Droplet vertical sizing in shallow marine clouds using passive satellite measurements

Alexander A. Kokhanovsky(1), Vladimir V. Rozanov(1),
Nicholas King(2)

(1)Institute of Remote Sensing, Bremen University
P. O. Box 330440 Bremen, Germany
(2) Centre for Atmospheric Science, University of Manchester,
Manchester, UK

alexk@iup.physik.uni-bremen.de

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- Variation of spectral cloud reflectance
- Algorithm
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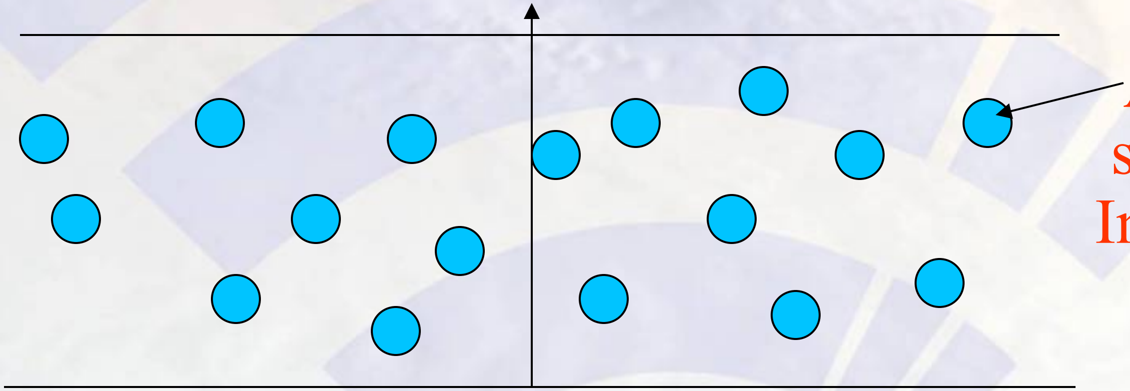
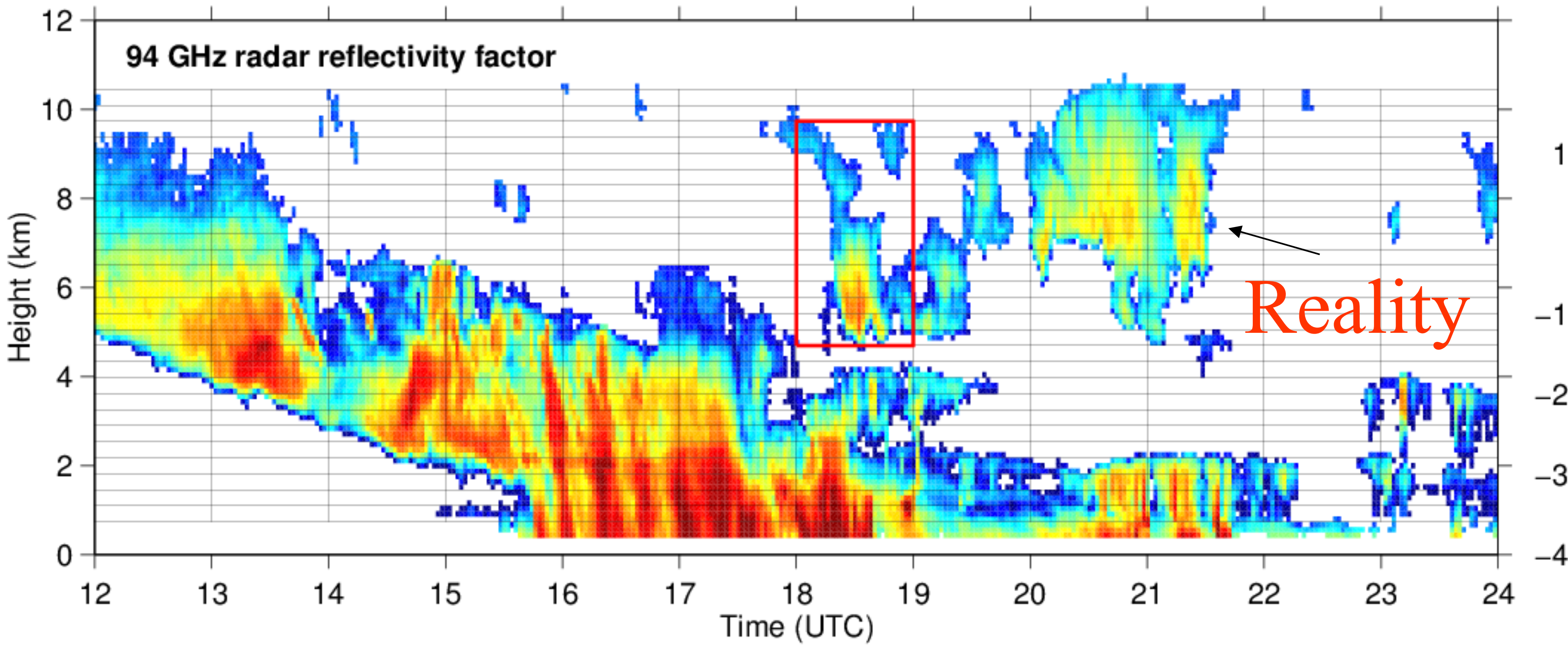
1. Introduction

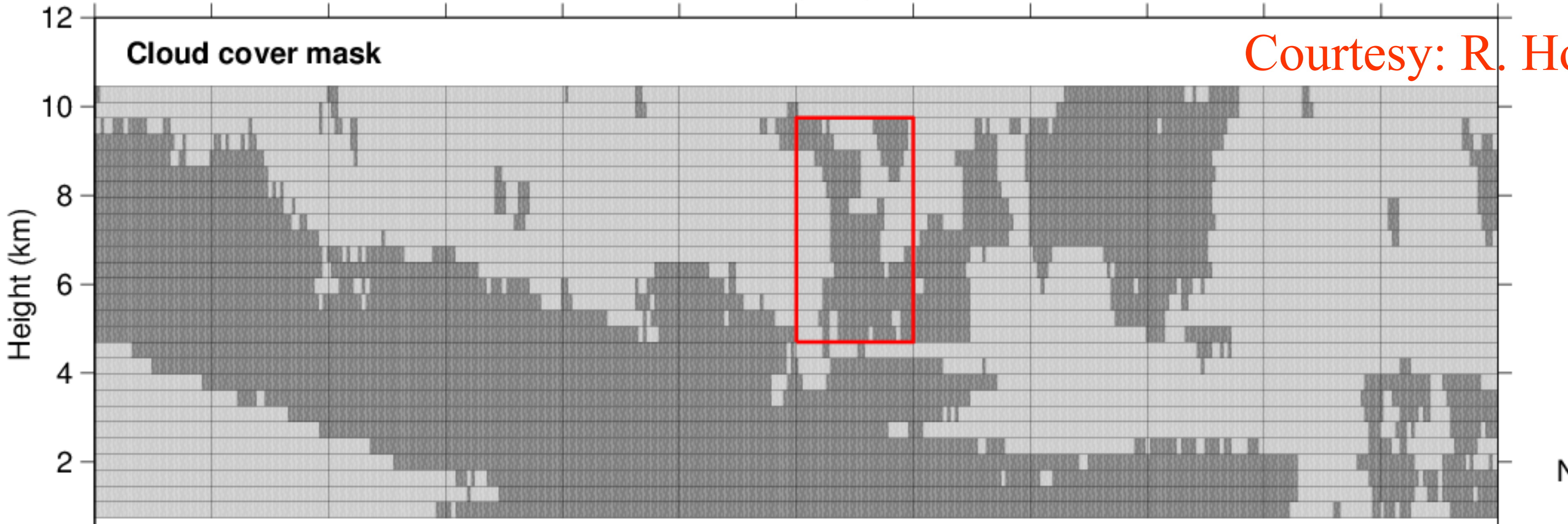
Clouds are vertically inhomogeneous media but homogeneous cloud model is used in satellite cloud retrieval algorithms – contradiction.



Average size is the same on all levels In the clouds



Reality



Courtesy: R. Ho

Question: Is it possible to make profiling of water clouds using passive (and not exclusively active) observations?

Answer: Yes – at least in some cases!

Idea: Use of multi-spectral and multi-angular polarimetric hyperspectral observations (penetration depth difference for different probing wavelengths, observation geometries and polarization --------> sampling of different cloud volumes)

References for use of MODIS observations:

Chang and Li, 2002, 2003;
Kokhanovsky and Rozanov, 2011

2. Theory

Variation of reflectance

functional derivative

$$\delta R_{a\_ef}(\lambda)=\int_0^1 \frac{\delta R(\lambda)}{\delta a_{ef}(z)}\left[\lambda,\bar{a}_{ef},z\right]\times\delta a_{ef}(z)\,dz$$

z=Z/H

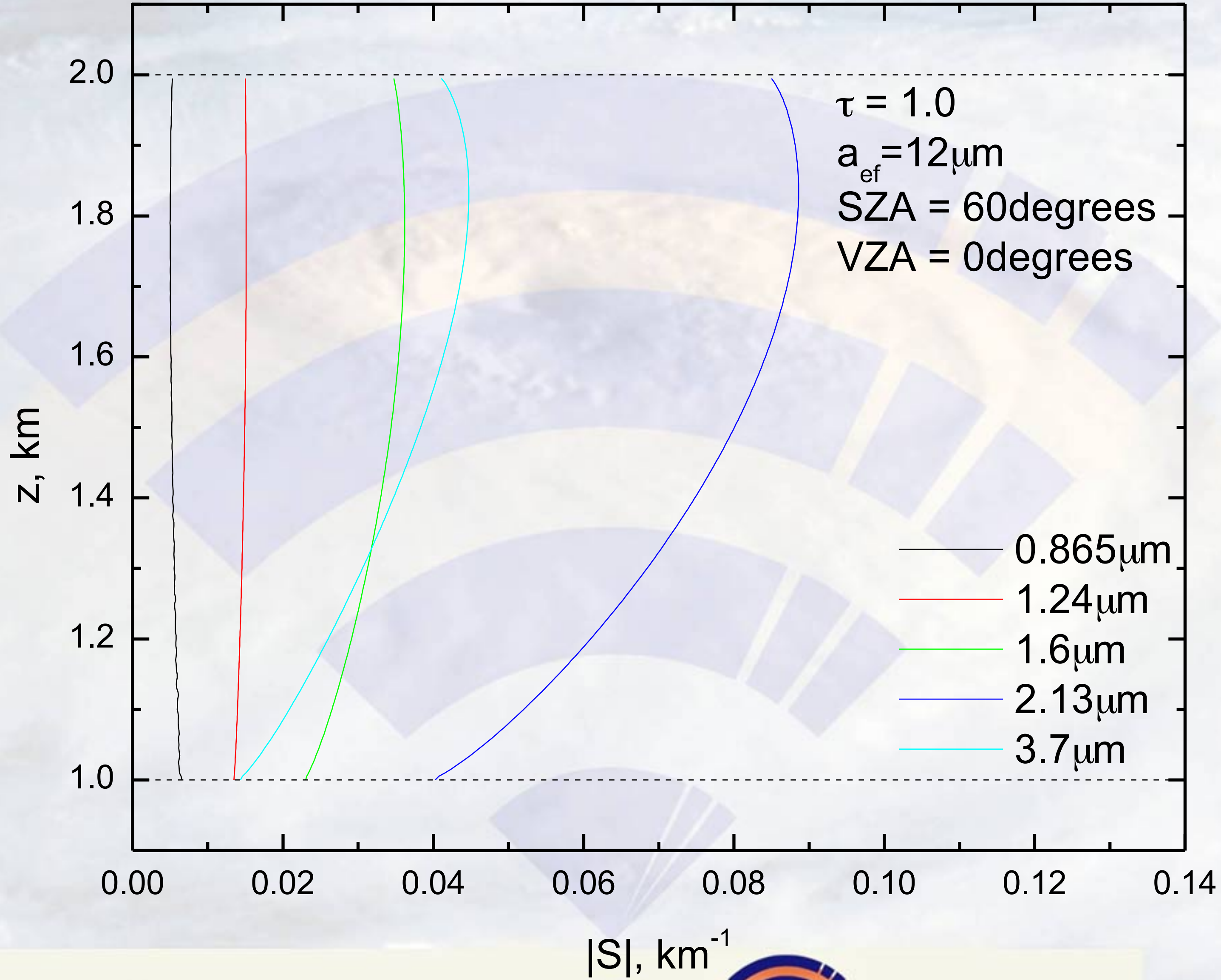
$$\delta R_{a\_ef}(\lambda)=\sum_{k=1}^{N_k} S_{a\_ef}(\lambda,z_k)\frac{a_{ef}(z_k)-\bar{a}_{ef}(z_k)}{\bar{a}_{ef}(z)}$$

