Uncertainty of SW Cloud Radiative Effect in Atmospheric Models Due to the Parameterization of Liquid Cloud Optical Properties

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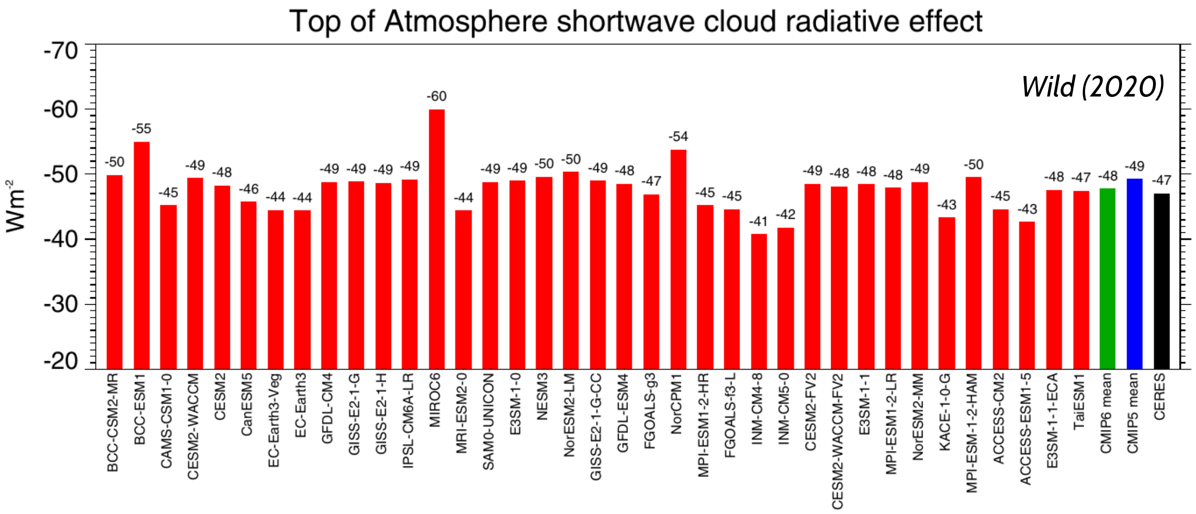
Context

- **SW cloud radiative effect** (CRE) as estimated by CMIP6 models **shows large variability** and has not converged from CMIP5 to CMIP6, despite important tuning on this quantity (*Wild, 2020*)
- **Cloud feedback** uncertainty still **dominates** overall **climate sensitivity uncertainty** (*Zelinka et al., 2020*)



	SW CRE ($W m^{-2}$)		LW CRE ($W m^{-2}$)	
	Spread	Stdev	Spread	Stdev
CMIP5	14.0	3.5	12.6	3.5
CMIP6	19.2	3.6	10.4	2.3

Can the diversity of cloud radiative treatment explain part of this spread?

Context

Active research on the radiative treatment of clouds in atmospheric models …

→ **cloud overlap** assumptions *(Hogan and Illingworth, 2000)*

→ **subgrid heterogeneity** *(Jouhaud et al., 2018)*

→ **ice cloud optical properties** *(Yang et al., 2013)*

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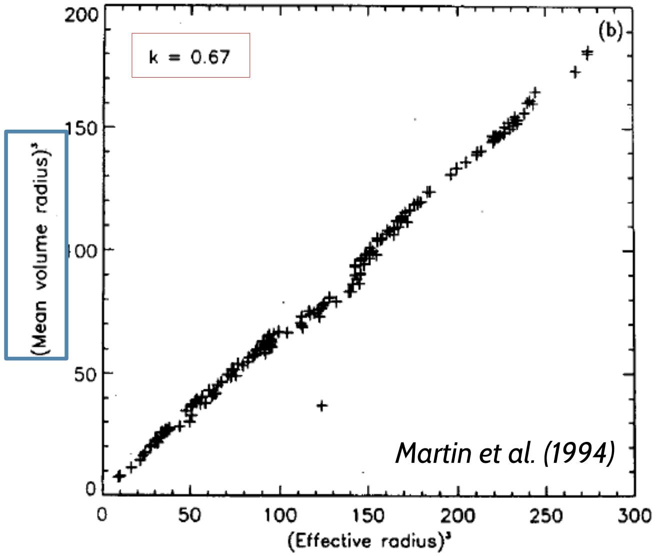
Estimation of cloud optical properties generally includes 2 steps

