i \langle Q_s \rangle} + \frac{g_w \langle Q_{sw} \rangle (1-\gamma)}{D_{ew} \rho_w \langle Q_s \rangle} \right] D_e \rho_e$$

$$\omega = 1 - \frac{\langle Q_a \rangle}{\langle Q_e \rangle}$$

Methodology

- FORWARD + RETRIEVAL → Simultaneous Atmospheric and Cloud Retrieval (SACR, *Di Natale et al. 2020, JQSRT*)
- Minimization of the cost function:

$$\chi^2 = (\mathbf{y} - \mathbf{F}(\mathbf{x}))^T \mathbf{S}_y^{-1} (\mathbf{y} - \mathbf{F}(\mathbf{x})) + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)$$

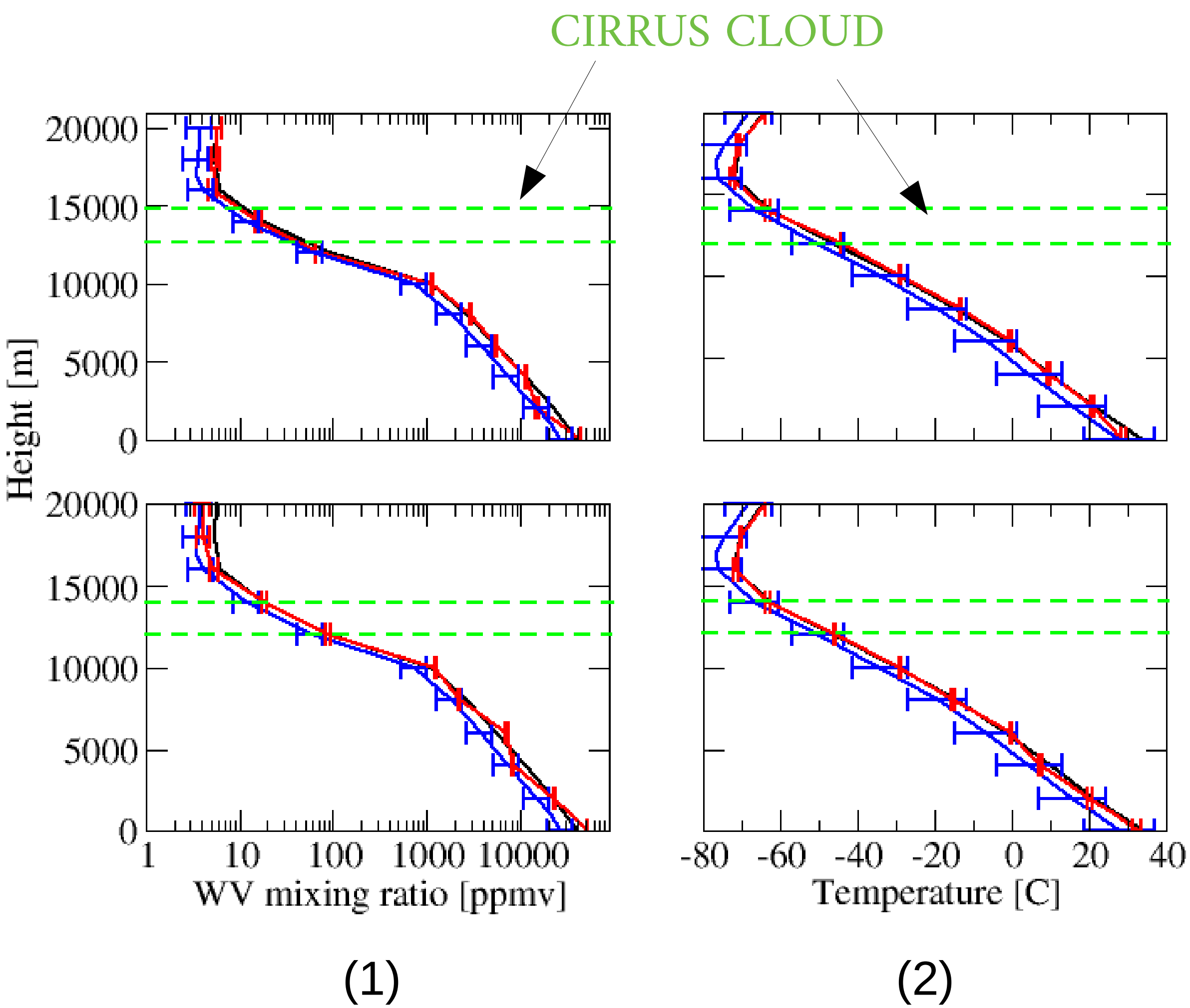
and the state vector represented by:

$$\mathbf{x} = (D_{ei}, OD_i, \gamma, D_{ew}, \mathbf{Q}, \mathbf{T}, Z_b, T_s)$$