$$\boxed{S_{a\_ef}(\lambda,z_k)=\left(\frac{\delta R(\lambda)}{\delta \ln a_{ef}}\right)_k f_k\Delta z_k}$$

plots

$\delta a_{ef}(z)$ variation of droplet size at depth z

Results of calculations



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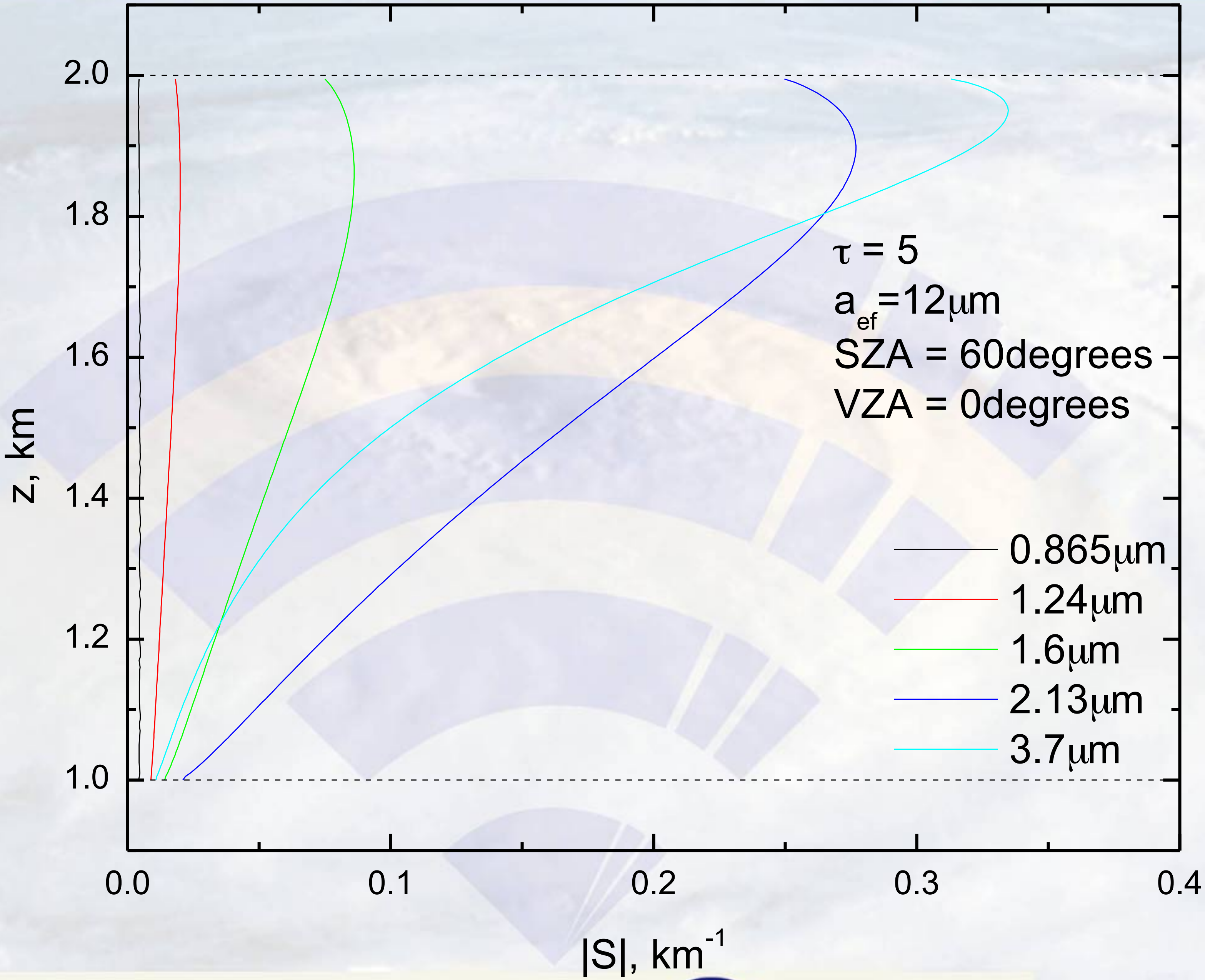
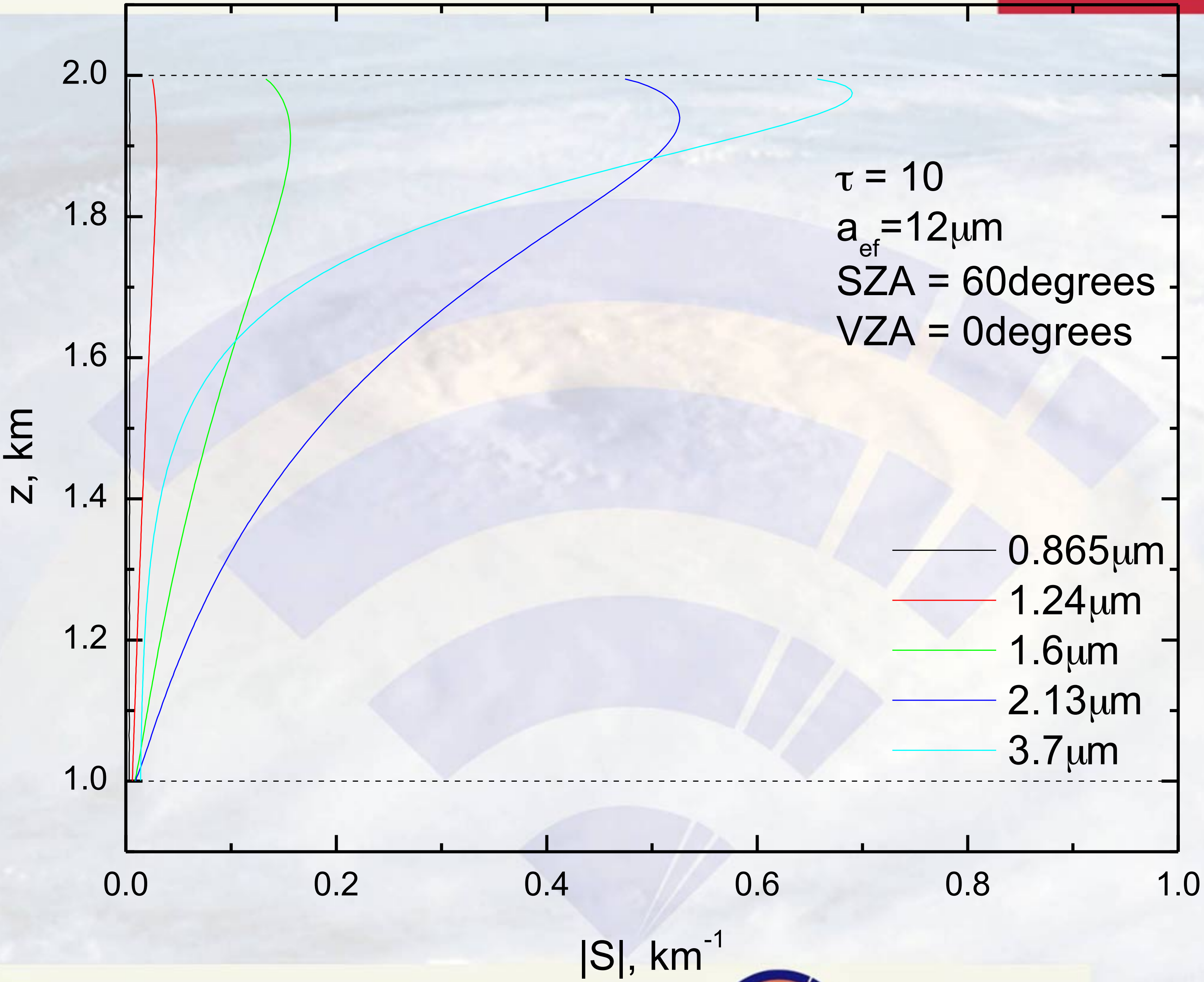
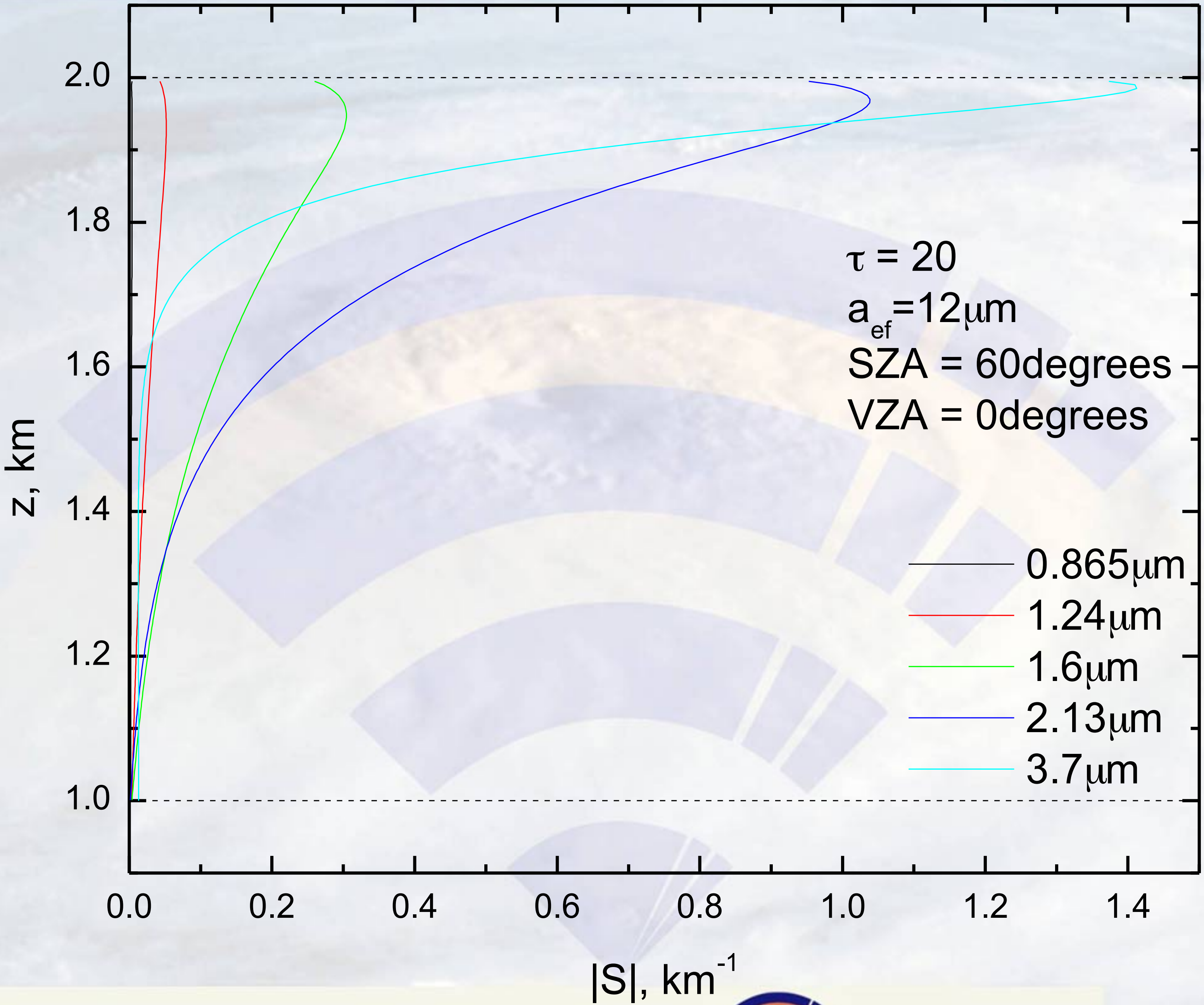
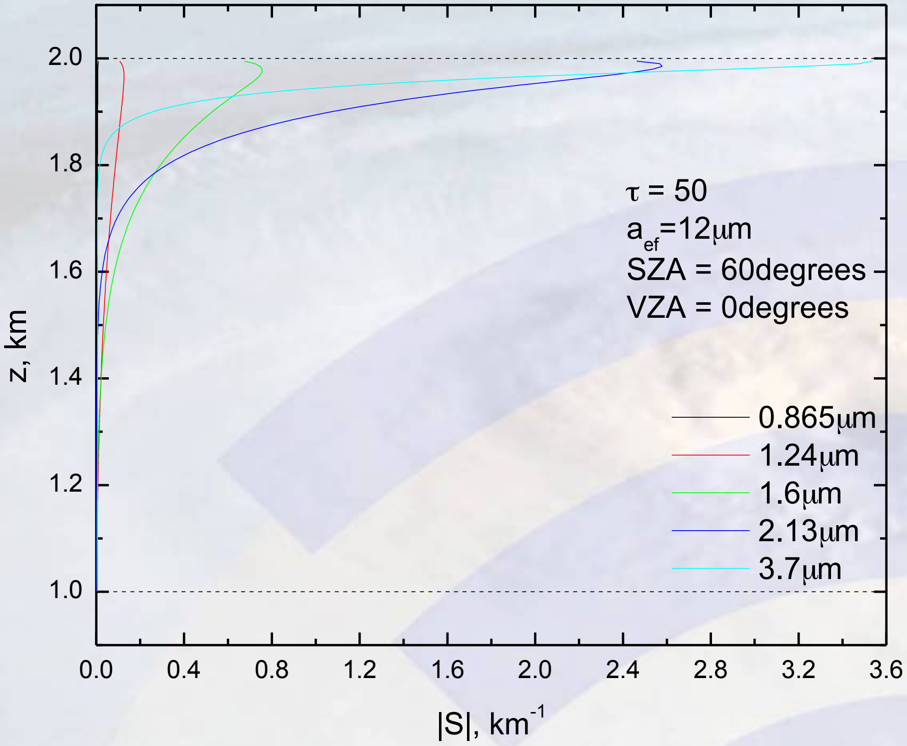
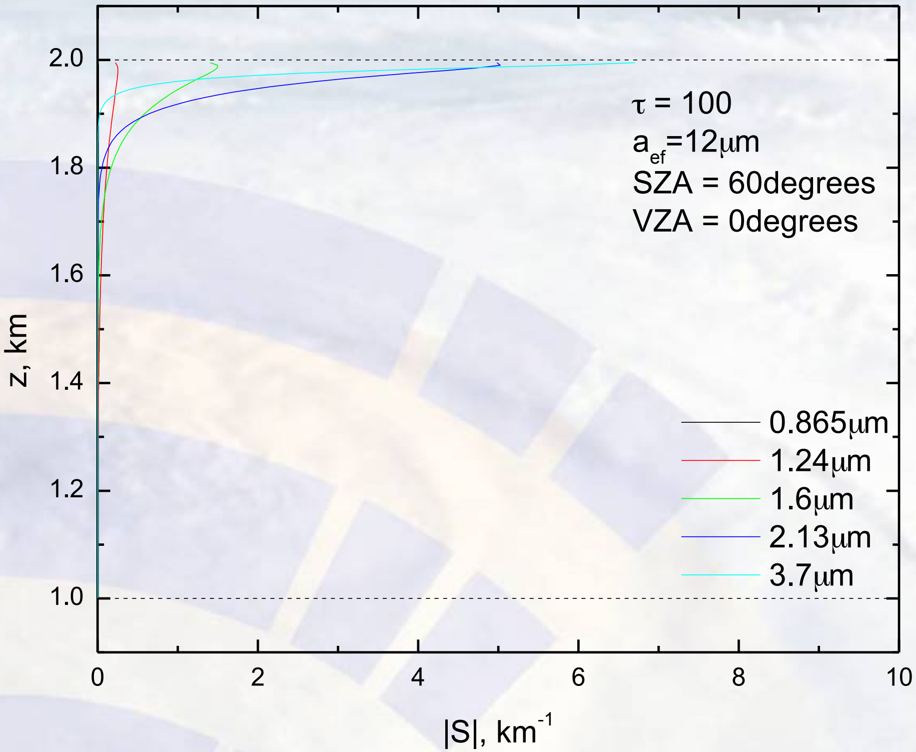
2.0
1.8
1.6
1.4
1.2
1.0
z, km
0.0
0.1
0.2
0.3
0.4
|S|, km^{-1}
τ = 5
a_{ef}=12μm
SZA = 60degrees
VZA = 0degrees
0.865μm
1.24μm
1.6μm
2.13μm
3.7μm


