FINNISH METEOROLOGICAL INSTITUTE

Parameterization of single-scattering properties of snow

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2 Nov 2015

*with thanks to: Alexander Kokhanovsky (EUMETSAT, Univ. of Bremen)
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Olivier Jourdan (Univ. Blaise Pascal)
Timo Nousiainen (FMI)

Academy of Finland (A4 project)

Introduction

When snow albedo or directional reflectance is computed using radiative transfer theory, **the single-scattering properties (SSPs) of snow grains** have to be defined. Especially:

- single-scattering albedo ω (or co-albedo β=1-ω)

  (~ relative strength of scattering vs. absorption)

- asymmetry parameter **g**

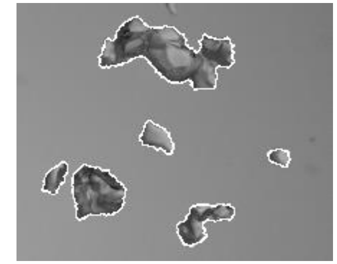
  (~ a gross measure of the directional distribution of scattering)

Also needed for remote sensing applications:

- scattering phase function $P_{11}(\theta_s)$

  (~ full directional distribution of scattering)

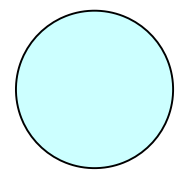
Introduction (2)



- Snow consists of non-spherical, often irregular grains of various shapes and sizes, and scattering can be sensitive to the fine details of the grain structure

  ⇒ Modelling of the snow SSPs based on the actual shapes and sizes of snow grains (almost) impossible?

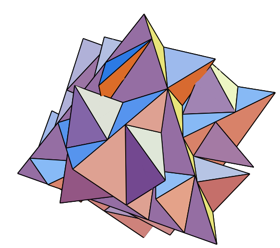
- In many radiative transfer applications, snow grains are still treated as spheres

  + SSPs easy to compute with Mie theory

  - Spheres **do not** represent well the scattering by snow

- Other shapes have also been considered

  * E.g. Koch fractals (Kokhanovsky et al.)

  * more realistic, but still an ad-hoc choice

Present approach

1) Define a reference phase function P_{11}^{ref} based on angular scattering measurements for blowing snow (CLIMSLIP campaign, Svalbard)

2) Select a shape combination that reproduces well the reference phase function (an ”optimized habit combination”, OHC)

3) Calculate SSPs for the OHC as a function of wavelength and snow grain size

4) Derive parameterization equations for the SSPs
   - single-scattering albedo **ω** (or co-albedo β=1-ω)
   - asymmetry parameter **g**
   - scattering phase function **$P_{11}(\theta)$**

