Global impact of 3D cloud-radiation interactions and importance of cloud geometry

Sophia Schäfer[1,2], Robin Hogan[3,4], Carolin Klinger[1], Mark Fielding[3], Najda Villefranque[5,6], Howard Barker[7]

[1]Ludwig-Maximilians-University Munich [2]Deutscher Wetterdienst [3]European Centre for Medium-Range Weather Forecasts [4]University of Reading
[5]CNRM, Université de Toulouse, Météo-France, CNRS [6]LAPLACE, Université de Toulouse, CNRS [7]Environment and Climate Change Canada

1) 3D cloud-radiation effects

3D Cloud-radiation effects

- **Reality:** Radiation in multiple directions interacts with complex clouds
- **Global models use 1D** schemes - radiation only moves vertically; **inhomogeneity / overlap** parametrised approximately
- Local **1D errors** of -25% to +100% in shortwave or up to 40% in longwave cloud radiative effect (CRE)
- Errors in heating rate profiles → in cloud development

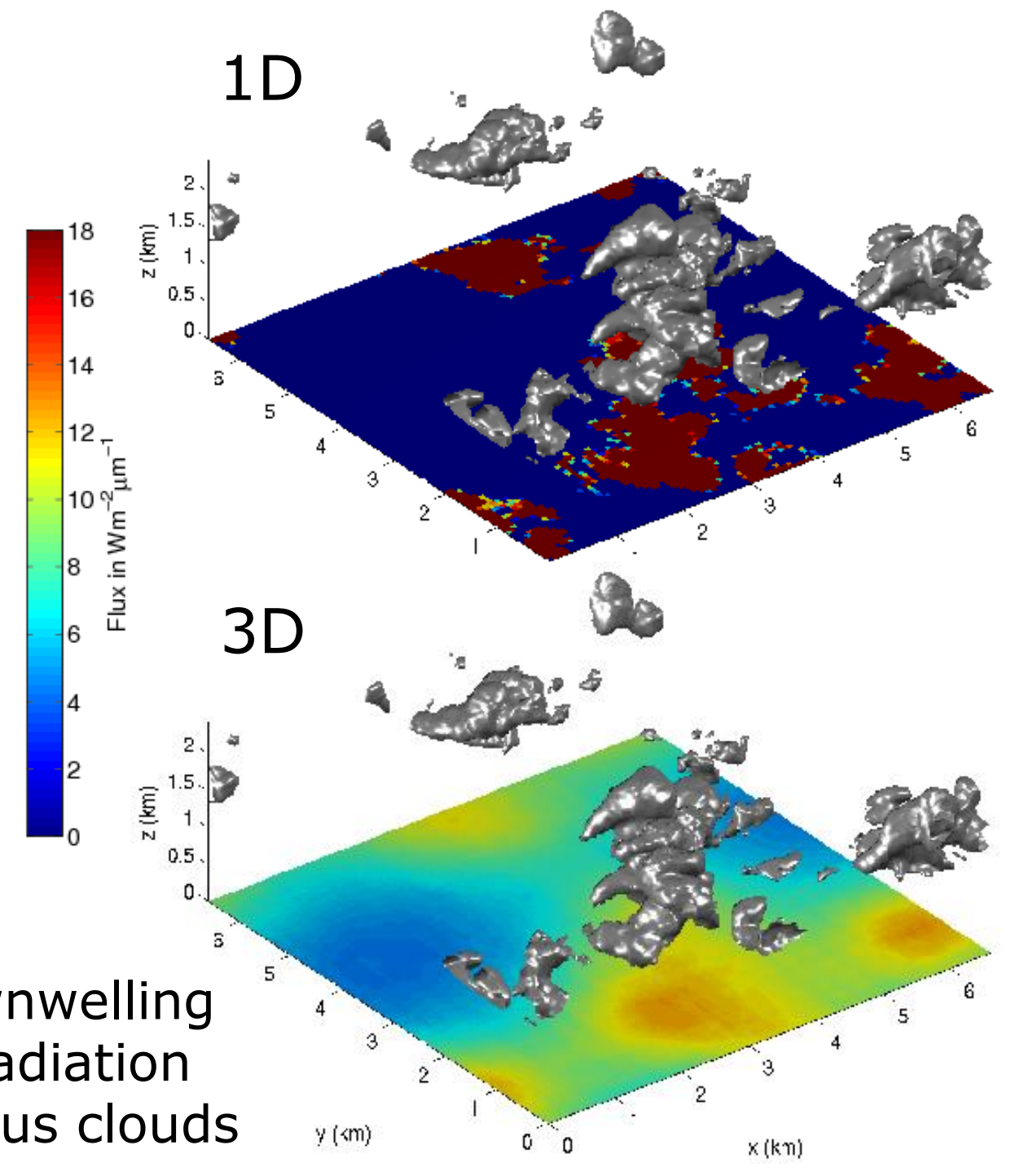


Fig. 1: Downwelling longwave radiation from cumulus clouds

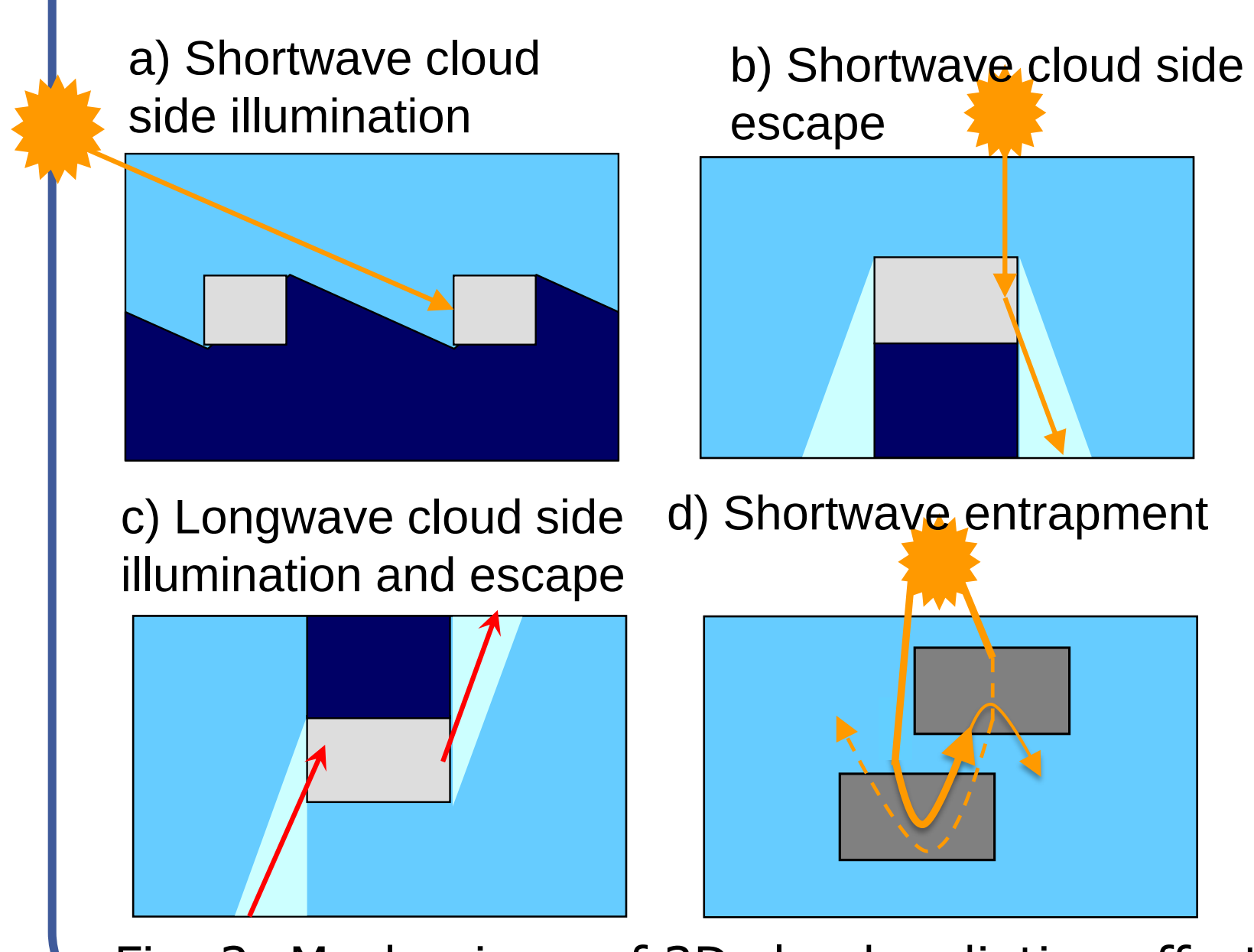


Fig. 2: Mechanisms of 3D cloud-radiation effects.

Physical mechanisms

- **Shortwave cloud side illumination** increases cloud reflectivity, **cloud side escape** decreases cloud reflectivity