τ = 10
a_{ef}=12μm
SZA = 60degrees
VZA = 0degrees
0.865μm
1.24μm
1.6μm
2.13μm
3.7μm
z, km
2.0
1.8
1.6
1.4
1.2
1.0
0.0
0.2
0.4
0.6
0.8
1.0
|S|, km^{-1}


τ = 20
a_{ef}=12μm
SZA = 60degrees
VZA = 0degrees
0.865μm
1.24μm
1.6μm
2.13μm
3.7μm
z, km
2.0
1.8
1.6
1.4
1.2
1.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
|S|, km^{-1}



τ = 50
a_{ef}=12μm
SZA = 60degrees
VZA = 0degrees
0.865μm
1.24μm
1.6μm
2.13μm
3.7μm
z, km
|S|, km^{-1}
2.0
1.8
1.6
1.4
1.2
1.0
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6



τ = 100
a_{ef}=12μm
SZA = 60degrees
VZA = 0degrees
0.865μm
1.24μm
1.6μm
2.13μm
3.7μm
z, km
|S|, km^{-1}
2.0
1.8
1.6
1.4
1.2
1.0
0
2
4
6
8
10

Algorithm

$$\delta R\left(\lambda, a_{ef}\left(z\right), \vec{\Omega}\right) = \int_{z_1}^{z_2} W\left(z, \overline{a}_{ef}(z), \lambda, \vec{\Omega}\right)\delta a_{ef}\left(z\right)dz$$

$$a_{ef}\left(z\right) = A + zB$$

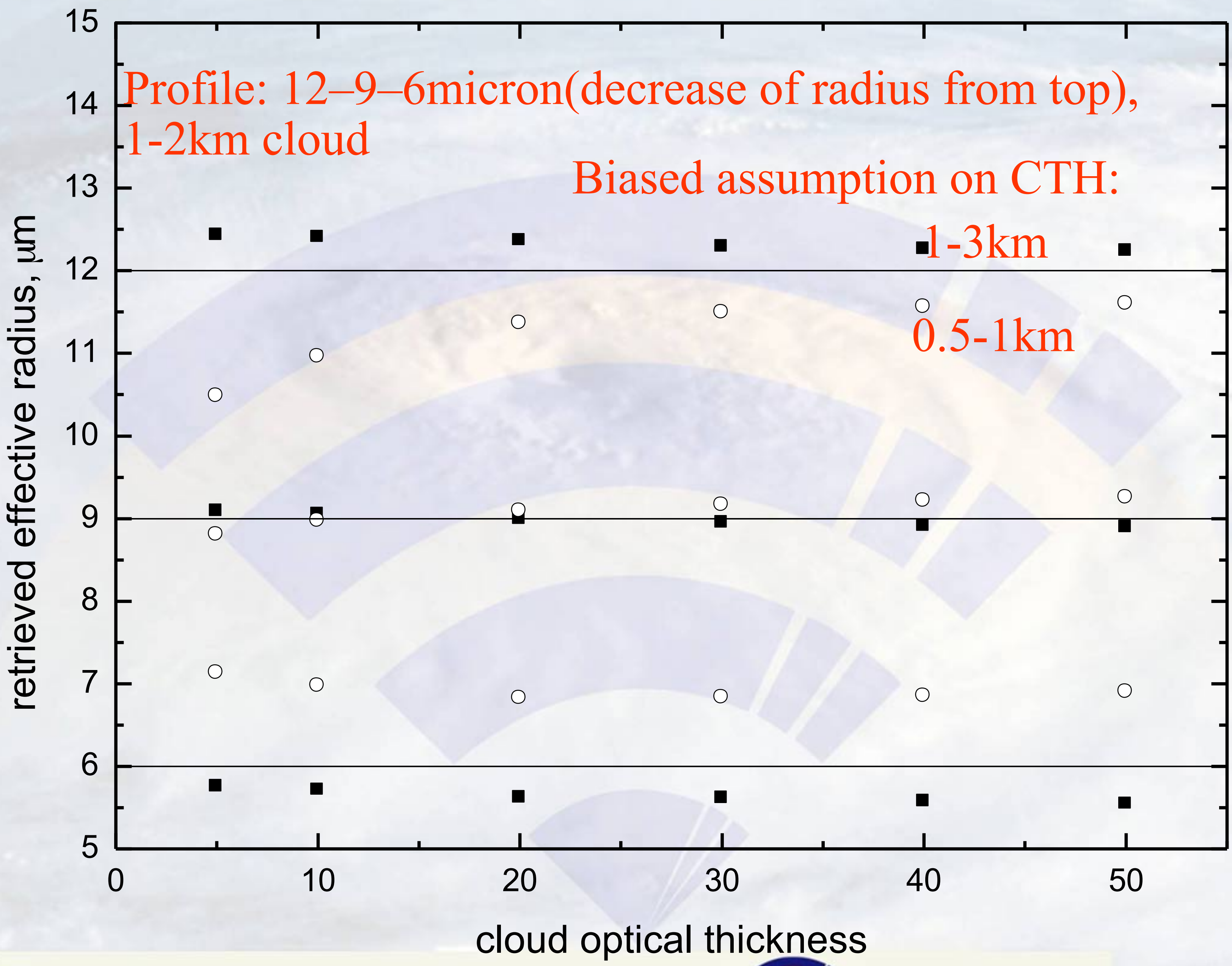
$$\delta a_{ef} = \delta A + z\delta B$$

