Current issues in atmospheric radiative processes

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Overview

- Context: Radiative transfer in atmospheric weather and climate models
- Approximations used in weather and climate models; *which improvements should we aim for?*
- Verifying weather models with observations

Radiative forcing from an *optics* point of view:

“Radiation” in weather and climate modelling is implicitly taken to mean *electromagnetic radiation*.

And God Said

$$\nabla \cdot \vec{D} = \rho_{\text{free}}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{H} = \vec{J}_{\text{free}} + \frac{\partial \vec{D}}{\partial t}$$

and *then* there was light.

Radiative forcing from a *dynamical meteorology* point of view:

$$c_p \frac{DT}{Dt} - \alpha \frac{Dp}{Dt} = J$$

The energy balance equation - from Holton (1992)

Basic state variables of *radiative transfer*

Poynting's vector:

$$\mathbf{S} = \mathbf{E} \times \mathbf{H} \ [W \cdot m^{-2}]$$

Net flux:

$$F = \frac{d^2 E}{dAdt} = F^{-} - F^{+} \ [W \cdot m^{-2}]$$

… or the other way around!

Spectral irradiances (fluxes):

$$F_\lambda = \frac{d^3 E}{dAdtd\lambda} \ [W \cdot m^{-2} nm^{-1}]$$

Spectral radiances (intensities):

$$I_\lambda = \frac{d^4 E}{dAdtd\omega d\lambda \cos(\theta)} \ [W \cdot m^{-2} sr^{-1} nm^{-1}]$$

Basic state variables of *radiative transfer*

Poynting's vector:

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Net flux: ← Main variable in the context of weather & climate models

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Spectral radiances vary in 7 dimensions (ignoring polarisation):

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- 1-3 : Longitude, latitude & height
- 4: Time
- 5: Wavelength
- 6-7: Zenith and azimuthal directions

Radiative transfer assumptions:

- Non-linear optical effects are excluded
- Inelastic scattering is excluced
- Objects are illuminated by quasi-monochromatic parallel beams of light;
- ...
- (Mischenko et al. 2007: "*Radiative transfer, a new look at an old theory*")

The 1D radiative transfer equation for scattered radiance:

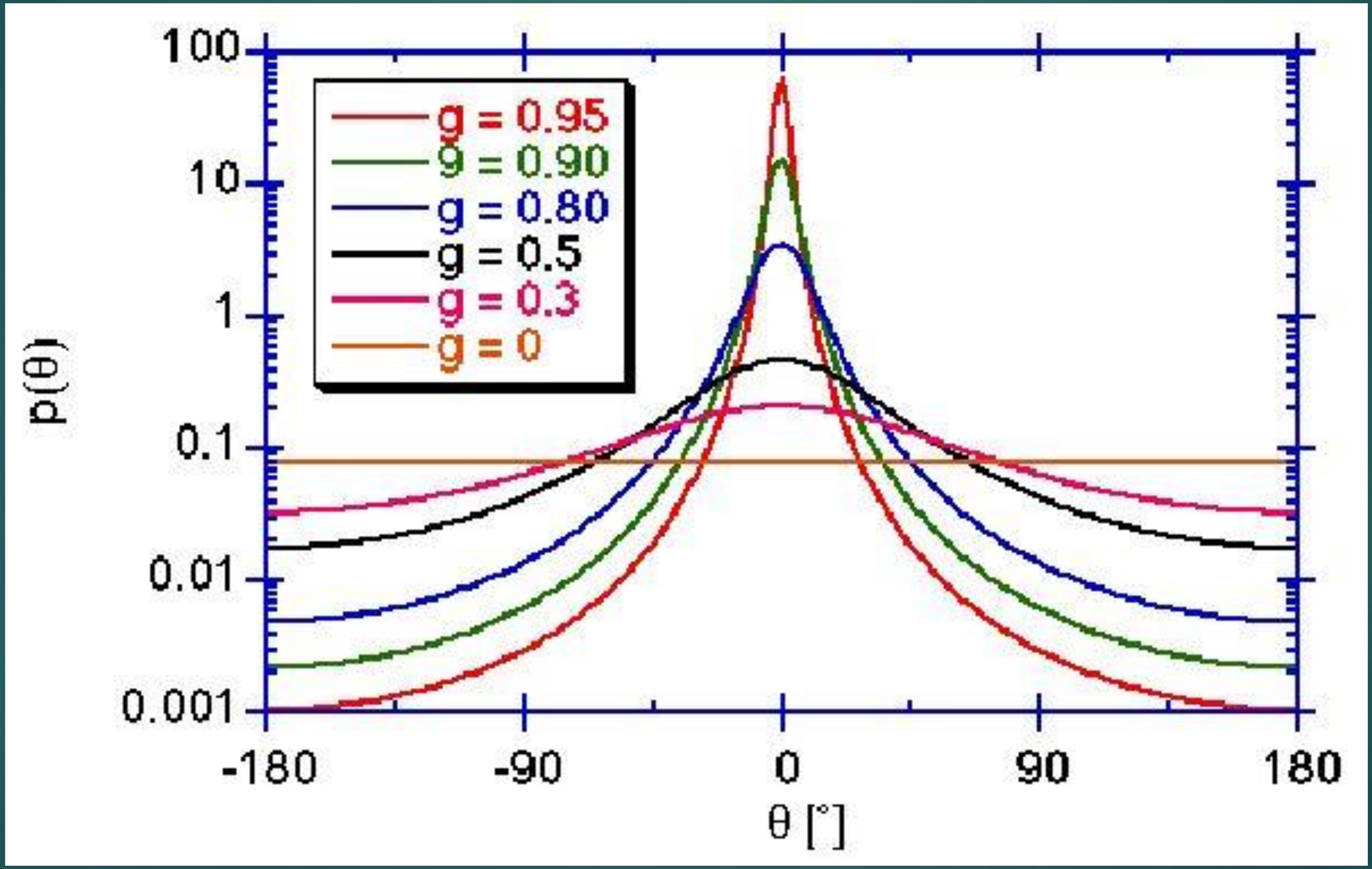
$$\mu \frac{dI_\lambda(\tau,\mu,\phi)}{d\tau} = -I_\lambda(\tau,\mu,\phi) + (1-a)B_\lambda(T;\tau) + \frac{a}{4\pi}\int_{4\pi} d\omega' p(\tau,\mu',\phi')I_\lambda(\tau,\mu,\phi) + S^*_\lambda(\tau,\mu,\phi)$$

On RHS first term: Basic extinction; second term: emission;
third term: multiple scattering; fourth term: solar beam first order scattering.

Inherent optical properties (1)

- τ: Optical depth [-], the integrated extinction;
- a: Single scattering albedo = 1 - emittance [-];
- p: Phase function [-], in practice a function only of the asymmetry factor g (Henyey & Greenstein 1941);
- Lower boundary albedo / BRDF [-].