- **Longwave cloud side illumination and escape** increase cloud warming effect
- **Shortwave entrapment** decreases cloud reflectivity

2) ecRad radiation scheme, 3D SPARTACUS solver

ecRad (Hogan & Bozzo 2018): New modular ECMWF radiation scheme

- Gas optics: RRTM-G (Iacono et al. 2008)
- Aerosol: variable species number / properties
- **Cloud optics - liquid:** SOCRATES (MetOffice)
  ice: Fu 1996, 1998 / Yi et al. 2013 / Baran et al. 2014
- **Cloud inhomogeneity:** treated as stochastic subcolumns (McICA solver) or two cloudy regions (Tripleclouds / SPARTACUS; Shonk & Hogan, 2008)
- **Solvers:** McICA (Pincus et al. 2003) / Tripleclouds / SPARTACUS: SPeedy Algorithm for Radiative TrAnsfer through CloUd Sides (Hogan et al. 2016):
  - Only scheme to treat 3D radiative effects in global model
  - **Cloud side transfer** incorporated as gain/loss terms in1D scheme ∝ **cloud edge length;** couple clear/cloudy regions
  - **Geometry parameters:** cloud scale, fractional standard deviation of cloud water
  - **Entrapment:** estimate horizontal path x
  - **Cost** ca. 4 x cost of 1D solvers, $10^4 - 10^7$ x cheaper than full 3D calculations