$$\delta R\left(\lambda\right) = c_1\left(\lambda\right)\delta A + c_2\left(\lambda\right)\delta B$$

$$\vec{y} = \hat{c}\vec{x}, \qquad \hat{c}^T\vec{y} = \hat{c}^T\hat{c}\vec{x}, \quad \vec{x} = [\hat{c}^T\hat{c}]^{-1}\hat{c}^T\vec{y}$$

3. Retrievals

3.1 Synthetic retrievals

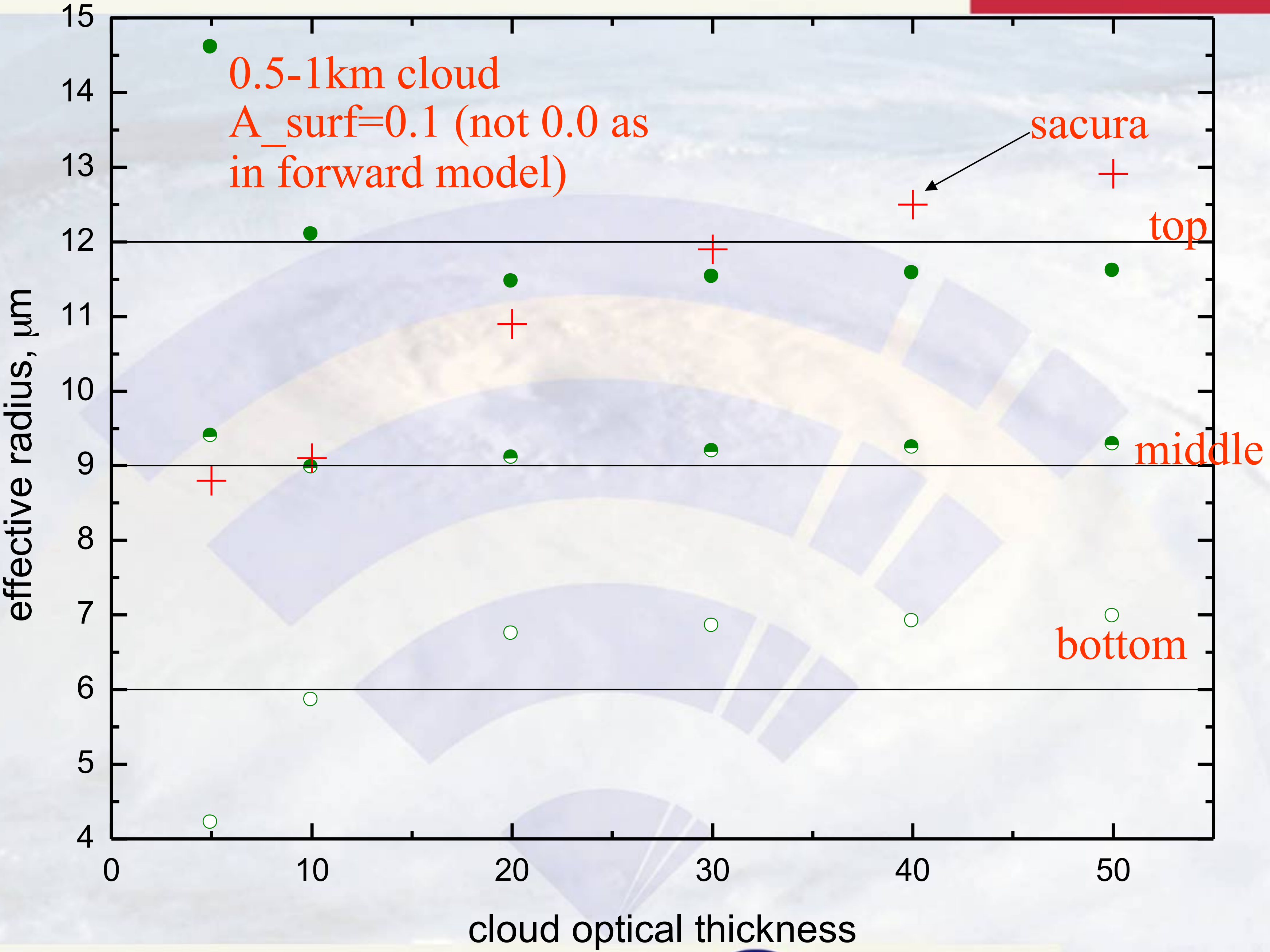


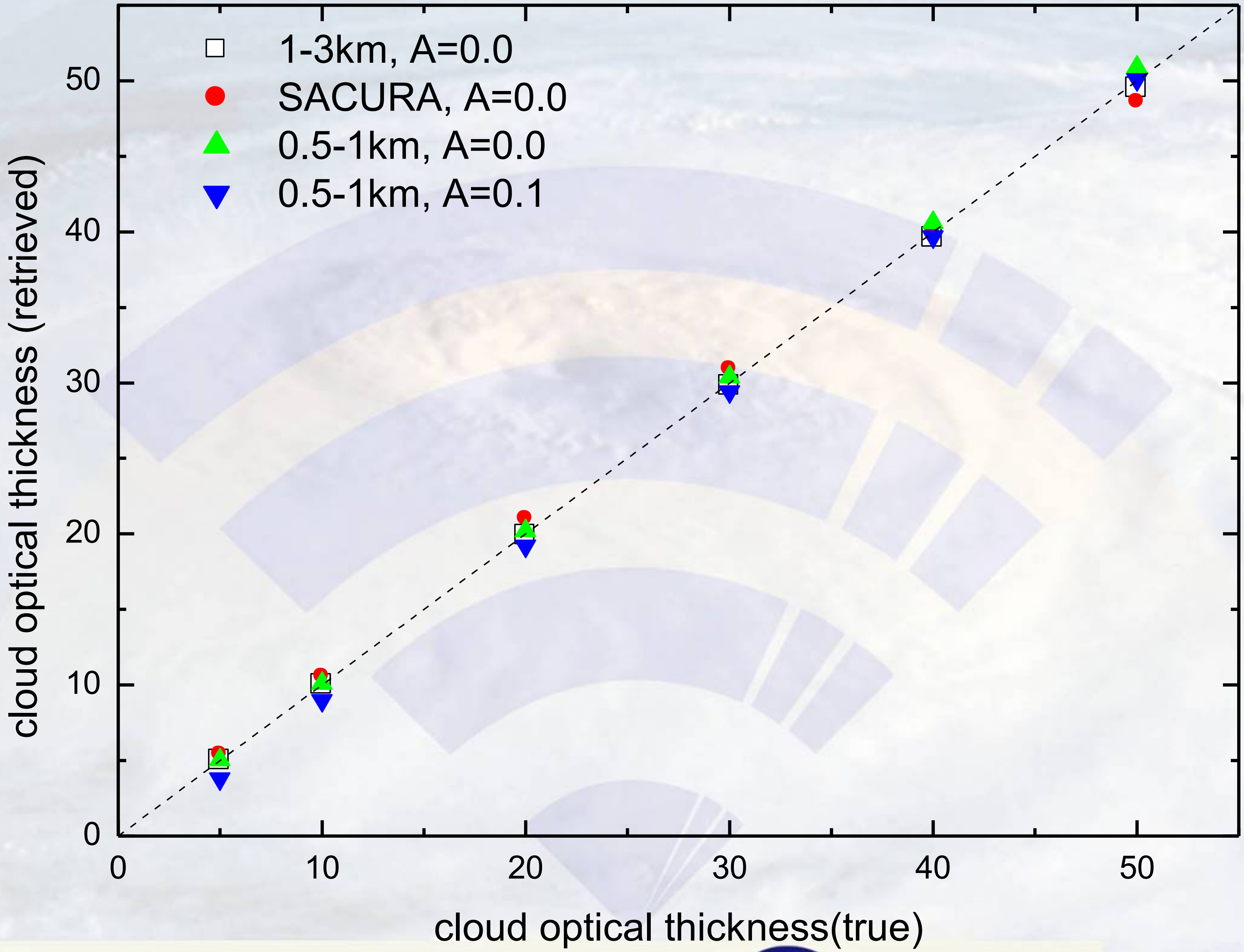
Profile: 12–9–6micron(decrease of radius from top), 1-2km cloud

Biased assumption on CTH:

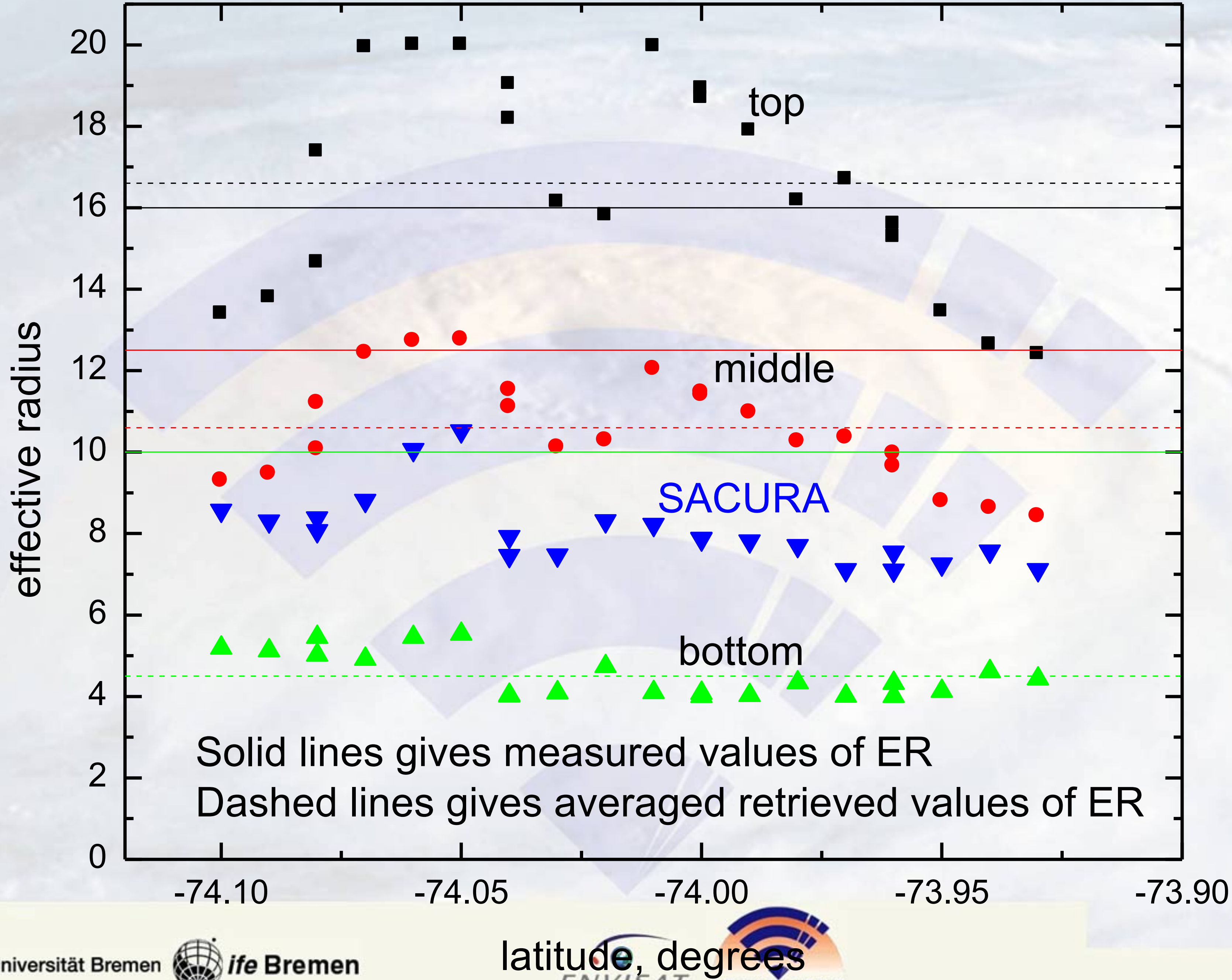
1-3km

0.5-1km

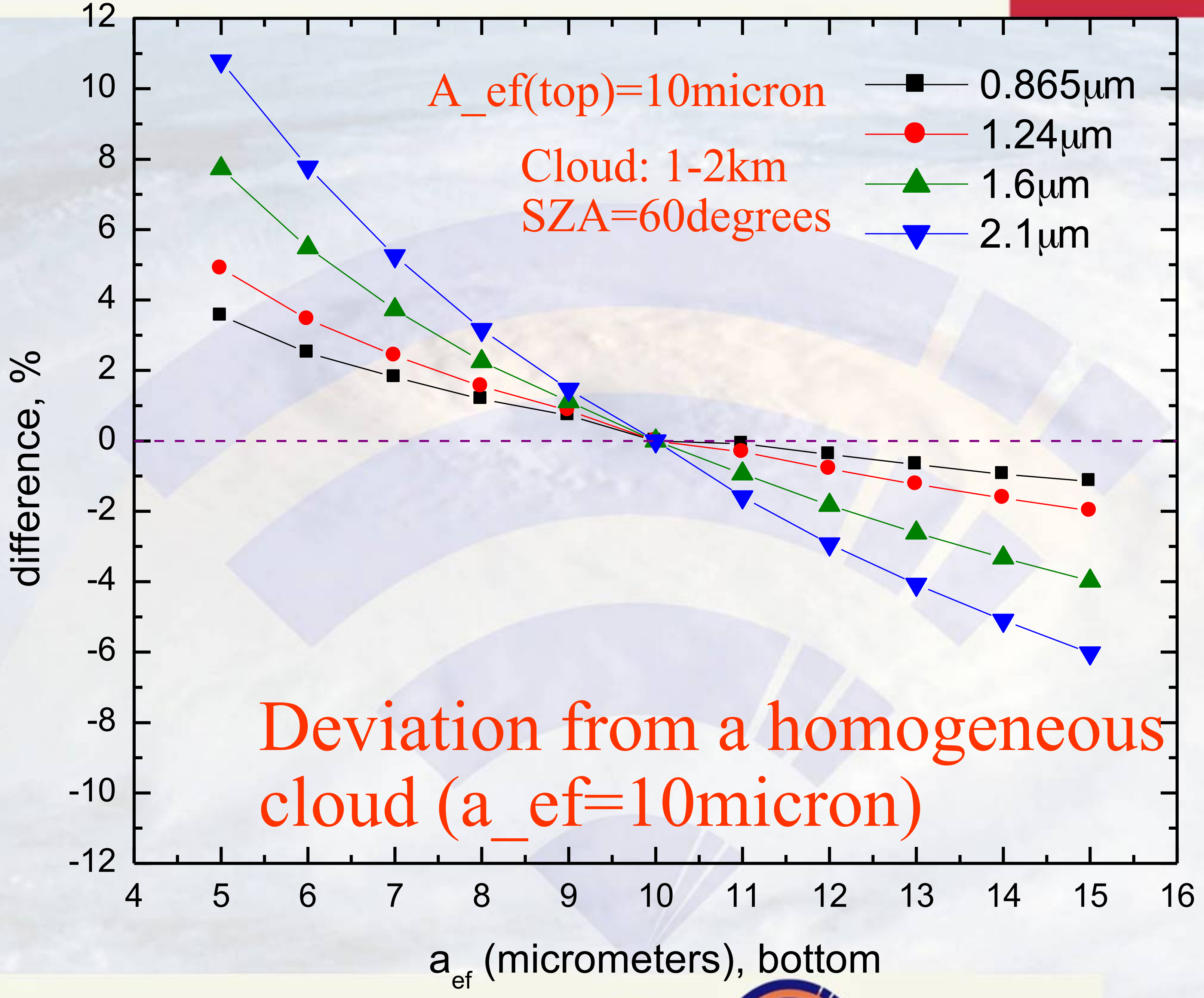

0.5-1km cloud
A_surf=0.1 (not 0.0 as in forward model)
sacura
top
middle
bottom
effective radius, μm
cloud optical thickness
15
14
13
12
11
10
9
8
7
6
5
4
0
10
20
30
40
50

☐ 1-3km, A=0.0
● SACURA, A=0.0
▲ 0.5-1km, A=0.0
▼ 0.5-1km, A=0.1
cloud optical thickness (retrieved)
0
10
20
30
40
50
cloud optical thickness(true)
0
10
20
30
40
50

Retrievals using aircraft data



Solid lines gives measured values of ER
Dashed lines gives averaged retrieved values of ER