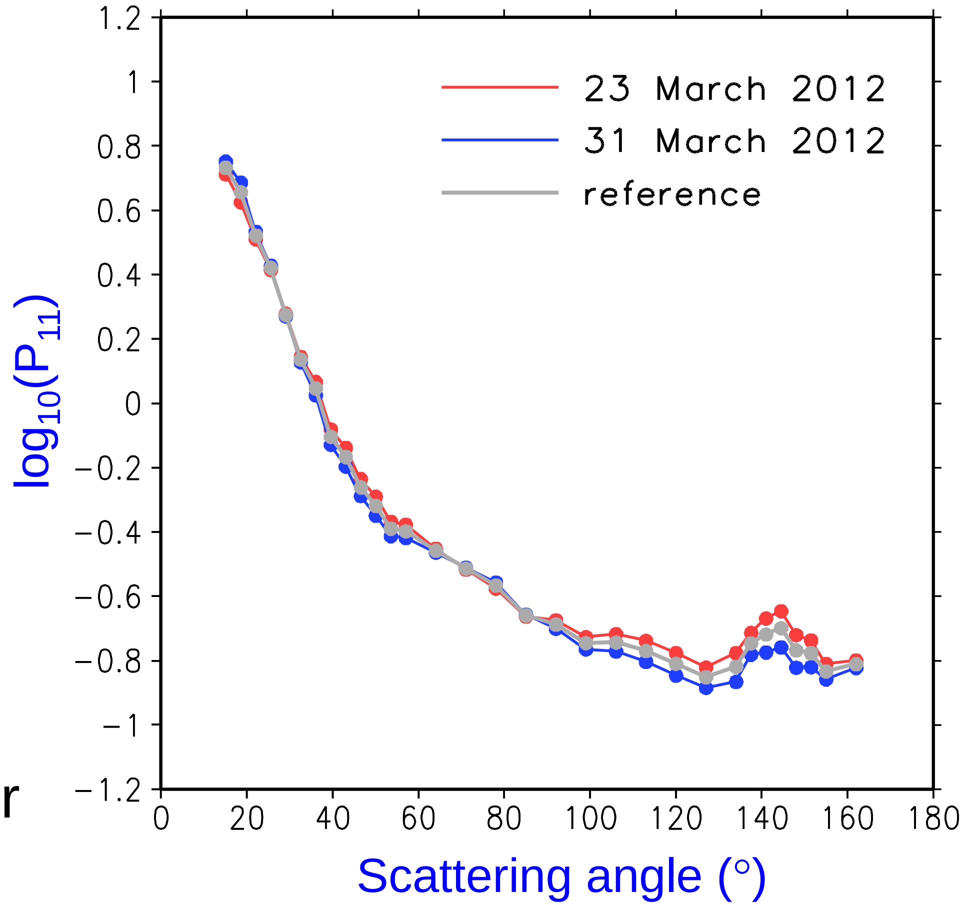
Reference phase function

- Polar nephelometer measurements for angular **scattering by blowing snow*** in CLIMSLIP campaign in Svalbard, 23 and 31 March 2012 (wavelength λ=0.8 µm, scattering angle θ_s=15-162°)

- Use the average for the 23 and 31 March cases as a reference

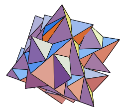
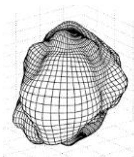
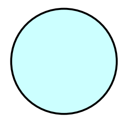
$$P_{11}^{\mathrm{ref}} = \frac{(P_{11}^{23\mathrm{March}} + P_{11}^{31\mathrm{March}})}{2}$$

(*Corresponding measurements for snow on ground not yet feasible)