Henyey-Greenstein phase-functions as a function of the asymmetry factor *g*



2-stream radiative transfer equations (used in atmos. models)

- $\bar{\mu}\frac{dI^{+}(\tau^{*})}{d\tau^{*}} = I^{+}(\tau^{*}) - \frac{a}{2}I^{-}(\tau^{*}) - (1 - a^{*})B$
- $-\bar{\mu}\frac{dI^{-}(\tau^{*})}{d\tau^{*}} = I^{-}(\tau^{*}) - \frac{a}{2}I^{+}(\tau^{*}) - (1 - a^{*})B$
- $\bar{\mu}$ is the mean inclination of the scattered radiances.
- $\bar{\mu} = {}^{1}/_{\sqrt{3}}$ two-point Gaussian quadrature.
- $\bar{\mu}$ = 0.60 IFS delta-Eddington
- $H(\tau^{*}) = 2\pi\alpha[I^{-}(\tau^{*}) + I^{+}(\tau^{*})] - 4\pi\alpha B$ <- Heating rate

Delta-scaled inherent optical properties for the 2-stream equations

$$\tau^* = (1 - ag^2)\tau$$

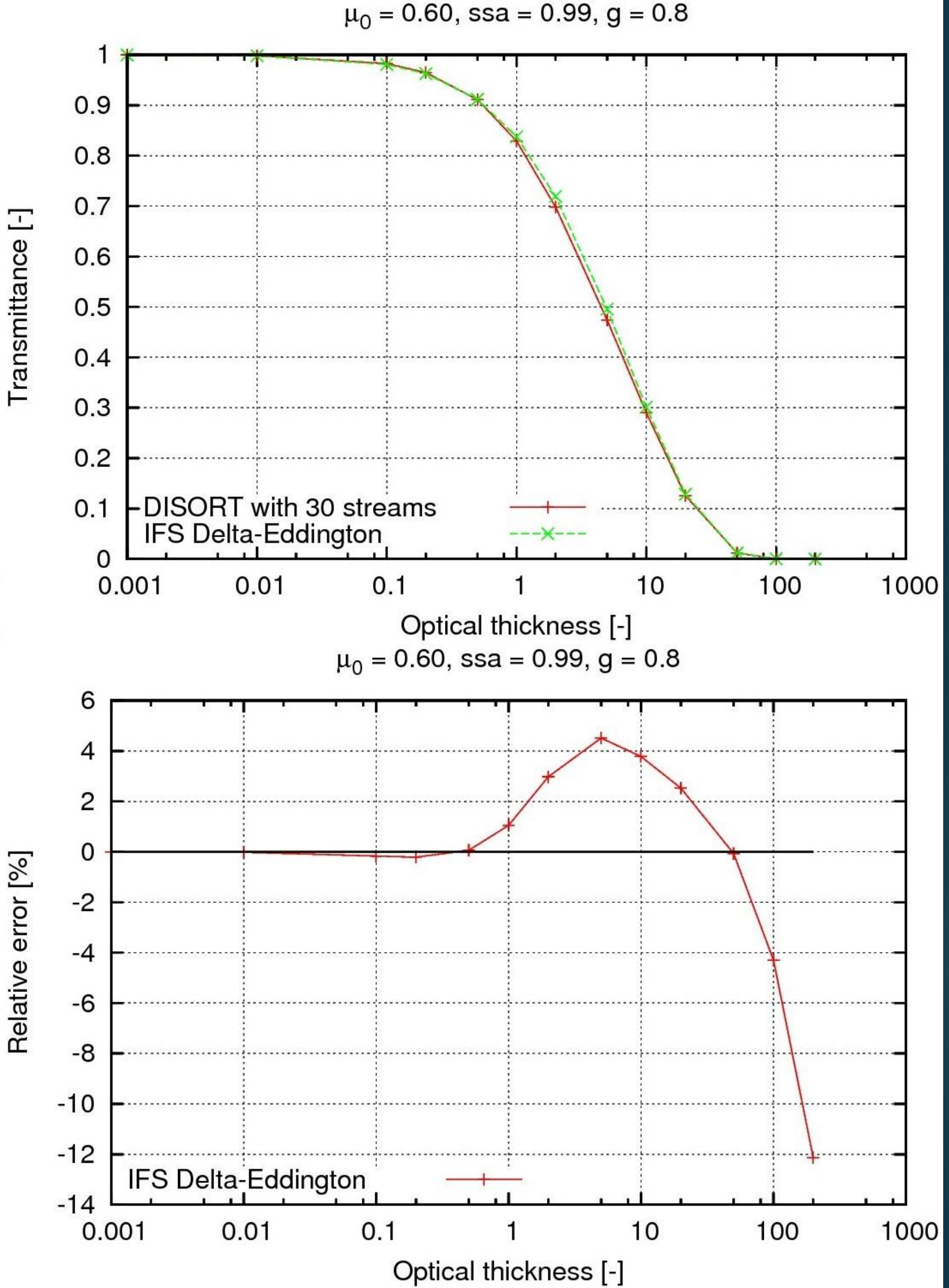
$$a^* = \frac{(1 - g^2)a}{(1 - ag^2)}$$

Scaled optical depth (τ^*) and scaled single scattering albedo (a^*). From Joseph et al. (1976).

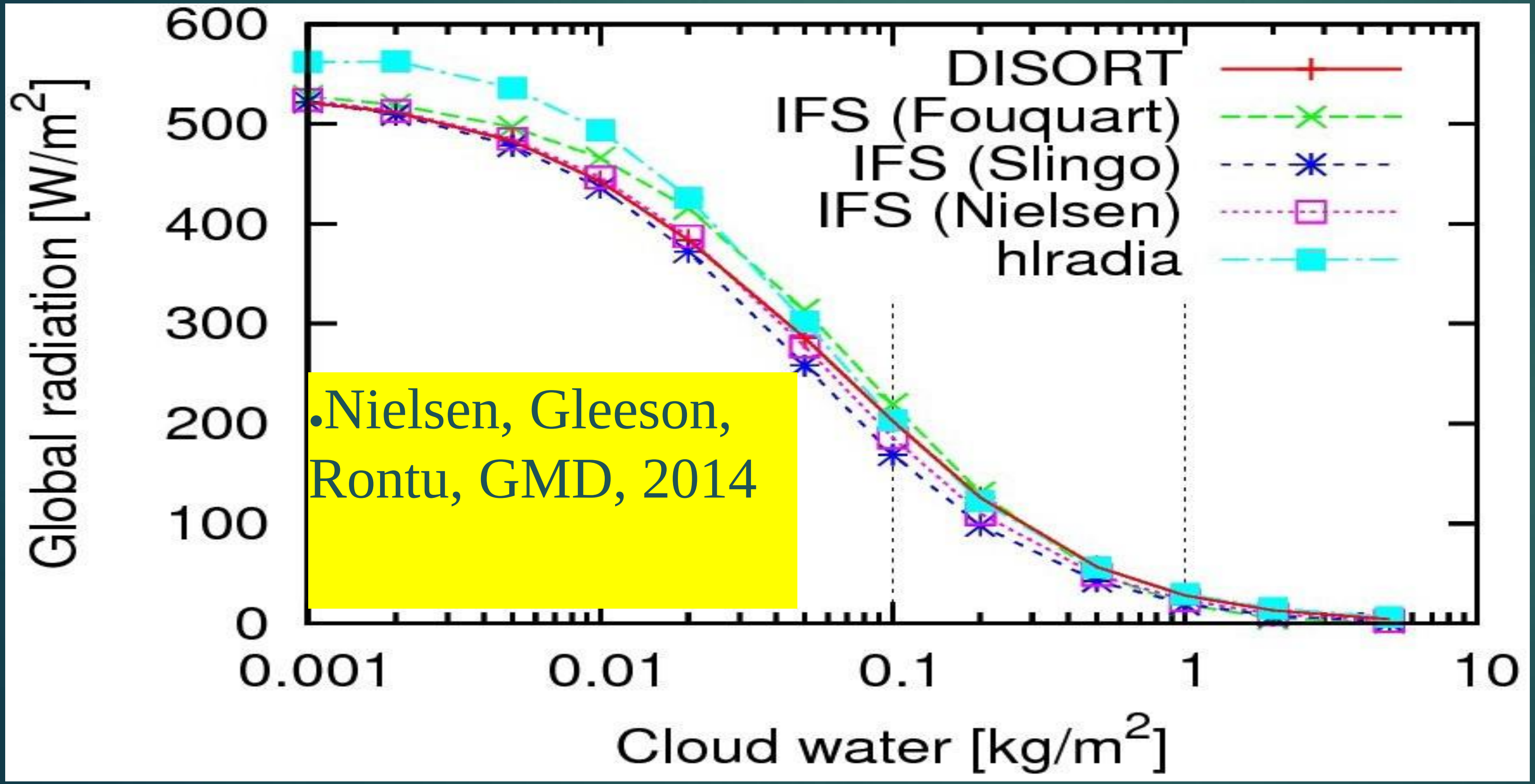
How accurate are the 2-stream equations?

Test of the IFS Delta-Eddington (2-stream) radiative transfer scheme.