1) Estimation of r_{eff} from LWC and N

$$r_{\mathrm{eff}} = \left(\frac{1}{k}\right)^{1/3} \left(\frac{3\mathrm{LWC}}{4\rho_w \pi N}\right)^{1/3}$$



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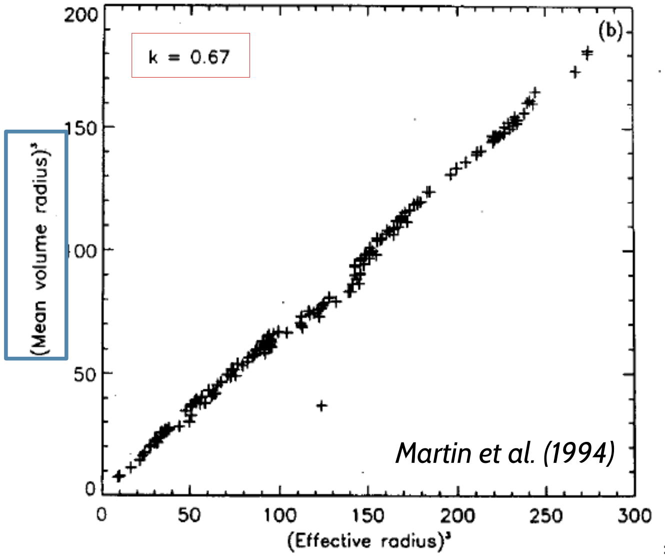
2) Estimation of single scattering properties (SSPs : Q_{ext}, ω, g) from r_{eff}

$$\beta_{\text{ext}}/\text{LWC} = a_1 r_e^{b_1} + c_1,$$

$$1 - \omega = a_2 r_e^{b_2} + c_2,$$

$$g = a_3 r_e^{b_2} + c_3,$$

Hu and Stamnes (1993)

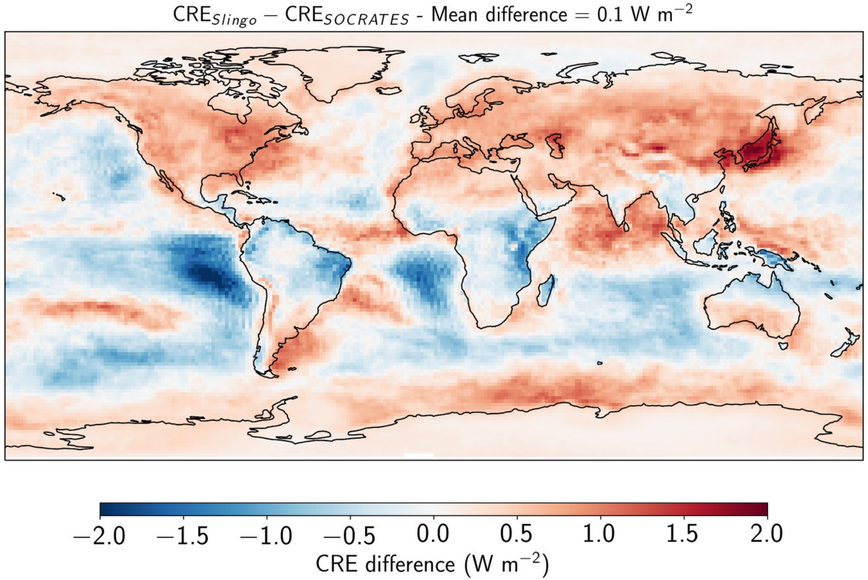


Context

Can SW liquid cloud optical properties explain part of model SW CRE spread?

Diverse cloud optical properties, not always fully documented …

Model name	*k* value	SSPs
IPSL-CM6A *(Madeleine et al., 2020)*	0.75	*Fouquart (1988)*
CNRM-CM6-1 *(Roehrig et al., 2020)*	0.75	*Slingo (1989)*
BCC-CSM2-HR *(Wu et al., 2020)*	0.22 – 0.45 (N = 500 – 50 cm^{-3})	–
MPI-ESM1.2 *(Mauritsen et al., 2019)*	0.67 (l)/0.8 (o)	lognormal distribution
MRI-ESM2-0 *(T. Koshiro, pers. comm.)*	–	*Hu and Stamnes (1993)*
CanAM4 *(Von Salzen et al., 2013)*	0.36	*Dobbie et al., (1999)*



… which can result in different cloud radiative impact

Questions and Objective

Questions

How does the shape of the droplet size distribution (DSD) affect *k*?

