Synergy of MERRA-2 modeling and Raman lidar measurements for characterization of aerosol properties over West Africa

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Motivation

- Study of inversion of MW Raman lidar measurements to particle properties started more than 15 years ago

  D. Muller et al., 1999; I. Veselovskii et al., 2002

- The most practical configuration of Raman lidar is based on tripled Nd:YAG laser (3β +2α)

- Typical uncertainties of estimation today are:

Volume	~ 20-30%
Effective radius	~20-30%
Real part of refractive index	± 0.05
Imaginary part (when Im>0.01)	~ 50%

- Experience accumulated was used for 3β +2α space lidar proposal (ACE)

Lidar measurement requirements

±15% accuracy for backscattering (β) at 355, 532, 1064 nm
±15% accuracy for extinction (α) at 355, 532 nm
$\alpha \geq 0.05\ km^{-1}$ at UV
$\alpha \geq 0.02\ km^{-1}$ at MV

So called 3β+2α set

Microphysical parameters

Aerosol effective radius
Aerosol refractive index
Aerosol concentration
Aerosol SSA
Aerosol absorption
Aerosol type

However…

- **Problem is underdetermined (only 5 input data). Information content of lidar measurements is limited.**

Burton et al., 2016; Kahnert and Andersson, 2017; Alexandrov and Mishchenko 2017

- **Moreover, refractive index can be spectrally and size dependent**

- **Additional information is needed. It can be obtained from passive instruments: sun radiometers or polarimeters**

- **Another possibility is synergy with aerosol transport models**

How model can be used in lidar inversion?

For example, model data can be used as a first guess, so minimized cost function is (Kahnert, 2017):

$$J = \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}\left[H(x) - y\right]^T R^{-1}\left[H(x) - y\right]$$

$$y = H(x) + \varepsilon$$

B, R – error covariance matrices

First step is to study how well the model predictions agree with lidar observed profiles of extinction (α) and backscattering (β). Ground based Raman lidar is capable to measure α and β with uncertainty below 10%.

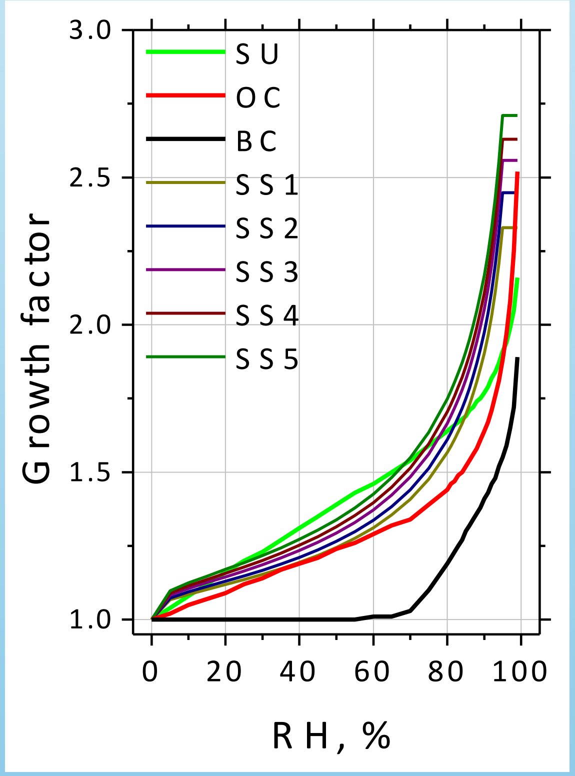
MERRA-2 (Modern-Era Retrospective analysis for Research and Applications)

Based on GEOS-5 (Goddard Earth Observing System)
Includes GOCART (Goddard Chemistry, Aerosol, Radiation and Transport model)
Assimilates AOD from MODIS, AVHRR, MISR, and AERONET

Model includes 5 aerosol components: dust, sea salt, black and organic carbon, sulfates

RH=0

Component		r_{min}, µm	r_{max} µm	r_{eff} µm	m_{R355}	m_{R532}	m_{R1064}	m_{I355}	m_{I532}	m_{I1064}
Dust	Bin 1	0.1	1.0	0.64	1.53	1.53	1.53	0.007	0.0026	0.0022
	Bin 2	1	1.5	1.32	1.53	1.53	1.53	0.007	0.0026	0.0022
	Bin 3	1.5	3.0	2.30	1.53	1.53	1.53	0.007	0.0026	0.0022
	Bin 4	3.0	7.0	4.17	1.53	1.53	1.53	0.007	0.0026	0.0022
	Bin 5	7.0	10.0	7.67	1.53	1.53	1.53	0.007	0.0026	0.0022
Sea Salt	Bin 1	0.03	0.1	0.08	1.51	1.50	1.47	2.9E-7	1.2E-8	1.97E-4
	Bin 2	0.1	0.5	0.27	1.51	1.50	1.47	2.9E-7	1.2E-8	1.97E-4
	Bin 3	0.5	1.5	1.07	1.51	1.50	1.47	2.9E-7	1.2E-8	1.97E-4
	Bin 4	1.5	5	2.55	1.51	1.50	1.47	2.9E-7	1.2E-8	1.97E-4
	Bin 5	5	10	7.3	1.51	1.50	1.47	2.9E-7	1.2E-8	1.97E-4
OC		0.01	0.29	0.09	1.53	1.53	1.52	0.048	0.009	0.016
BC		0.01	0.29	0.04	1.75	1.75	1.75	0.46	0.44	0.44
SU		0.01	0.29	0.157	1.45	1.43	1.42	1E-8	1E-8	2.9E-6



The SHADOW campaign in Senegal 2015

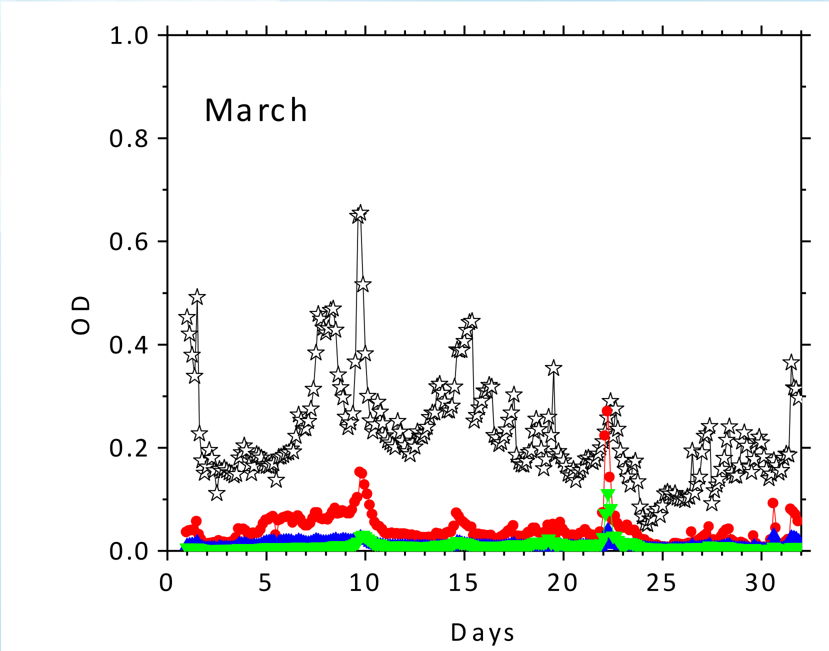
Organized by Lille University

Multiwavelength Raman lidar

$3\beta+2\alpha+1\delta$

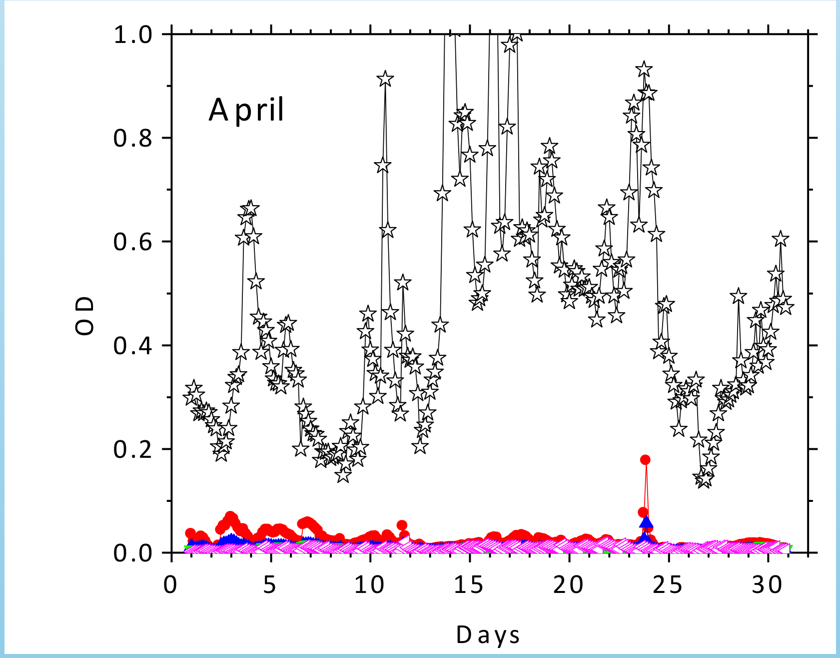
Measurements were performed at 47 deg to horizon

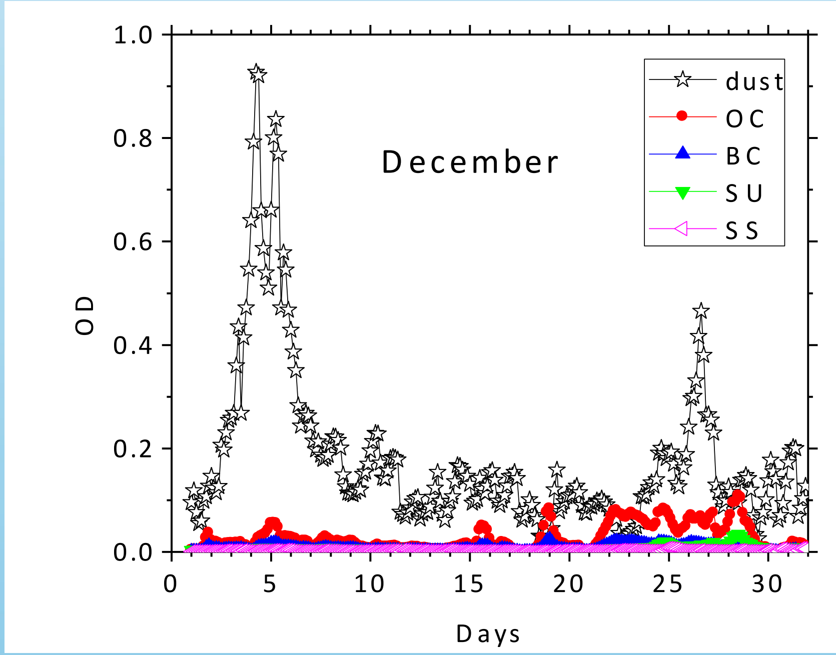
MERRA-2 modeling



OD in 0.88-5.04 km at 532 nm

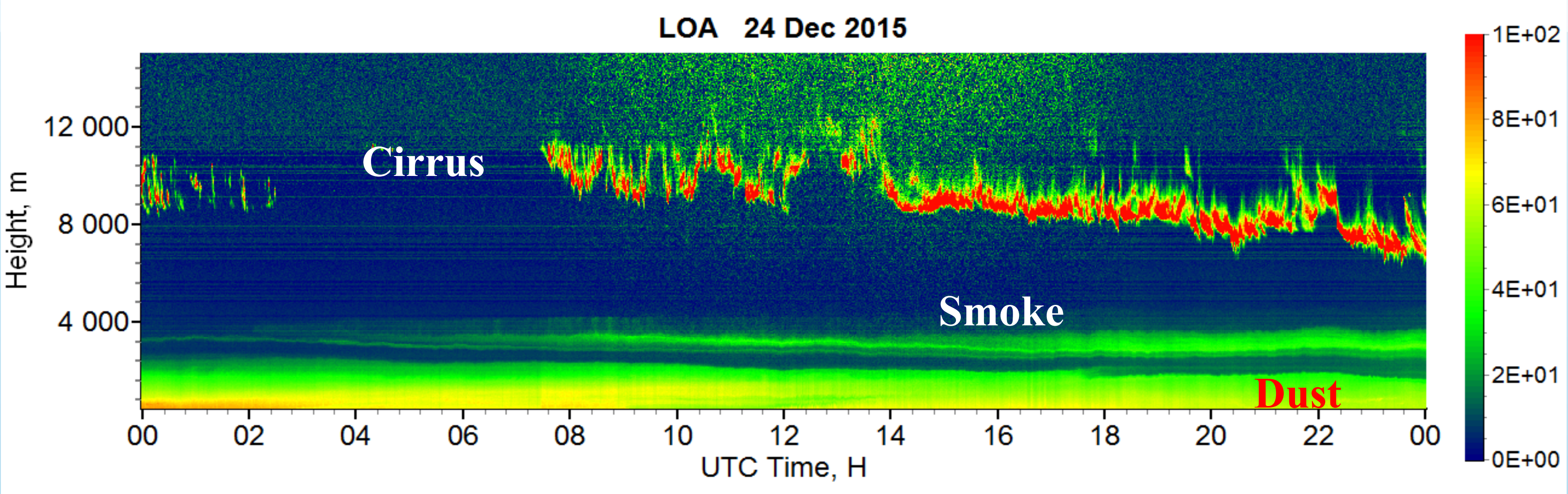
dust, organic carbon, black carbon, sulfates, sea salt

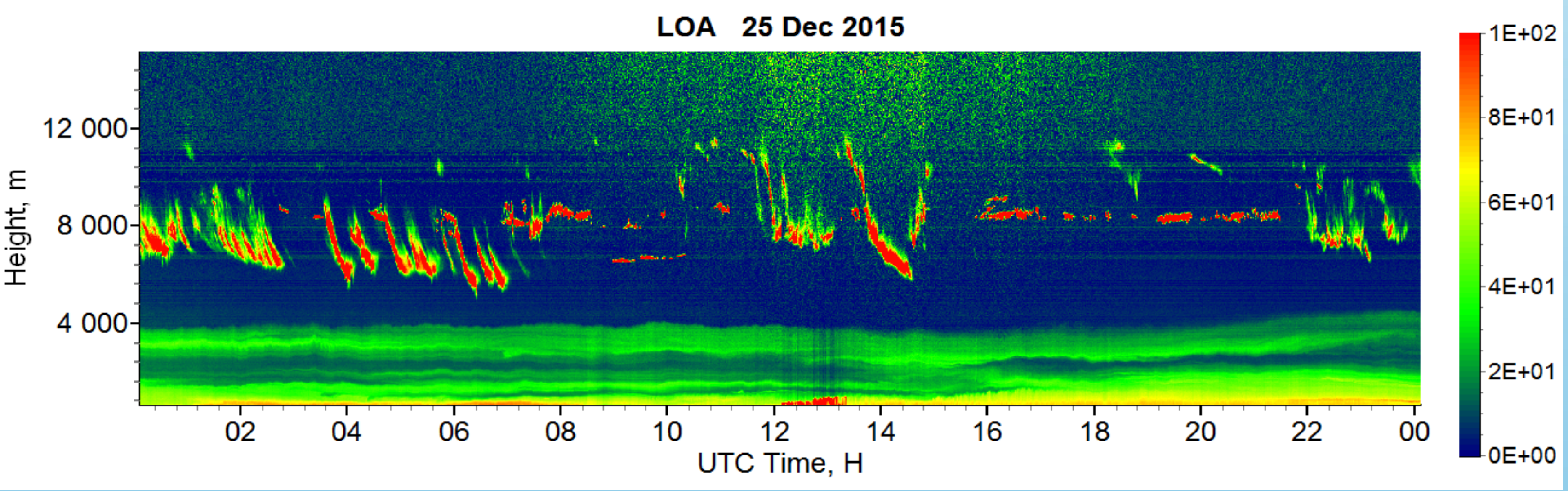




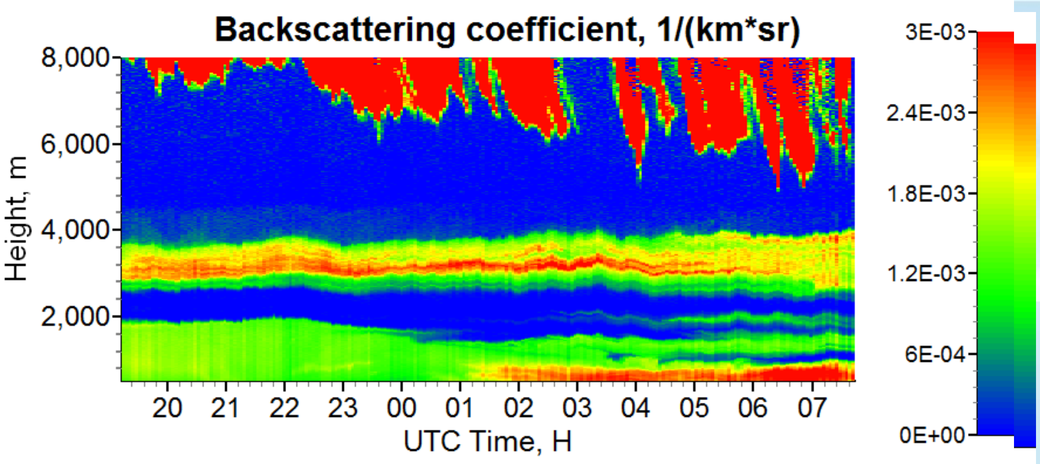
Strong smoke episode on 24-25 December 2015