Figure from Nielsen, Gleeson and Rontu (2014) in Geosci. Model Dev.

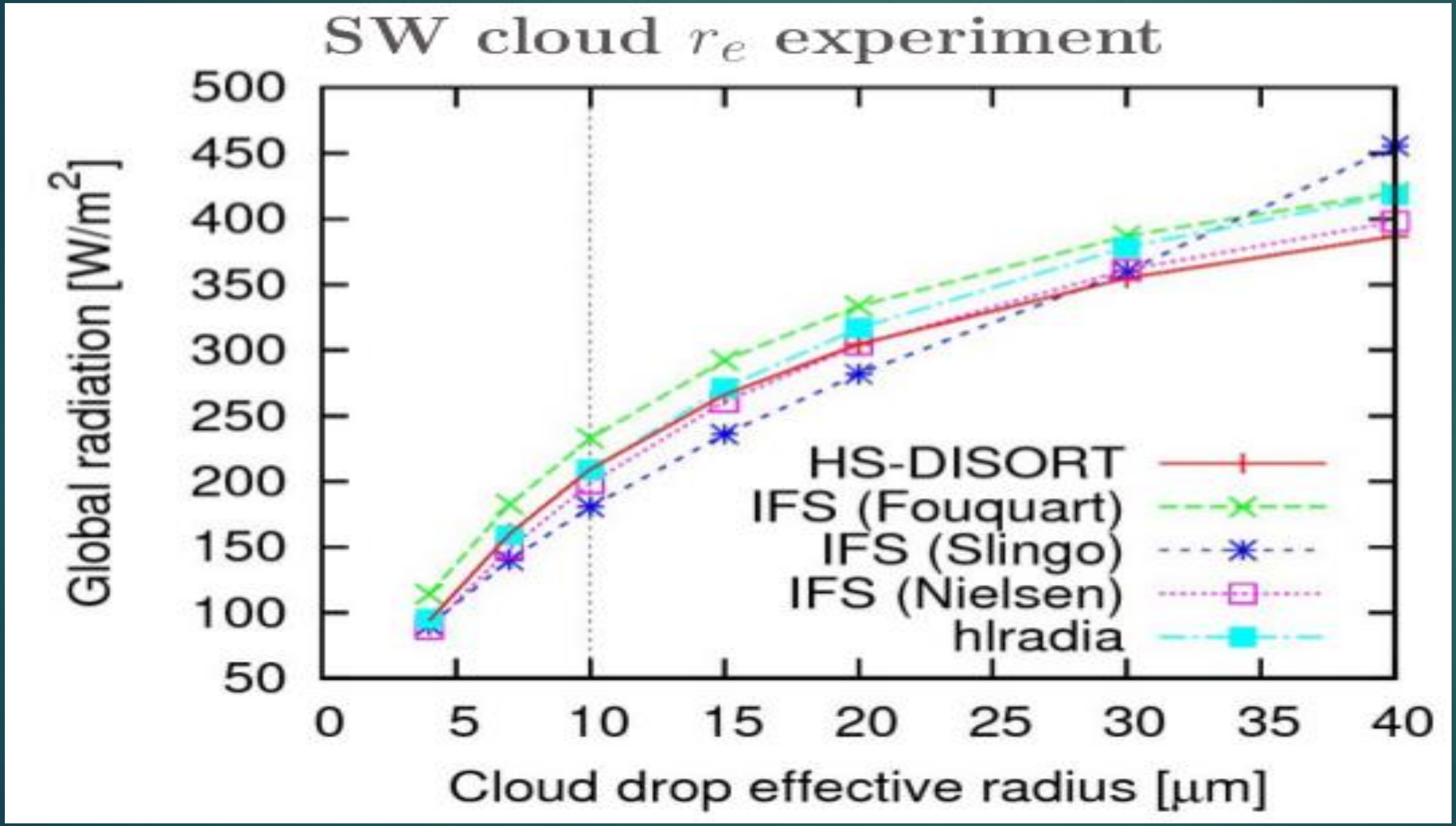


Testing cloud IOP schemes in a weather model vs libRadtran/DISORT



- Importance of accurately describing the optical properties SSA and g in order to get the cloud transmittance correct

Testing cloud IOP schemes in a weather model vs libRadtran/DISORT



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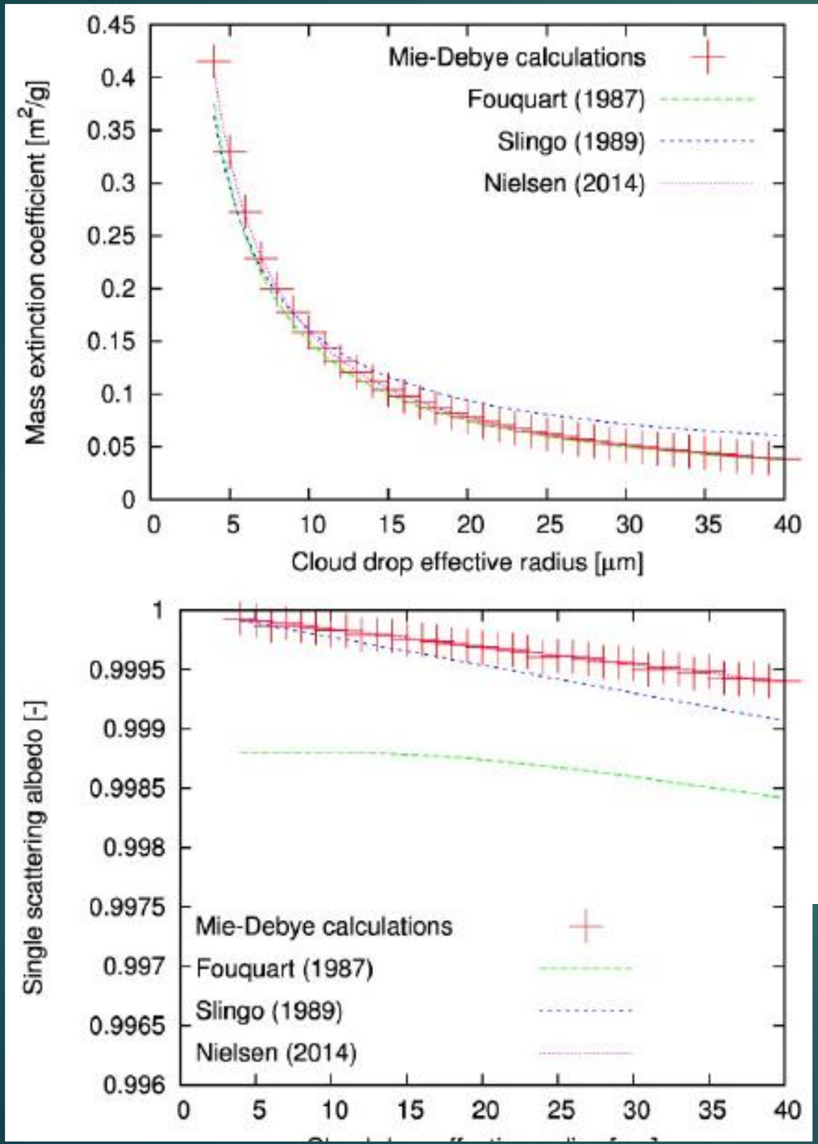
Testing the IFS cloud optical properties