Are the SSPs sensitive to the DSD?

Objective

Quantifying the uncertainties in cloud radiative impact due to the uncertainty on the DSD

Methodology

1) Using profiles of LWC and *N*
2) Assuming a DSD shape
3) Computing r_{eff} + SSPs
4) Computing SW cloud radiative impact
5) Comparing various DSDs

Estimating the shape parameter *k*

- *k* can be estimated from the DSD shape parameters

$$r_{\text{eff}} = \frac{M_3}{M_2}$$

$$k = \frac{(M_2)^3}{(M_3)^2}$$

Distribution function	k	r_{eff}
Lognormal	$e^{-3\sigma^2}$	$r_n e^{\frac{3}{2}\sigma^2}$
Gamma	$\frac{\Gamma(\nu+2/\alpha)^3}{\Gamma(\nu)\Gamma(\nu+3/\alpha)^2}$	$r_n \frac{\Gamma(\nu+3/\alpha)^3\Gamma(\nu)}{\Gamma(\nu+2/\alpha)^2}$
Gamma ($\alpha = 1$)	$\frac{(\nu^2+\nu)}{(\nu+2)^2}$	$r_n(\nu+2)$

Estimating the shape parameter *k*

- *k* can be estimated from the DSD shape parameters
- Range of *k* estimated from 94 DSD *(Miles et al., 2000)*
  - σ in [0.15 – 0.78] $\leftrightarrow$ *k* in [0.16 - 0.93]
  - 5.8 factor for k $\leftrightarrow$ 1.8 factor for r_{eff}

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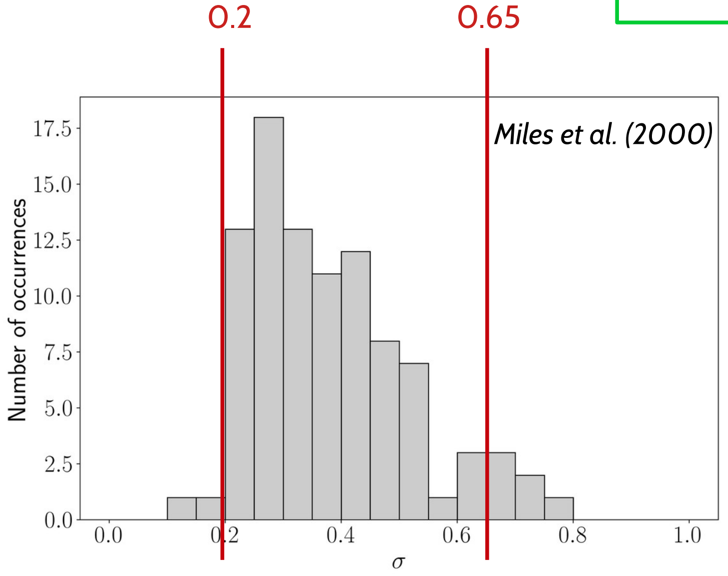
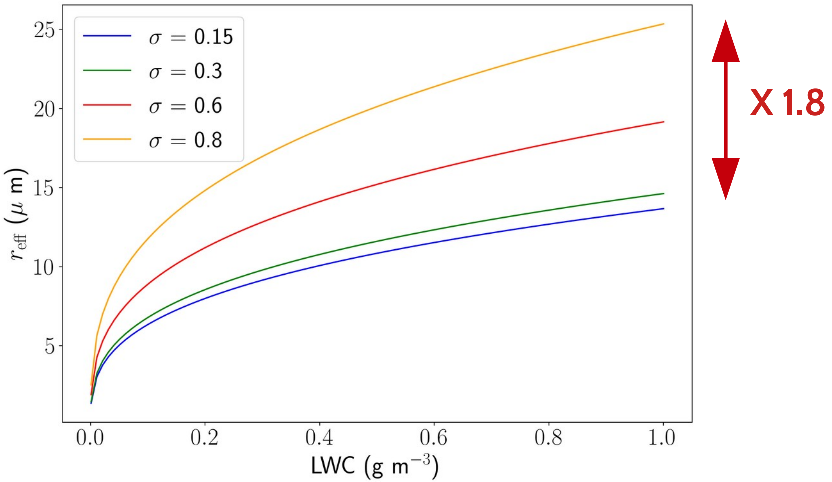
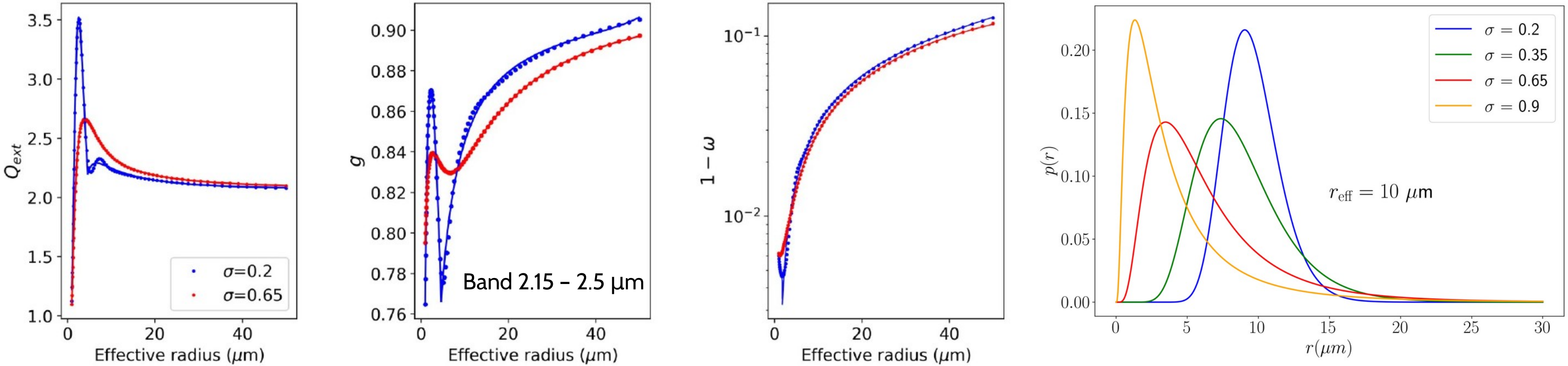