Selecting the habit(s) for representing the single-scattering properties of snow

- **Consider the following snow grain shapes (habits)**

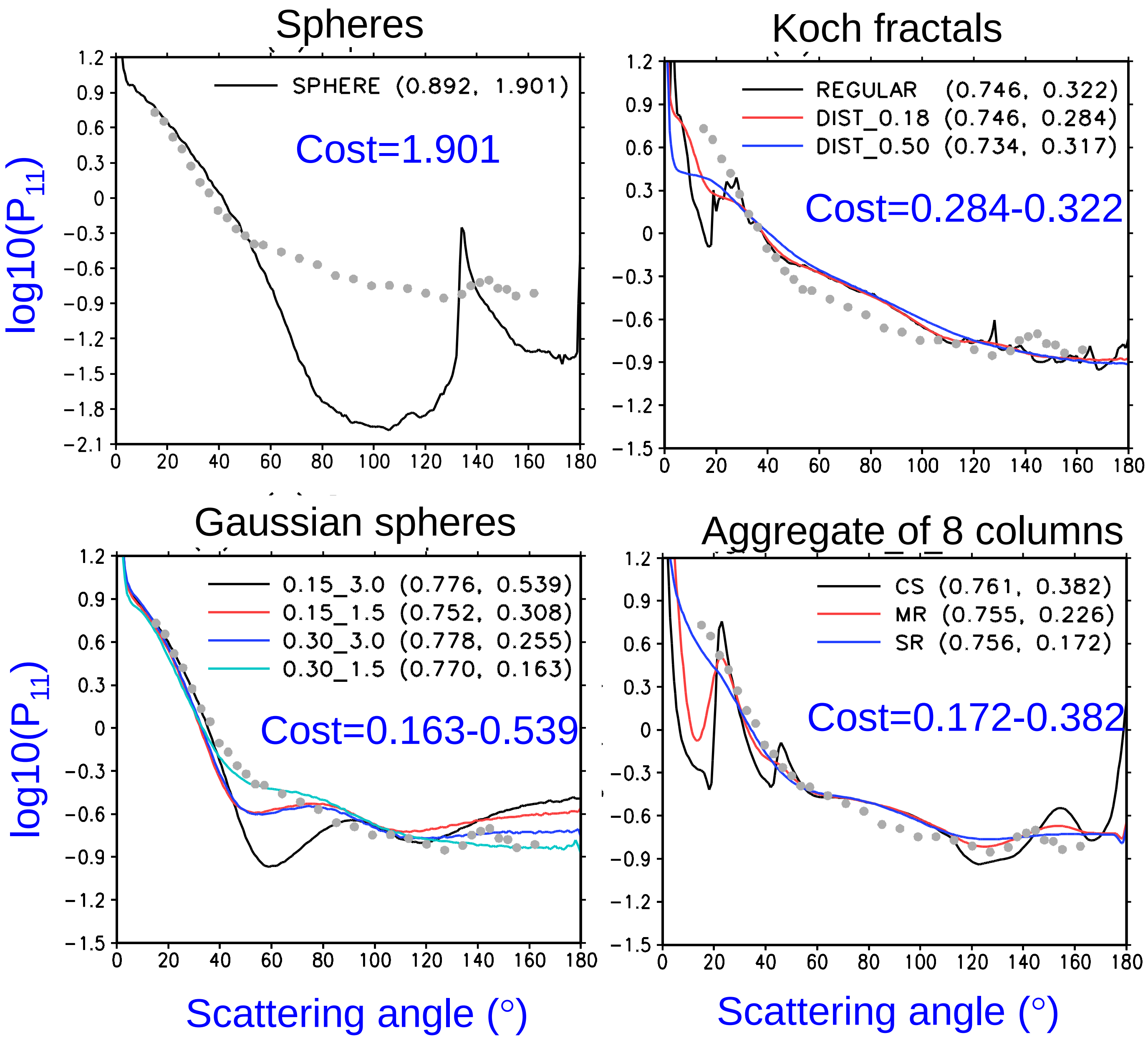
- Koch fractals 
- Gaussian spheres 
- 9 habits in the Yang et al. (JAS 2013) database (with 3 ”roughness” options)
- spheres (just for comparison) 

- **Single habits, and 2- or 3-habit combinations**

- **Try to fit the reference phase function.** Quantify the differences with a **cost function**

$$\text{cost} = \sqrt{\frac{\int_{15^\circ}^{162^\circ} \left(\ln P_{11}^{\text{model}} - \ln P_{11}^{\text{ref}}\right)^2 \sin\theta_s \, d\theta_s}{\int_{15^\circ}^{162^\circ} \sin\theta_s \, d\theta_s}}$$

Some examples (single habits)