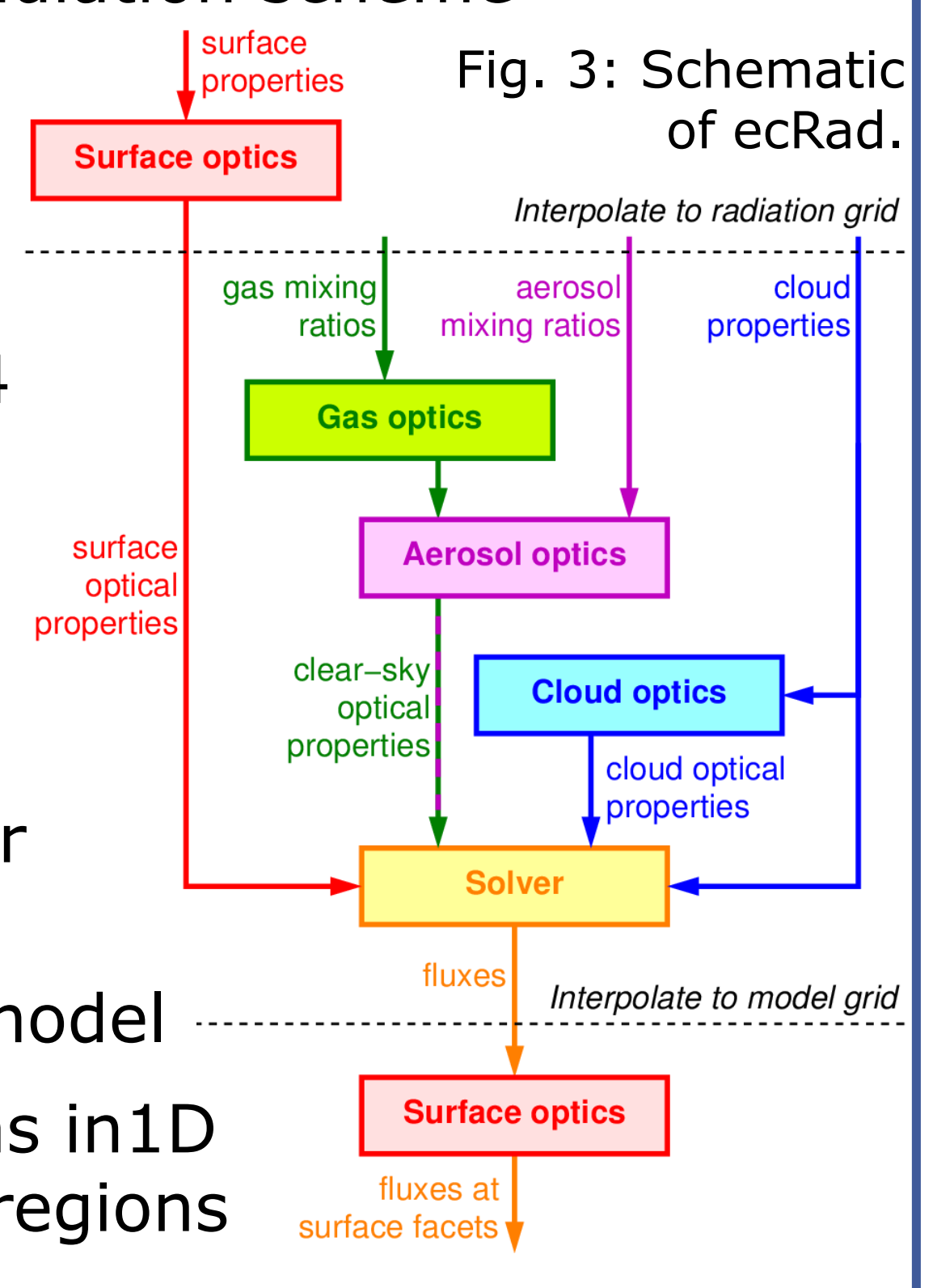


Fig. 3: Schematic of ecRad.