Estimating the SSPs from r_{eff}

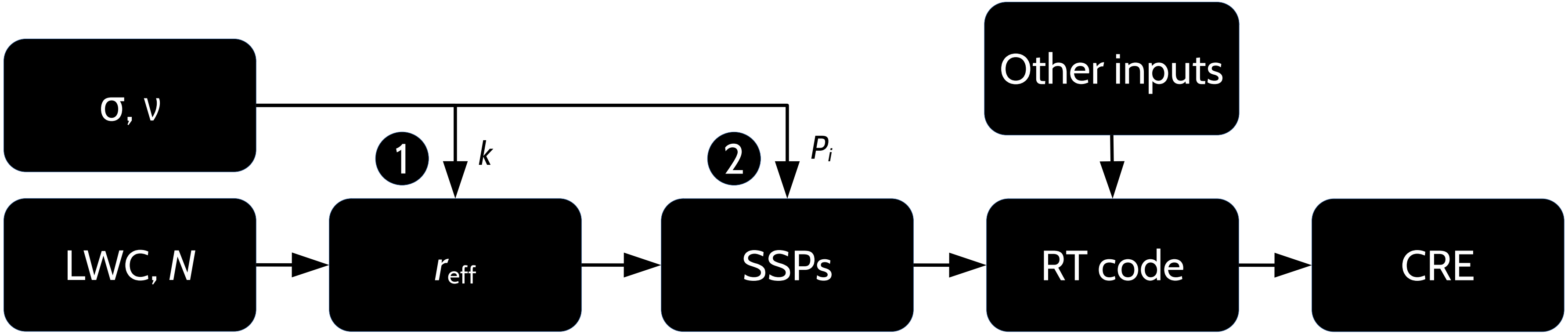
- Various shapes (σ, ν), r_{eff} in 1 - 50 microns (80 values)
- For each r_{eff} DSD reconstructed over 0.01 – 500 µm (10000 points)
- Lorenz-Mie computations for these DSDs
- Two-part fits based on Padé approximants *(Manners et al., 2015)*
- Implemented in ecRad *(Hogan and Bozzo, 2018)*
- SSPs datasets available at *https://github.com/erfanjhn/liq-cloud-opt-param/*