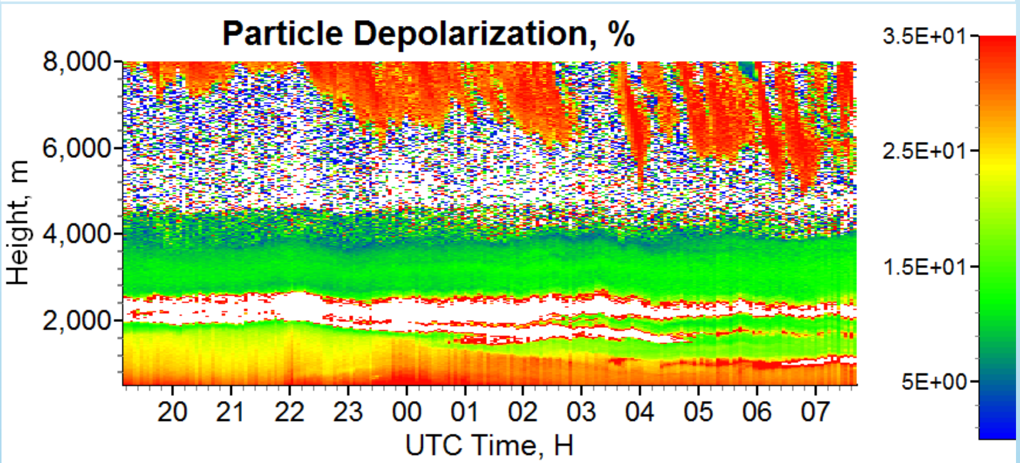
Cimel MPL measurements

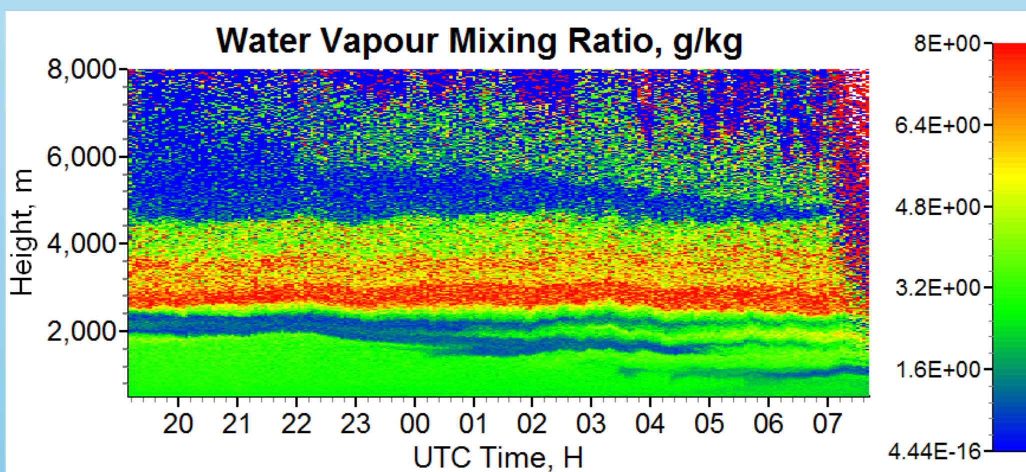


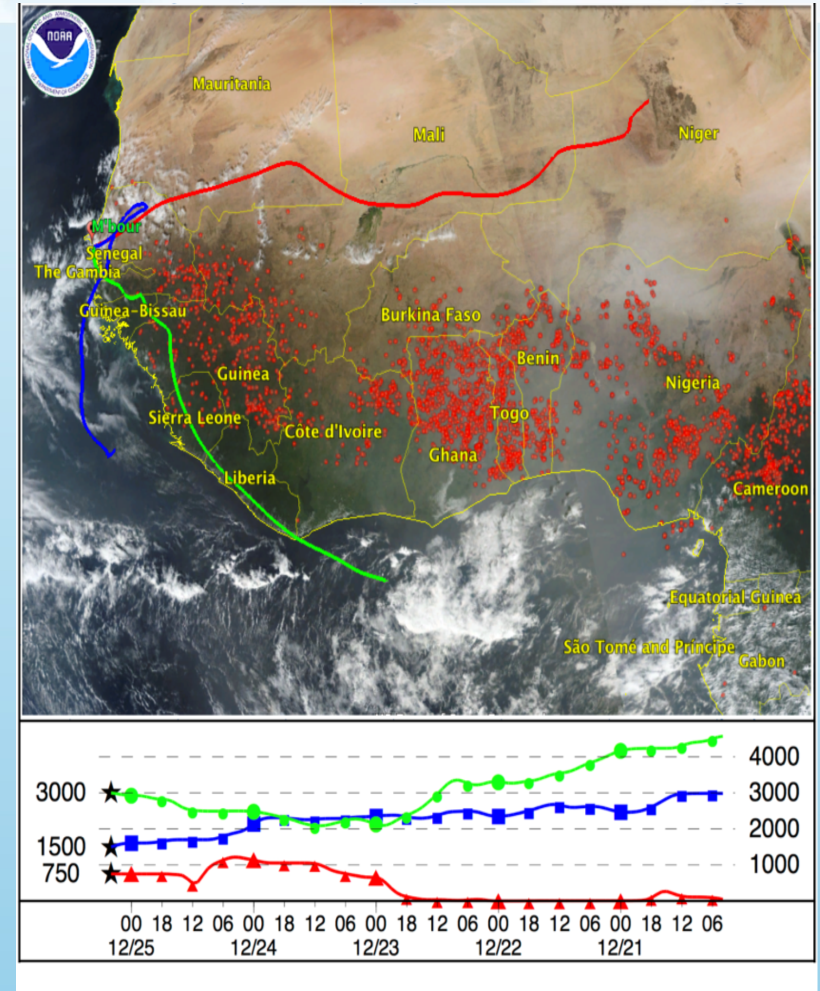


Raman lidar measurements on 24-25 December 2015





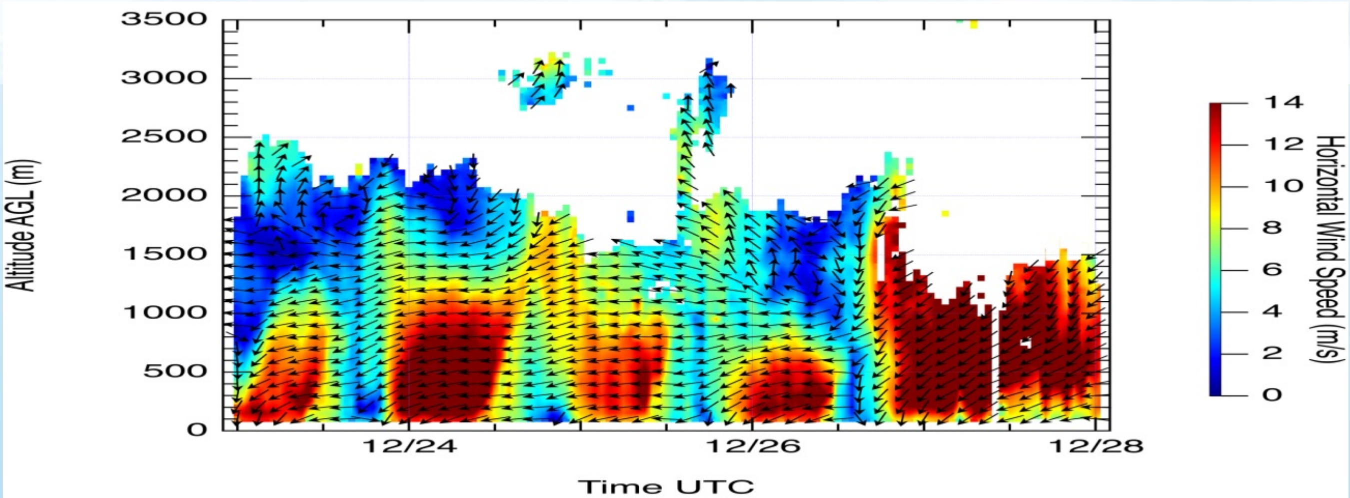




Back trajectories at 04:00

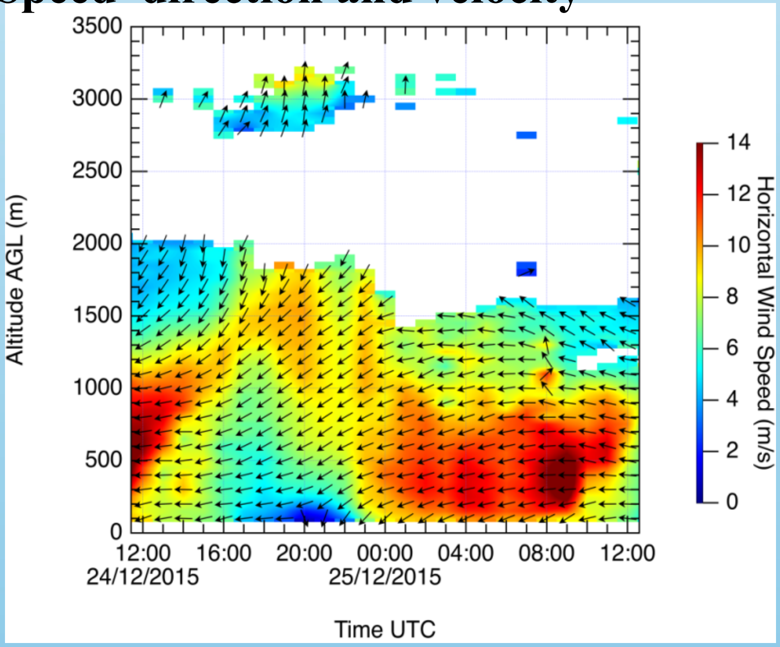
Wind measurements with Doppler lidar

Speed direction and velocity on 24-28 December

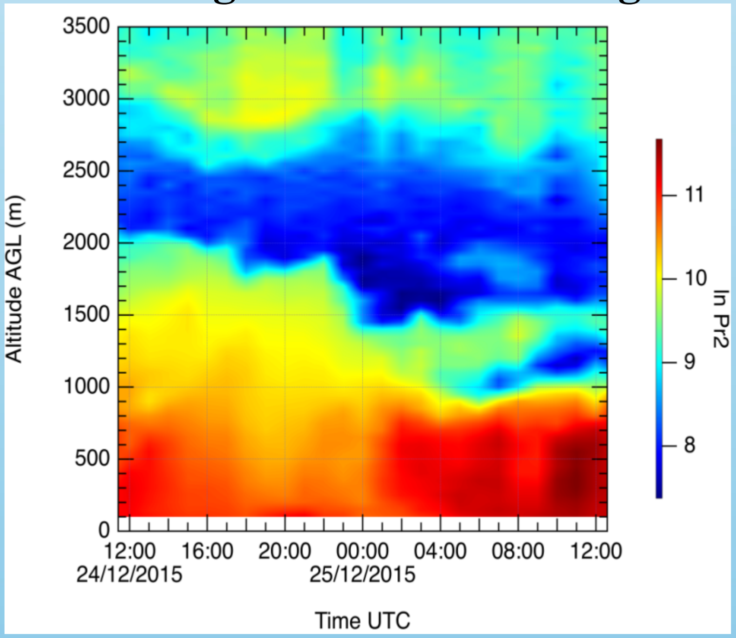


24-25 December

Speed direction and velocity

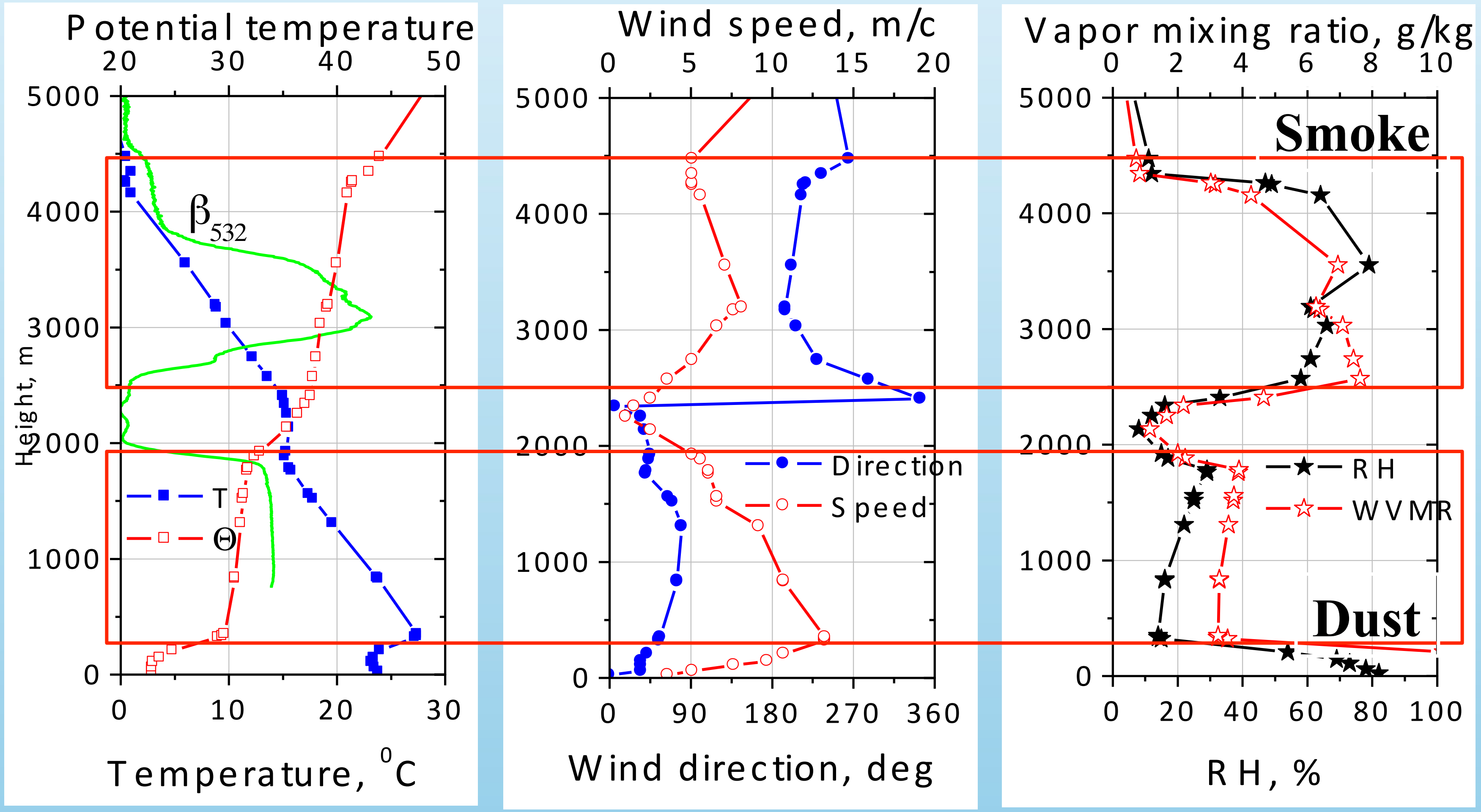


Range corrected lidar signal

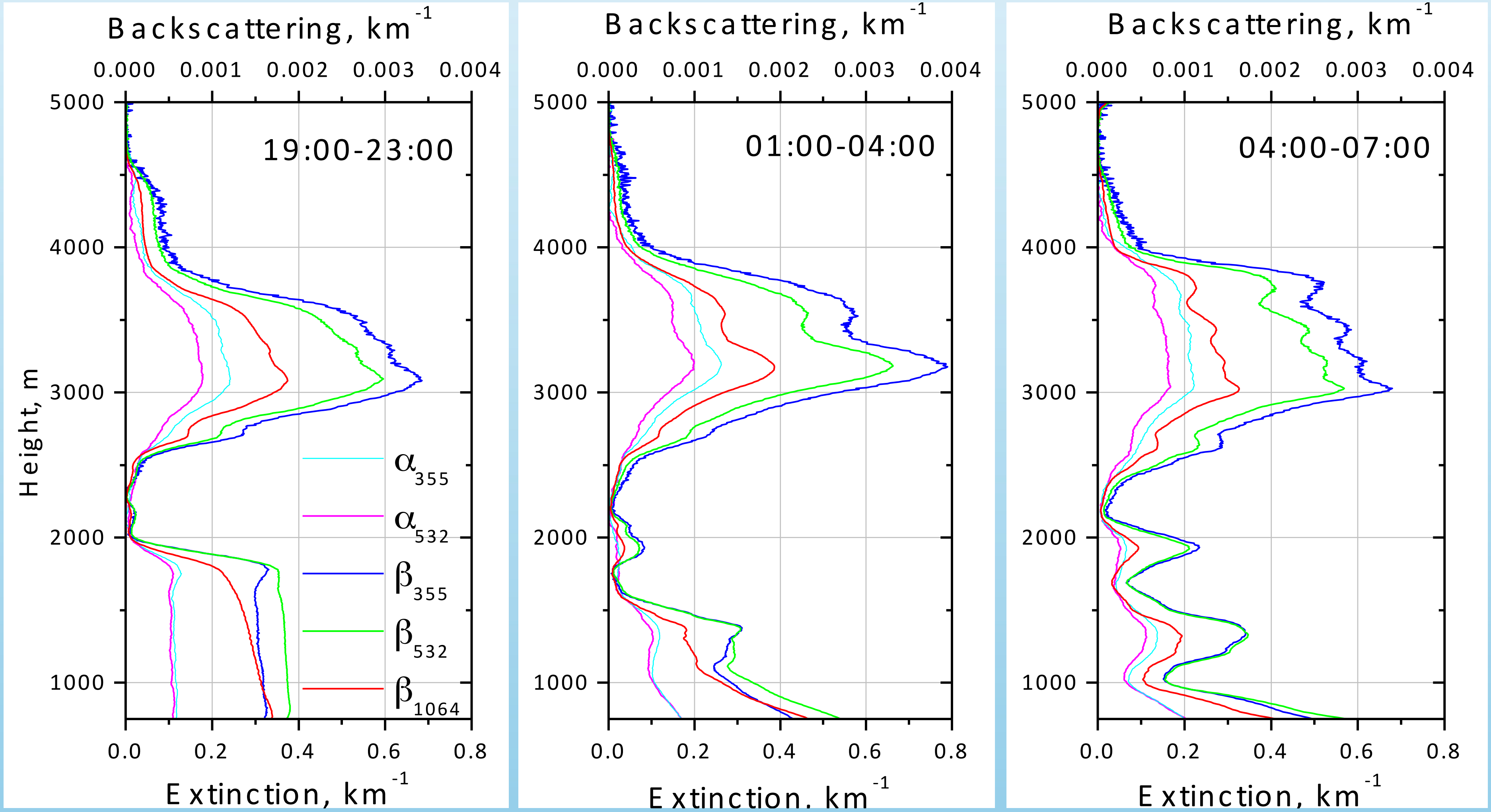


Atmospheric parameters 25 December 00:00

Sonde measurements

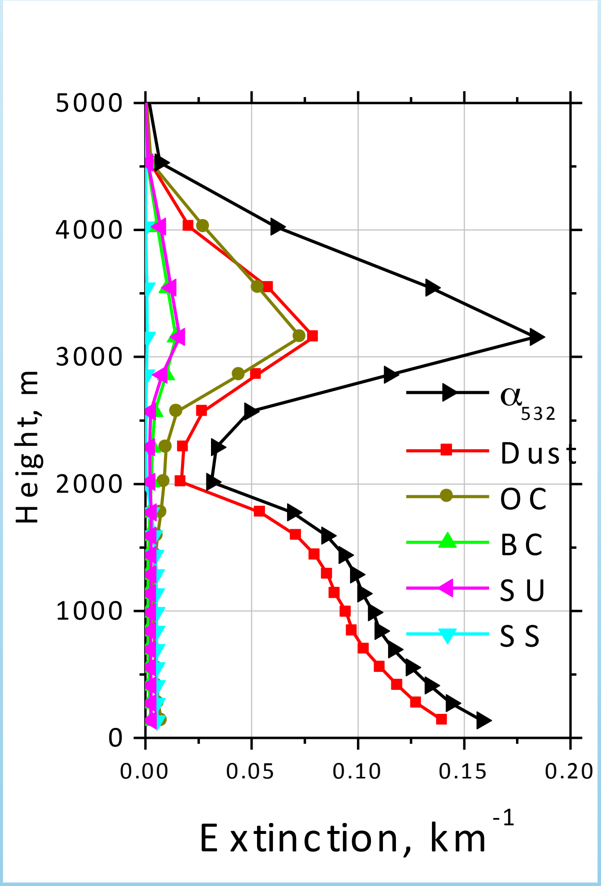


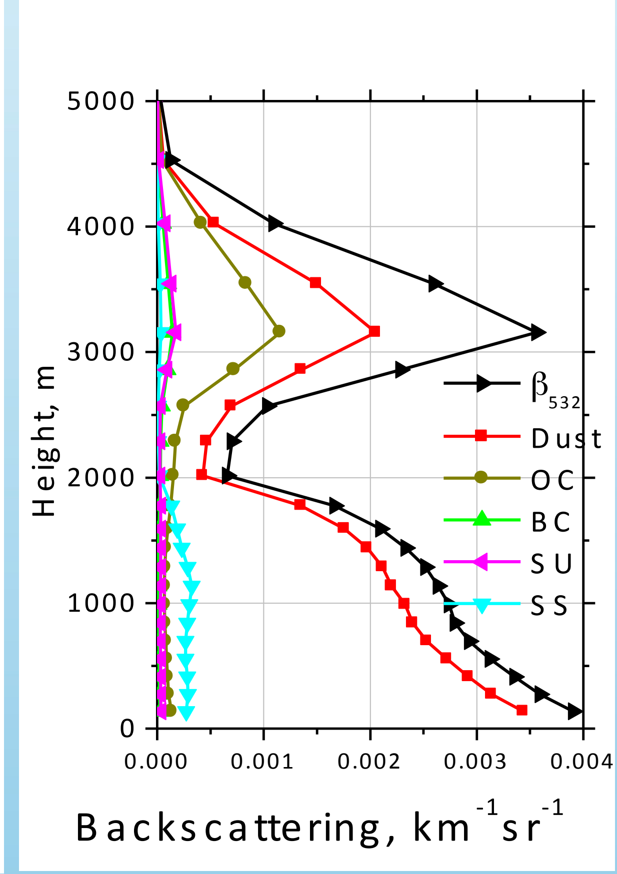
Backscattering and extinction coefficients measured by Raman lidar



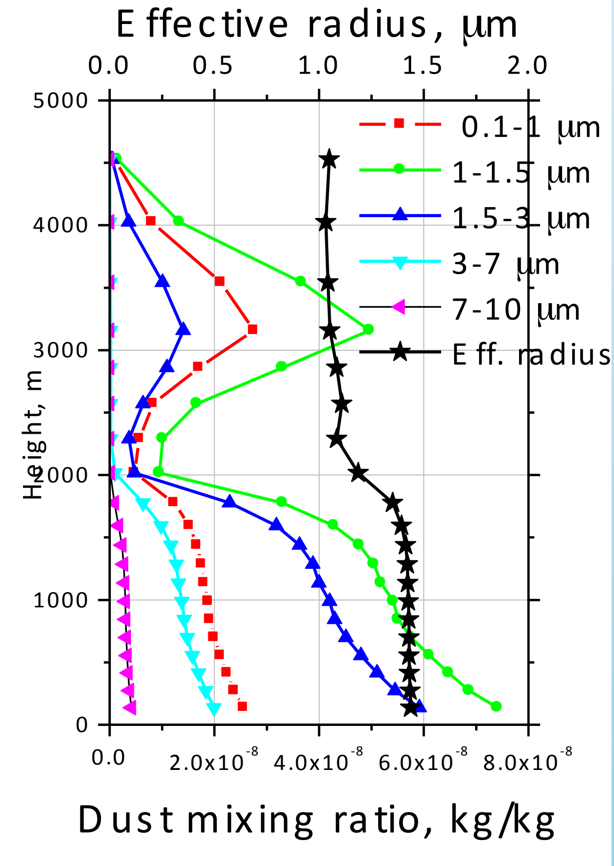
Model predictions

Contribution of different components to backscattering and extinction at 532 nm at 21:00.