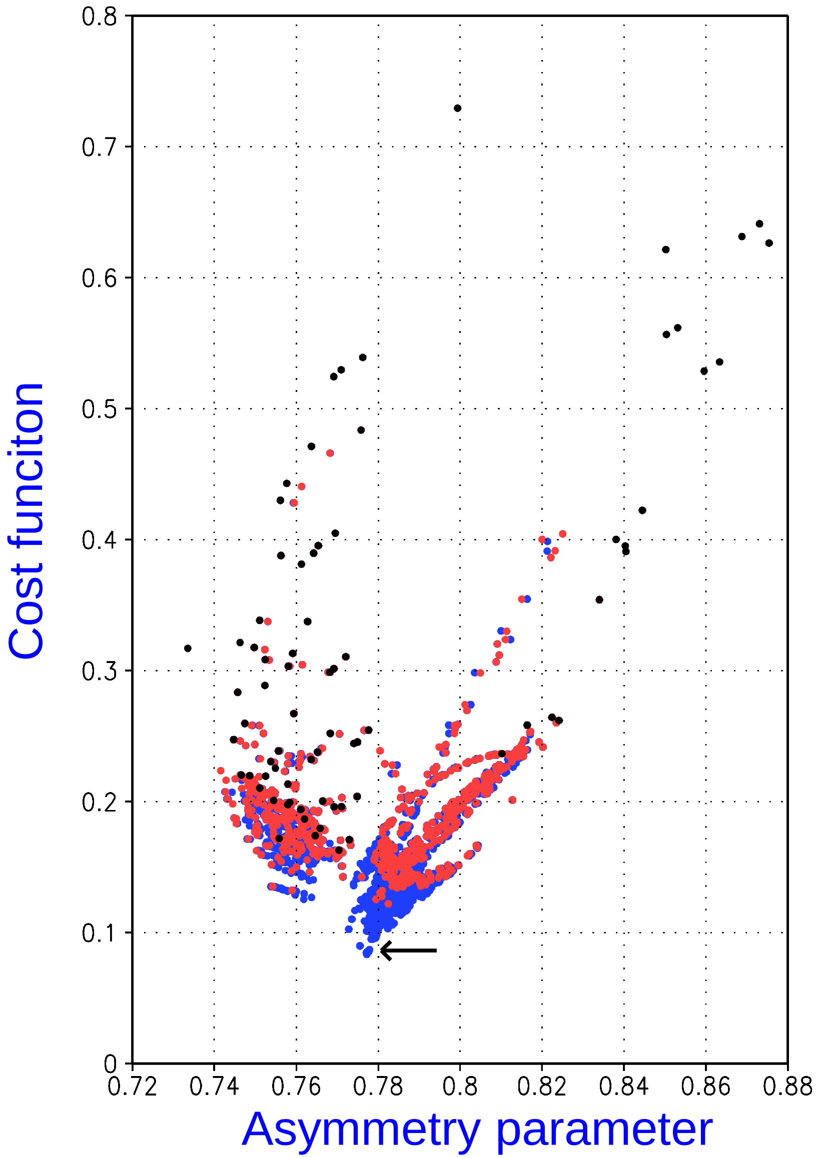


Spheres work very badly!

Ice crystals with roughness/ irregularities work better than smooth crystals

No single habit works quite satisfactorily
⇒try combinations of 2 or 3 habits!

Asymmetry parameter vs. cost function



Black dots: single habits
Red dots: 2-habit combinations
Blue dots: 3-habit combinations

There is no unique solution: many 3-habit combinations are ≈ equally good (COST ≈ 0.085)

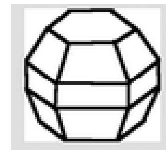
The asymmetry parameter is constrained quite well
(g≈0.78 at λ=0.80 μm)

- for spheres g ≈ 0.89

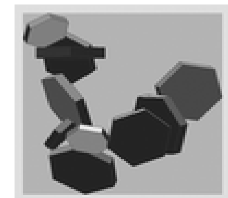
An ”Optimized habit combination” (OHC) was selected for representing the snow SSPs

Fraction of projected area

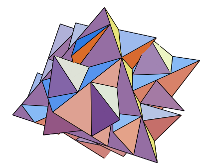
34 % severely roughened droxtals

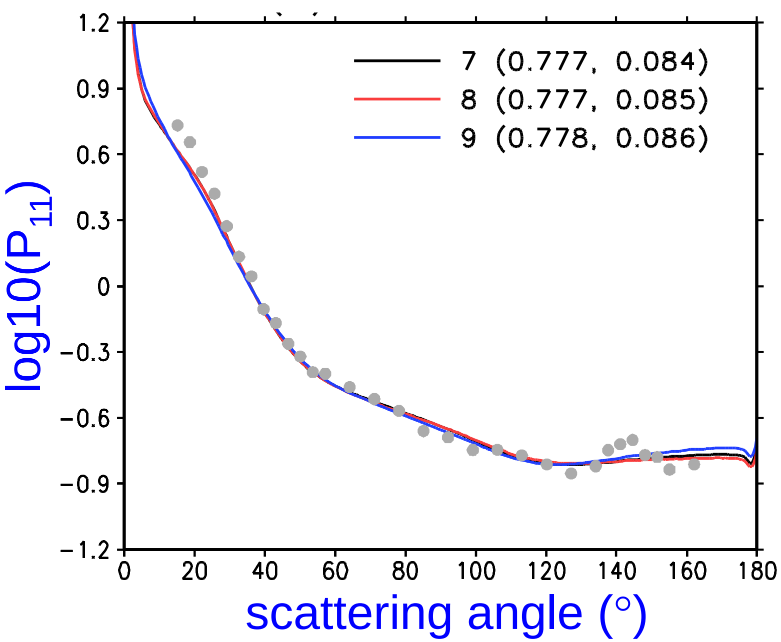


34 % severely roughened aggregates of plates



32 % strongly distorted Koch fractals





This is how the optimized habit combination (in blue) (+ two other ”good” combinations) compare with the reference phase function