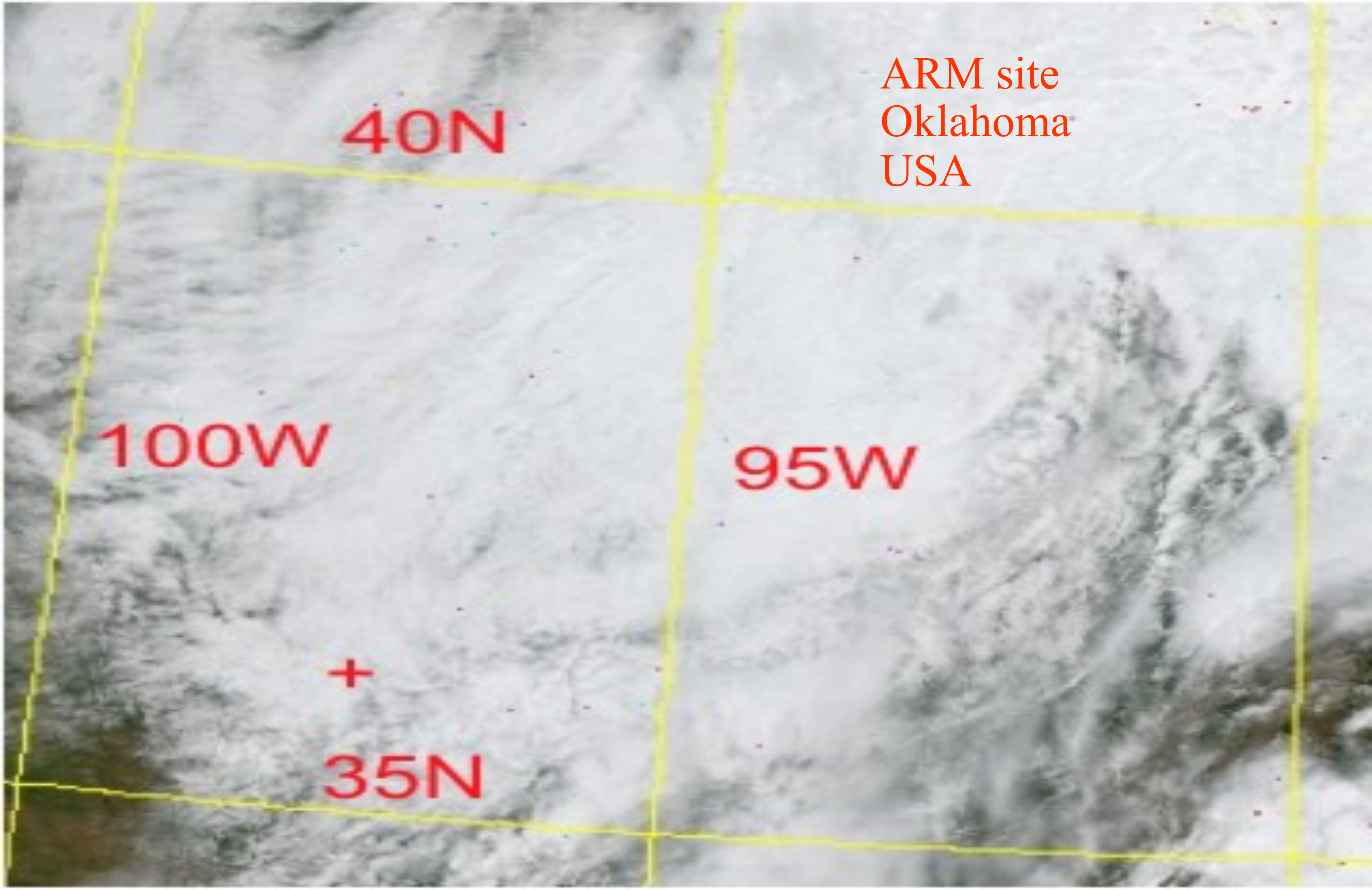
A_ef(top)=10micron

Cloud: 1-2km
SZA=60degrees

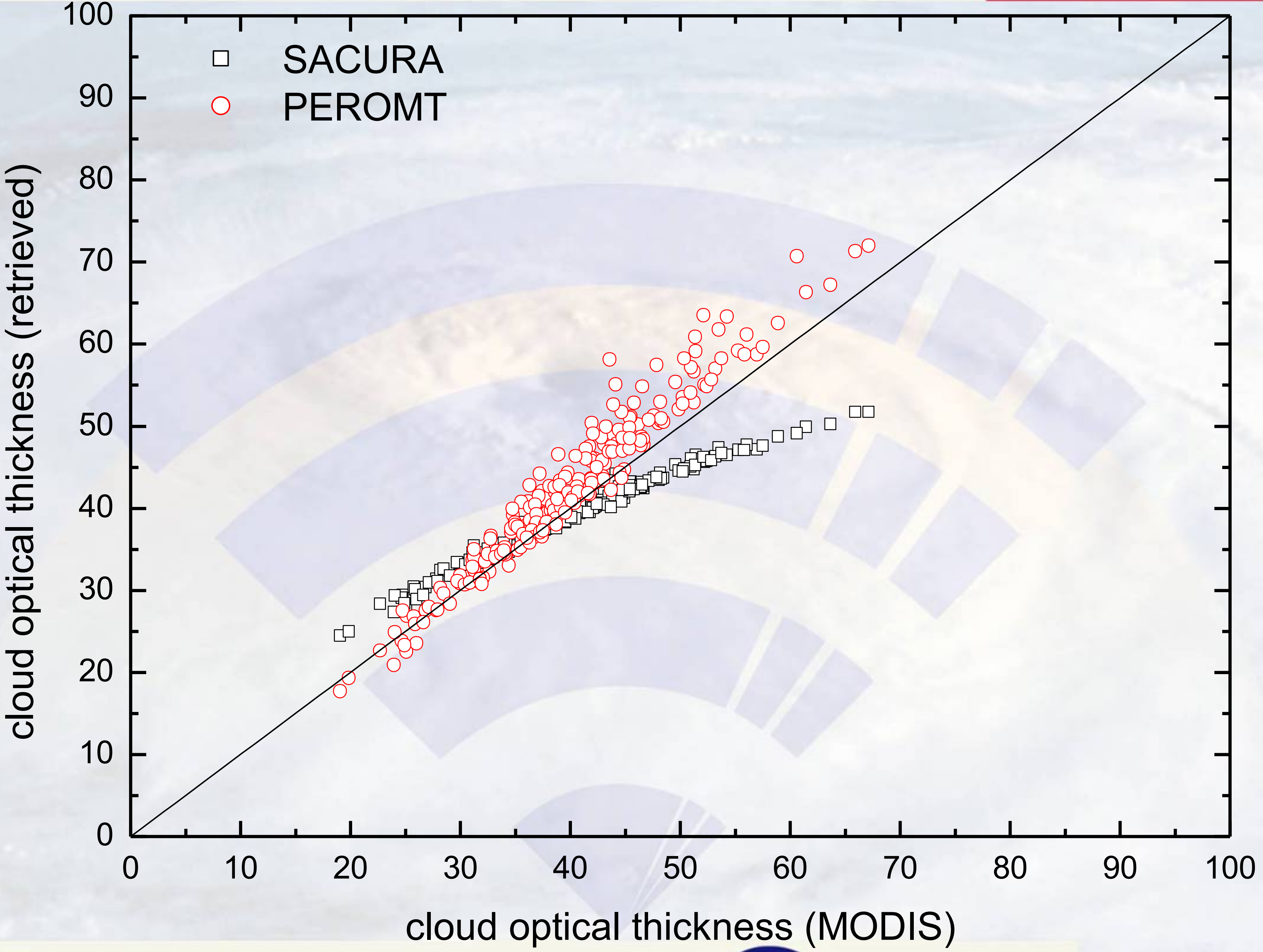
Deviation from a homogeneous cloud (a_ef=10micron)