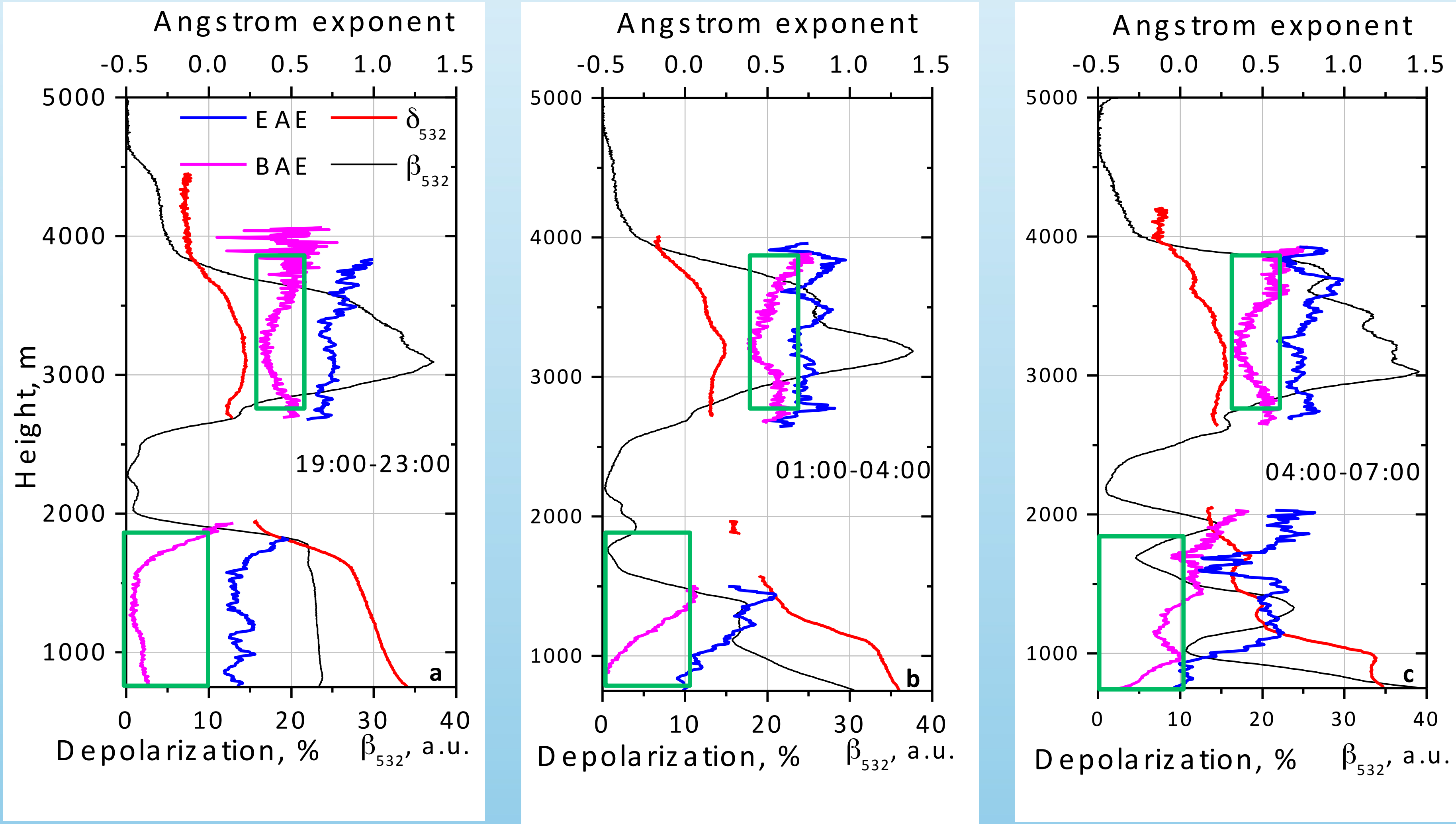




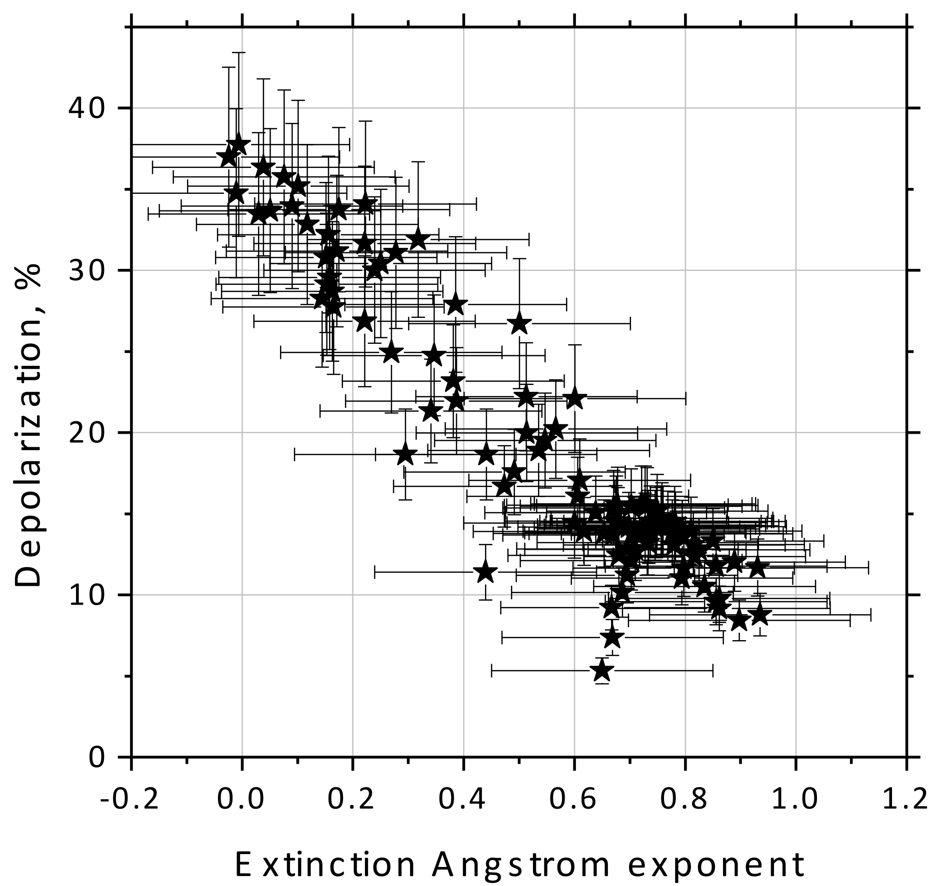
Dust sedimentation



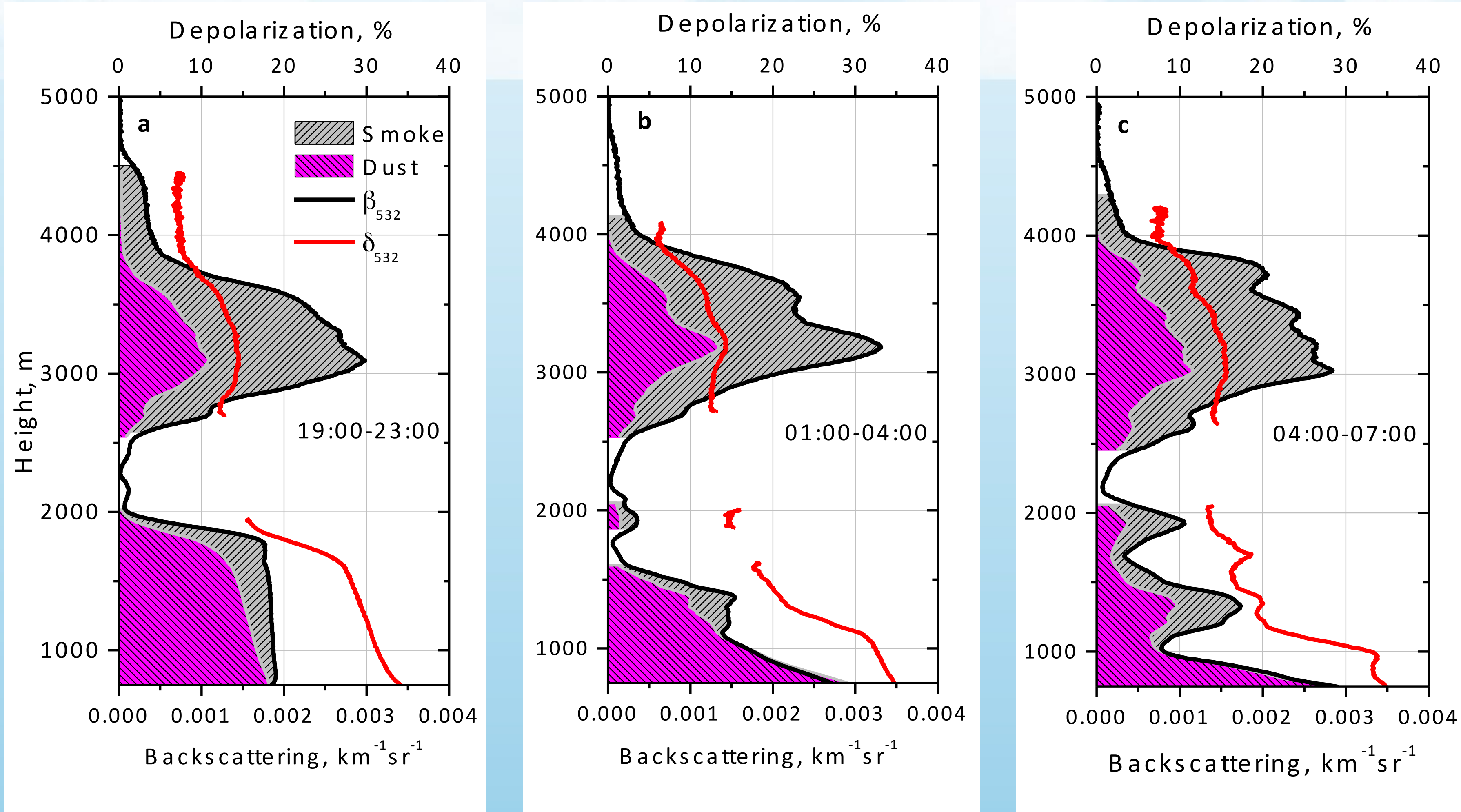
Extinction (EAE) and backscattering (BAE) Angstrom at 355/532 nm together with depolarization



Depolarization vs extinction Angstrom exponent



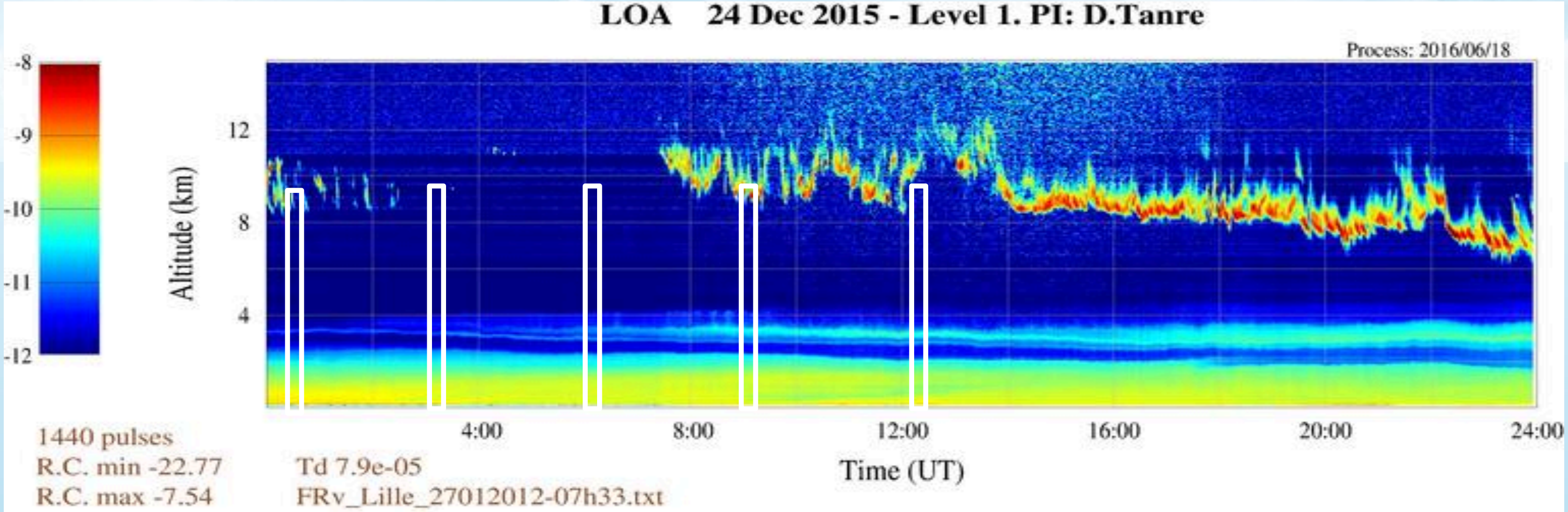
Use of depolarization measurements for separation the smoke and dust contributions to backscattering at 532 nm



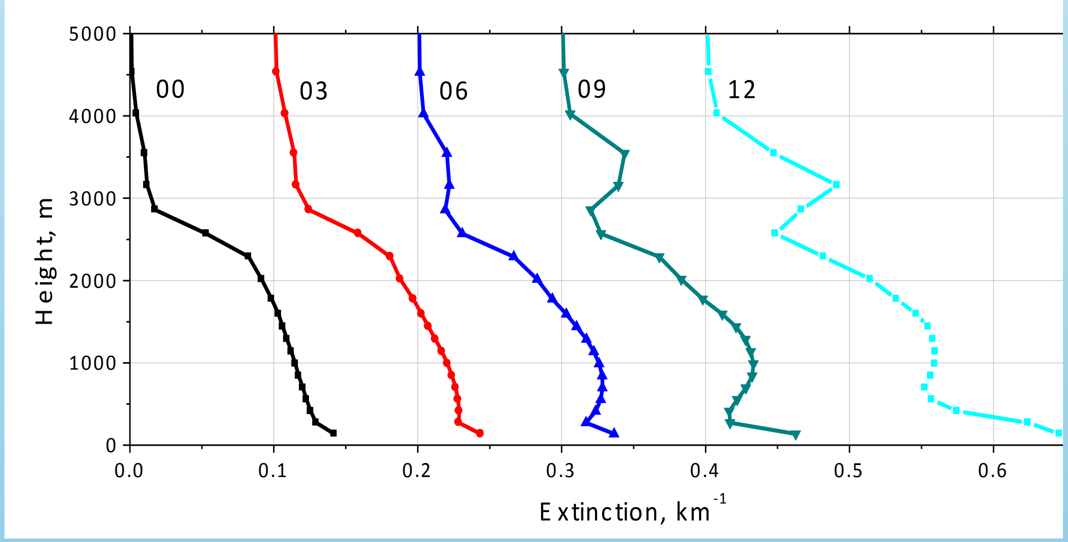
Assuming the depolarization of dust and smoke is 35% and 7% respectively, their contributions were separated.

Contribution of dust to α_{532} in the center of elevated layer is 30% (model predicts 40%).

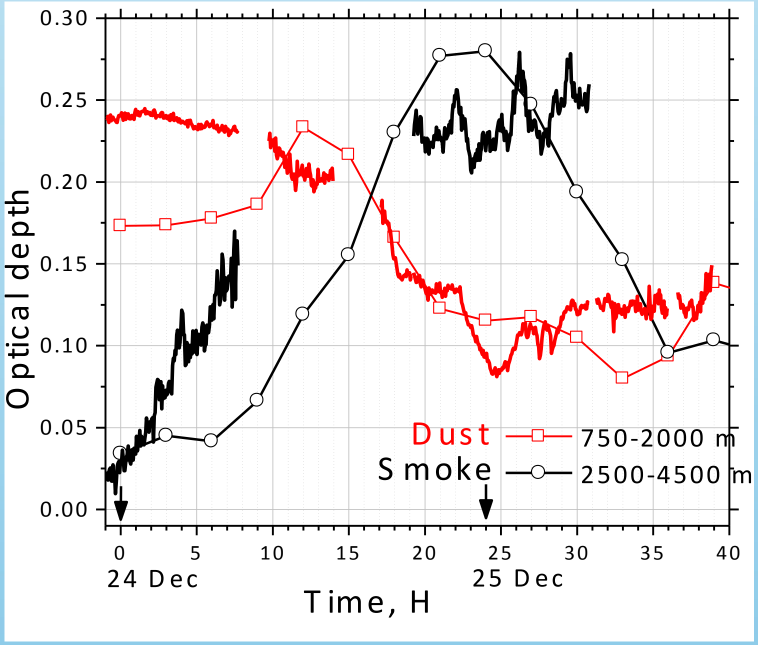
Comparison with model. Arrival of smoke layer



Temporal sequence of model extinction profiles



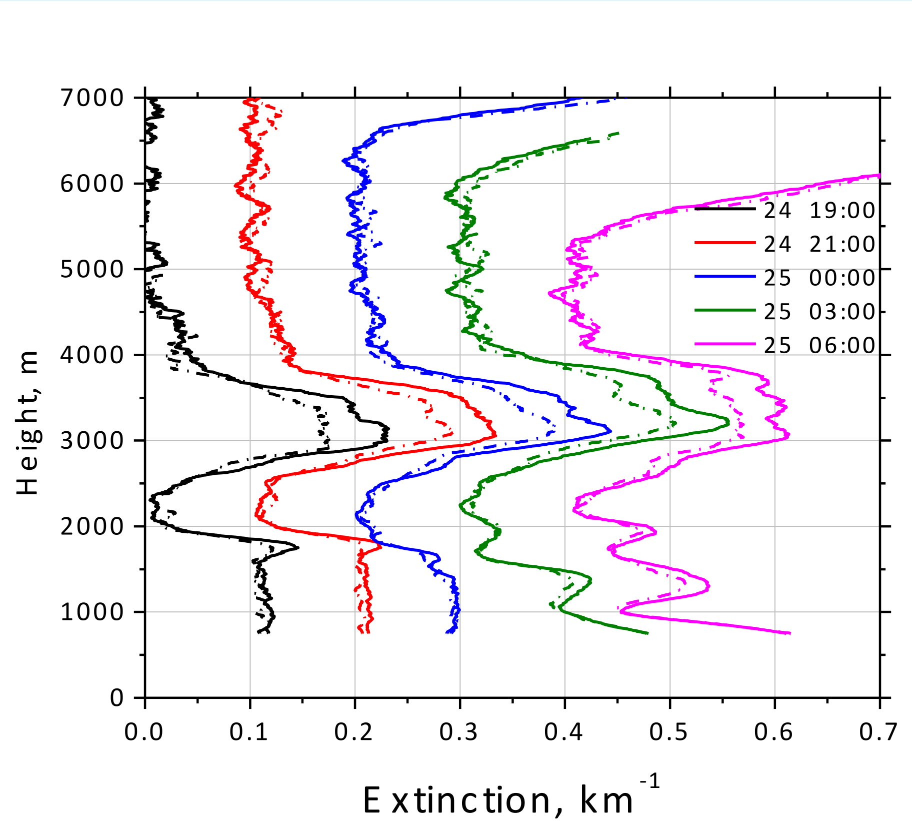
Optical depth at 355



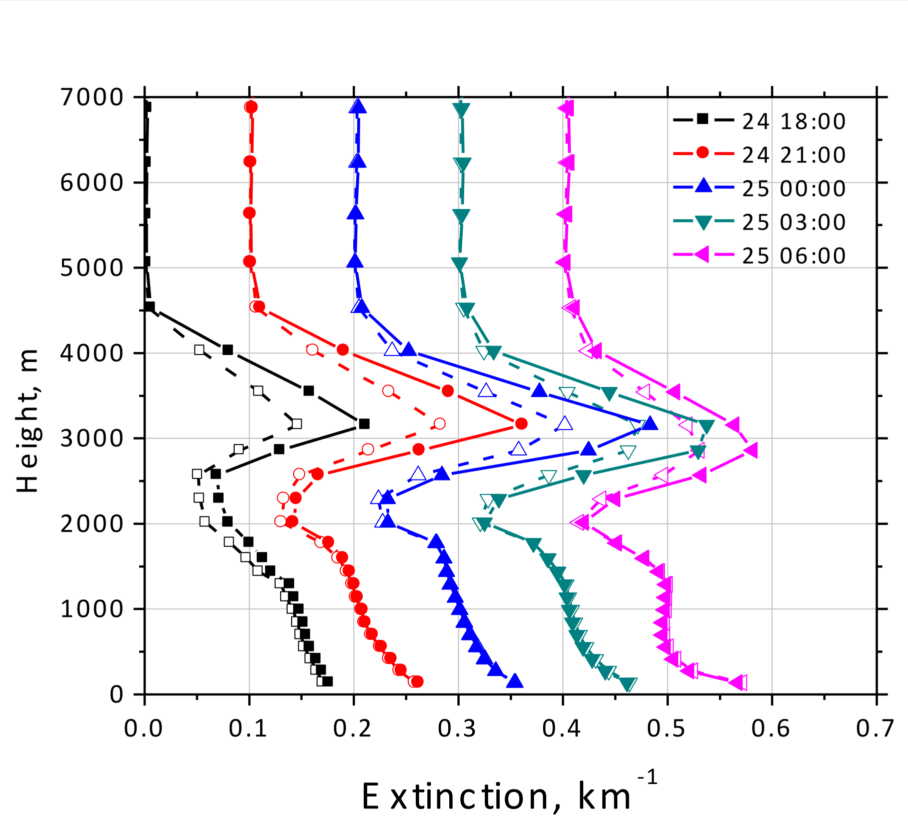
Extinction profiles at 532 nm are shifted by 0.1 km^{-1}