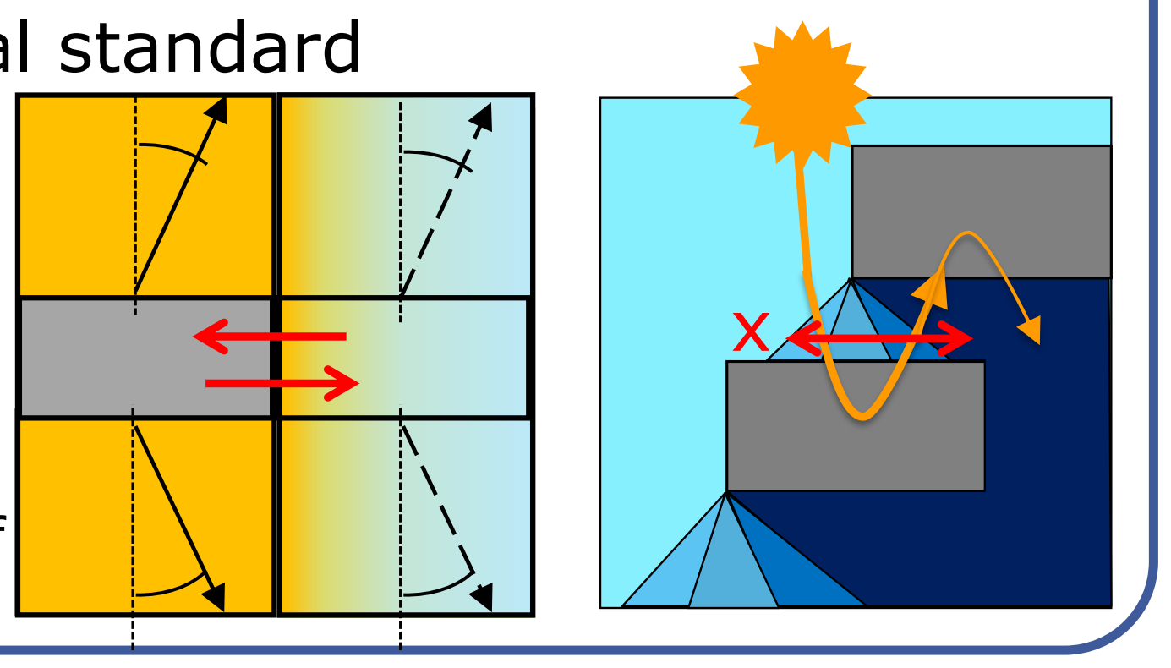


Fig. 4: SPARTACUS treatment of cloud side transfer and entrapment.

3) Evaluation against Monte Carlo benchmarks

For scattered, homogeneous cumulus in vacuum, SPARTACUS agrees well with 3D Monte Carlo results (Schäfer et al. 2016, Hogan et al. 2016). More general cases:

Shortwave (Hogan et al. 2019)

- Parametrised **mean horizontal path** profile **agrees** with Monte Carlo results to within 6% for direct and 25% for diffuse radiation.

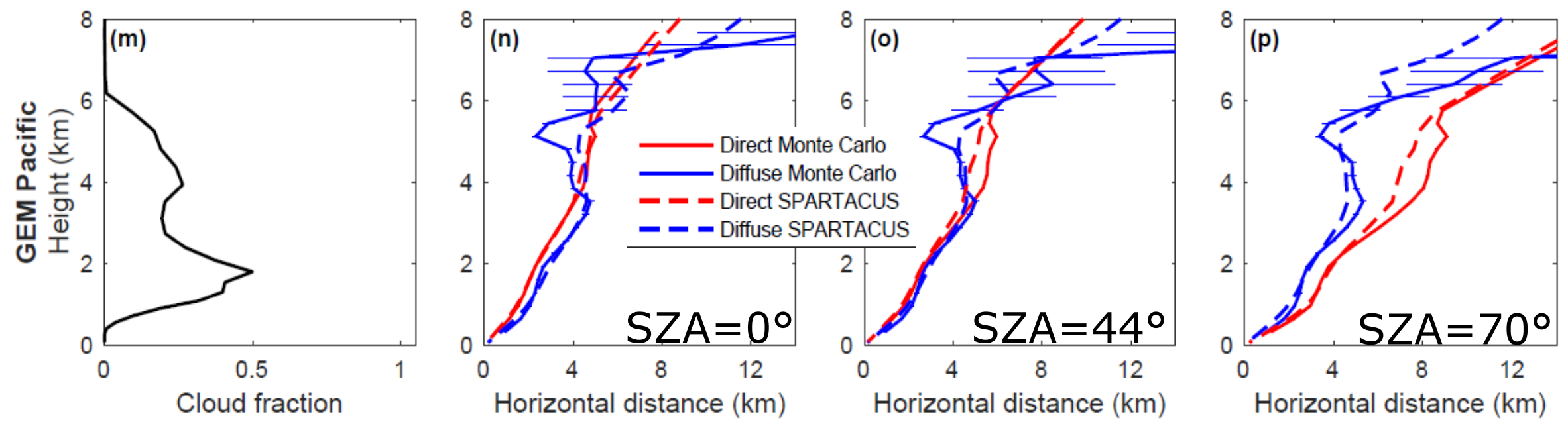


Fig. 5: Profiles of cloud fraction and mean horizontal path at different solar zenith angles (SZA) for a liquid cumulus congestus case