$$Q_{\text{ext}} = \frac{4}{3}\left(\frac{P_1 r_{\text{eff}} + P_2 r_{\text{eff}}^2 + P_3 r_{\text{eff}}^3}{1 + P_4 r_{\text{eff}} + P_5 r_{\text{eff}}^2 + P_6 r_{\text{eff}}^3}\right) \quad g = \frac{P_{12} + P_{13} r_{\text{eff}} + P_{14} r_{\text{eff}}^2}{1 + P_{15} r_{\text{eff}} + P_{16} r_{\text{eff}}^2} \quad \ln(1-\omega) = \ln\left(\frac{P_7 + P_8 r_{\text{eff}} + P_9 r_{\text{eff}}^2}{1 + P_{10} r_{\text{eff}} + P_{11} r_{\text{eff}}^2}\right),$$

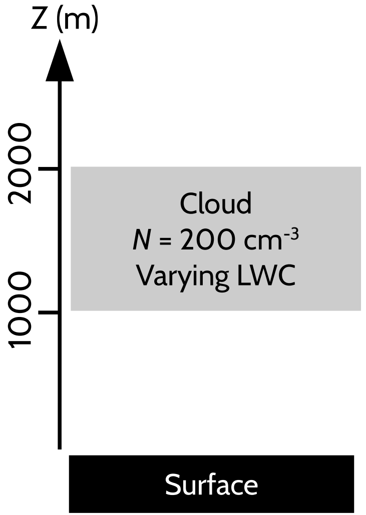


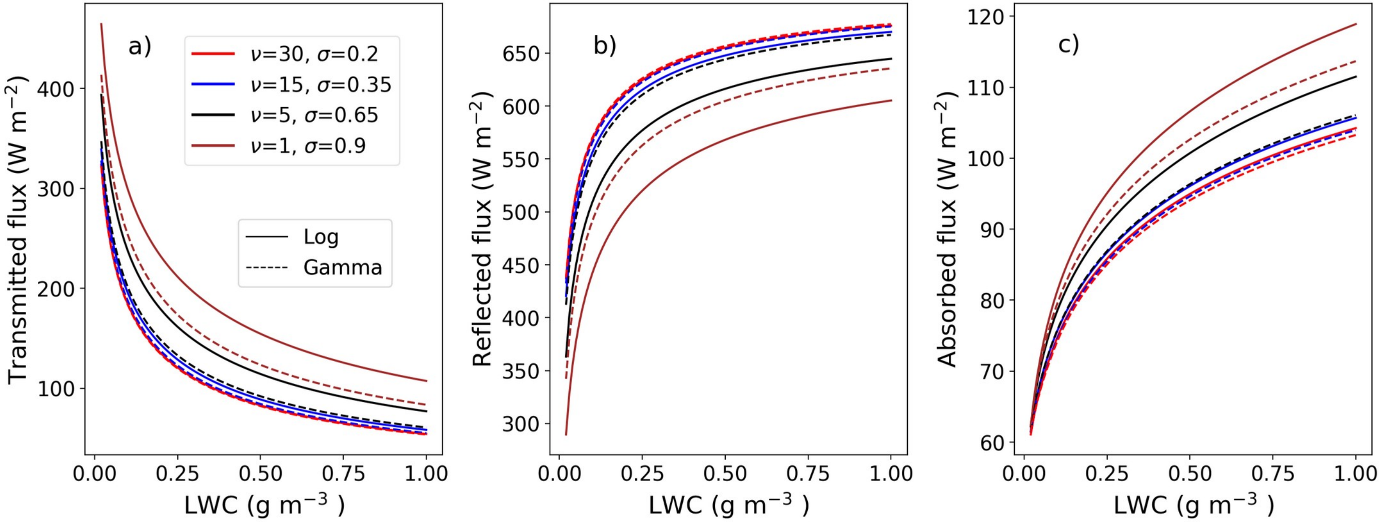
Estimating the cloud radiative effect uncertainty

- Various (LWC, *N*) profiles: ideal, LES, GCM outputs
- Accounting for the impact of DSD shape on:
  - r_{eff} → r_{eff}-uncertainty ❶
  - SSPs → SSPs-uncertainty ❷
  - r_{eff} + SSPs → overall uncertainty
- Computing clear-sky and all-sky surface/TOA fluxes → CRE
- Comparing the CRE for distinct DSD shapes