Extinction profiles at 355 and 532 nm

Lidar



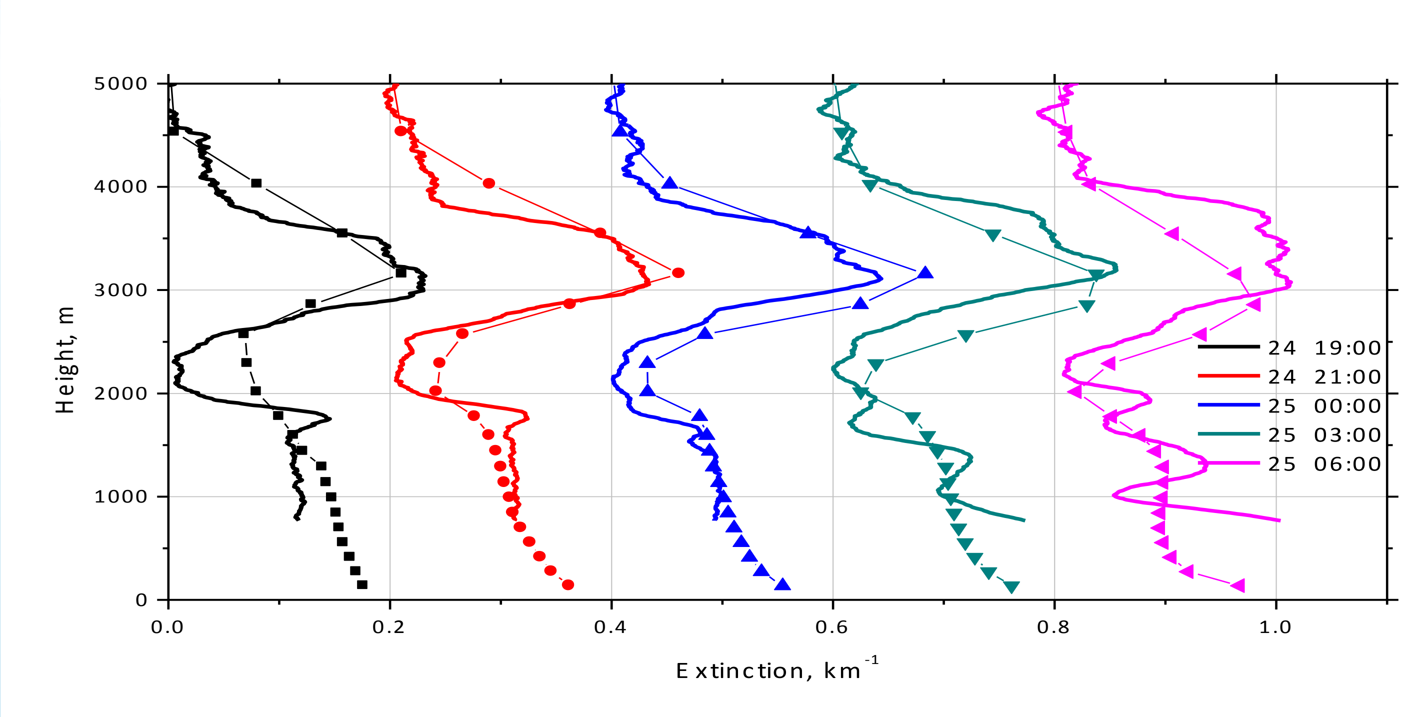
Model

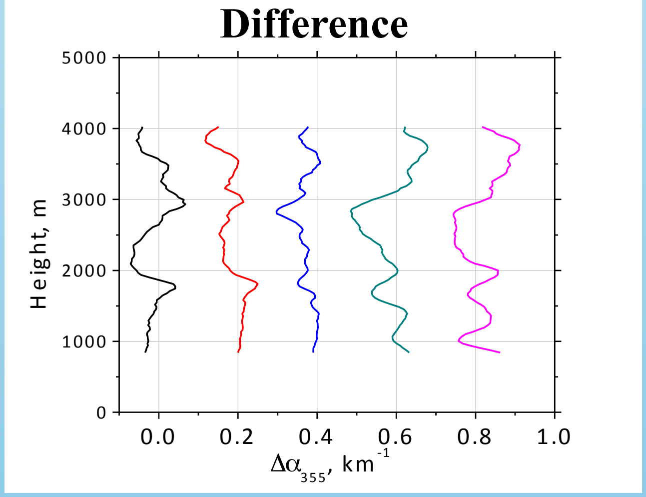


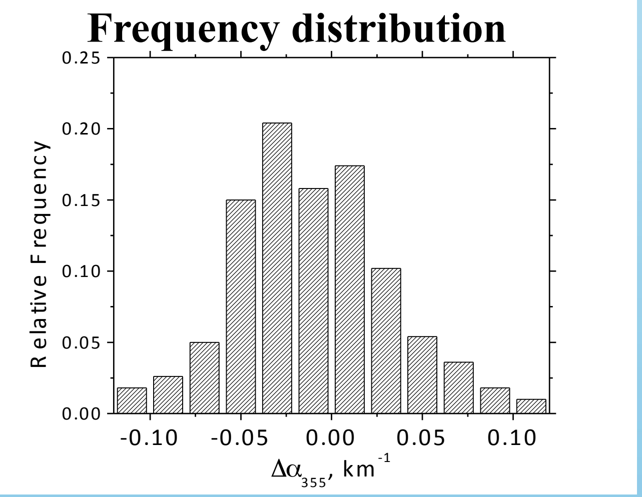
Profiles are shifted on 0.1 km^{-1}

Extinction weakly depends on particle shape and imaginary part of RI, so comparison is straightforward

Comparison of lidar and model extinction at 355 nm





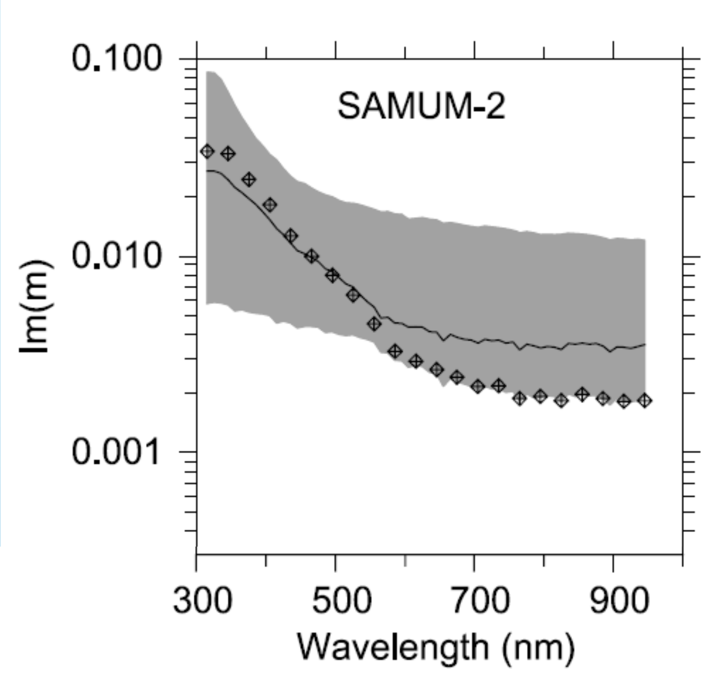


Mean difference 0.01 km-1
Stand. deviation 0.042 km-1

Comparison of backscattering

Comparison of backscattering for dust is more challenging:

- **Backscattering is sensitive to the particles shape**
- **We don't know imaginary part of RI**



From Ansmann et al., 2011
Imaginary part of dust during SAMUM campaign (symbols)

In measurements of dust over West Africa the mean values are:

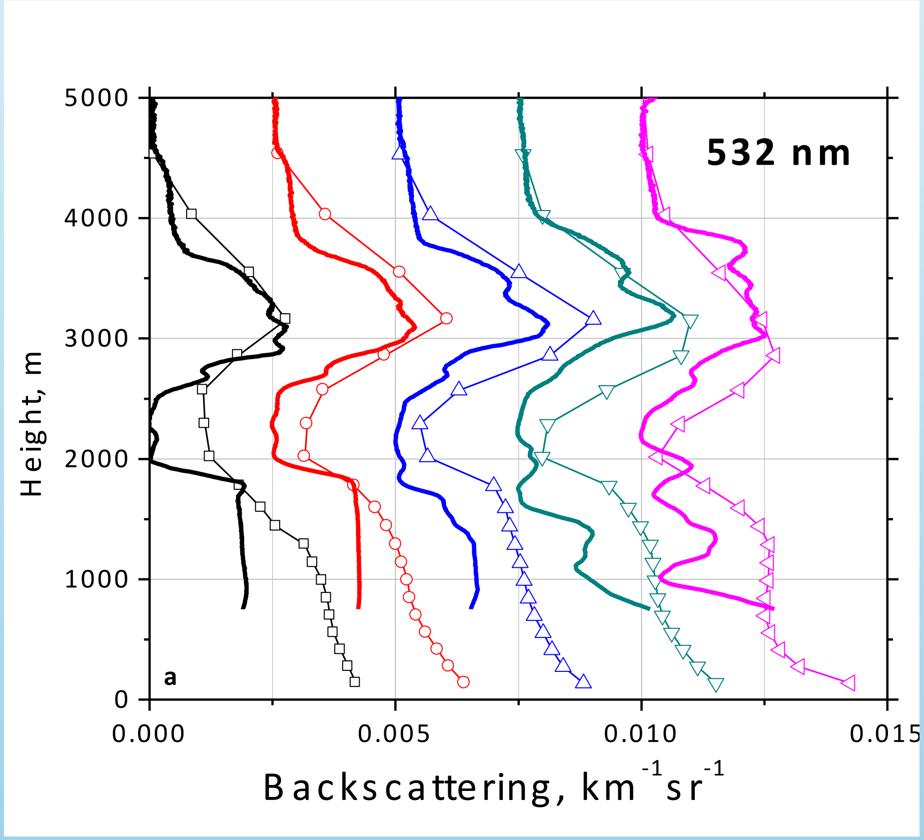
Im(532)=0.003-0.005
Im(355)=0.02 – 0.03

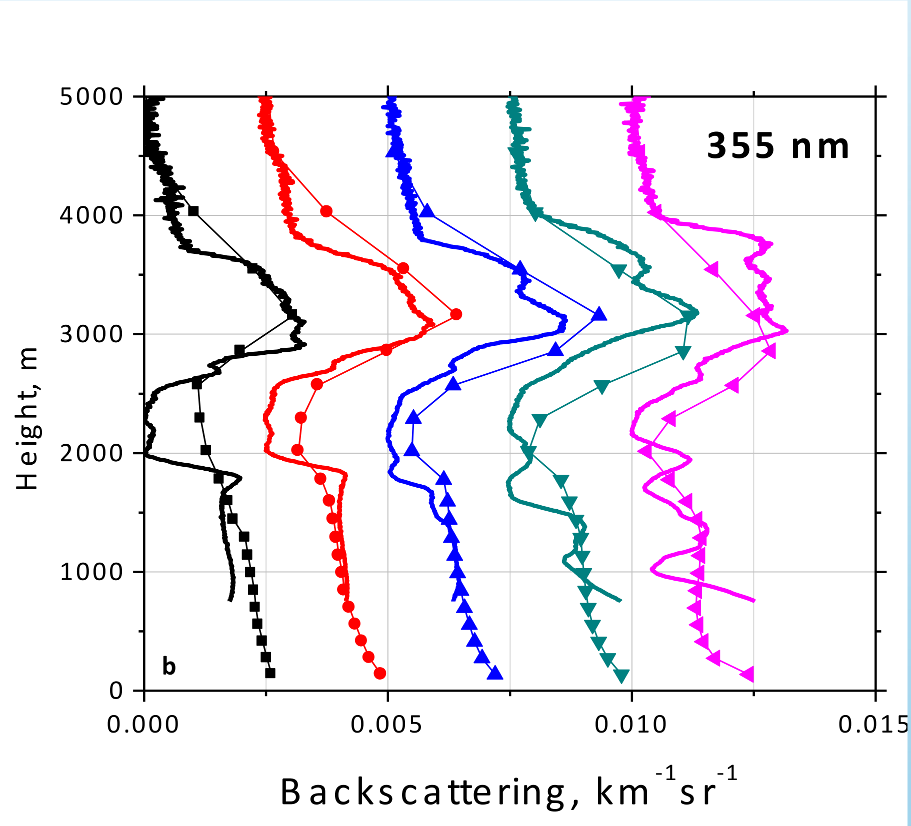
In model for dust:

Im(532)=0.0025 Im(355)=0.007

(basing on OMI)

Comparison of backscattering coefficients obtained with lidar and model

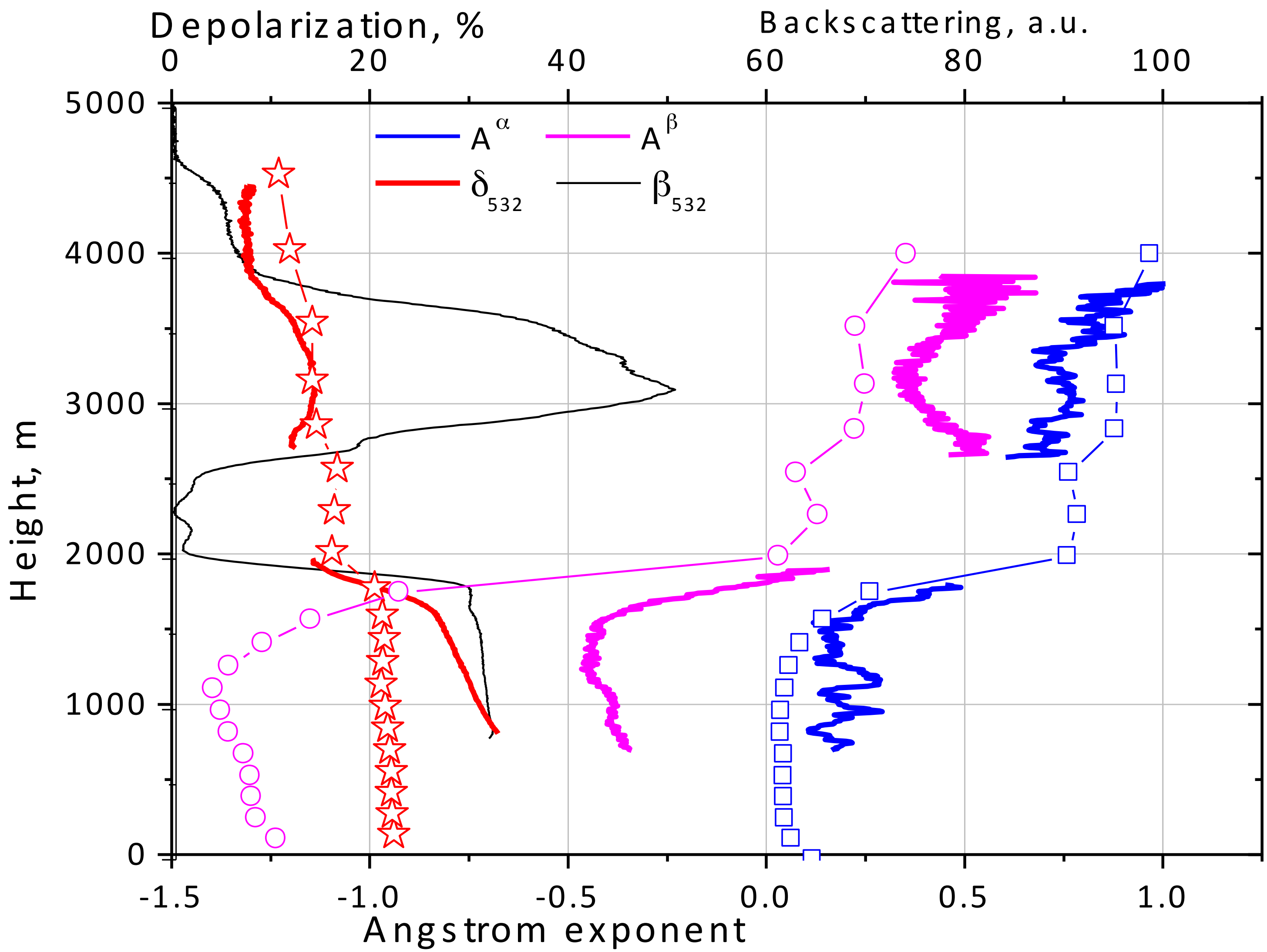




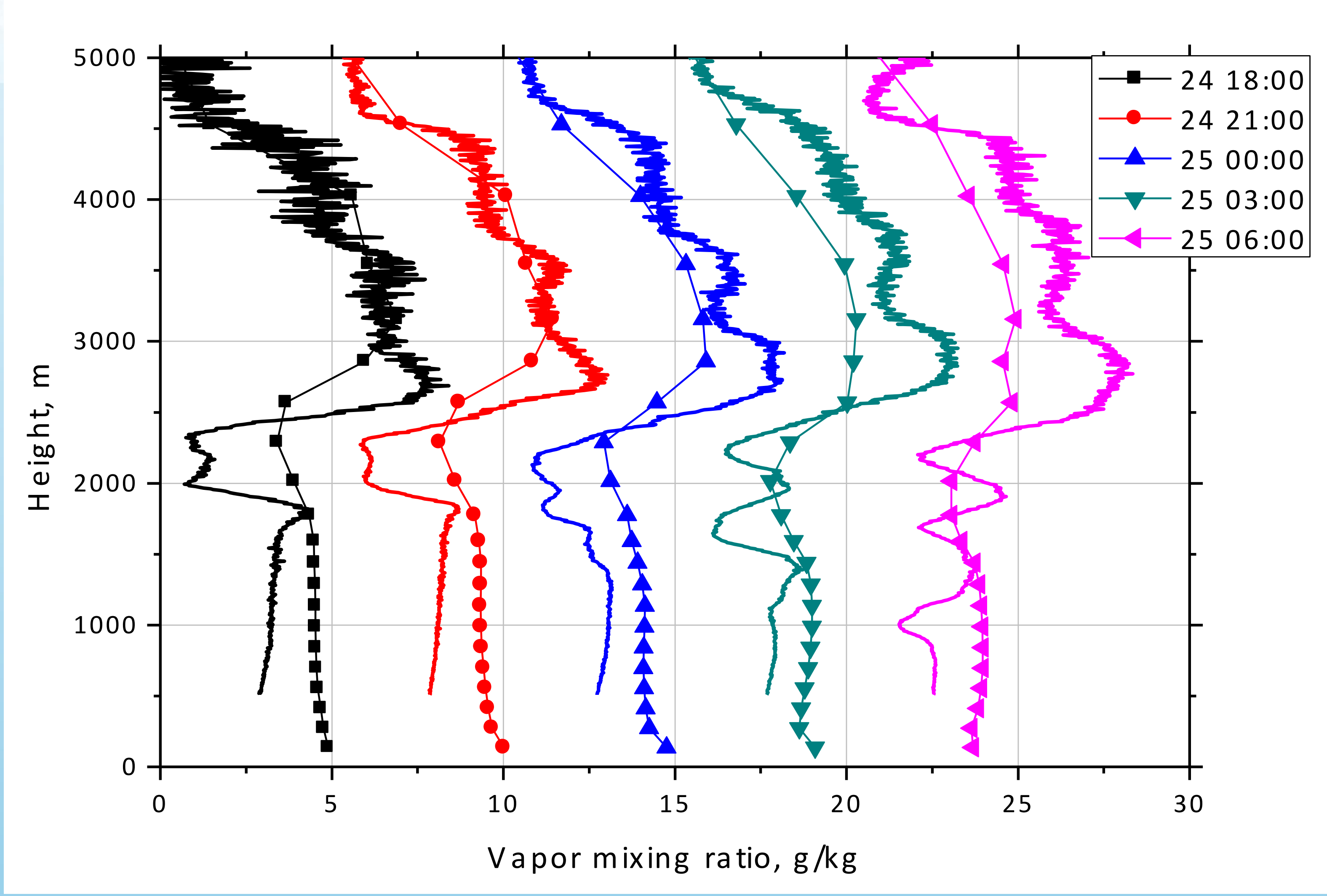
Choice of Im(355)=0.007 is very reasonable.