- SPARTACUS captures **3D change to CRE** and its dependence on SZA to within 10%; slightly overestimates **atmospheric absorption**.
- **Entrapment** decisive for 3D effect

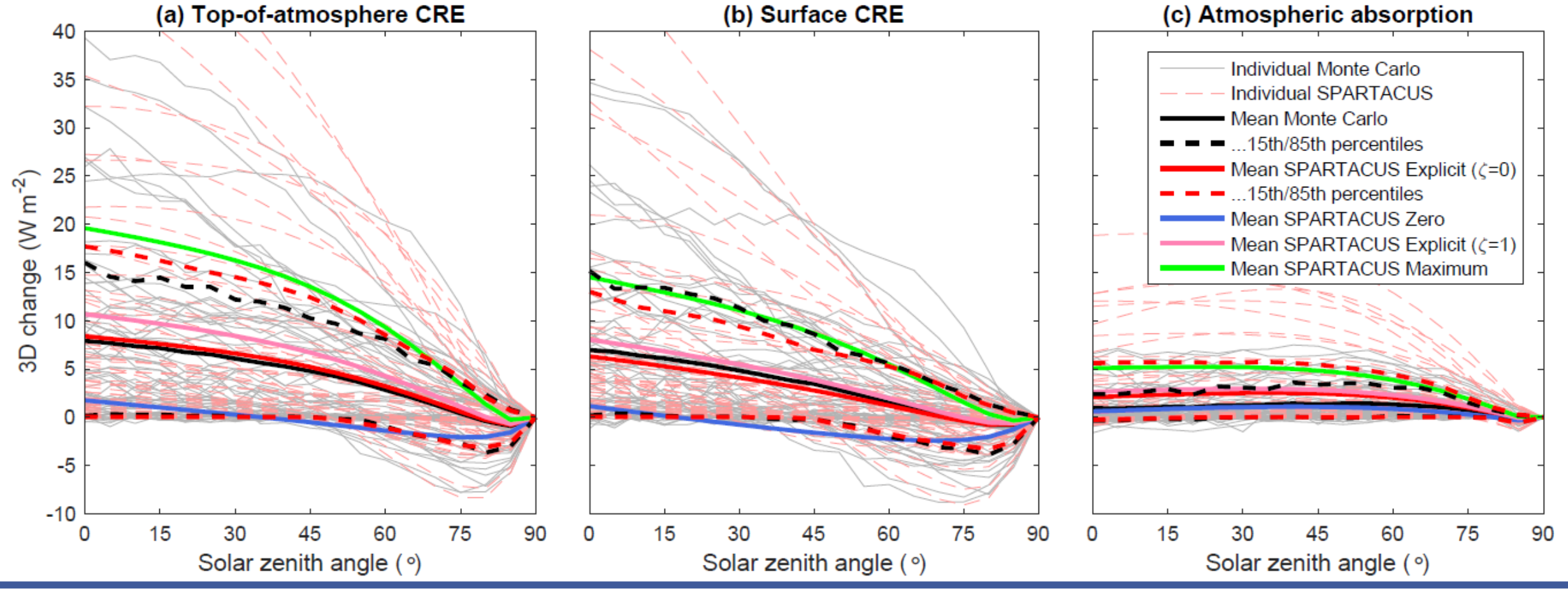


Fig. 6: 3D change to CRE and atmospheric absorption depending on SZA.
Blue line without entrapment, green line with maximum entrapment (assumed in traditional two-stream schemes)

Longwave

- ecRad and Monte Carlo fluxes **agree well** in **clear or overcast** cases with **only water or only ice.**