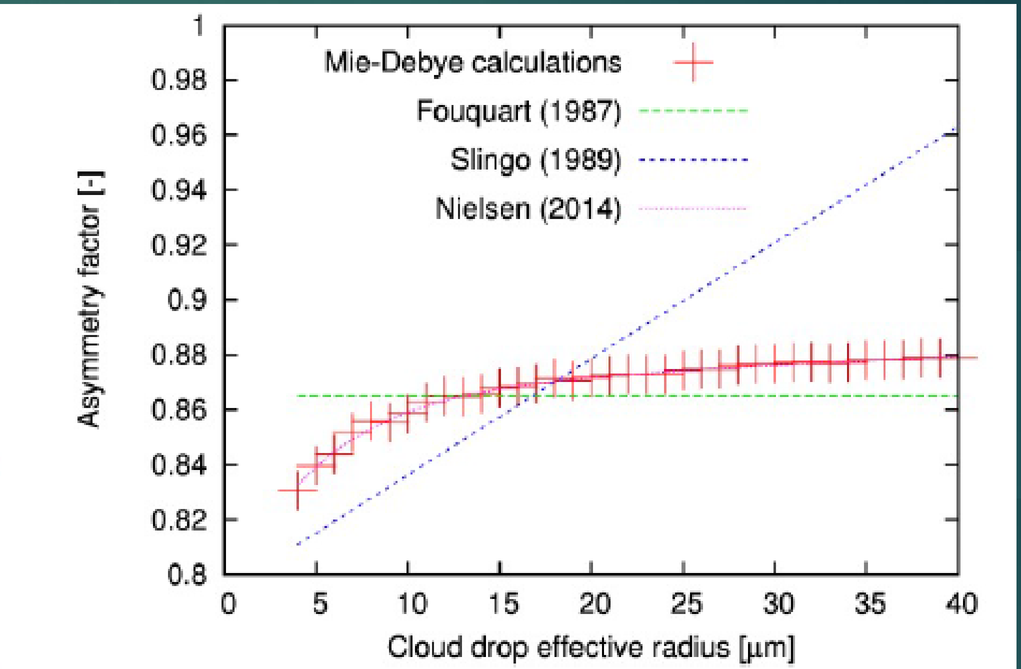
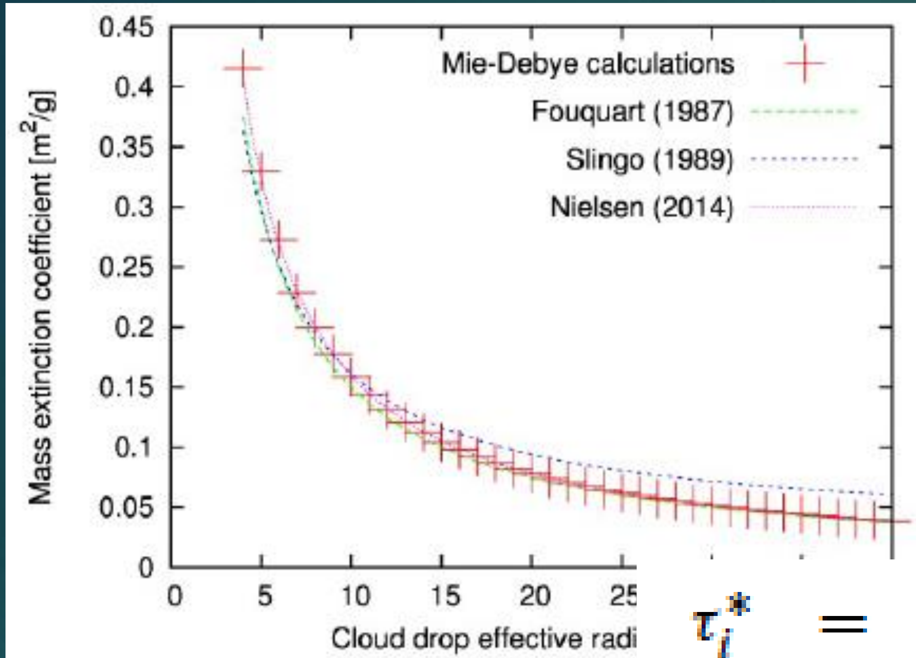
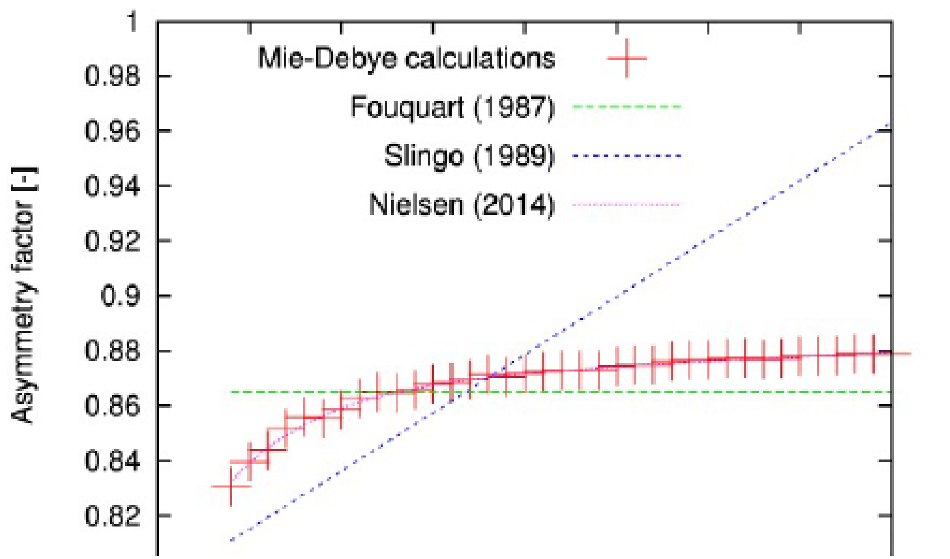
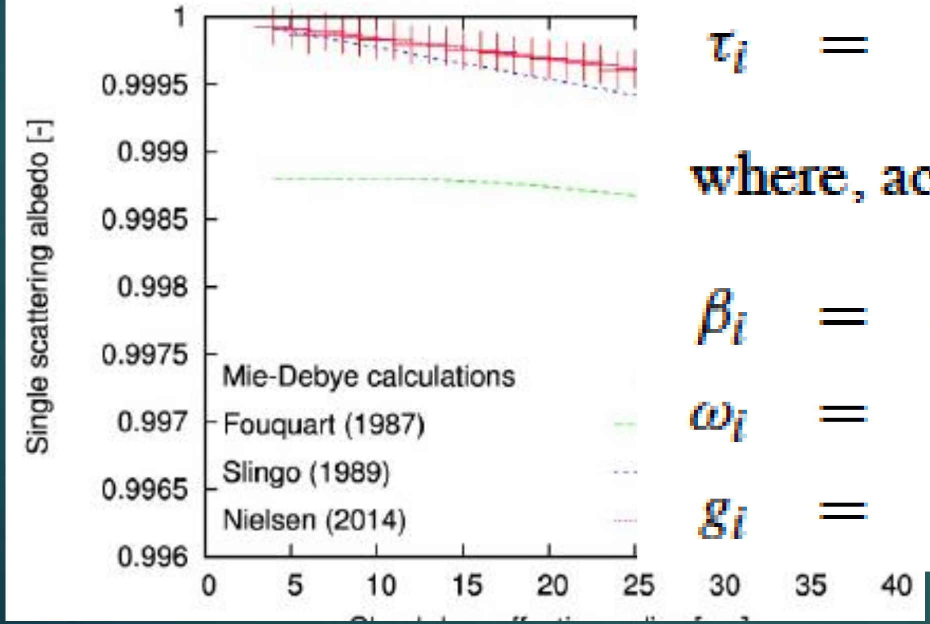


Figure 8. Comparison of mass extinction coefficient parameterisations (upper), single scattering albedo parameterisations (middle) and asymmetry factor parameterisations (lower) for spectral band 4 in the HARMONIE IFS radiation scheme.