Lidar ratios at 355 agree well with observations (70 sr), but at 532 nm the model value (40 sr) is lower than measured one (50 sr).

Extinction, backscattering Angstrom (355/532) and depolarization. Model and lidar values.



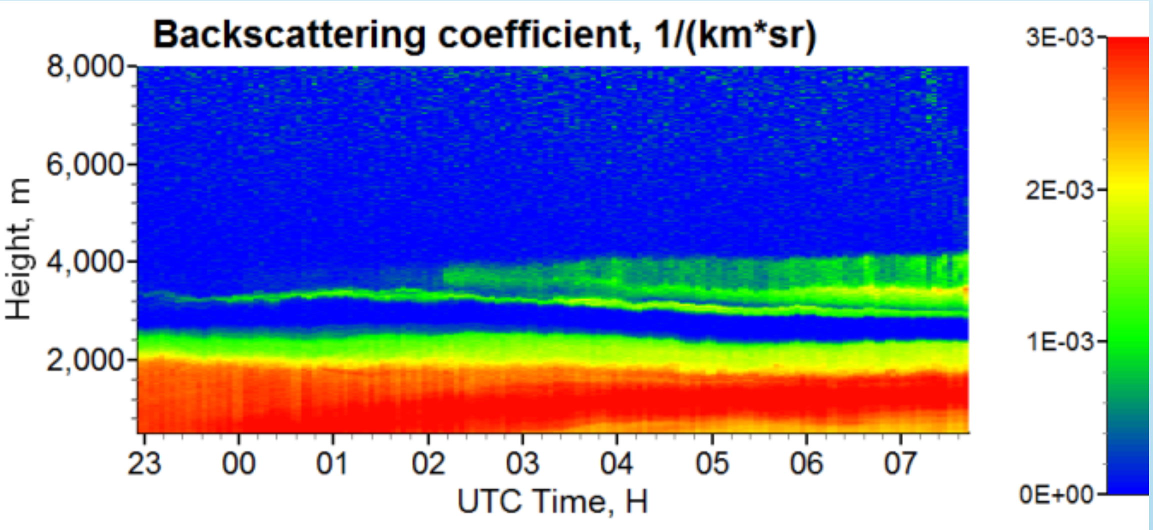
Comparison of water vapor profiles

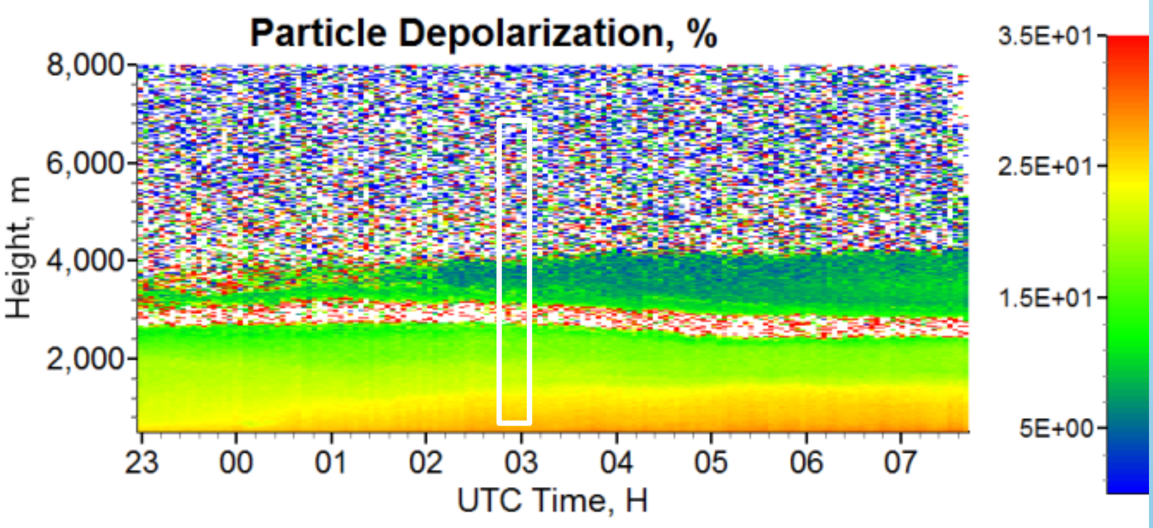


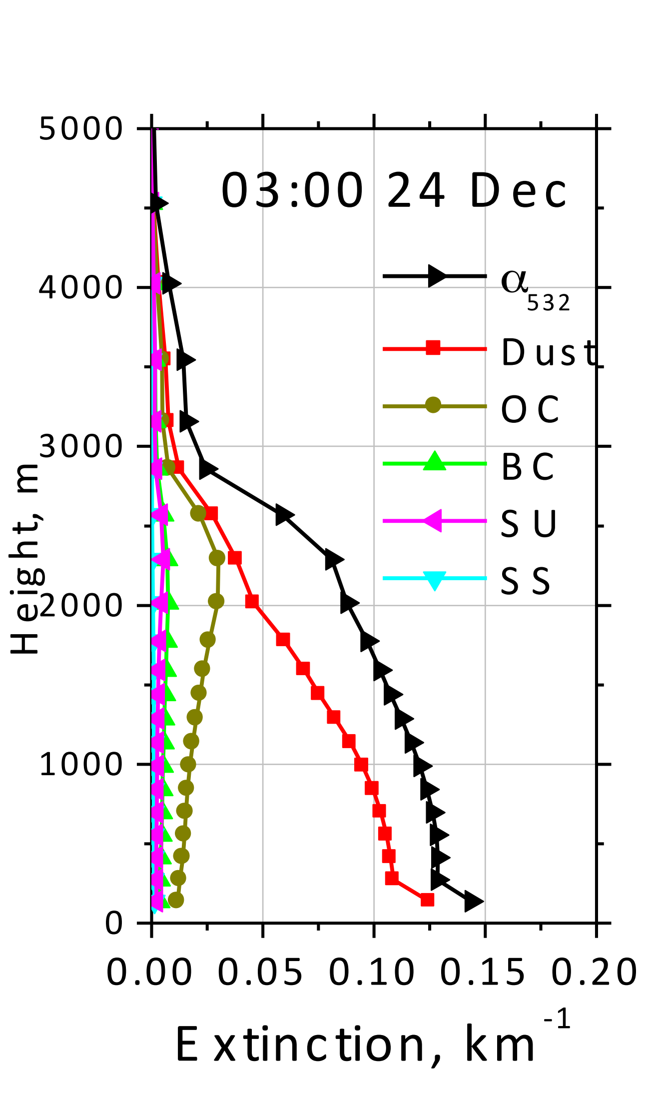
Mean difference 0.04 g/kg
Stand. deviation 1.6 g/kg

Model helps to understand observations

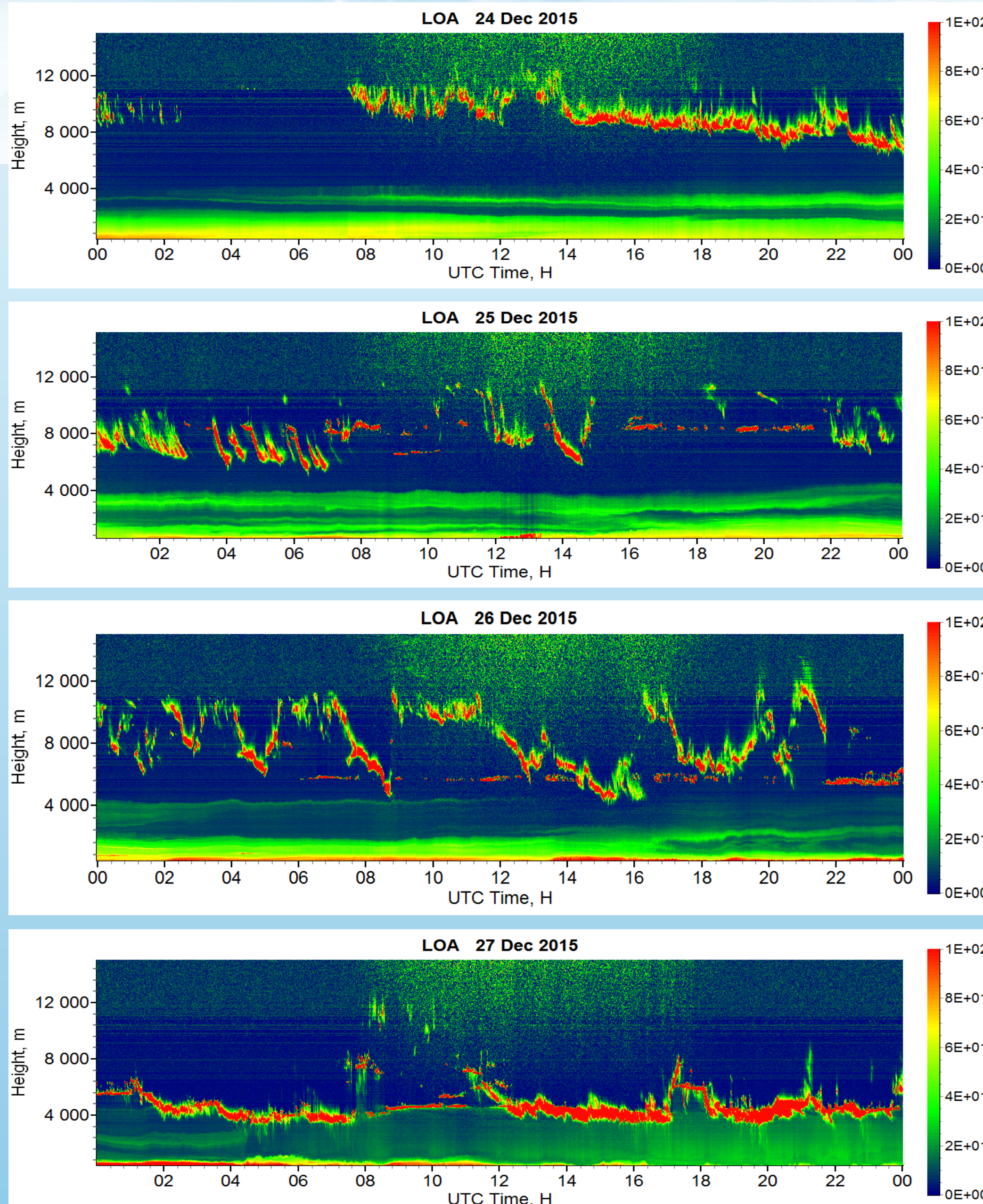
On 24 Dec we have low depolarization in near surface layer



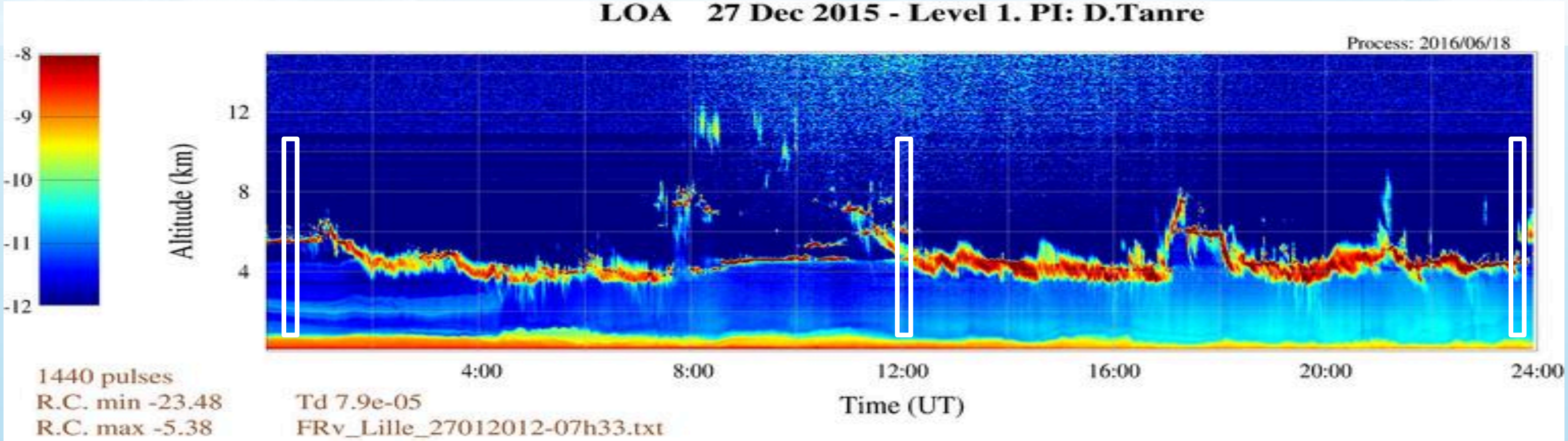


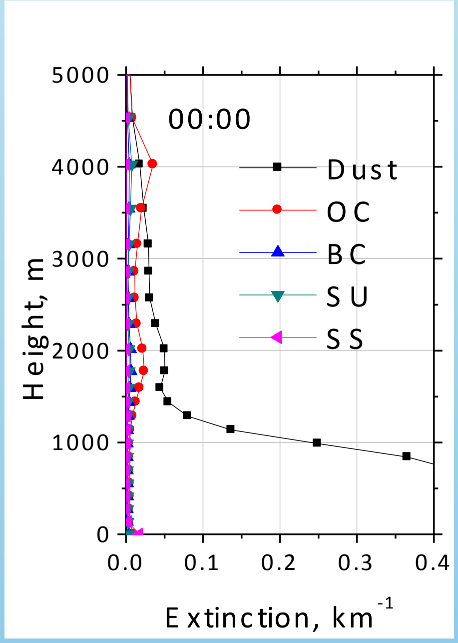


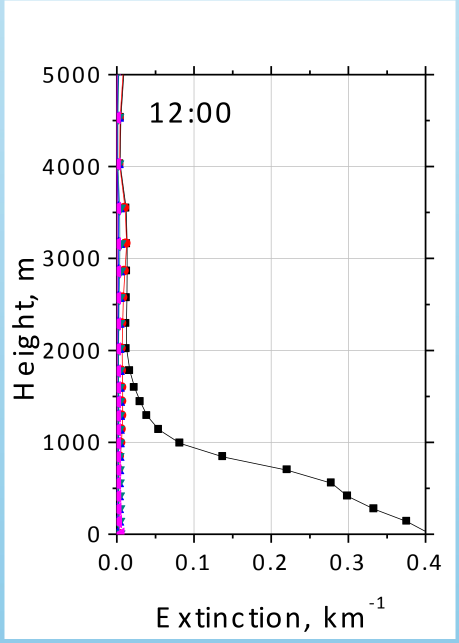
Evolution of cirrus clouds on 24 – 27 Dec.

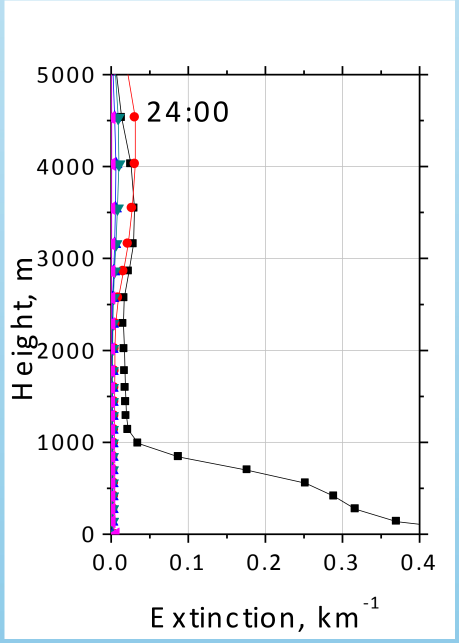


Plans for future: application of model for study of clouds formation









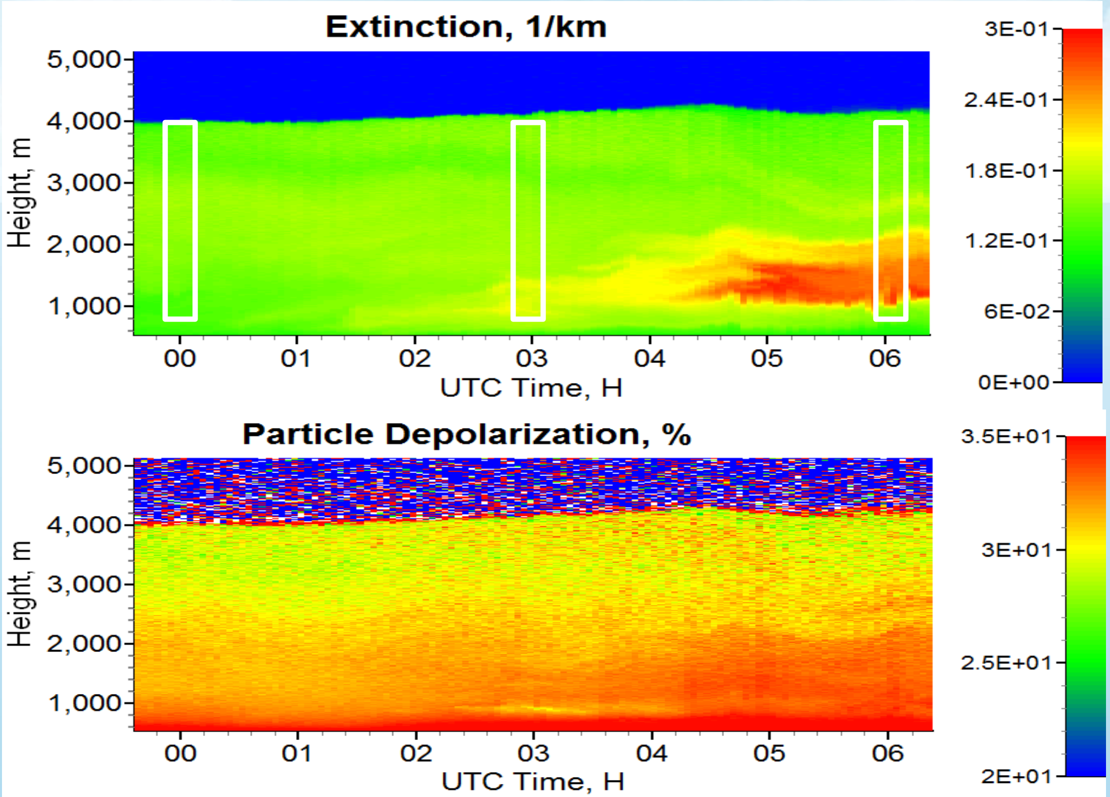
What did we learn?