Results – Ideal profile





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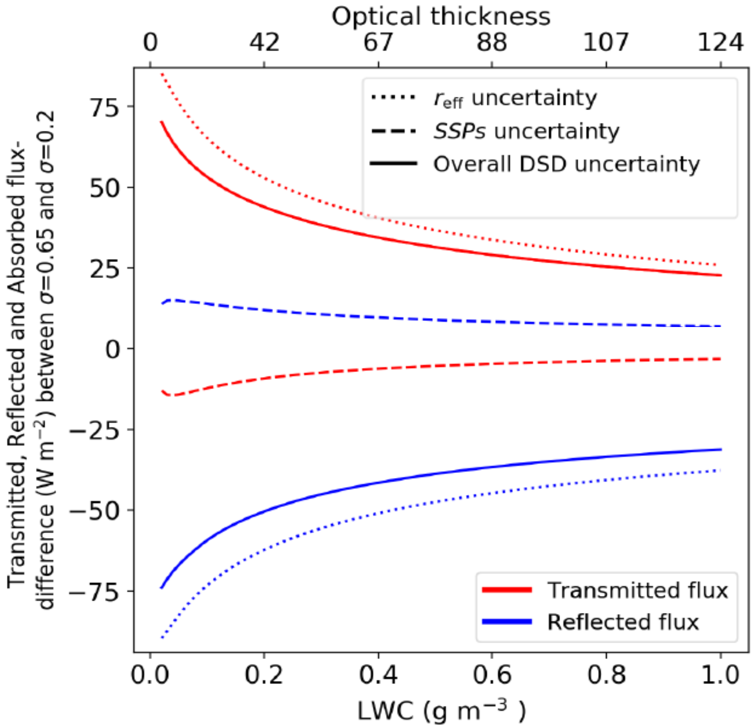
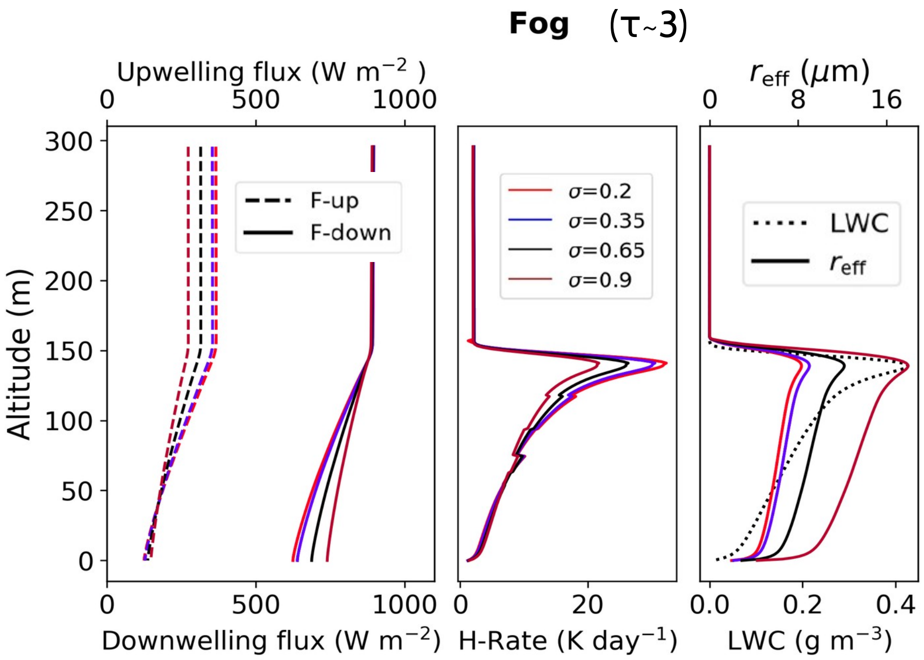