Nielsen, Gleeson & Rontu
(Geosci. Model Dev., 7, 1433–1449, 2014.)







$$\tau_i^* = (1 - \omega_i g_i^2)\tau_i \tag{1}$$

$$\tau_i = \beta_i C, \tag{2}$$

where, according to the suggested new scheme,

$$\beta_i = a_i r_{\mathrm{e,liq}}^{-b_i} \tag{3}$$

$$\omega_i = c_i - d_i r_{\mathrm{e,liq}} \tag{4}$$

$$g_i = e_i + f_i r_{\mathrm{e,liq}} - h_i \exp(-j_i r_{\mathrm{e,liq}}). \tag{5}$$

The Padé approximation of optical properties

$$K_{ext} = \frac{p_1 + p_2 r_e + p_3 r_e^2}{1 + p_4 r_e + p_5 r_e^2 + p_6 r_e^3};$$

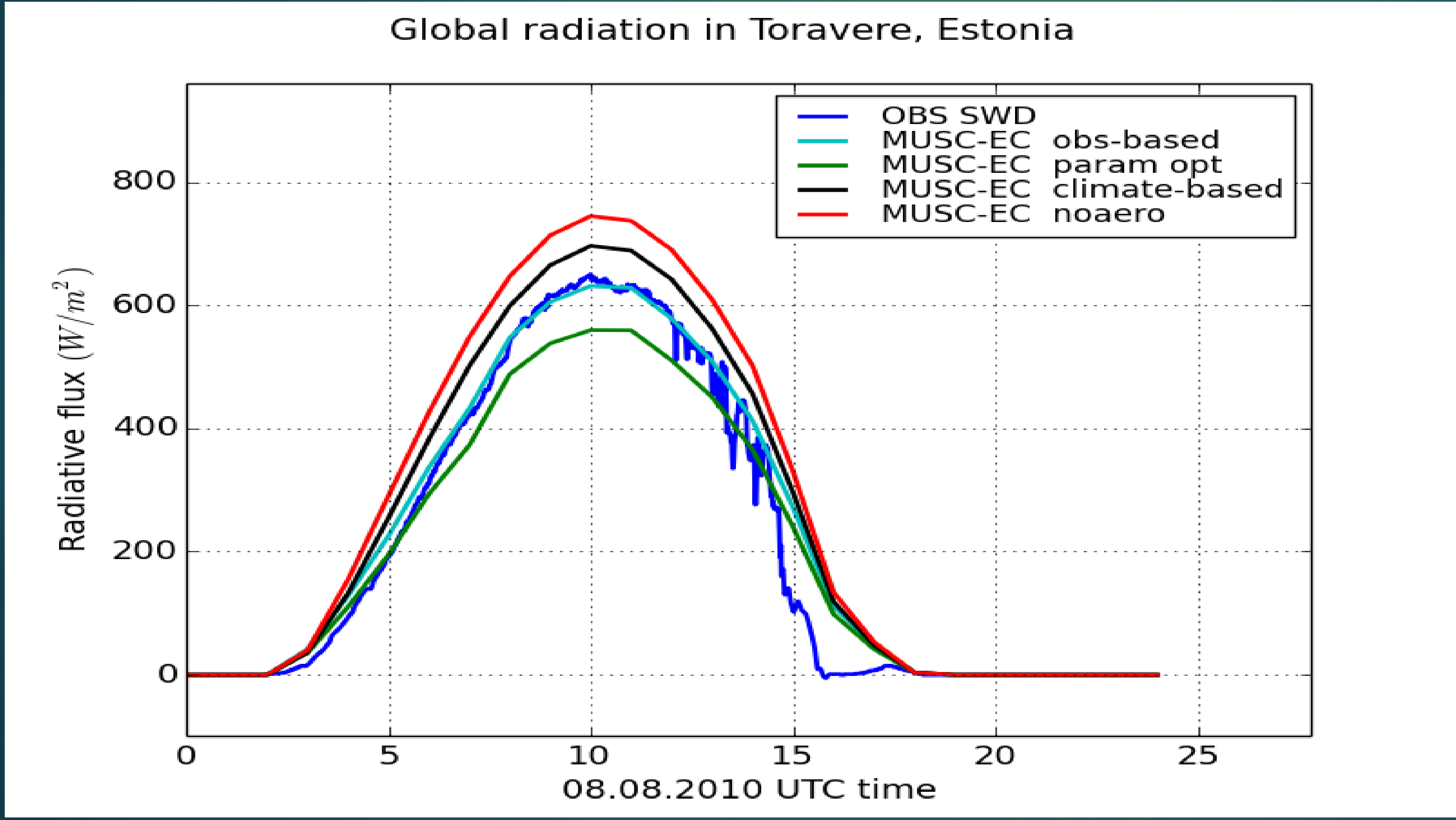
$$\omega = 1 - \frac{p_7 + p_8 r_e + p_9 r_e^2}{1 + p_{10} r_e + p_{11} r_e^2};$$

$$g = \frac{p_{12} + p_{13} r_e + p_{14} r_e^2}{1 + p_{15} r_e + p_{16} r_e^2},$$

(Hogan & Bozzo JAMES, 2018: "The ECRAD scheme")

Clear sky aerosol study

- Russian 2010-08 wildfire case
- MUSC **IFS** global radiation v.s. BSRN observations (Gleeson et al. 2016)



optical properties and AOD 550nm based on observations

parametrized optical properties, observed AOD 550nm land aerosol

parametrized optical properties, climatological AOD 550nm

No aerosol

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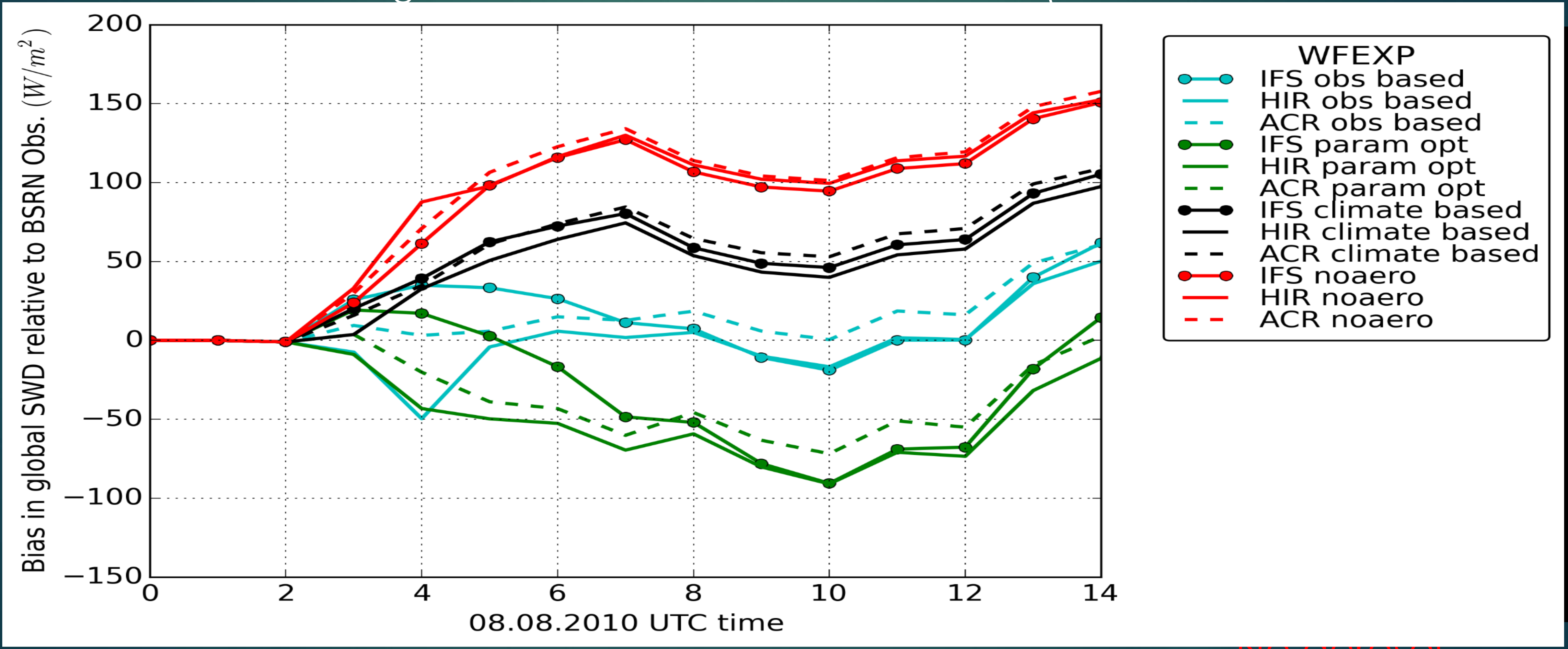


No aerosol

Take-home message 1

Getting the cloud and aerosol inherent optical properties (IOPs) right is important;

the optical depth is not enogh!