Snow single-scattering properties as a function of wavelength and size

Use the optimized habit combination to represent snow SSPs at ”all” wavelengths and ”all sizes”

- volume-to-projected area equivalent radius r_{vp}=10-2000 µm
- wavelength λ=0.199–2.7 µm

- SSPs for droxtals and aggregates of plates taken from the database of Yang et al. (2013)
- SSPs for disorted Koch fractals computed using a geometric optics model by Andreas Macke

Parameterization of snow SSPs

When the shape distribution is fixed (as here), the single-scattering properties depend only on

- Real part of refractive index **Re(m)**
- Imaginary part of refractive index **Im(m)**
- **Size parameter** (defined here in terms of volume-to-projected area equivalent radius r_{VP})

$$x = x_{\mathrm{VP}} = 2\pi \frac{r_{\mathrm{VP}}}{\lambda} \sim \frac{\mathrm{size}}{\mathrm{wavelength}}$$

Parameterization equations for the snow SSPs were developed in terms of these fundamental parameters, for

- volume-to-projected area equivalent radius $\mathbf{r_{vp}}$=10-2000 µm
- wavelength λ=0.199-2.7 µm

Parameterization equations

1) Extinction efficiency: $Q_{ext}=2$ (for simplicity)

2) Single-scattering co-albedo:

$$\beta = 0.470\left\{1-\exp\left[-2.69x_{abs}(1-0.31\min(x_{abs},2))^{0.67}\right]\right\}$$

where $$x_{abs} = \frac{2\pi r_{vp}}{\lambda}\,\mathrm{Im}(m)\,\mathrm{Re}(m)^2$$ ("A size parameter for absorption")

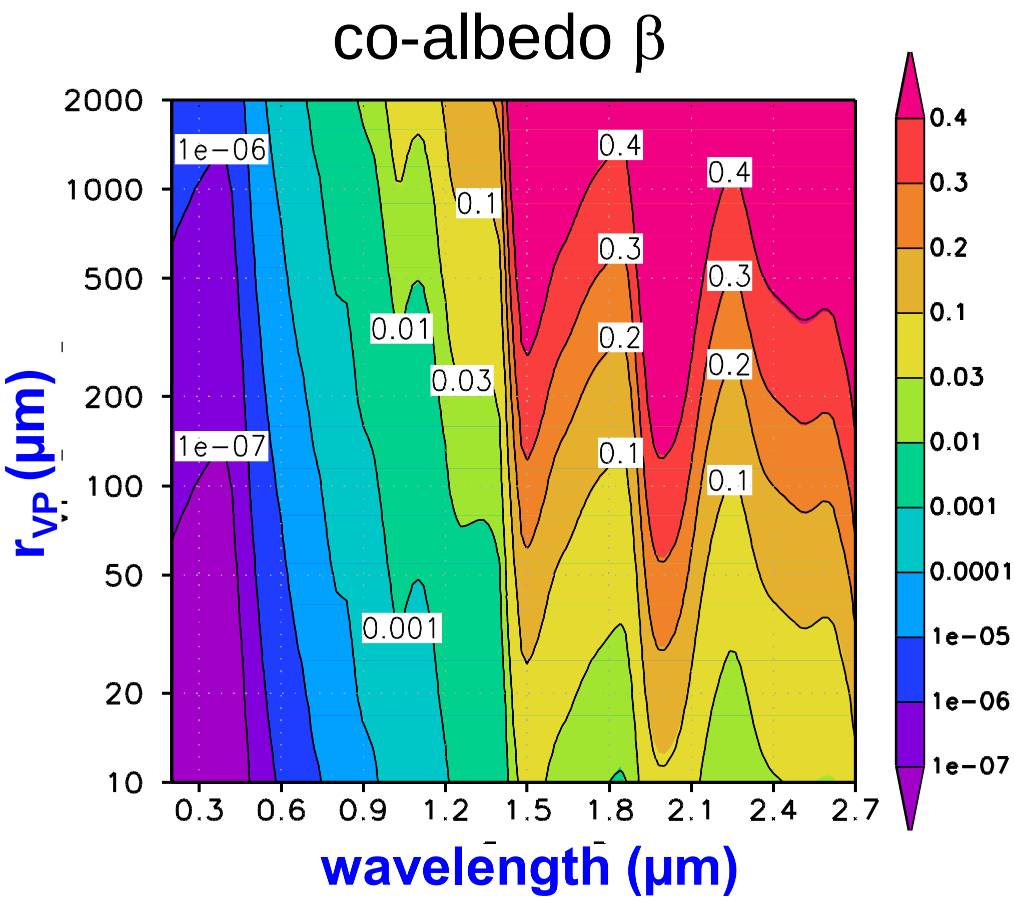
3) Asymmetry parameter:

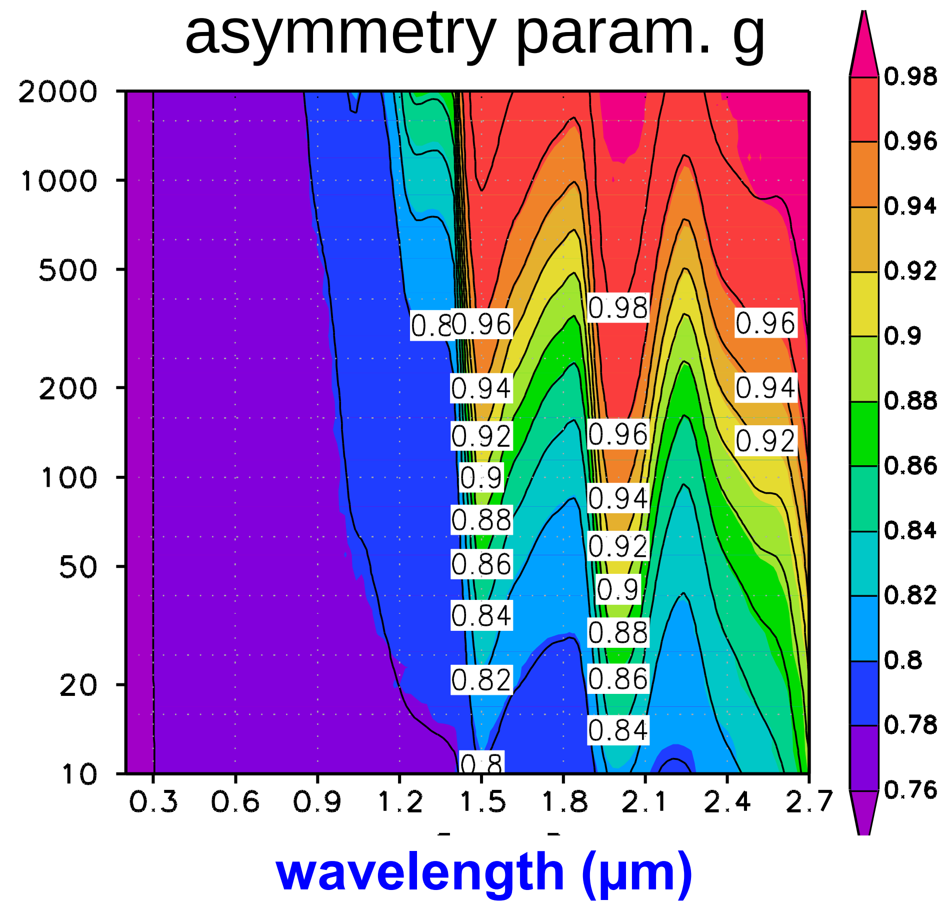
$$g = 1-1.146\left[\mathrm{Re}(m)-1\right]^{0.8}\left[0.52-\beta\right]^{1.05}\left[1+8x^{-1.5}\right]$$

4) Phase function: (not that long, but too long for this talk …)

How does it work?