- Atmospheric retrieval grid with vertical resolution 2 km
- A priori information about surface temperature and atmospheric profiles (WV, T and O3) from ERA5; the remaining species from IG2. Error set to 30% for WV and 1% for T with correlation length 5 km
- A priori information about clouds from climatology and in situ measurements and error set to 100%
- The parameter Ω of the Instrument Line Shape (ILS) can be also fitted:

$$\mathrm{ILS}_\nu(\Omega) = \alpha_\nu(\Omega) \cdot \mathrm{sinc}\left(\frac{\nu}{\Delta\nu}\right) + (1 - \alpha_\nu(\Omega)) \cdot \mathrm{sinc}^2\left(\frac{\nu}{2\Delta\nu}\right)$$

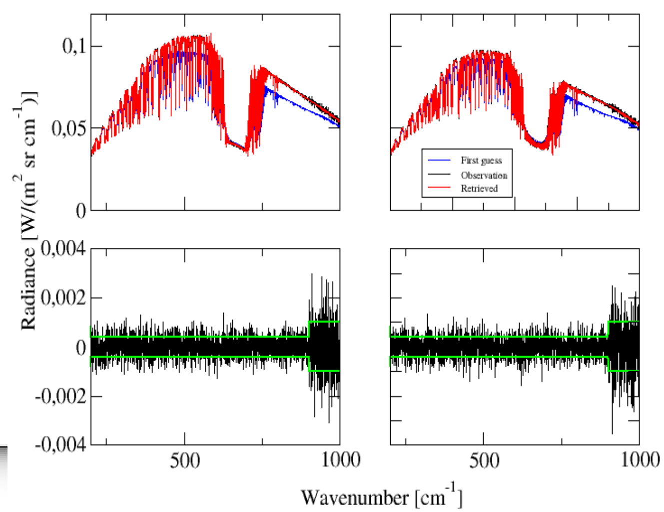
Tests on simulated observations at tropics



WV true profiles perturbed of 30%, T true profiles perturbed of 1% and Ts perturbed of 1 K to get the initial guesses