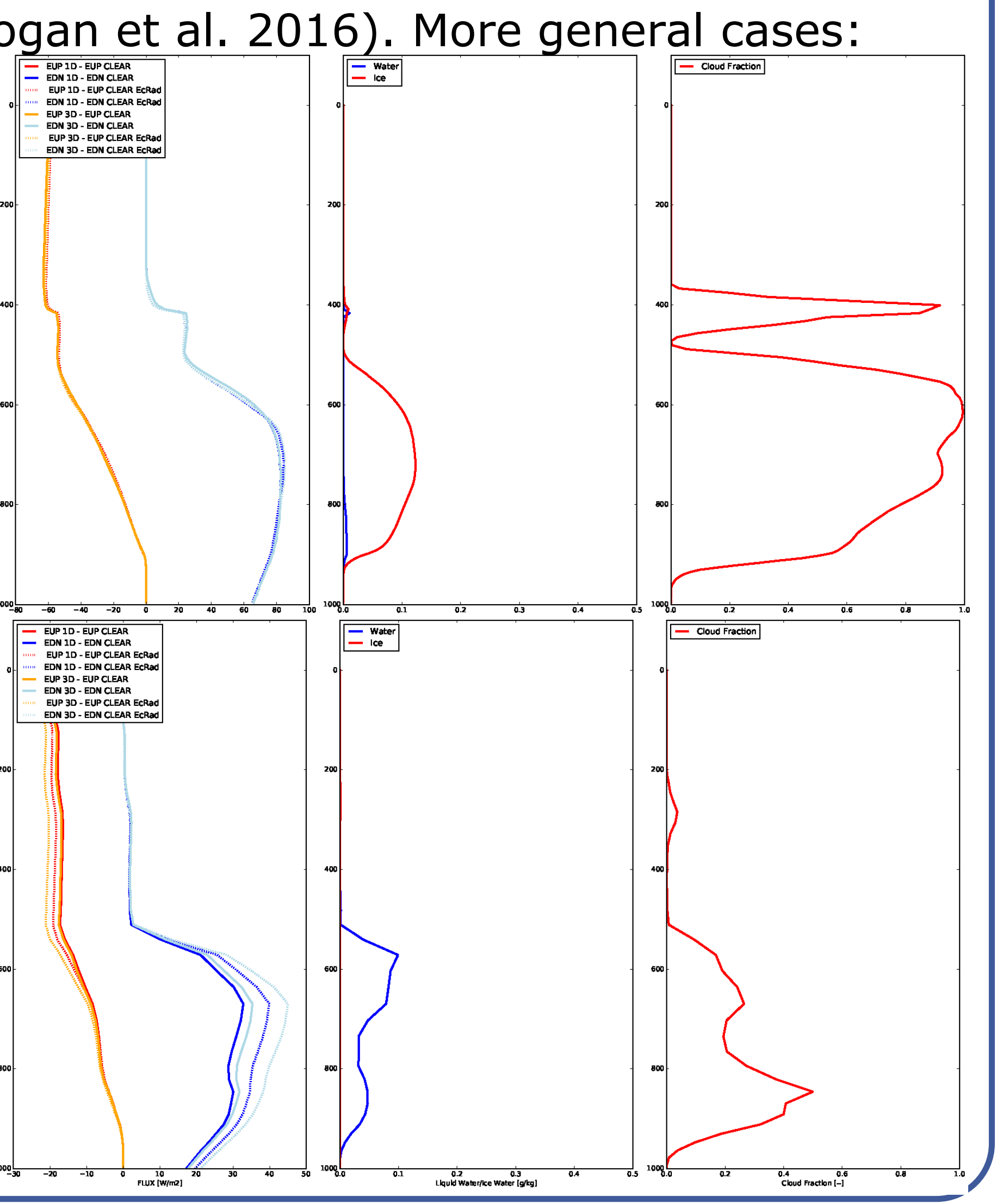


Fig. 7: Profiles of longwave fluxes, cloud water / ice and cloud fraction for an overcast case (top) and a broken congestus case (base).