Below: shading = reference values for the OHC, contours = parameterization



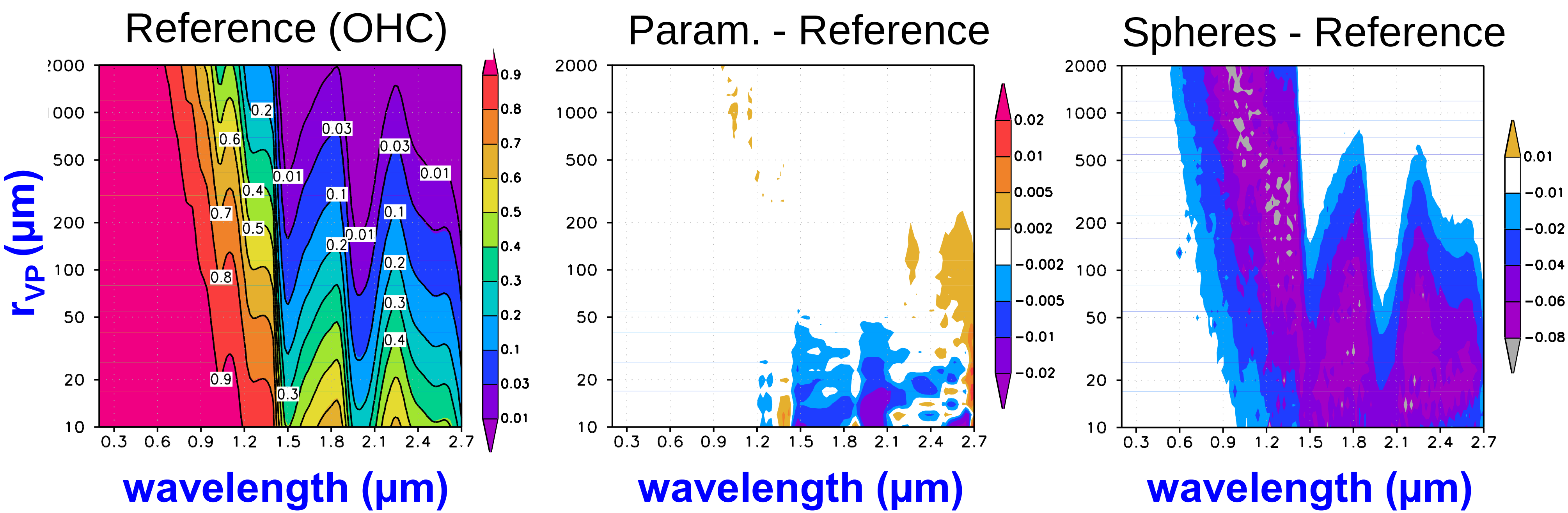


RMS(Δβ/β) = 0.014
RMS(Δg) = 0.0019

⇔ A very successful ”fitting exercise”!

An example of radiative transfer applications: the albedo of a semi-infinite snow layer

- Direct illumination, zenith angle θ_0=60°



- The parameterization reproduces the reference values mostly within 0.002
- For spheres, for a given snow grain size r_{VP}, the albedo is lower by up to 0.08

Final remarks

- The parameterizations are **simple to use in radiative transfer models** such as DISORT

- **Their numerical accuracy** (compared to the ”exact” SSPs computed for the OHC) is **very high**, for both the co-albedo **β** and the asymmetry parameter **g**, and even for the **phase function** (except for strongly absorbing cases with low snow reflectance).

- The parameterizations are **based on a rather limited amount of data** (only two cases, a single weakly-absorbing wavelength, blowing snow instead of snow on ground)

$\Rightarrow$ **real-world accuracy $\neq$ the accuracy of the numerical fits**

- Then why bother to procude such a parameterization?

Even though not perfect, it is **likely to be substantially better than Mie theory (spheres),** which is still used widely for snow for simplicity

Final remarks (2)

Follow-up research topics (ongoing work, though slowly!)

- Validation against BRDF measurements for snow on ground
- Climate model experiments with NorESM

For more information, see

Räisänen, P., Kokhanovsky, A., Guyot, G., Jourdan, O., and Nousiainen, T.: Parameterization of single-scattering properties of snow, *The Cryosphere*, **9**, 1277-1301, doi:10.5194/tc-9-1277-2015, 2015.

A fortran code for the parameterization:

https://github.com/praisanen/snow_ssp