(1) D_{ei} = 20 mμ, OD = 1.0

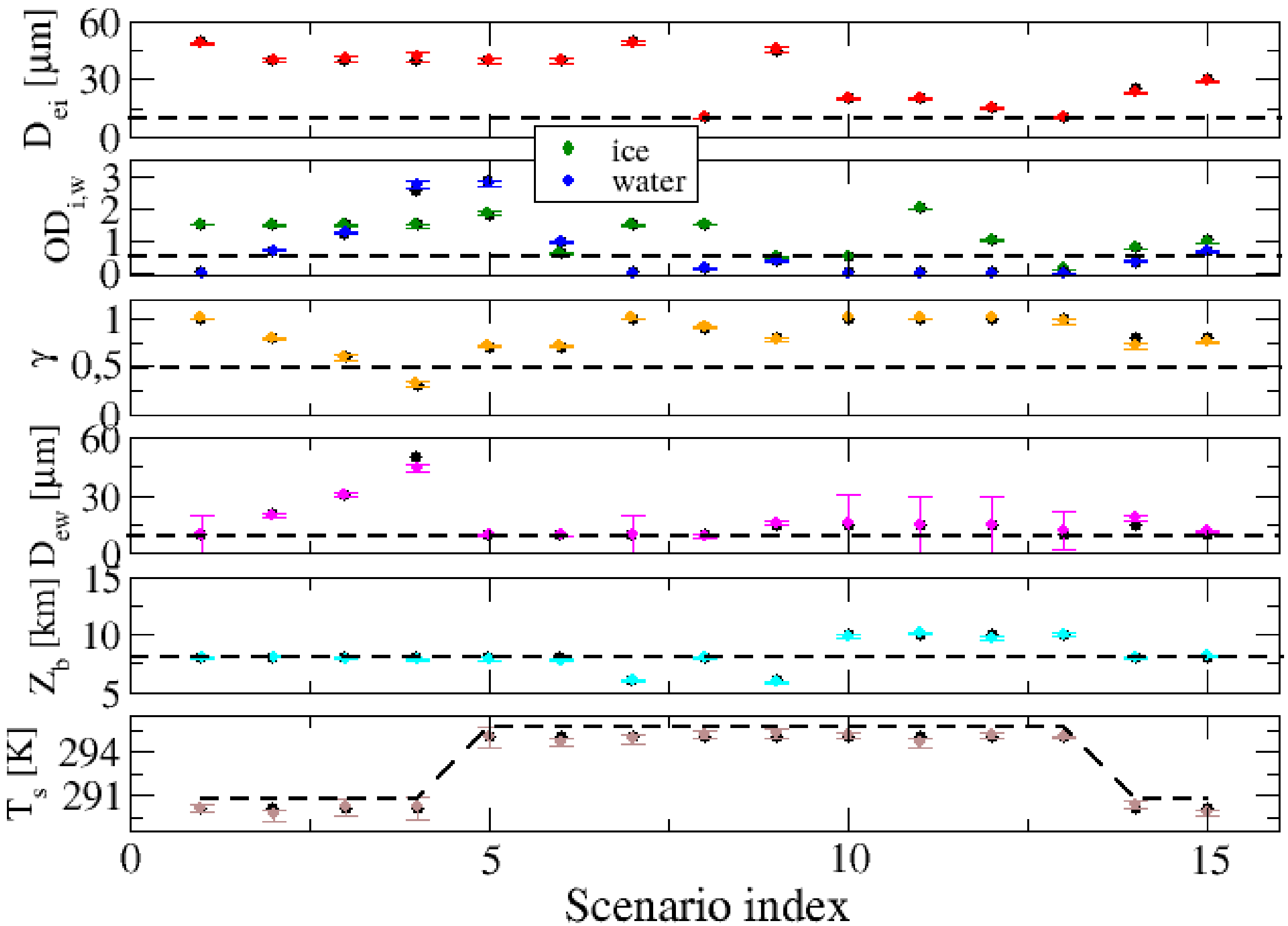
(2) D_{ei} = 50 mμ, OD = 0.5



Retrieval consistency of cloud parameters

Observations generated in tropical atmospheric scenarios taken from ERA5 and IG2