Radiative transfer in atmospheric models is 1D. Is that OK?

Intra-column 3D radiation scheme

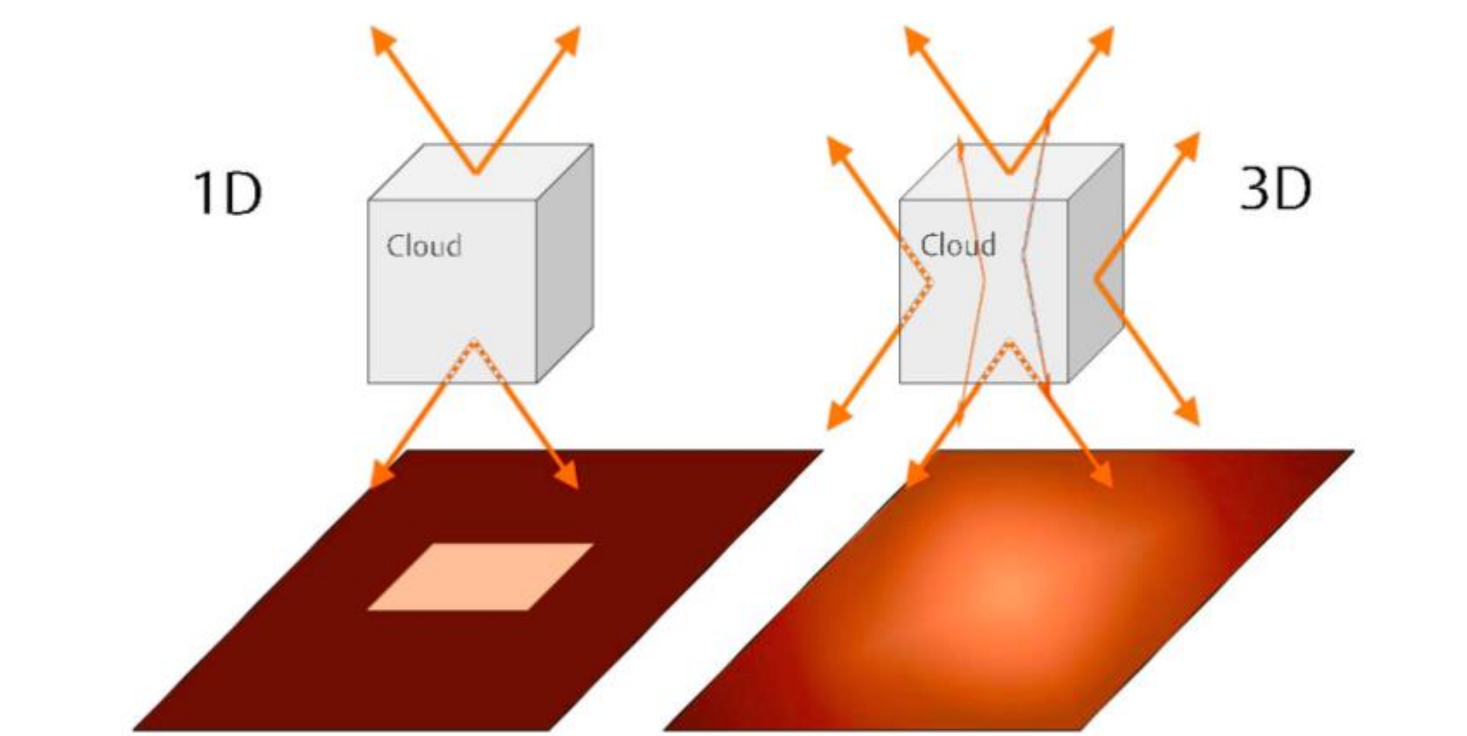
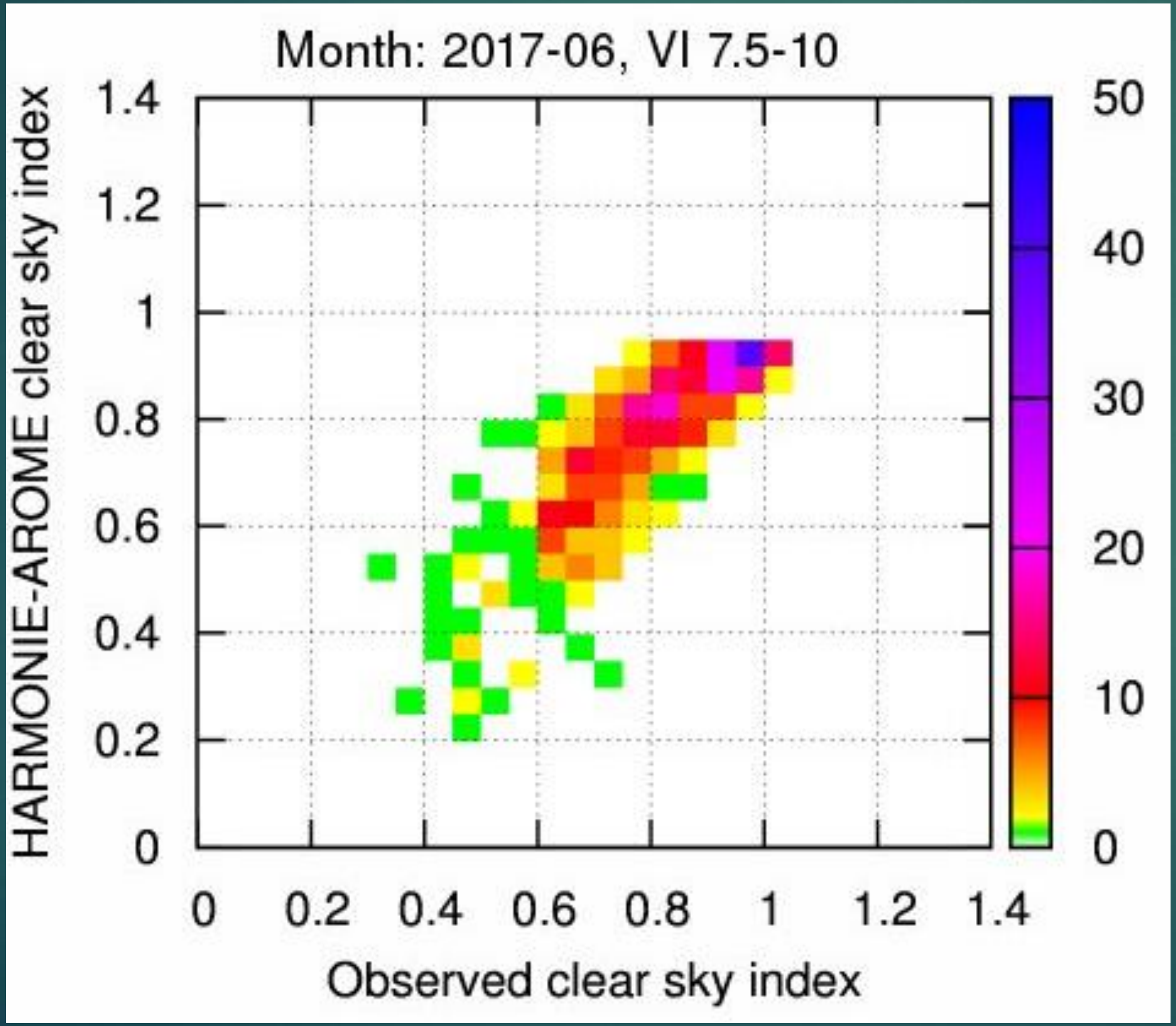


Figure 1. Schematic of outgoing fluxes and their contributions to total downwelling flux in 1-D and 3-D schemes for a cubic cloud. Because of symmetry, the total outward flux *G* through every cloud face is the same, as discussed in section 2. Every arrow symbolizes a flux of *G*/2 through the respective face. At cloud sides, half of the outgoing radiation is at an upward angle, the other half at a downward angle. The distribution of downwelling flux at the surface is shown below: in a 1-D scheme, we only see downwelling flux directly underneath the cloud, while in a 3-D scheme, cloud side fluxes result in a more spread-out distribution as well as in higher total downwelling flux.