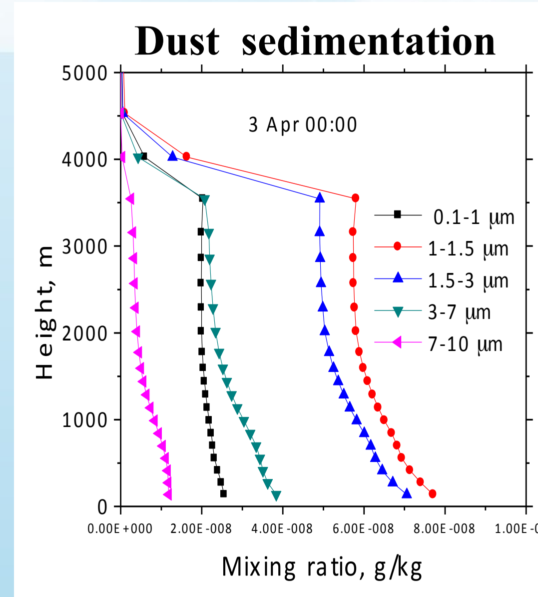
Model provides:

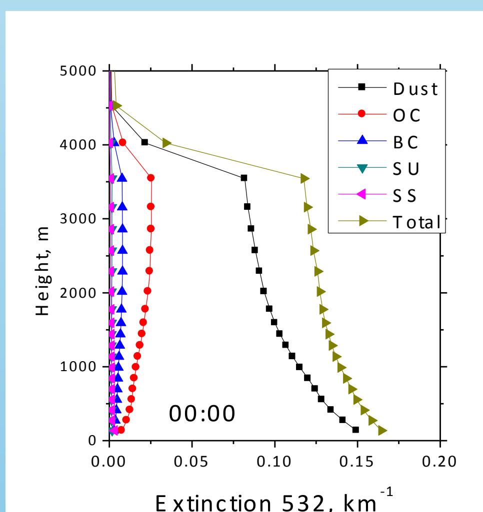
- Correct location of near ground and elevated layers.
- Correct composition (dust, smoke) of layers.
- Correct values of extinction (in many cases).

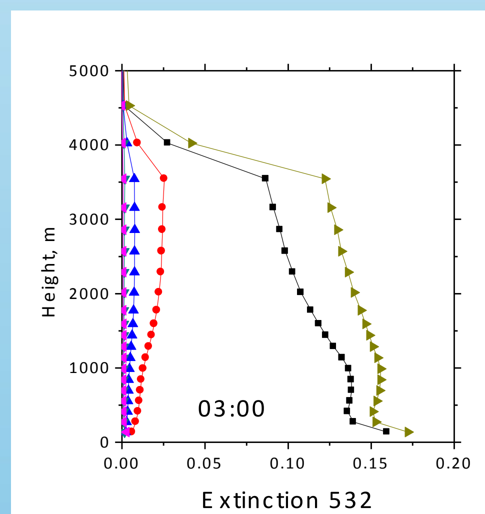
However dust is mixed with smoke. It is desirable to consider the episodes with pure dust with layers extended up to 4-5 km.