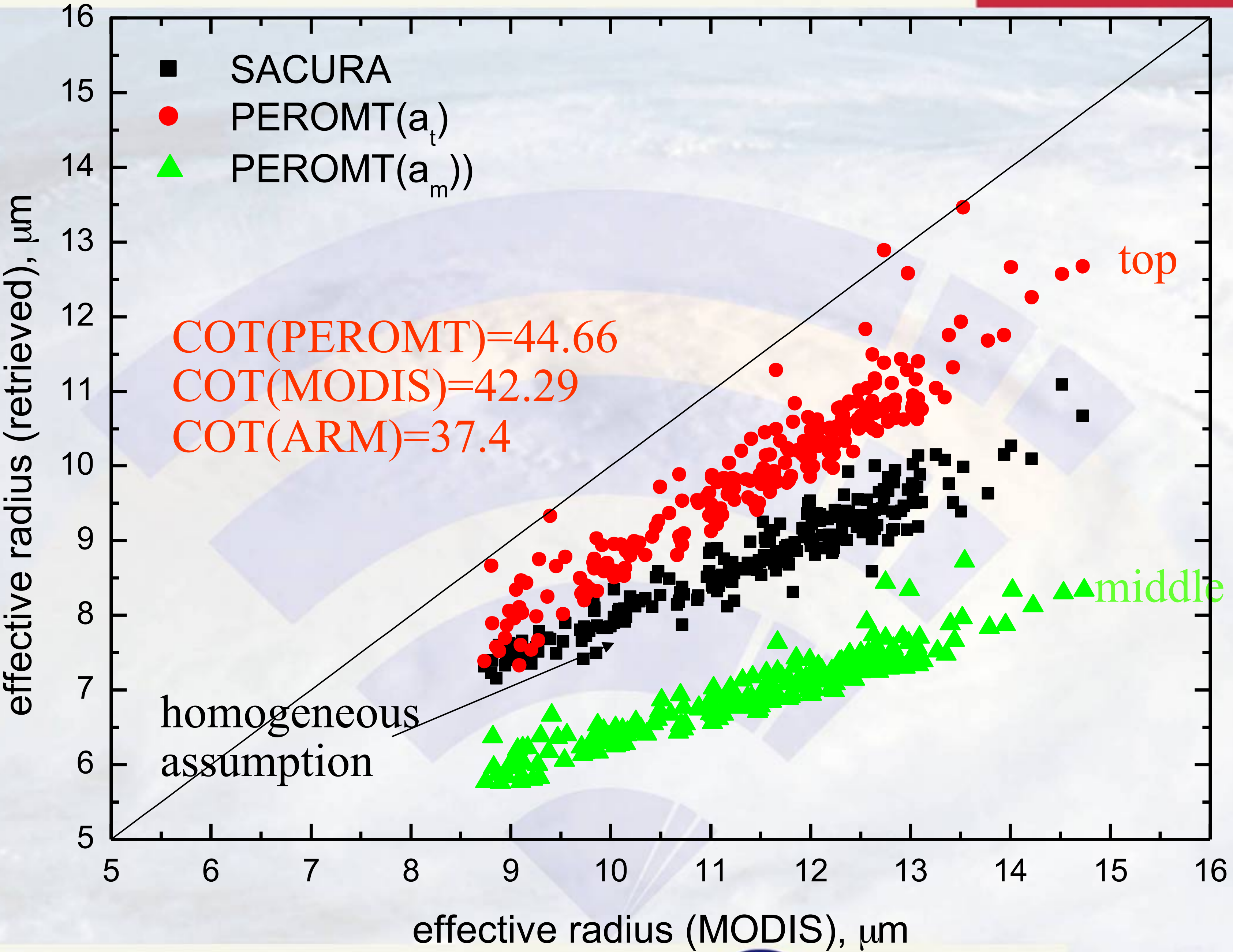
Retrievals using MODIS data

1. Retrievals over land

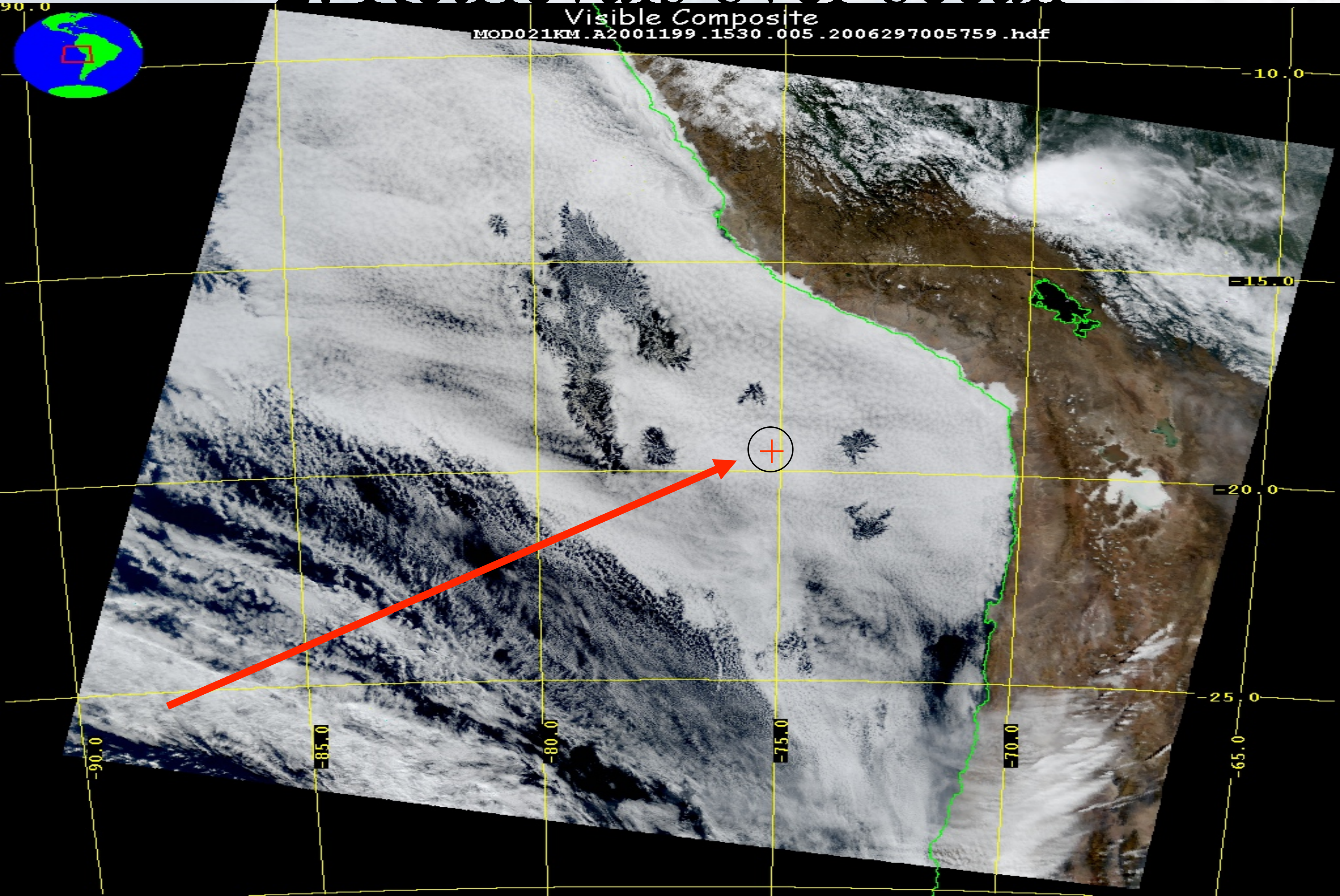


ARM site
Oklahoma
USA

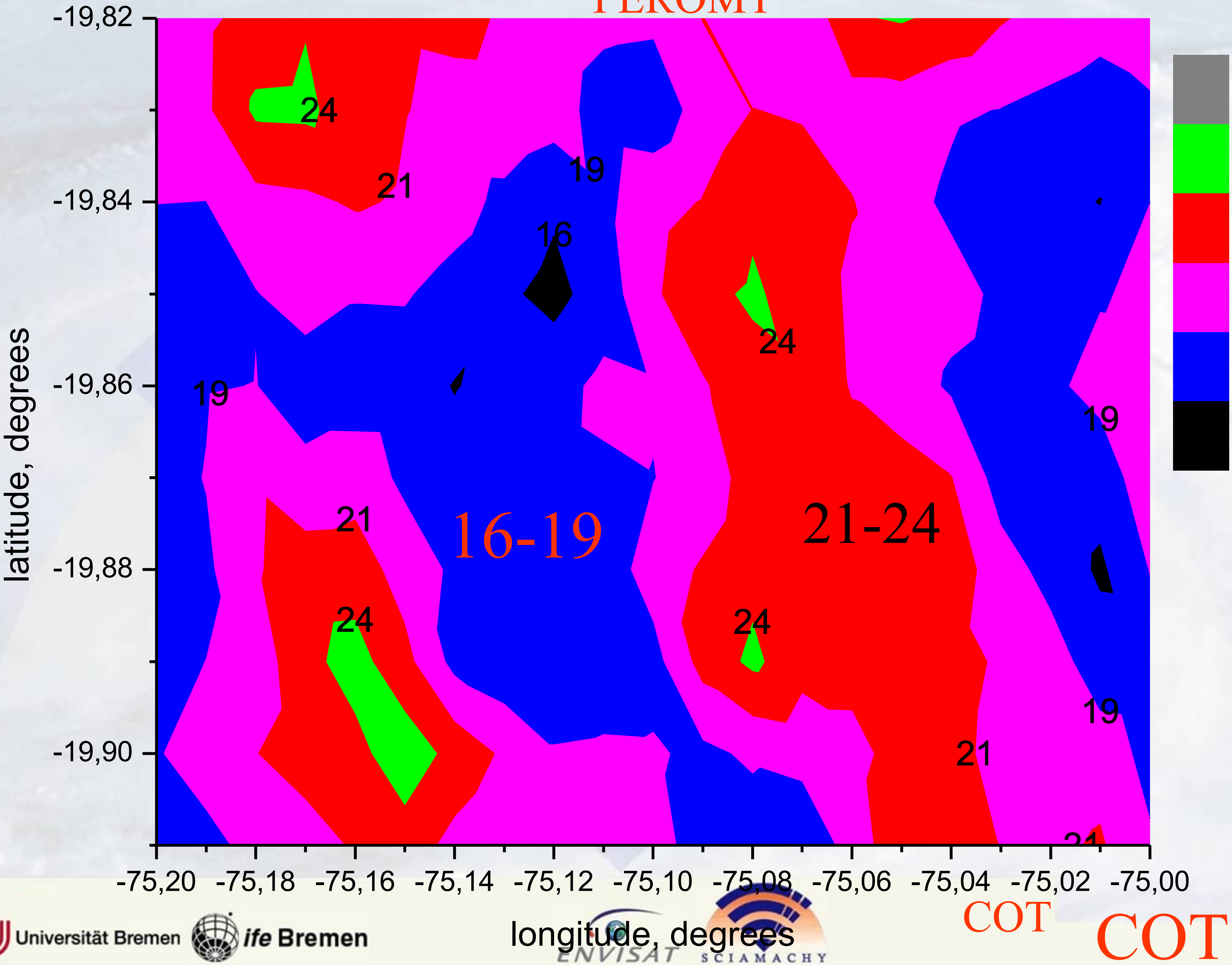

□ SACURA
○ PEROMT
cloud optical thickness (retrieved)
0
10
20
30
40
50
60
70
80
90
100
cloud optical thickness (MODIS)


SACURA
PEROMT(a_t)
PEROMT(a_m))
COT(PEROMT)=44.66
COT(MODIS)=42.29
COT(ARM)=37.4
top
middle
homogeneous assumption
effective radius (retrieved), µm
effective radius (MODIS), µm
5
6
7
8
9
10
11
12
13
14
15
16