Schäfer, Hogan et al. (JGR, 2016, doi:10.1002/2016JD024875: « SPARTACUS »)

What are the "1D errors" in weather models at present?



Nielsen & Gleeson (Atmosphere, 2018)

Variability Index (VI) Stein et al. (2012)

Take-home message 2

Accounting for 3D cloud effects is a key challenge in current radiation algorithm development!

The time dimension

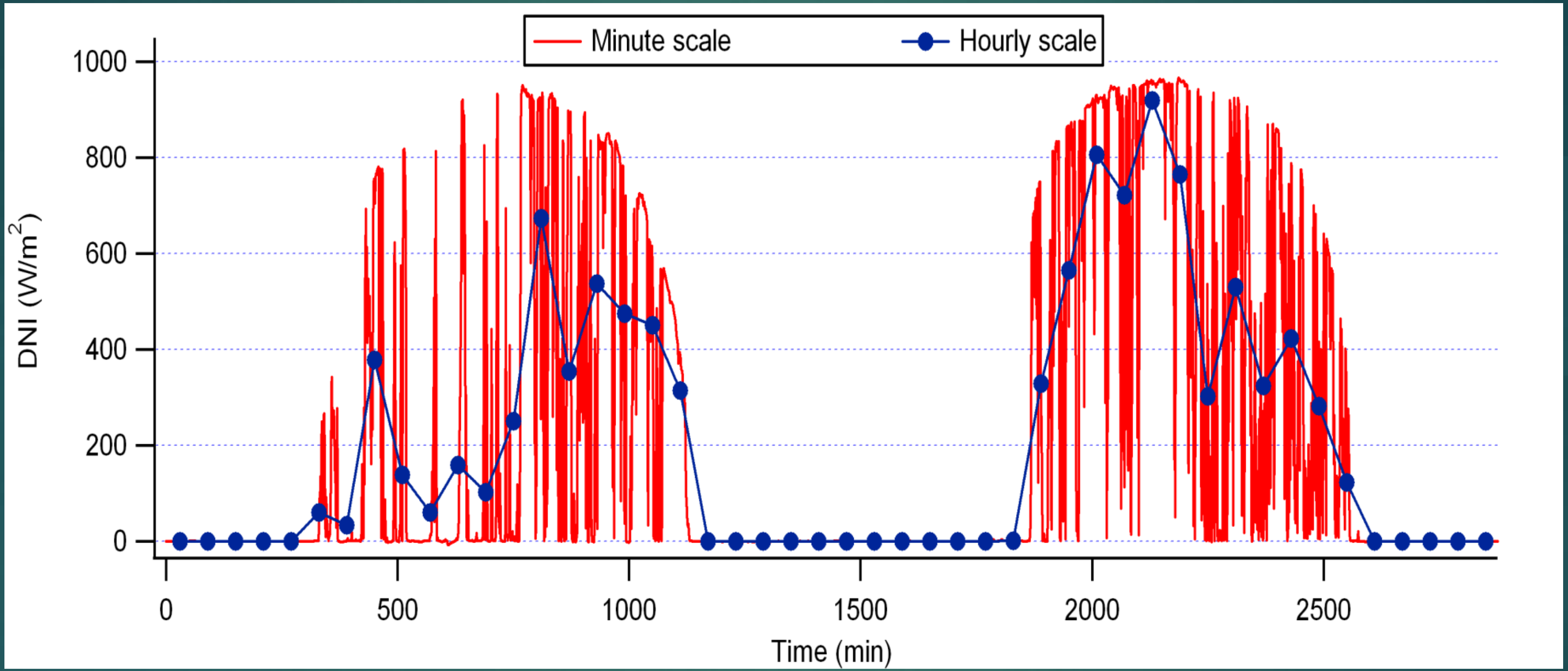
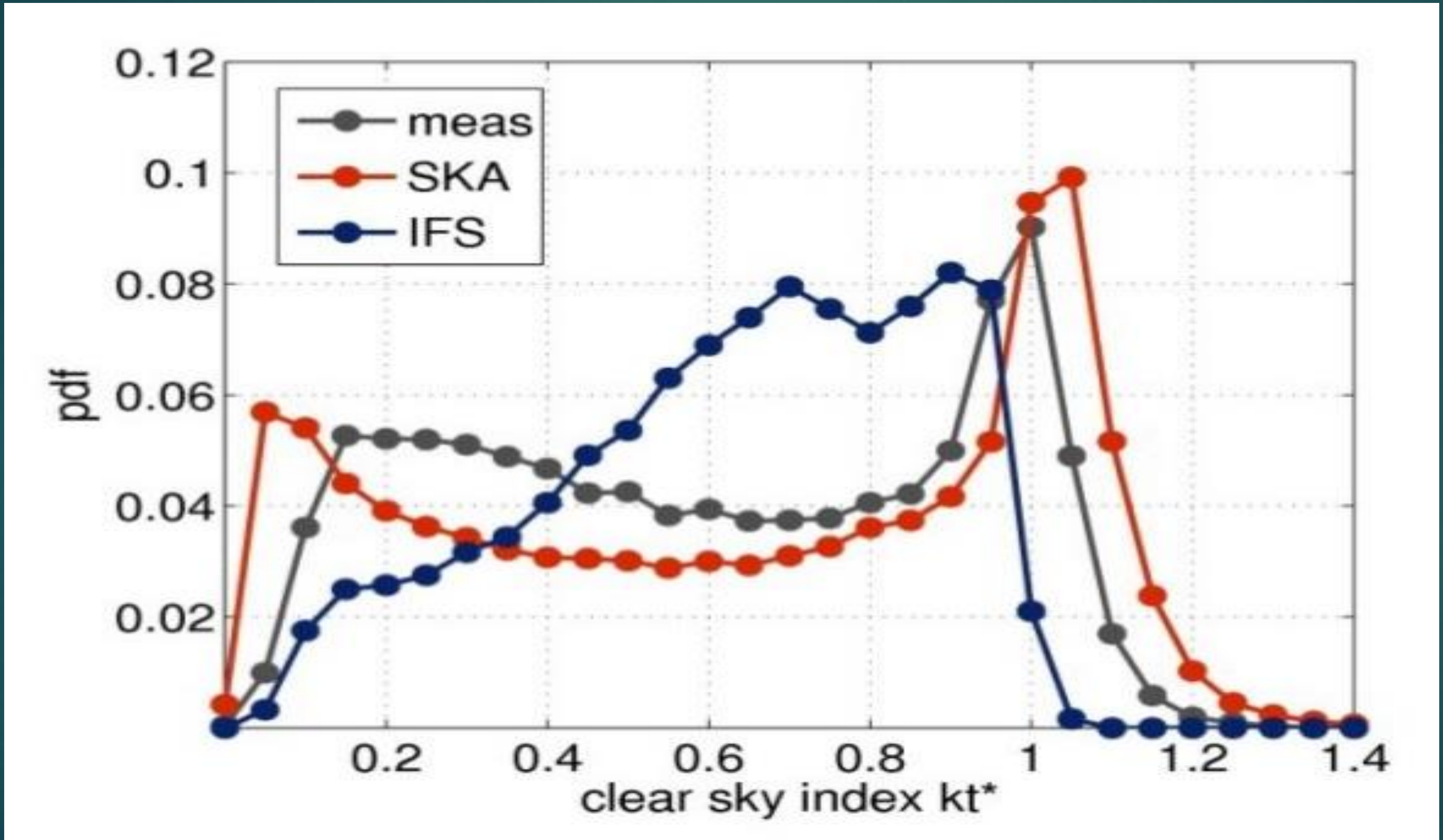


Figure from Mauel Blanco for the SolarPACES *Beyond TMY* project

Nielsen *et al.* (2017) *IEA report available from the SolarPACES Task V website*