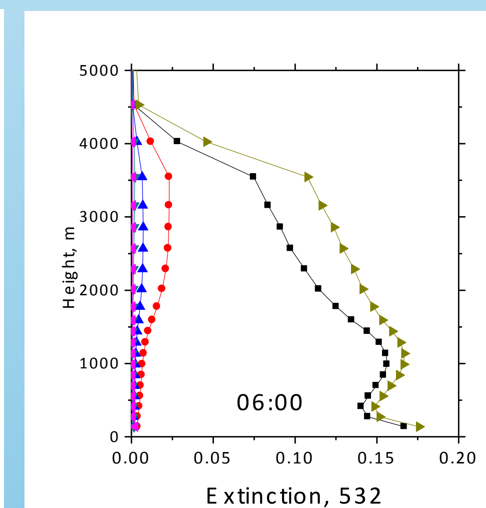
Dust event 2-3 April 2015



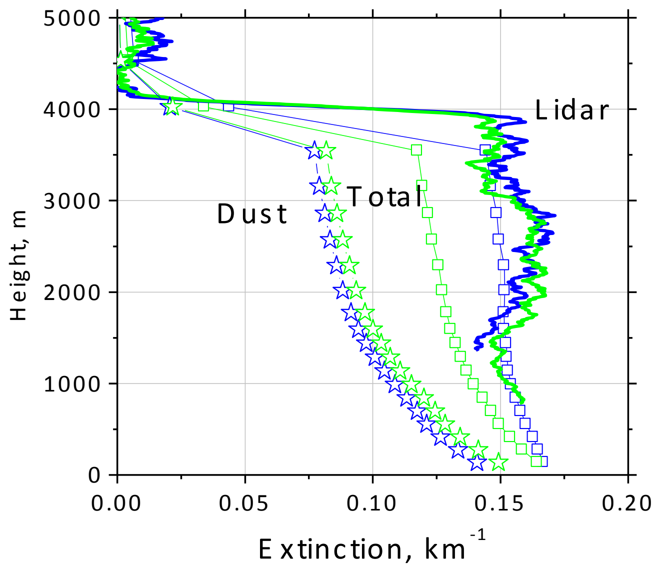


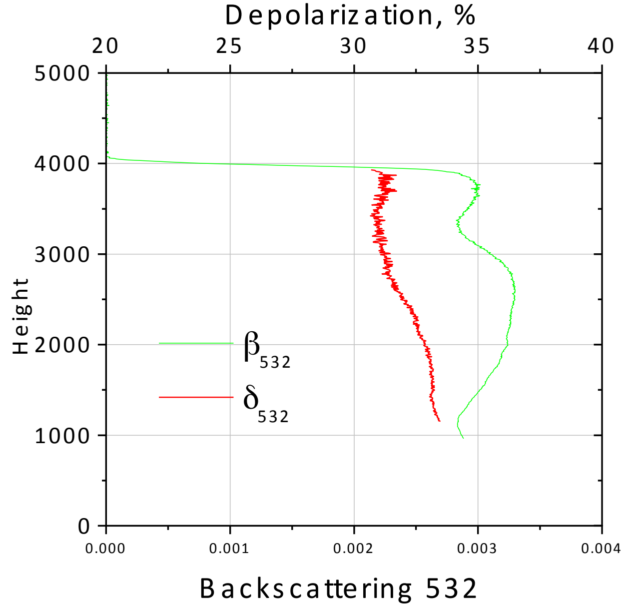


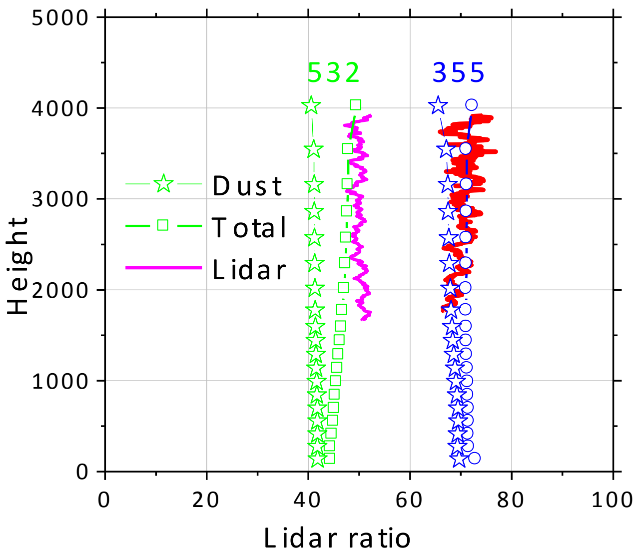


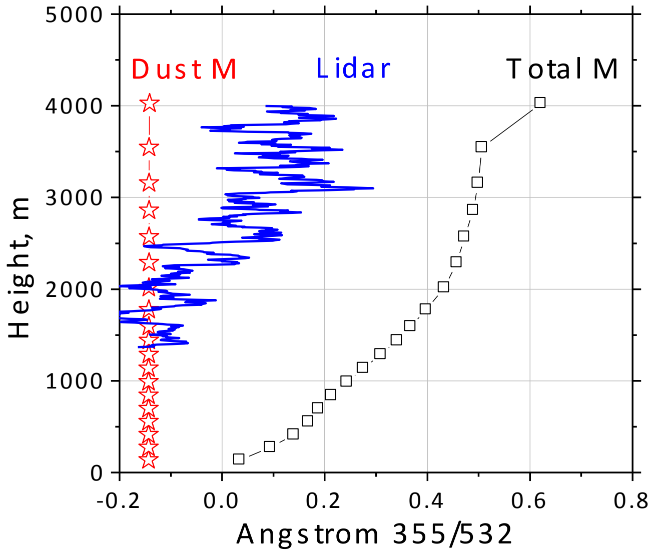


3 April 00:00. Modeled and measured profiles

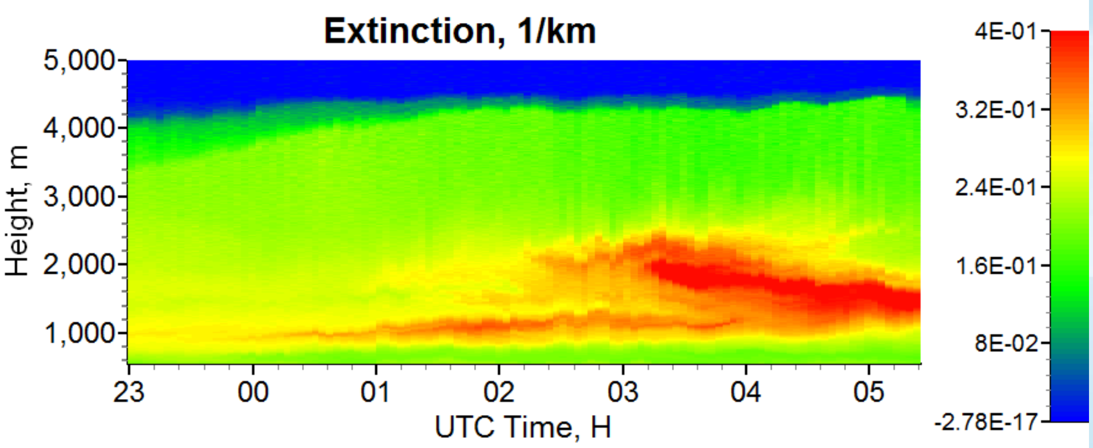


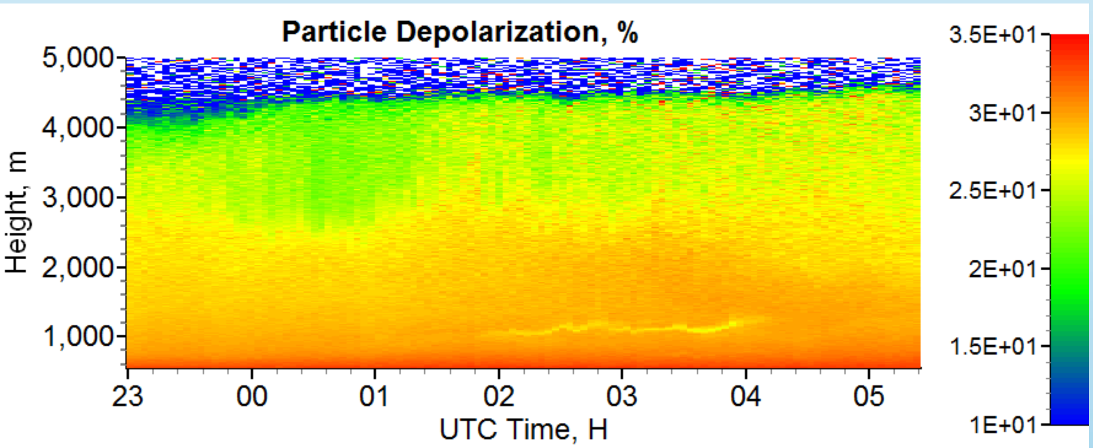


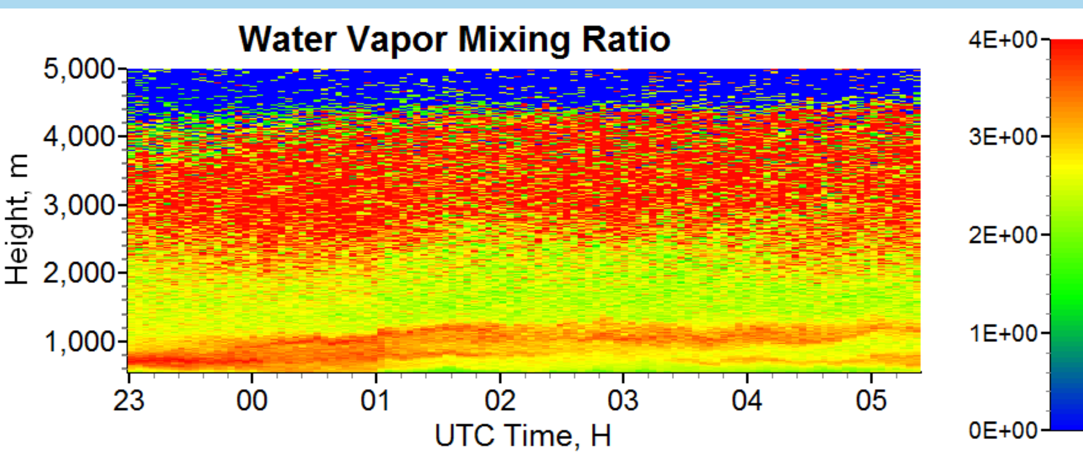




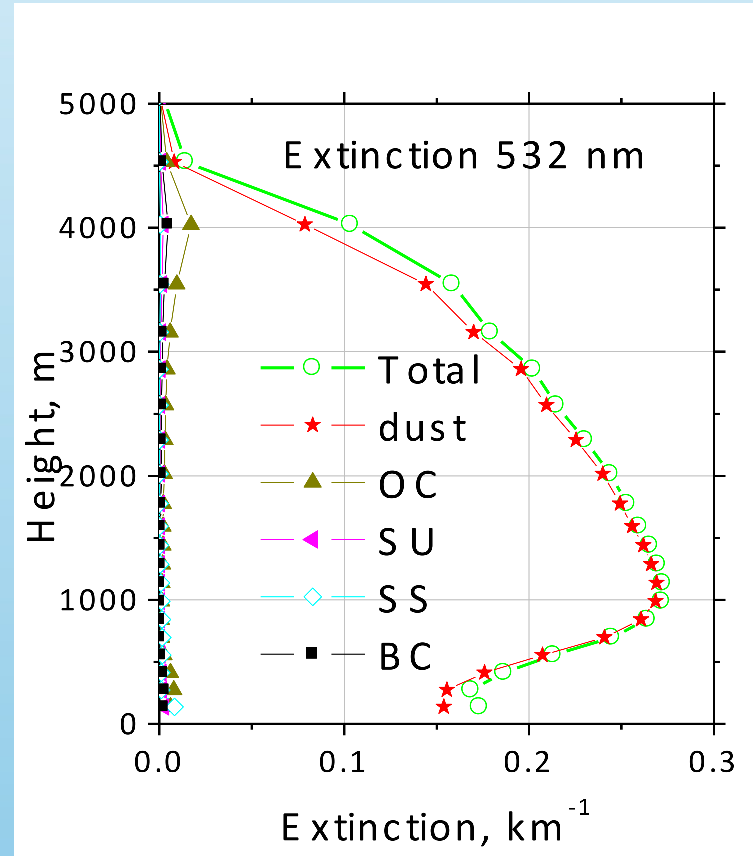
Dust episode 3-4 April 2015



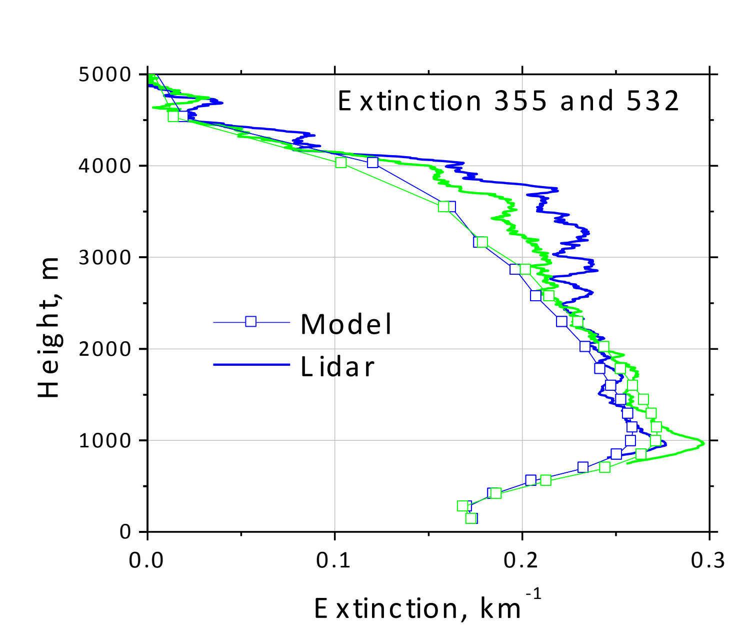


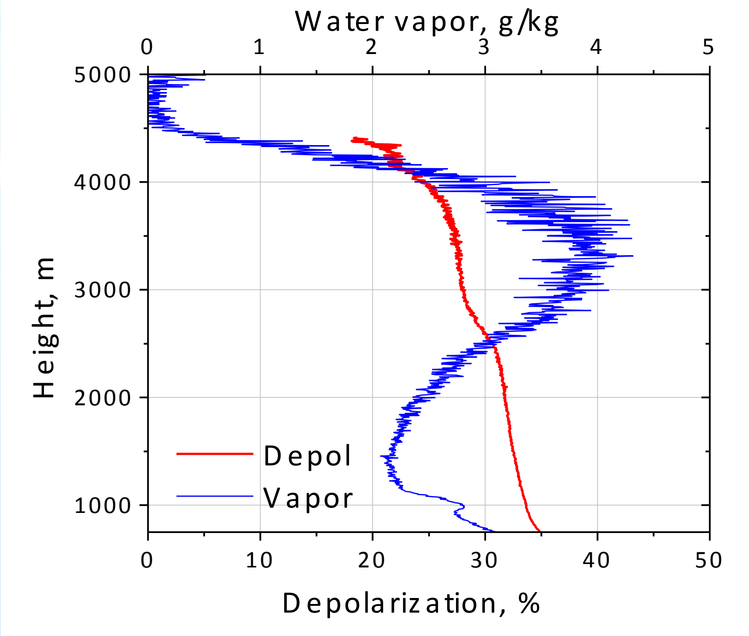


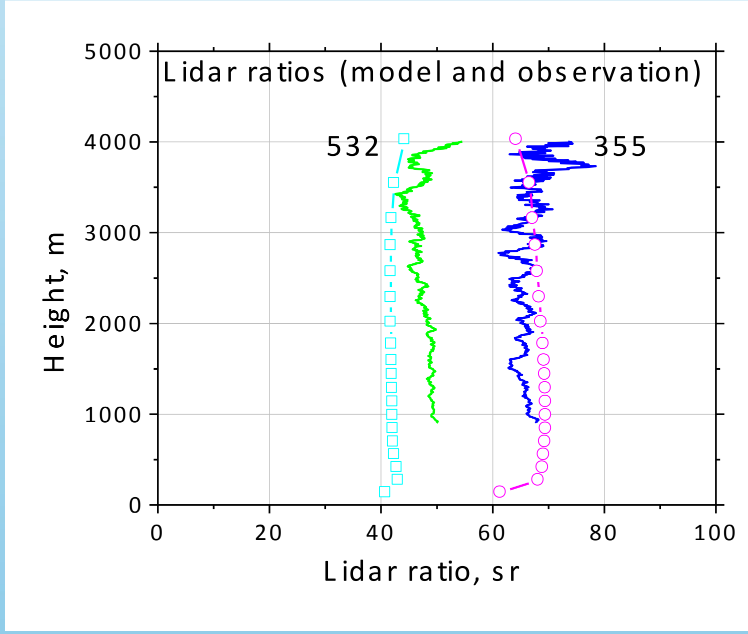
MERRA-2 prediction

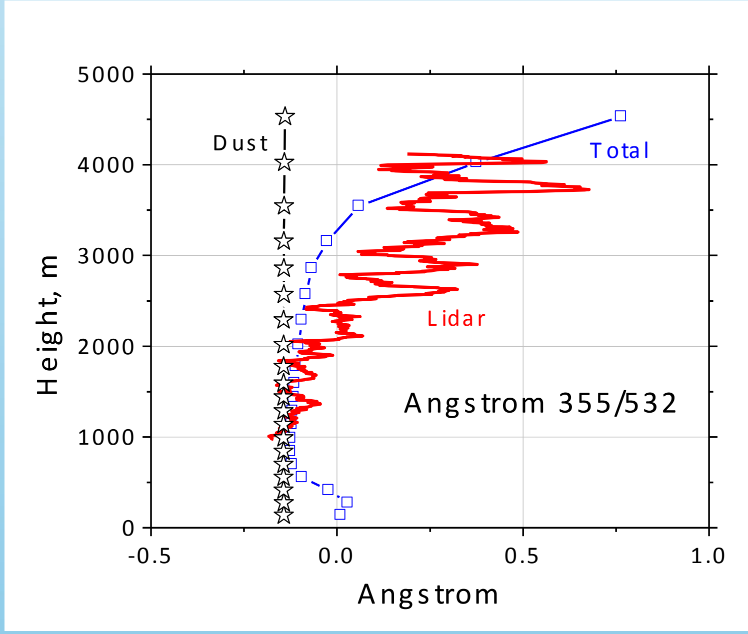


4 April 00:00 UTC







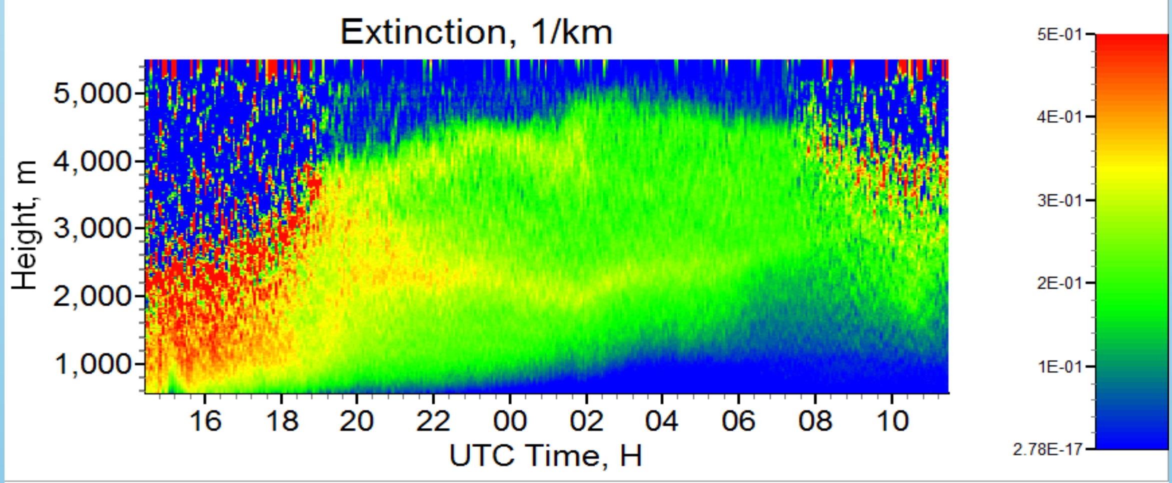


What can we conclude from considered dust episodes?

Modeled and measured intensive parameters show good agreement

	LR 355	LR 532	Angstrom
MERRA-2	70 sr	41 sr	-0.12
Lidar	70±7 sr	50±5sr	-0.12±0.05

- **Observed Angstrom exponent for all cases rises with height. Dust is always "polluted". Model provides it.**
- **Modeled extinction profiles in general agree well with observations, though for some cases difference may reach~100%.**



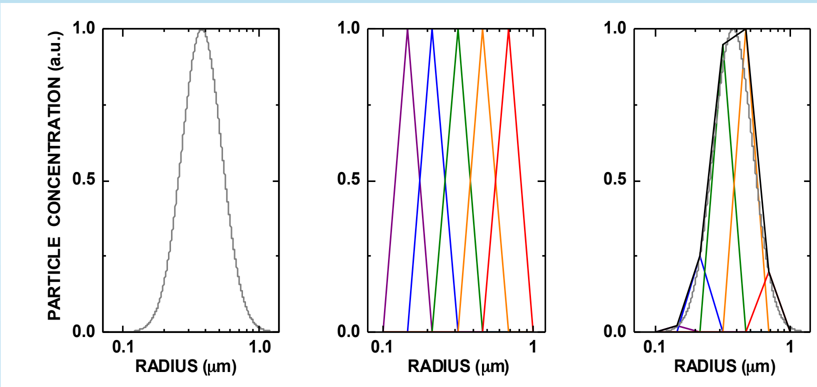
Two approaches to inversion of lidar data

Optical data (α or β) at different λ are calculated from equation:

$$g_i = \int_0^\infty K_i\,(m,r,\lambda)\,\frac{dV(r)}{dr}\,dr \;\Rightarrow\; \mathbf{K}^T\,\mathbf{v} = \mathbf{g}$$

K – discrete kernels
v – discrete volume

Inversion with regularization

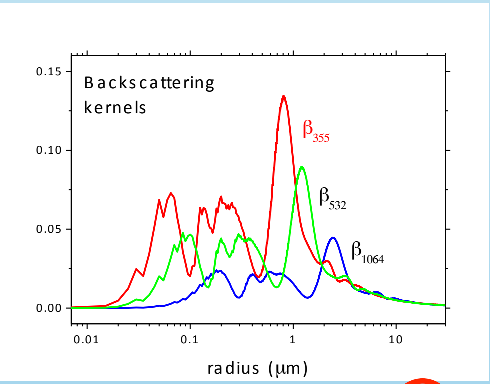


$$\mathbf{v} = \mathbf{Bx}$$

$$\mathbf{g} = \mathbf{K}^{\mathrm{T}}\mathbf{Bx} = \mathbf{Ax}$$

$$\mathbf{x} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{A} + \gamma\mathbf{H}\right)^{-1}\mathbf{A}^{T}\mathbf{g}$$

Kernels expansion



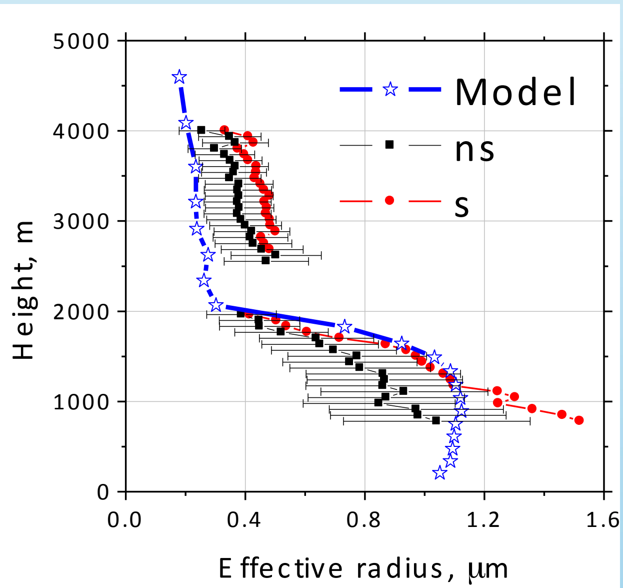
$$\mathbf{v} = \mathbf{Kx} + \mathbf{v}_\perp = \mathbf{v}_g + \mathbf{v}_\perp$$

$$\mathbf{g} = \mathbf{K}^{\mathrm{T}}\mathbf{K}\,\mathrm{x} + \mathbf{K}\,\mathbf{v}_\perp = \mathbf{K}^{\mathrm{T}}\mathbf{K}\,\mathrm{x}$$

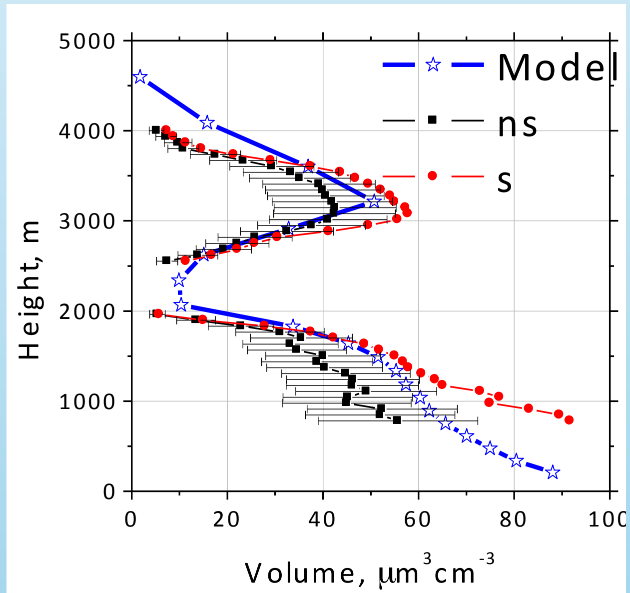
$$\mathbf{x} = \left(\mathbf{KK}^{\mathrm{T}}\right)^{-1}\mathbf{g}$$

Inversion of lidar observations on 25 Dec

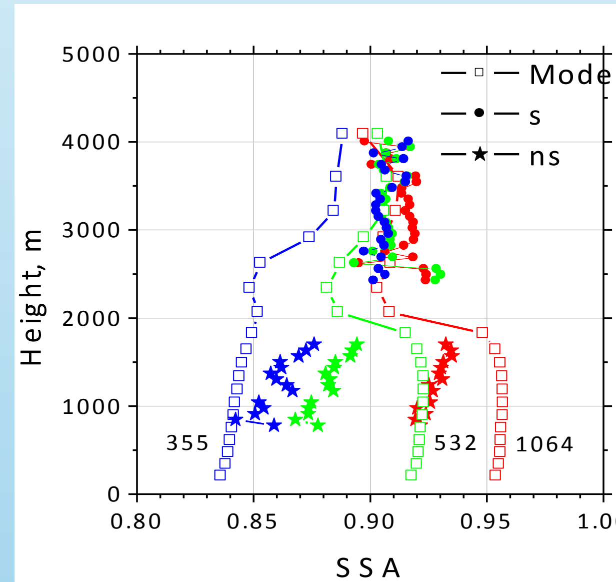
Effective radius



Volume



SSA



Spheres (s) and spheroids (ns) are used in inversion

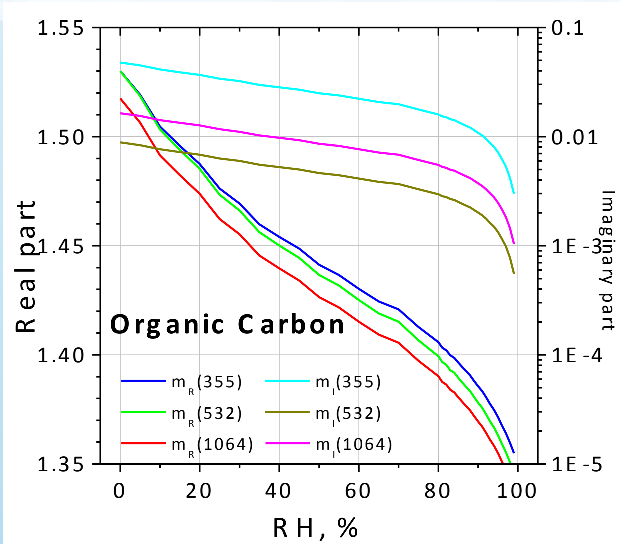
Spectral dependence of mI is not accounted for

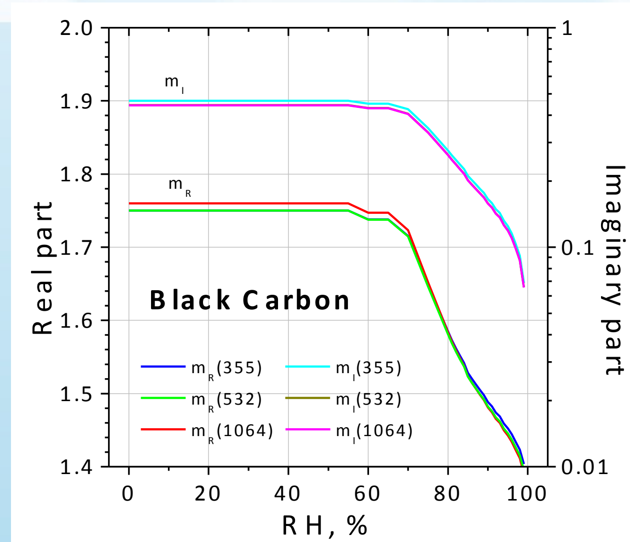
Another approach to inversion

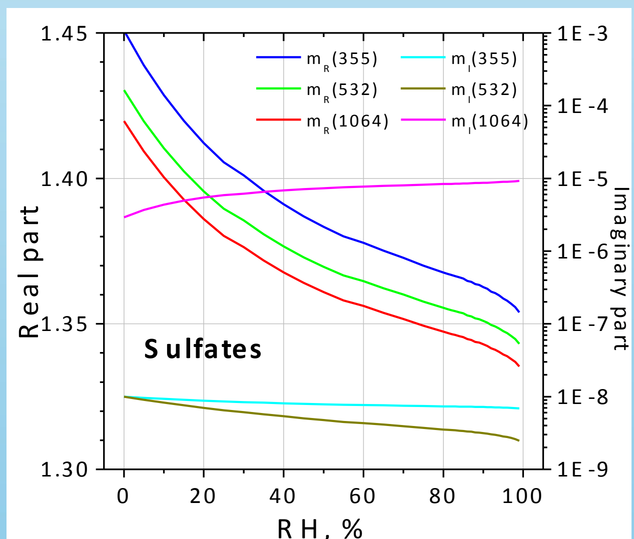
- Instead PSD we can try to retrieve concentrations of 5 aerosol components used in MERRA-2: dust, organic carbon, black carbon, sulfates, sea salt.
- Problem becomes determined
- Spectral and size dependence of RI is accounted

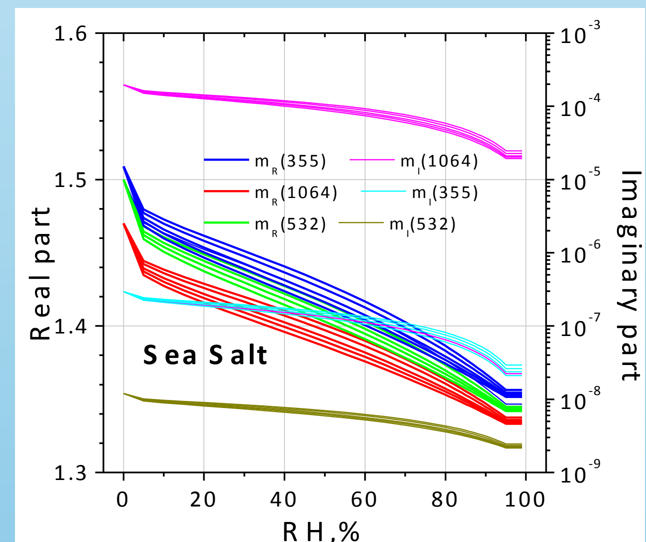
- This is standard inverse problem of mixture separation by spectral signatures. Negative concentrations are normally the issue.
- We should be confident in components properties.

Dependence of refractive index on relative humidity used in MERRA-2

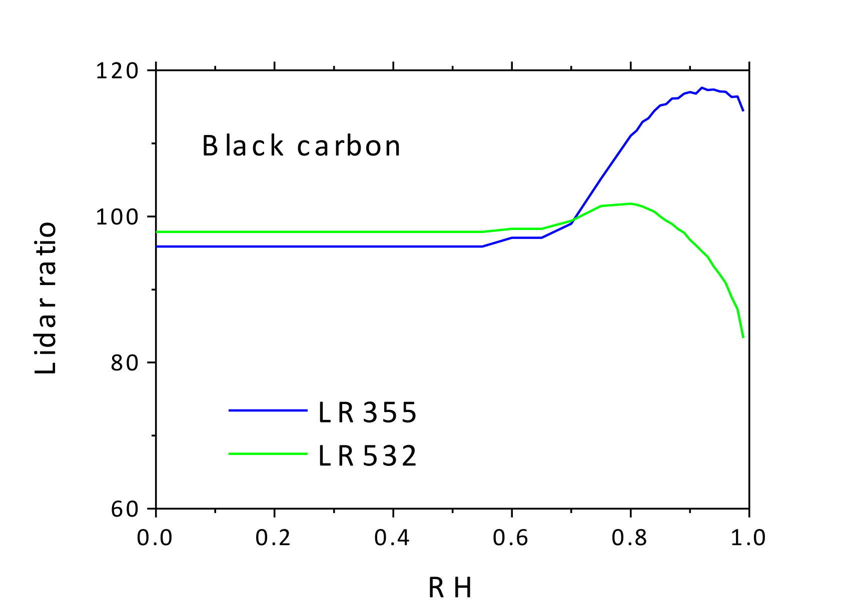


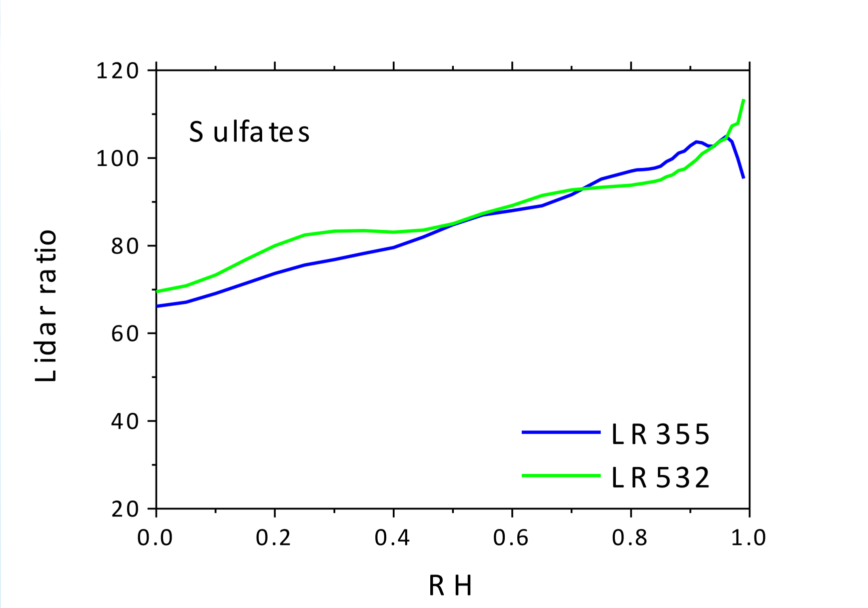


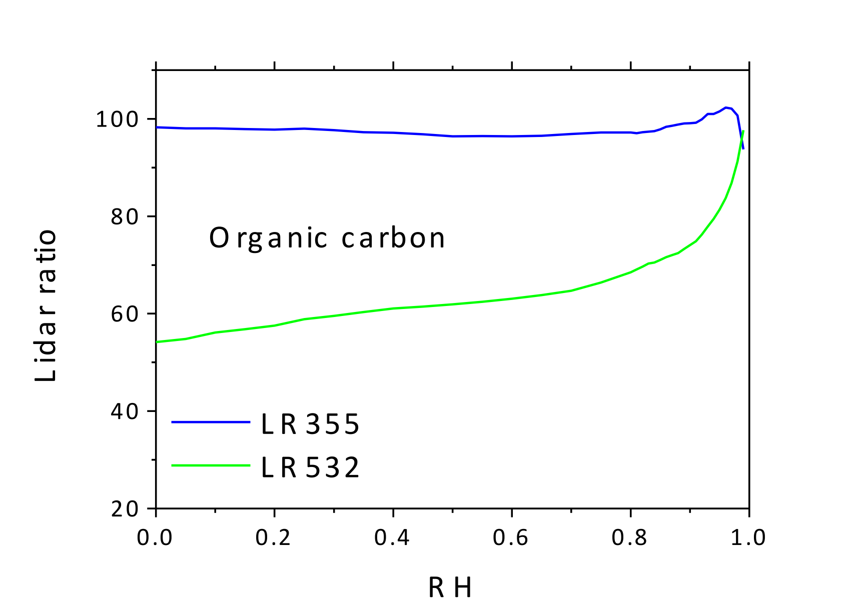




Can we trust model?