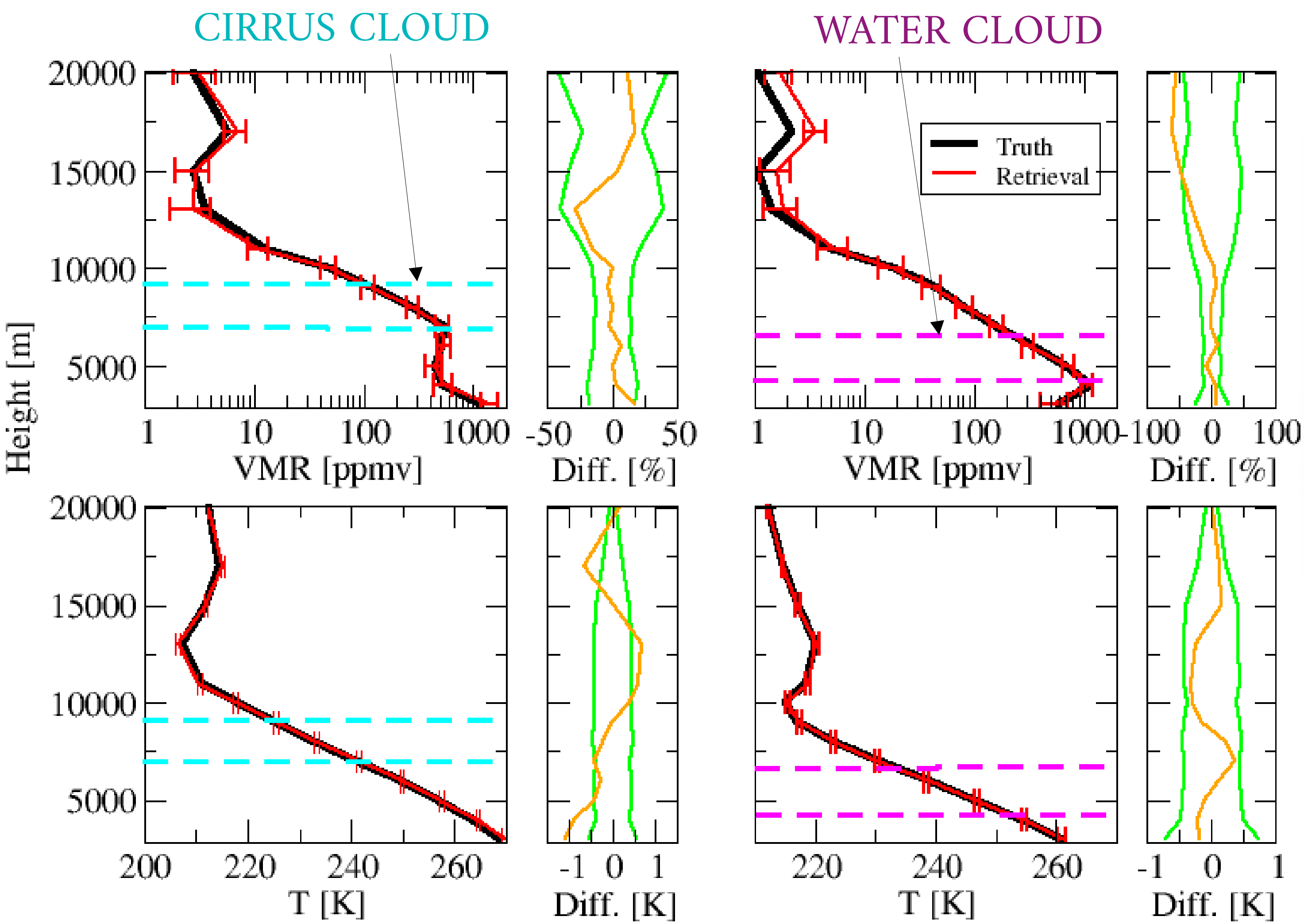
Retrieval of cloud parameters & Ts

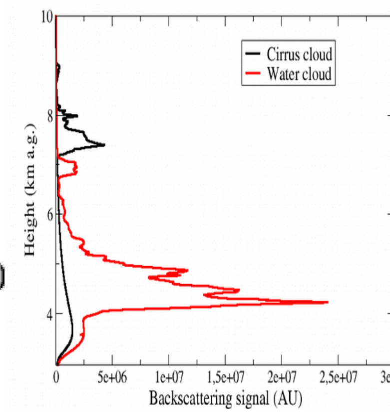


Tests on simulated observations at mid-latitudes

Observations generated in mid-latitude atmospheric scenarios taken from ERA5 and IG2