- **Disagreements** of up to 30 Wm^{-2} in both 1D and 3D in some **more complex cases.**

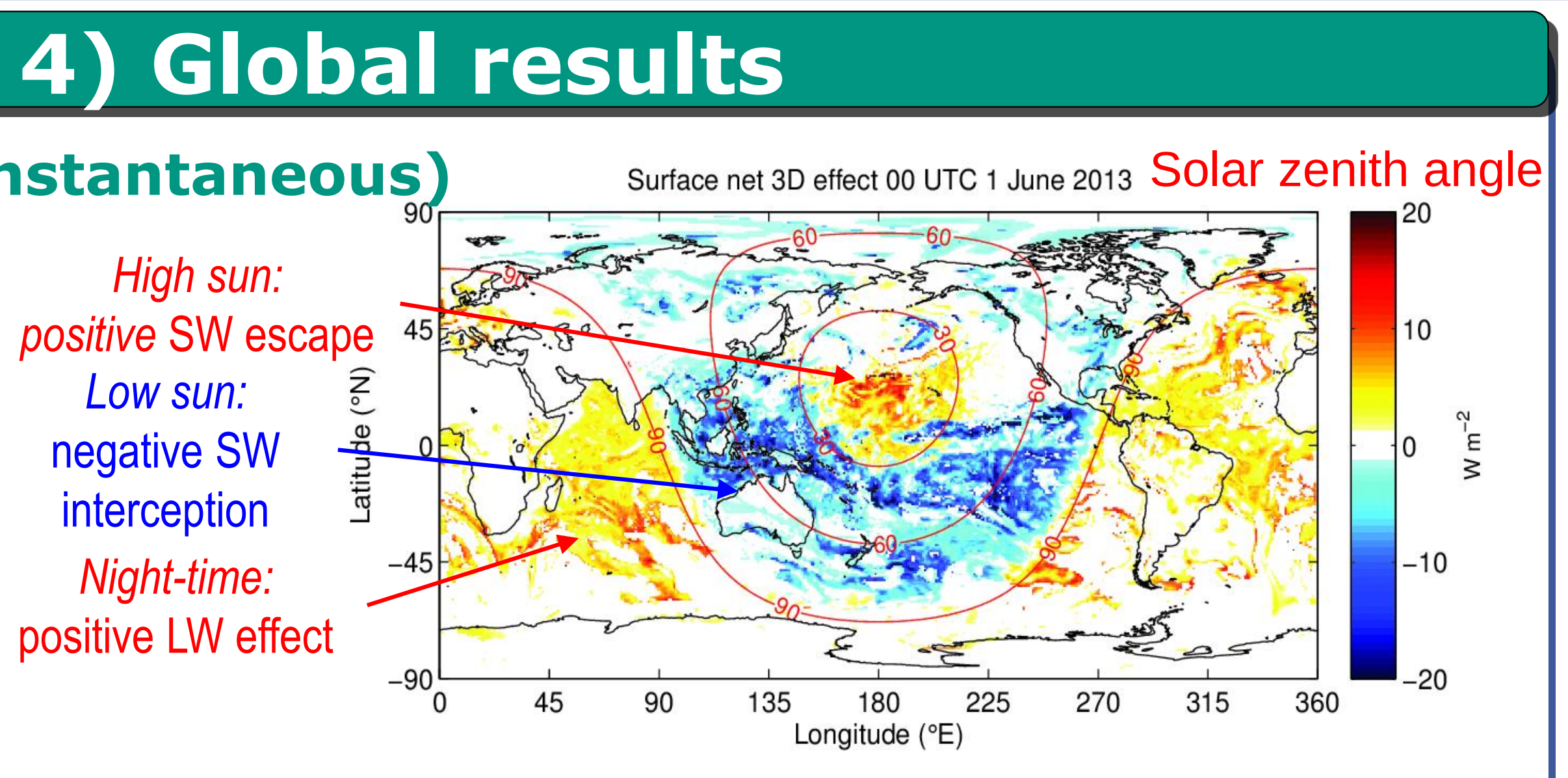
→ **Check ecRad cloud geometry assumptions** (cloud overlap, inhomogeneity).