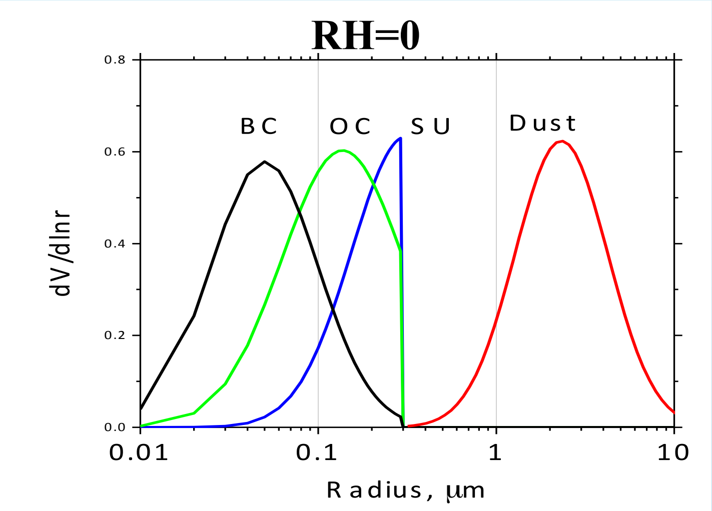


1. Spectral dependence of Im for OC is probably too strong. We never observed LR355>75.

2. Spectral dependence of mR for SU is questionable. It assumes LR532>LR355.

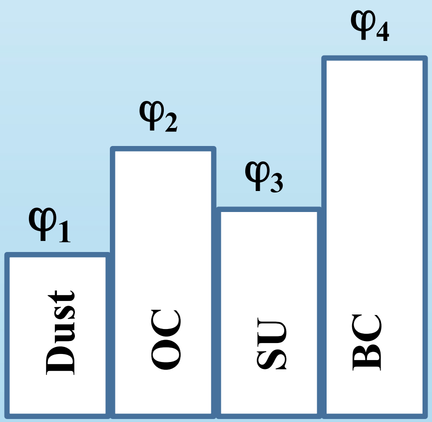
Simplified approach to inversion

Four aerosol components :



φ is varied from 0 to 1.0 with step 0.01
Usually α_{532} is considered

- **Dust**
- **Organic carbon**
- **Black carbon**
- **Sulfates**
- **Sea salt**



$$\alpha = \varphi_1\alpha_1 + \varphi_2\alpha_2 + \varphi_3\alpha_3 + \varphi_4\alpha_4$$

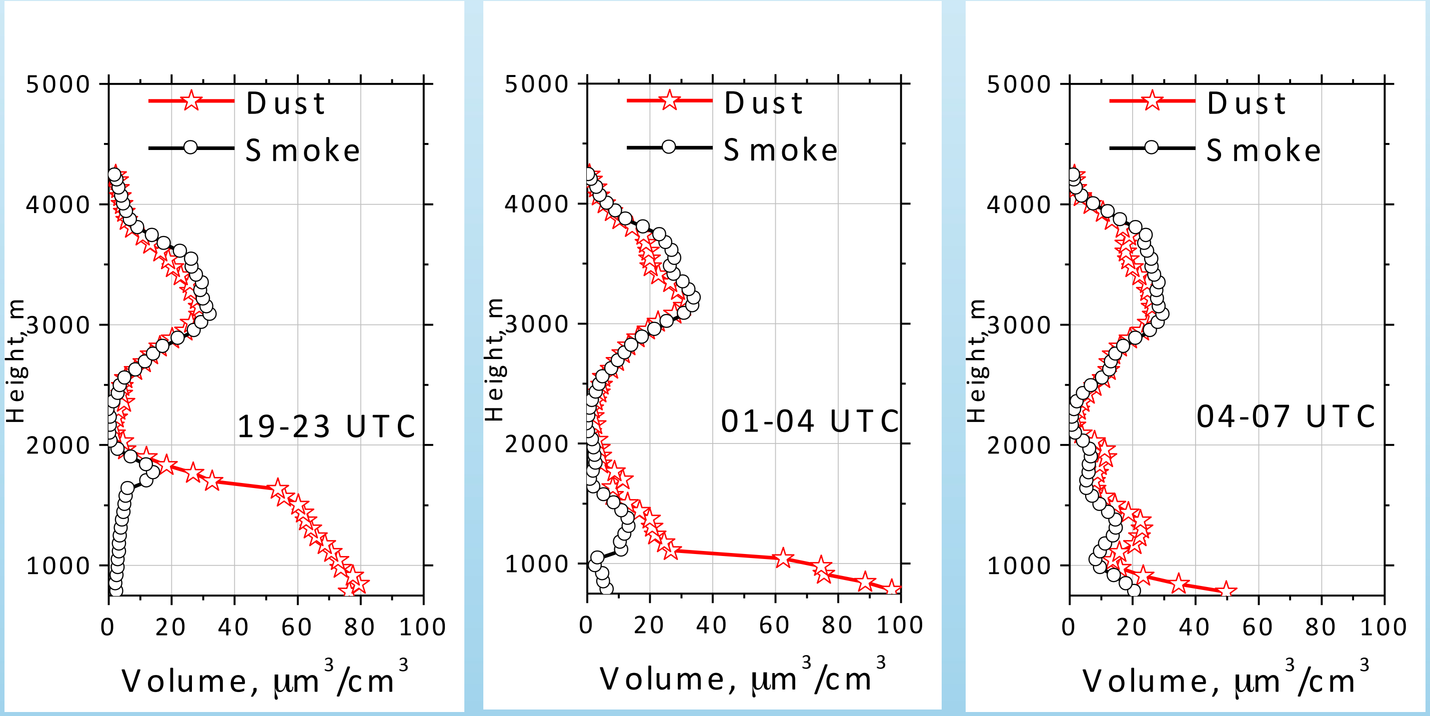
$$\varphi_1 + \varphi_2 + \varphi_3 + \varphi_4 = 1$$

φ - the fraction of extinction attributed to a given component

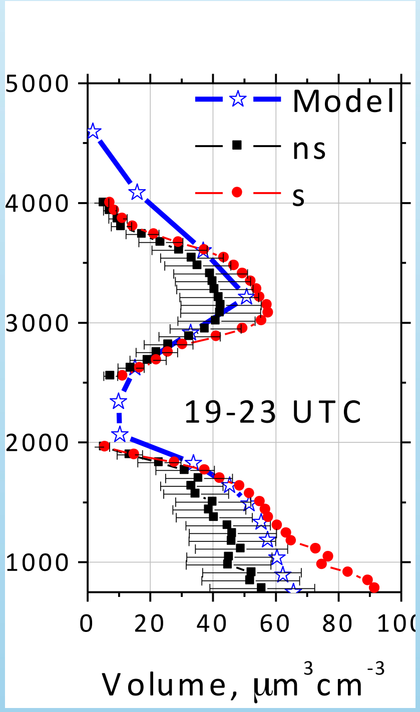
For minimization we use 3β+2α+1δ data
Depolarization of pure dust is assumed to be 35%.
For dust we assume also
LR_{355}=70 sr
LR_{532}=50 sr
β_{532}/β_{1064}=1.1

Preliminary results of inversion on 24-25 Dec

Three consequent temporal intervals



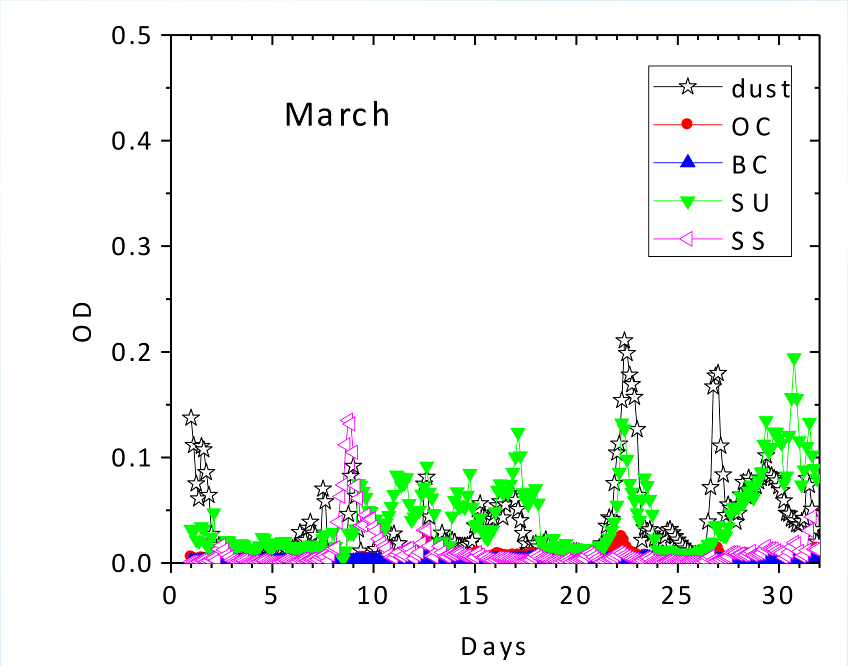
Inversion with regularization



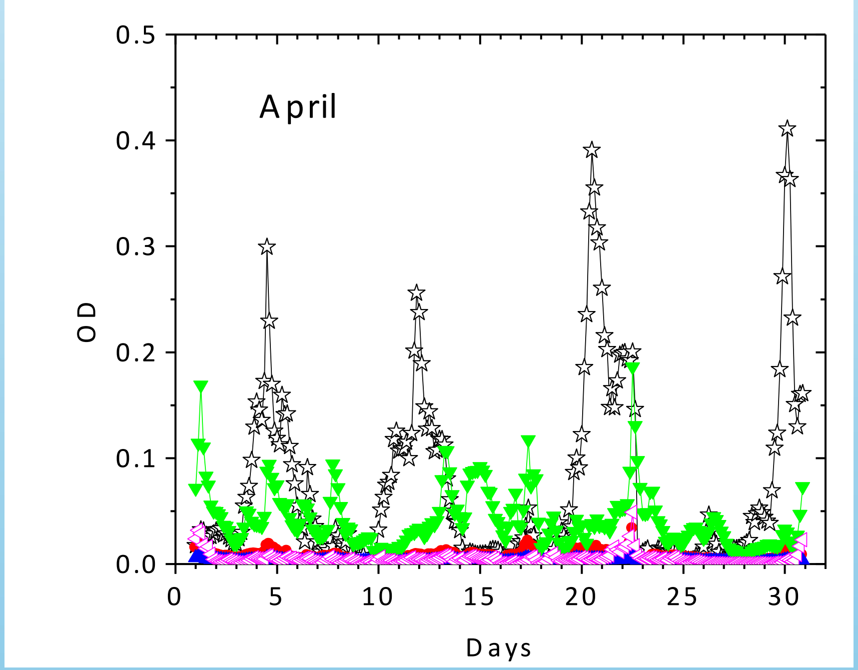
Future plans

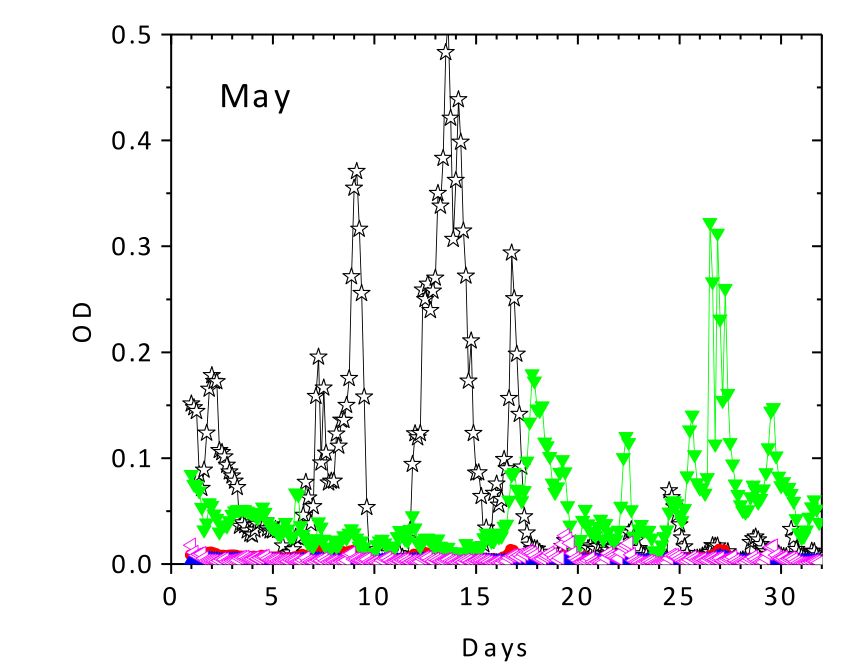
- **Development of inversion scheme including MERRA-2 predictions.**
- **Use the MERRA-2 in analysis the field campaign data. In March-May 2017 the Raman lidar measurements in Crete, Cypress and Israel (Haifa) were performed.**

Crete
MERRA-2 modeling

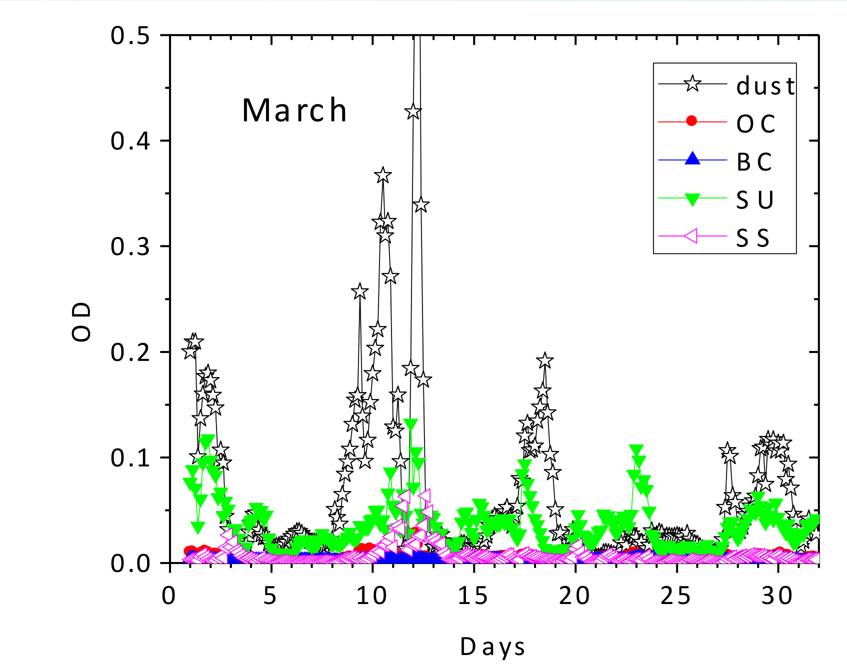


OD in 0.9-5.0 km at 532 nm

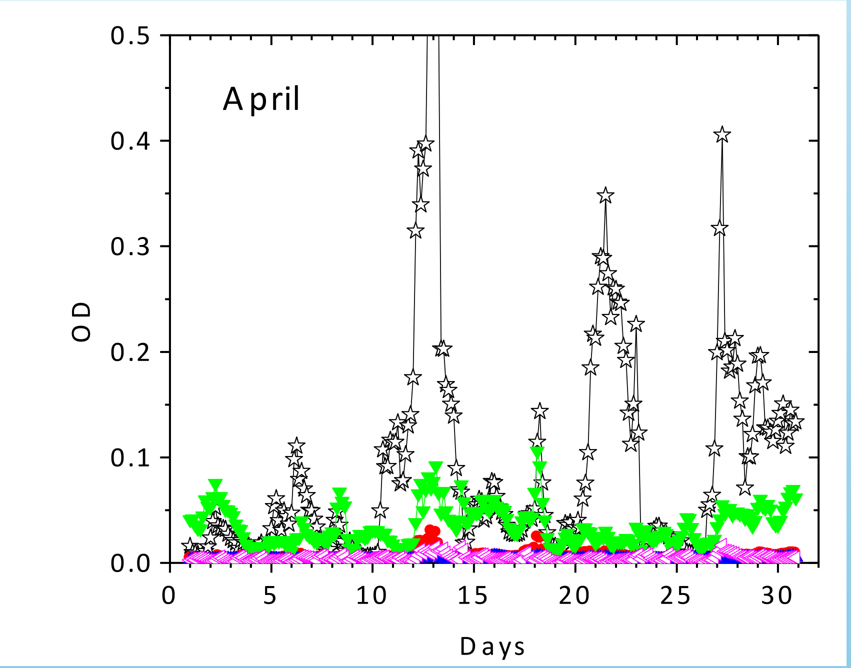


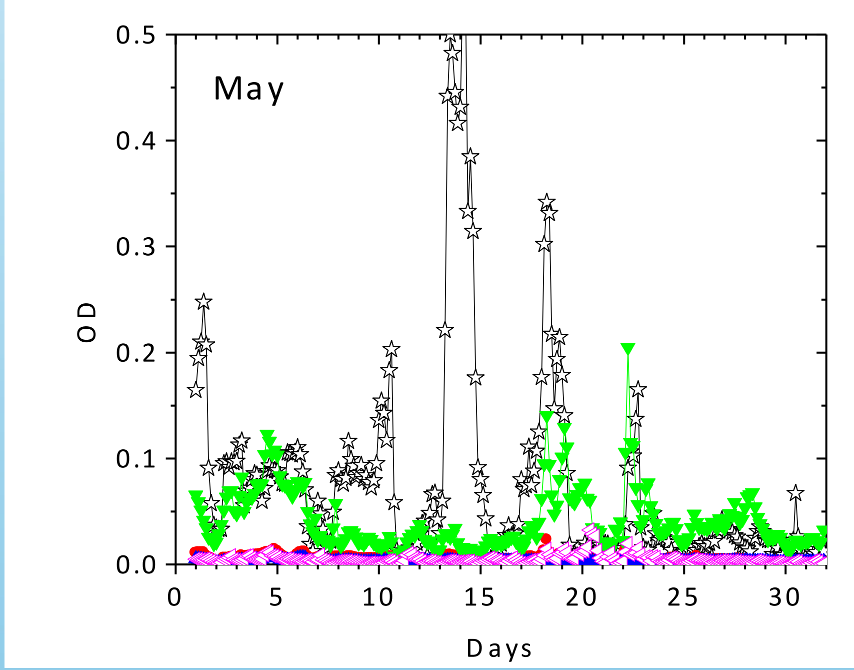


Cypress
MERRA-2 modeling

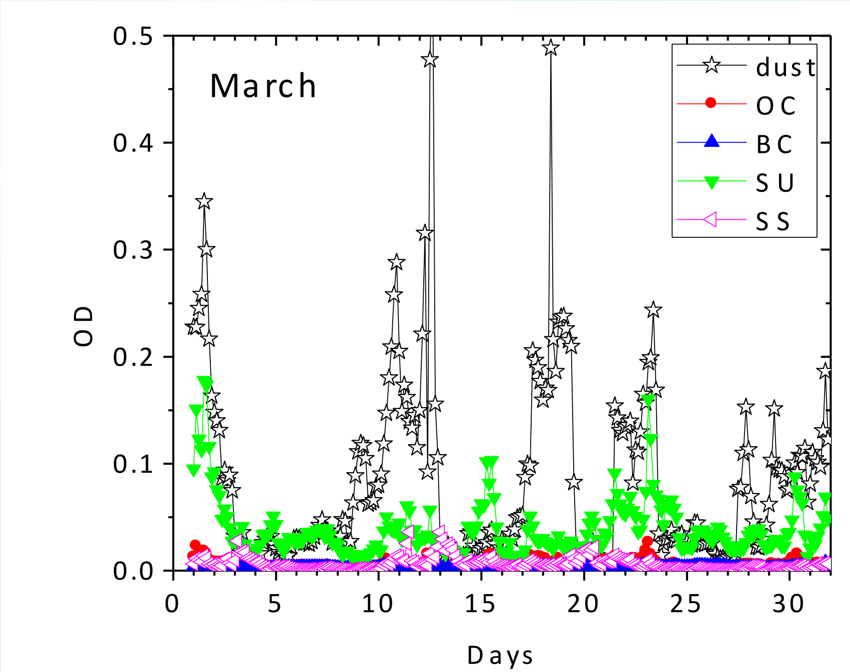


OD in 0.9-5.0 km at 532 nm





Haifa
MERRA-2 modeling



OD in 0.9-5.0 km at 532 nm