2. Retrievals over ocean

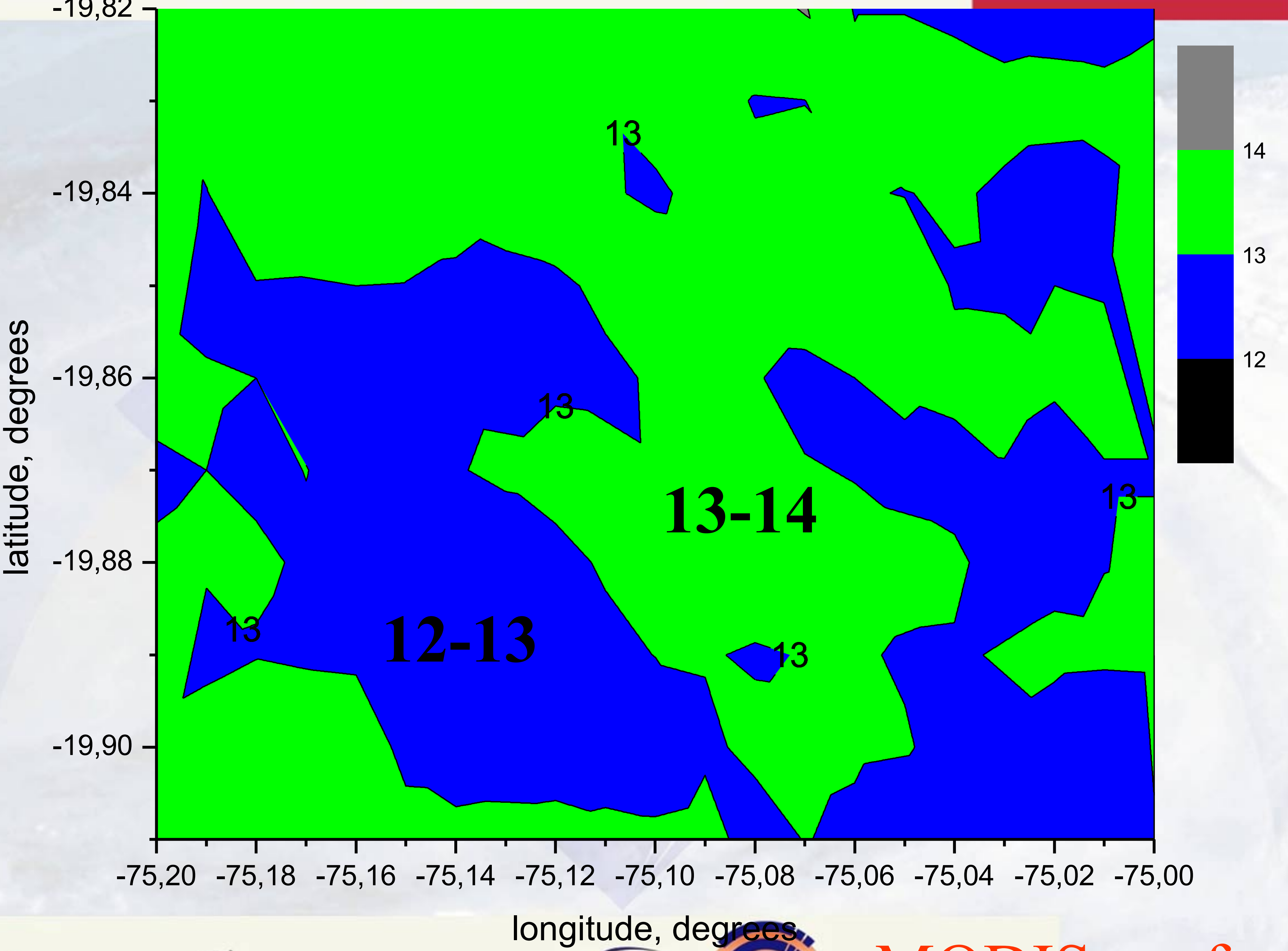


PEROMT



COT

COT



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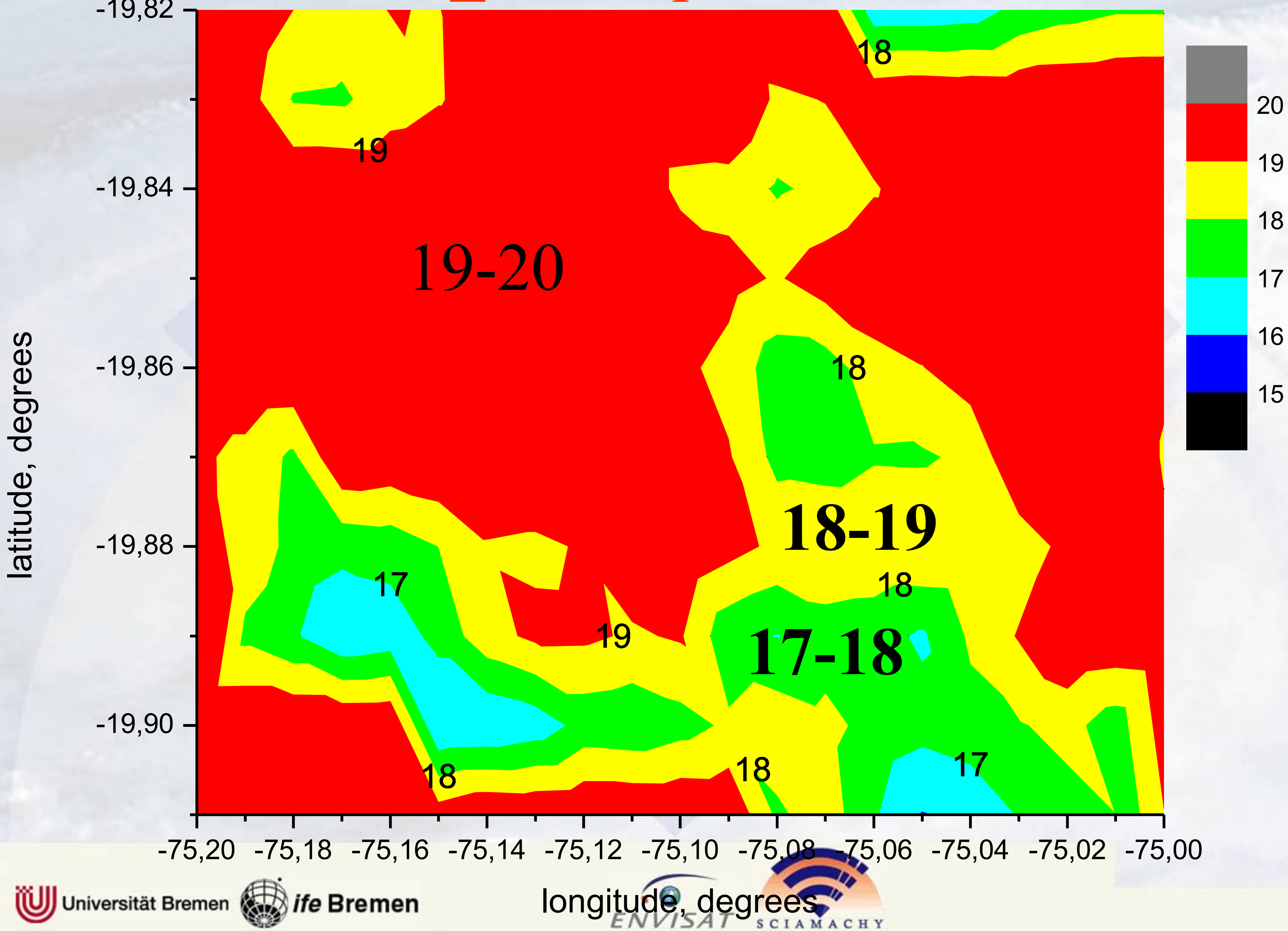
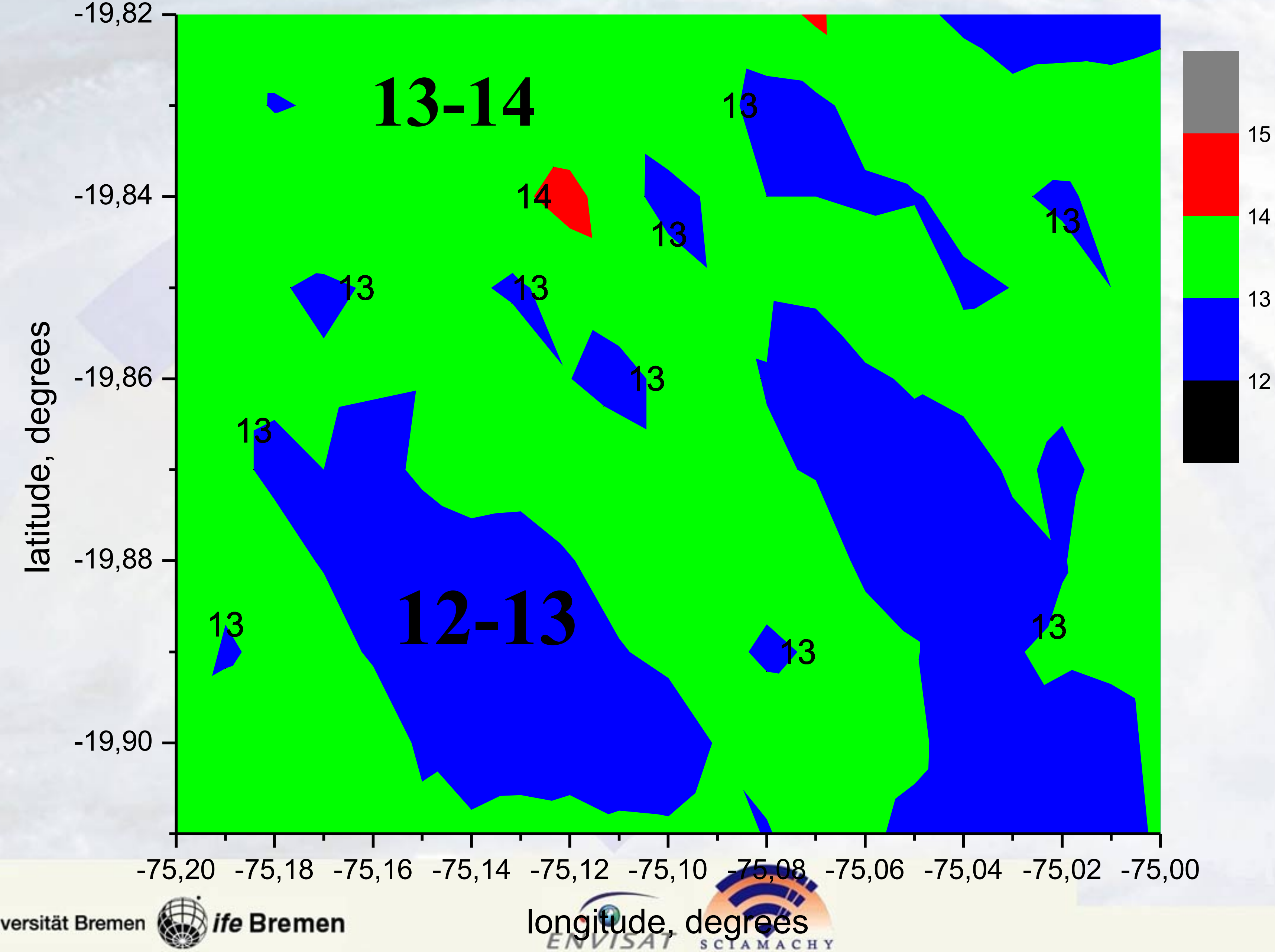
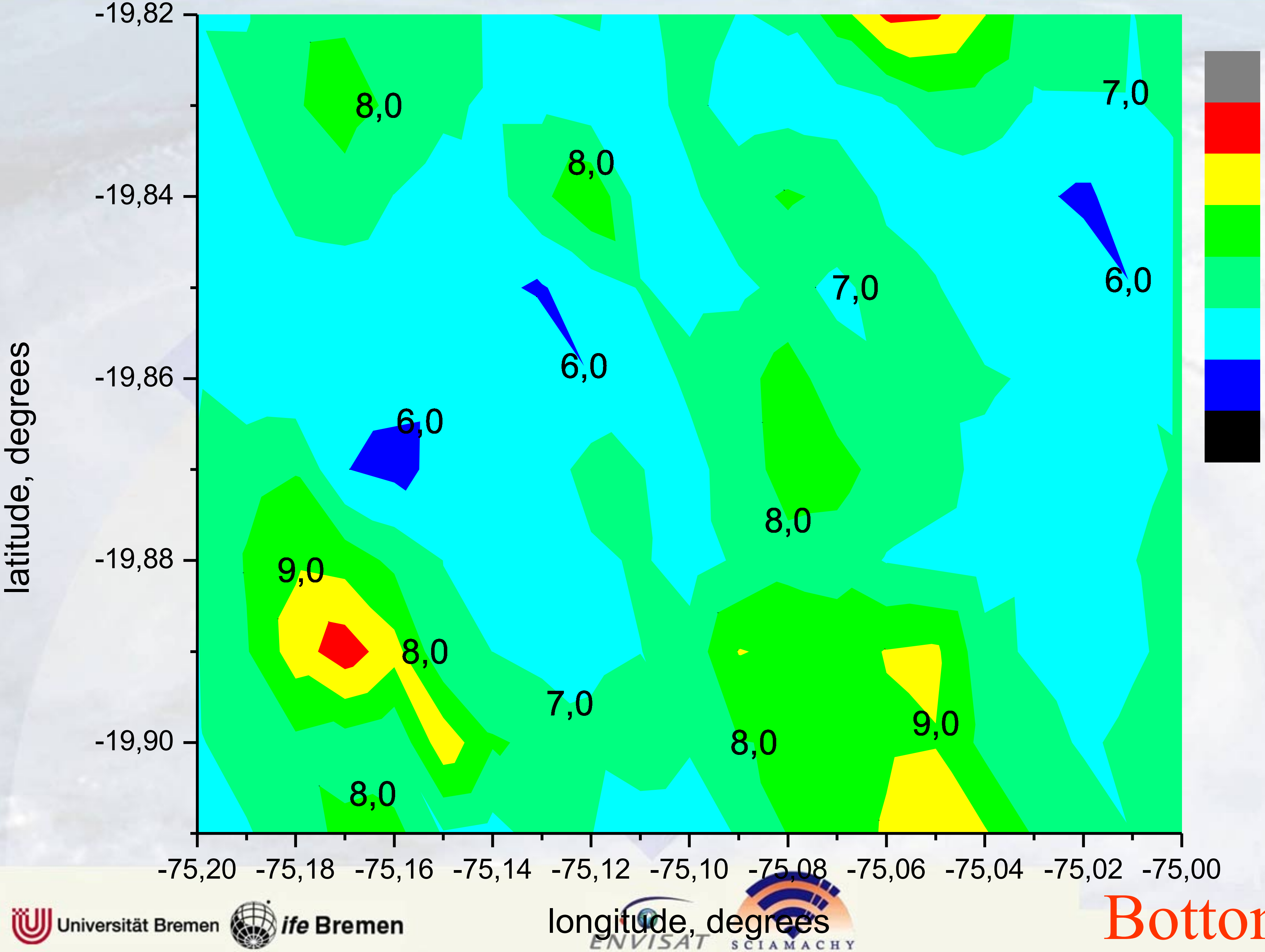
MODIS a_ef

a_ef at top of cloud



a_ef at middle of a cloud




-19,82
-19,84
-19,86
-19,88
-19,90
latitude, degrees
-75,20
-75,18
-75,16
-75,14
-75,12
-75,10
-75,08
-75,06
-75,04
-75,02
-75,00
longitude, degrees
8,0
8,0
7,0
7,0
6,0
6,0
6,0
8,0
9,0
8,0
7,0
8,0
9,0
8,0
11
10
9,0
8,0
7,0
6,0
5,0

Bottom

Conclusions and outlook

- It is possible to retrieve vertical profiles of effective radius of droplets in clouds using passive spectral measurements in some cases as demonstrated in the presentation. Further validation using in situ measurements is needed.
- The developed technique assumes that the cloud optical thickness is known from retrievals in the visible. Therefore, the problem is reduced to the case of finding a_ef(z) because for a fixed assumed N(z) profile (up to a constant multiplier) and known COT, profiles a_ef(z) and N(z) are inter-related.
- The technique also enables the improvement of the liquid water path estimation

Acknowledgements

- NASA
- ESA
- DFG
- Aircraft team
- VOCALS-UK team