ecRad assumes **water and ice** are homogeneously mixed in each layer / region – valid? (Ongoing work)

4) Global results

Cloud side effects (instantaneous)

- Sign of total cloud side effect depends on cloud type and SZA.
- Except for low sun: weaker than entrapment



High sun:
positive SW escape
Low sun:
negative SW interception
Night-time:
positive LW effect

Fig. 8: Cloud side effects on net downwelling surface flux in ERA-Interim scene

Total 3D effect on climate

- **Global fluxes (net down, surface):**
  Longwave +1.6 Wm^{-2}
  Shortwave +0.8 Wm^{-2}
  Total +2.4 Wm^{-2}
- **Temperature increases** by around 1K.
- Sensitive to entrapment and cloud geometry.

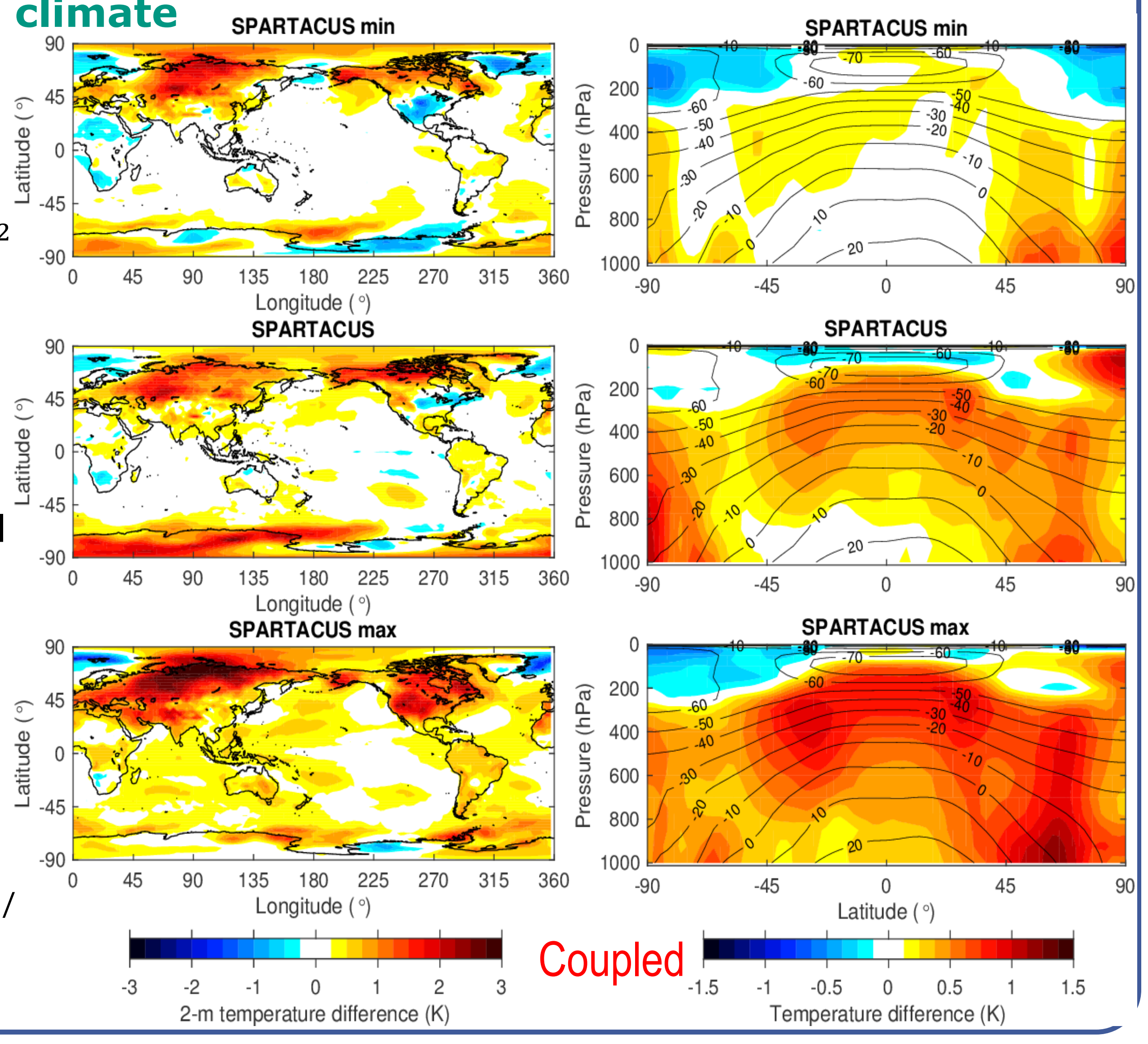


Fig. 9: Mean 3D effect on temperature in four 1-year simulations with coupled ocean, with minimum (top) / calculated (middle) / maximum (base) entrapment.

5) Conclusions

- **Cloud 3D effects on radiation are globally appreciable; in total, they warm the Earth by about 2.4 Wm^{-2} or 1K.**
- **Shortwave: Different 3D effects have opposite sign; warming entrapment effect dominates.**
- **Cloud side effects strongest for broken clouds, entrapment effect strongest for deep multilayer clouds.**
- **Longwave: warming effect.**

- **SPARTACUS can capture 3D effects efficiently.**
- **ecRad results mostly agree well with Monte Carlo codes.**
- **ecRad and SPARTACUS will be implemented in ICON soon.**

References:
Baran, A.J., P. Hill, K. Furtado, P. Field and J. Manners (2014), 'A coupled cloud physics – radiation parametrization of the bulk optical properties of cirrus and its impact on the Met Office unified model global atmosphere 5.0 configuration', *J.Clim.*, **27**
Fu, Q. (1998), 'An accurate parametrization of the solar radiative properties of cirrus clouds', *J.Clim.*, **9**
Fu, Q.,P. Yang and W.B. Sun (1998), 'An accurate parametrization of the infrared radiative properties of cirrus clouds of climate models', *J.Clim.*, **11**
Hogan, R.J., S.A.K. Schäfer, C. Klinger, J.C. Chiu and B. Mayer (2016), 'Representing 3-D cloud radiation effects in two-stream schemes – 2. Matrix formulation and broadband evaluation', *J.Geophys.Res.Atm.*, **121**
Hogan, R.J and A. Bozzo (2018), 'A flexible radiation scheme for the ECMWF model', *J.Adv. Modeling.Earth Sys.*, **10**
Hogan, R.J., M.D. Fielding, H.W. Barker, N. Villefranque and S.A.K. Schäfer (2019), 'Entrapment: An important mechanism to explain the shortwave 3D radiative effect of clouds', *submitted to J.Atm.Sci.*
Iacono, M.J., J.S. Delamere, E.J. Mlawer, M.W. Shephard, S.A. Clough and W.D. Collins (2008), 'Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models', *J.Geophys.Res.*, **113**
Pincus, R., H.W. Barker and J.-J. Morcrette (2003), 'A fast, flexibla, approximate technique for computing radiative transfer in inhomogeneous cloud fields', *J.Geophys.Res.*, **103**
Shonk, J.K., and R.J. Hogan (2008), 'Tripleclouds: An efficient method for representing horizontal cloud inhomogeneity in 1D radiation schemes by using three regions at each height', *J. Clim.*, **21**
Schäfer, S.A.K., R.J. Hogan, C. Klinger, J.C. Chiu and B. Mayer (2016), 'Representing 3-D cloud radiation effects in two-stream schemes – 1. Longwave considerations and effective cloud edge length', *J.Geophys.Res.Atm.*, **121**
Yi, B., P. Yang, B.A. Baum, T. L'Ecuyer, L. Oreopoulos and E.J. Mlawer (2005), 'Influence of ice particle surface roughening on the global cloud radiative effect', *J.Atm.Sci.*, **70**

Contact: sophia.schaefer@dwd.de