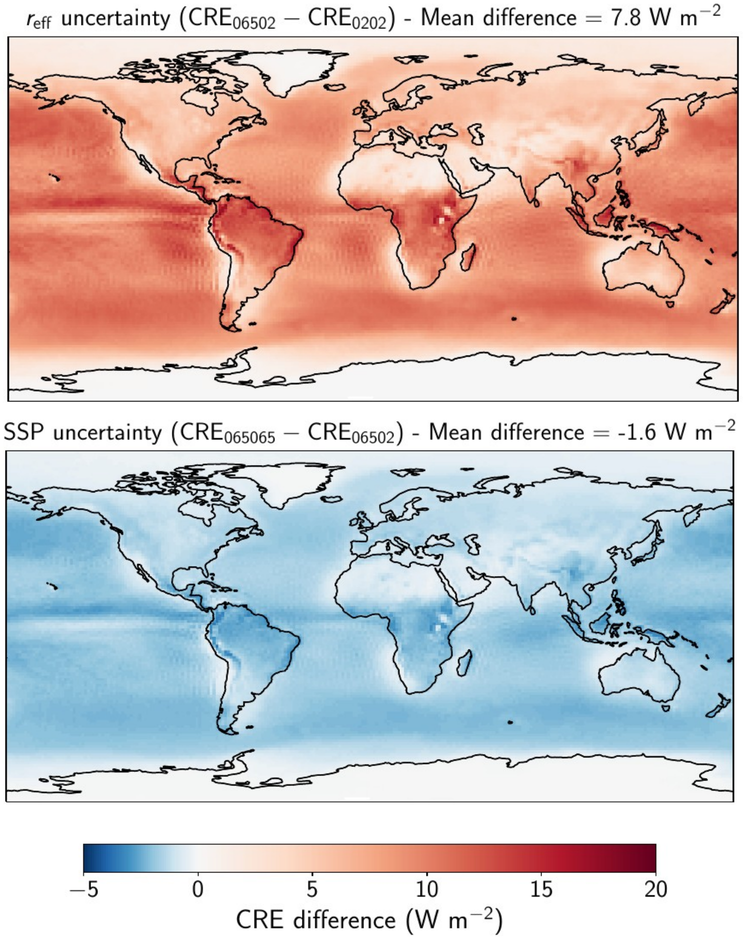
- Uncertainty defined as difference between σ = 0.2 and 0.65 (k = 0.88 and 0.28 → 1.5 factor in r_{eff})
- Overall uncertainty of 20-30% (varies with LWC)
- Uncertainty mostly due to r_{eff} -uncertainty
- SSPs-uncertainty offsets (by ~20%) the r_{eff} -uncertainty

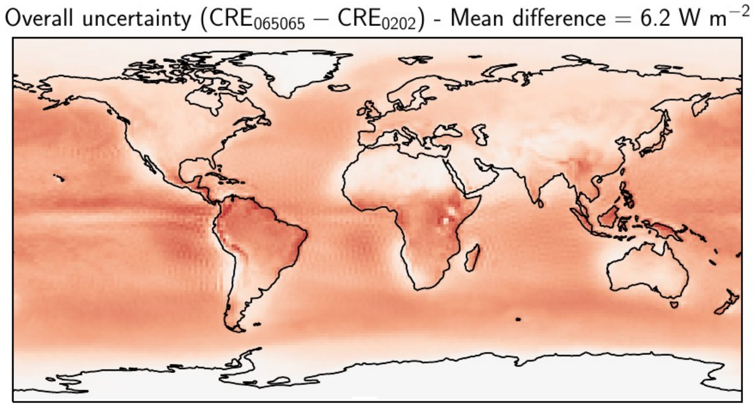
Results – LES fog profile



- Profile obtained from averaged Meso-NH *(Lac et al., 2018)* LES cloudy columns *(Ducongé et al., 2020)*
- Uncertainties on fluxes similar to ideal profile
  - r_{eff} -uncertainty dominates
  - offset by SSPs-uncertainty
- 20% uncertainty on heating rates

Results – GCM outputs





- 5 years of CNRM-CM6-1 3-hourly *amip* simulation
- SW CRE overall uncertainty of 13% (16.5 r_{eff} – 3.5 SSPs)

Conclusions and perspectives

Take-home messages

- DSD should not be overlooked in radiative codes
  - *k* spans a large range
  - *k* could be parameterized *(Peng and Lohmann, 2003; Liu et al., 2006)*
  - changing *k* can significantly alter the Earth radiative budget
- DSD impact on r_{eff} much more critical than on SSPs
- Spectral averaging also has to be treated carefully (impact on absorbed radiation)
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Next steps

- What value(s) of *k* should be used?
- Online implementation in Meso-NH and AROME *(Seity et al., 2011)* models
  - → feedbacks and couplings allowed
  - → consistency with microphysical schemes
- Extension to the LW (and to ice particles)


Thank you for your attention

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