CLEAR SKY INDEX FREQUENCY PLOTS FOR IFS AND HIRLAM



From Sengupta et al. (2015) NREL/TP-5D00-63112 Report for IEA SHC Tasks 36 and 46

Figure by E. Lorenz (Fraunhofer ISE)

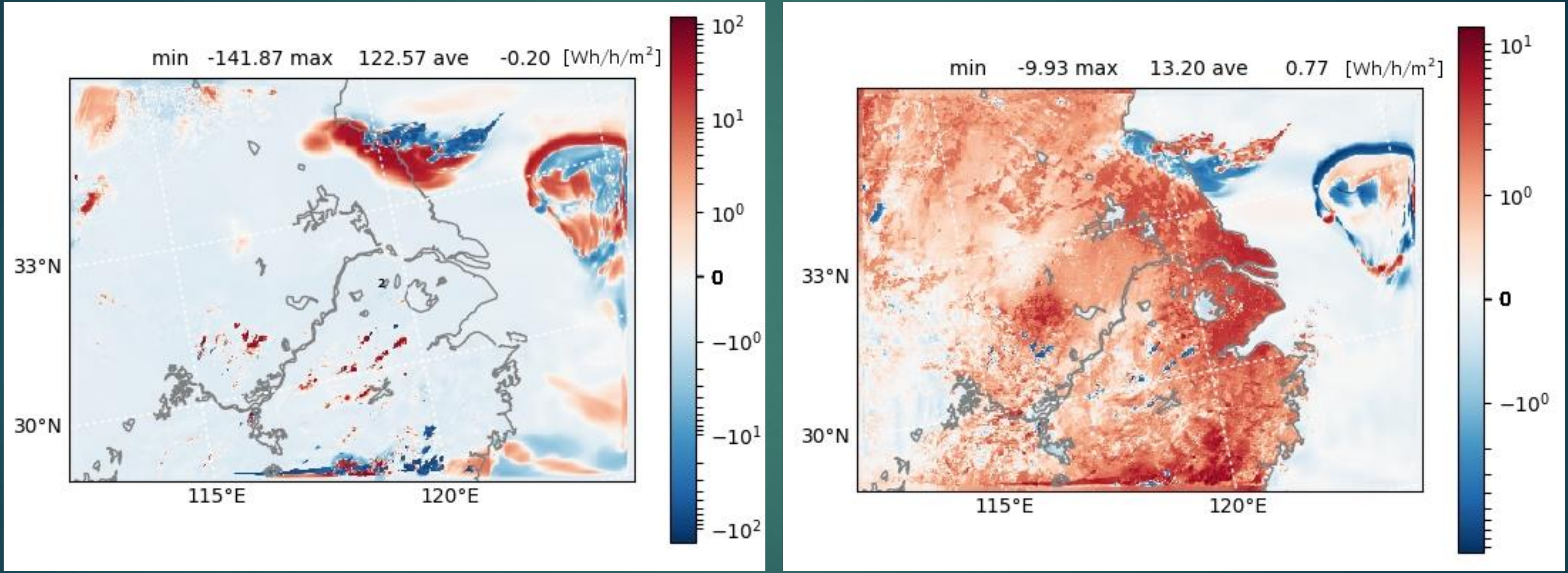
The time dimension

- Radiation is expensive to run!
- Many radiation schemes are run intermittently.
- The IFS radiation scheme is only run <u>once every hour.</u>
- The (IFS) radiation scheme in the HARMONIE-AROME weather model is run <u>once every 15 minutes</u>.
- At the time steps in between only the solar zenith angle and the surface temperature is updated.
- That means that the clouds, gases and aerosols are frozen!

- The ACRANEB2 radiation scheme has been designed to update cloud movements at each time step!
- … at the expense of spectral resolution, however, this is less important in a limited area model.

Clear sky radiation errors from 15 minute intermittency

From Rontu et al. (2017), ALADIN-HIRLAM

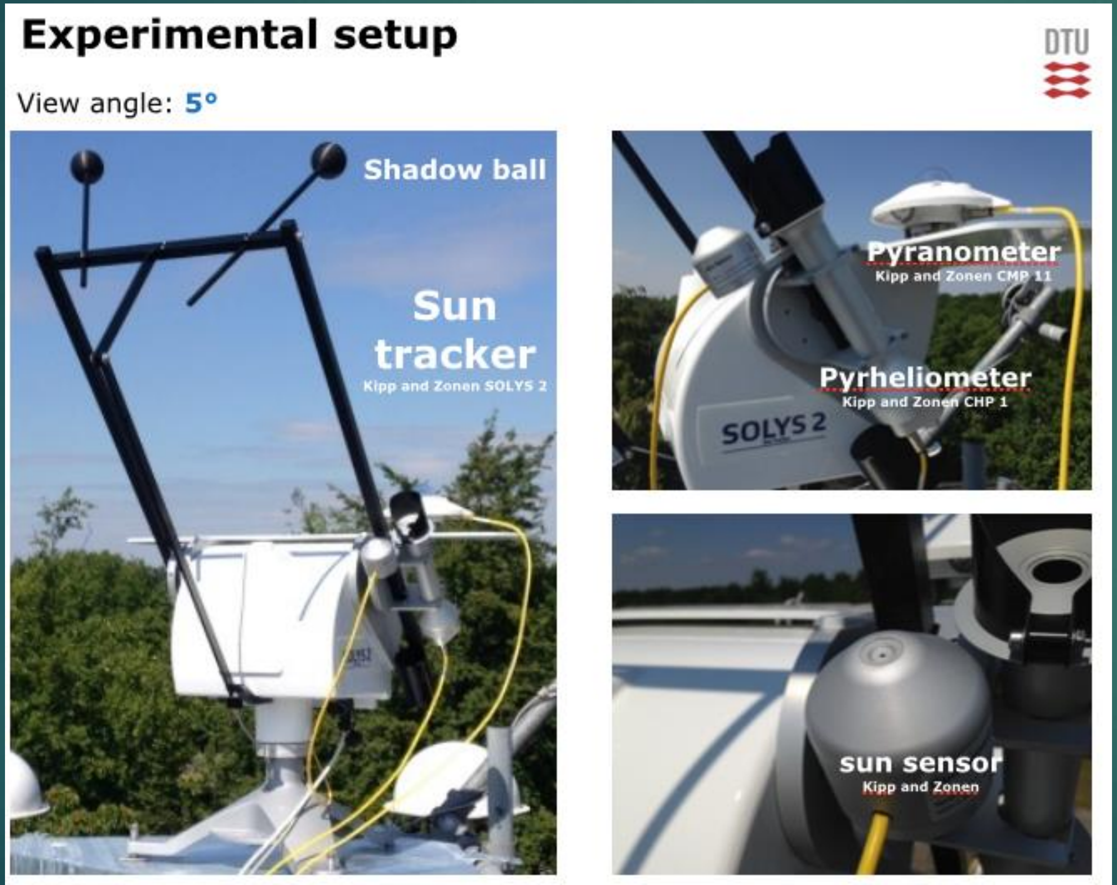


Intermittency errors in average irradiances: SW (left), LW (right) The time interval is 1 hour from 0 to 1 UTC (8-9 AM local time) on the 30th of July 2010. Model: HARMONIE-AROME (cy40h1).

Take-home message 3

Performing radiation computations only intermittently comes at a price!

Model quality control with global, direct and diffuse solar irradiances



See also: Roesch et al. (2011): BSRN QA proceedures &

Sengupta et al. (2017) NREL/TP-5D00-68886, Report for IEA SHC Tasks 46

Figure by J. Dragsted (DTU Civil Engineering)

Thank you for your attention!

Contact: Kristian Pagh Nielsen; kpn@dmi.dk

Summary of take-home messages

1. Cloud and aerosol inherent optical properties (IOPs) right are important
2. 3D cloud effects is a key challenge in current radiation algorithm development!
3. Performing radiation computations only intermittently comes at a price
4. Better ground-based irradiance measurements are needed!