Retrieval of atmospheric profiles



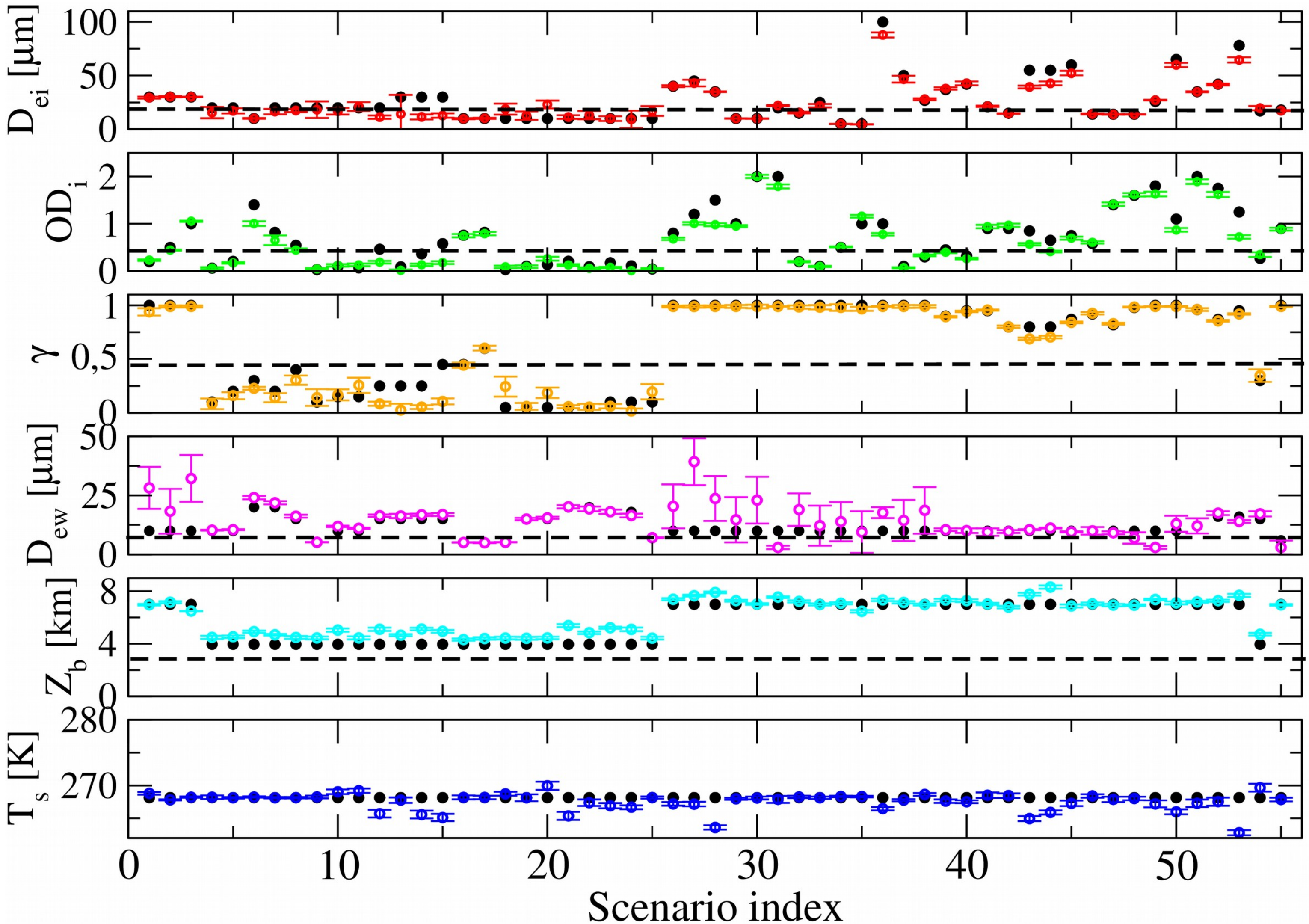


$$\mathrm{OD_v}(z) = \mathrm{OD_v} \cdot S(z)$$

$\mathrm{OD_v}$ modulated with the normalized backscattering lidar signal S

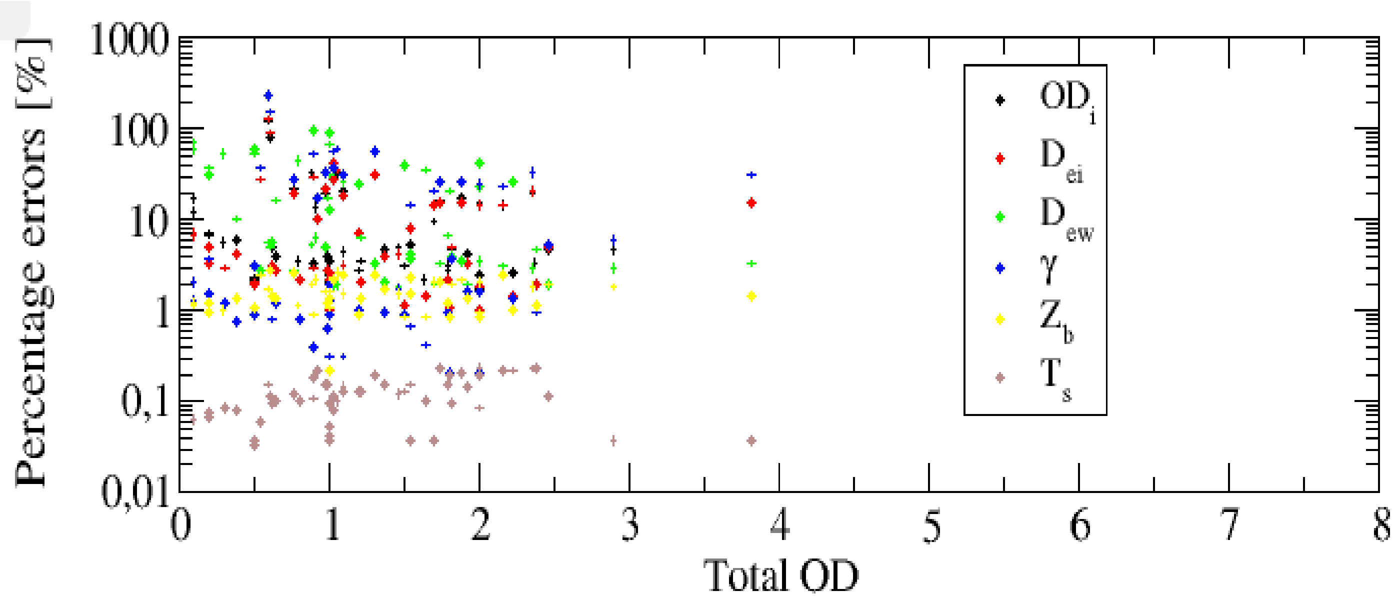
Retrieval consistency of cloud parameters

Mid-latitude atmospheric scenarios, retrieval of cloud parameters & Ts



Retrieval errors and degrees of freedom (DOF)

Retrieval errors as a function od the retrieved optical depth



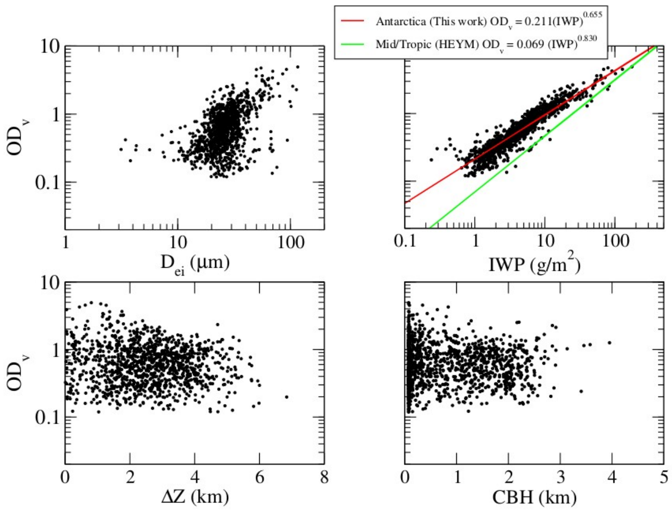
Mean DOF WV = 6

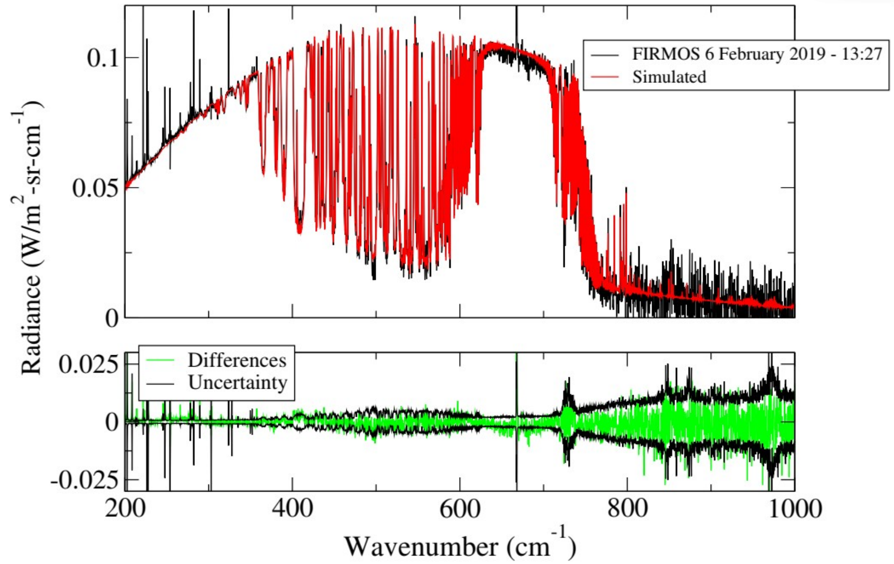
Mean DOF T = 7

Mean DOF cloud = 5

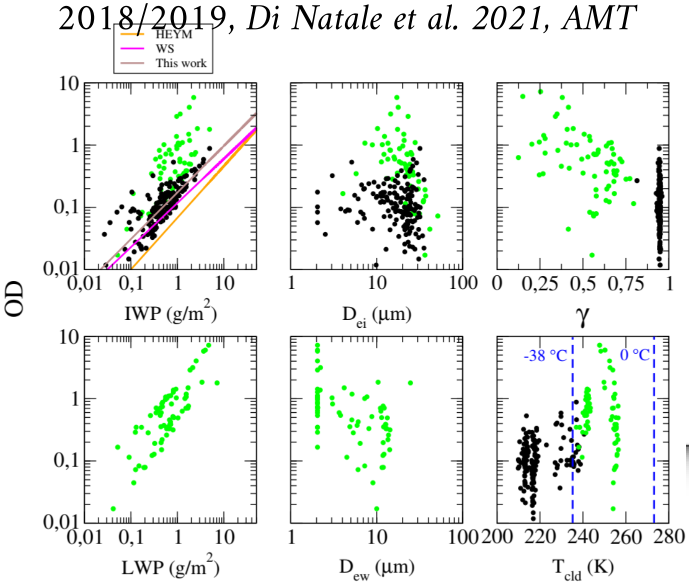
Applications to down-welling measurements

Dome-C, Antarctica, REFIR-PAD since 2012, *Di Natale et al. 2020, Rem. Sens.*

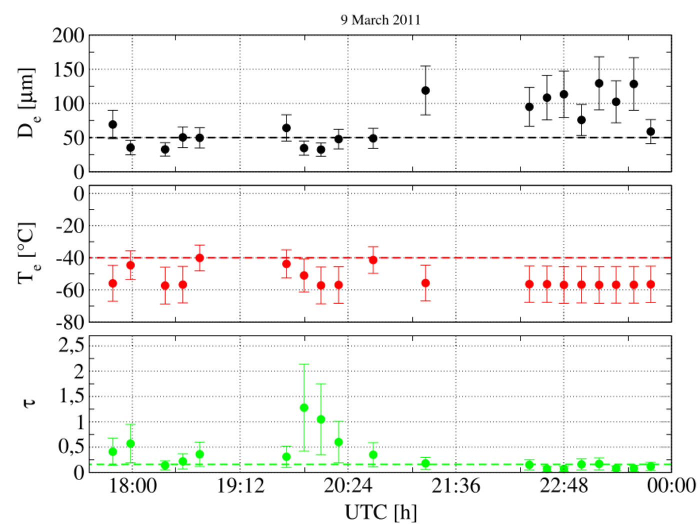




Zugspitze Mountain, Germany, FIRMOS, 2018/2019, *Di Natale et al. 2021, AMT*



Testa Grigia, Italian Alps, REFIR-PAD, 2017 & 2011, *Palchetti et al. 2016, JGR*



Conclusions and future perspectives

- The Simultaneous Atmospheric and Clouds Retrieval (SACR) is suitable tool to perform the retrieval of clouds and atmospheric properties from upwelling far infrared spectral observations in perspective of FORUM measurements. The code was already succesfully used for the analysis of many down-welling measurements in Antarctica and the Alps.

- The atmospheric profiles of WV and T can be retrieved simultaneously with the cloud parameters, surface temperature and the instrument line shape

- Synthetic observations were simulated in different atmospheric scenarios at mid-latitudes/ tropics and the retrieval of WV and T profiles together with the effective diameters of ice crystals, optical depth, ice fraction and water droplets effective size (in case of mixed-phase clouds), bottom(top) height and surface temperature was tested and turned out to be reliable in most cases

- Most of the retrieval errors of the D_{ei}, D_{ew}, OD_i and γ were found below 10%, the mean DOF of WV, T and cloud were found to be 6, 7 and 5, respectively

- Other works about the retrievability of crystal habits are ongoing (under revision on JQSRT)

Thanks for your attention!!