New radiation scheme ecRad in ICON + uncertainties in radiation modelling

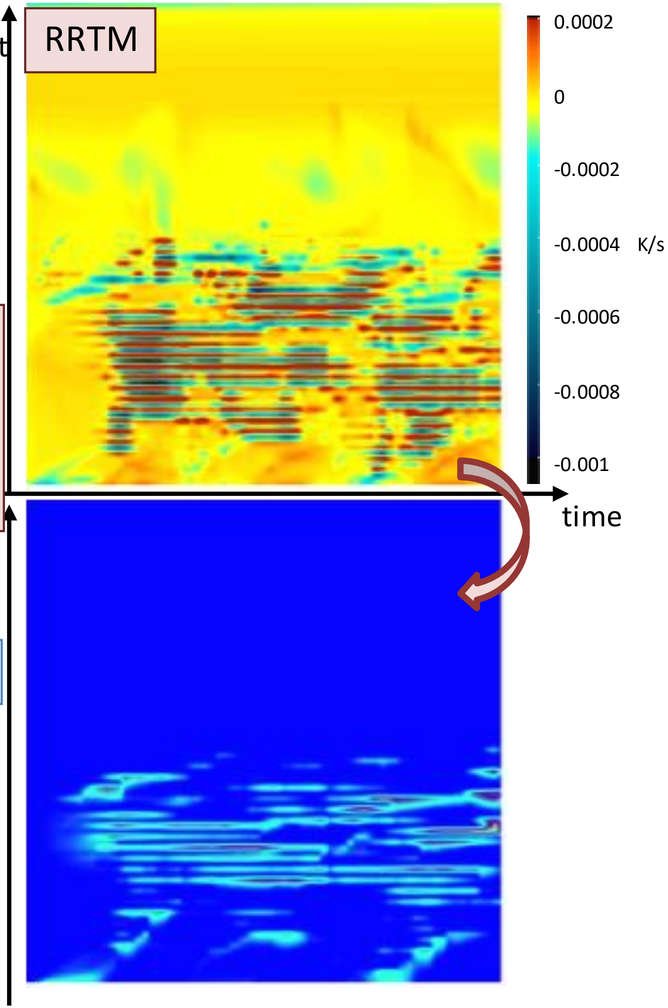
Sophia Schäfer[1], *Martin Köhler*[1], *Robin Hogan*[2,3], *Carolin Klinger*[4] ,
Daniel Rieger[1], *Alberto de Lozar*[1]
[1] Deutscher Wetterdienst, [2] ECMWF, [3] University of Reading, [4] Ludwig-Maximilians-Universität München

Issues in current RRTM radiation scheme

Longwave heating rate

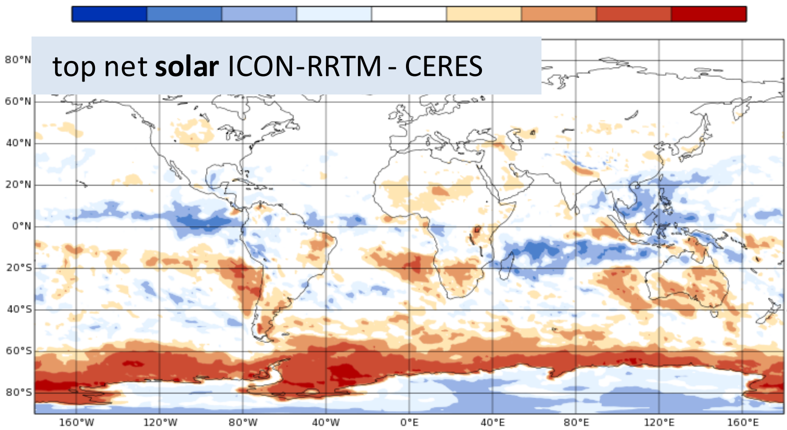
Heating rate oscillation bug (single column model)

Cloud water



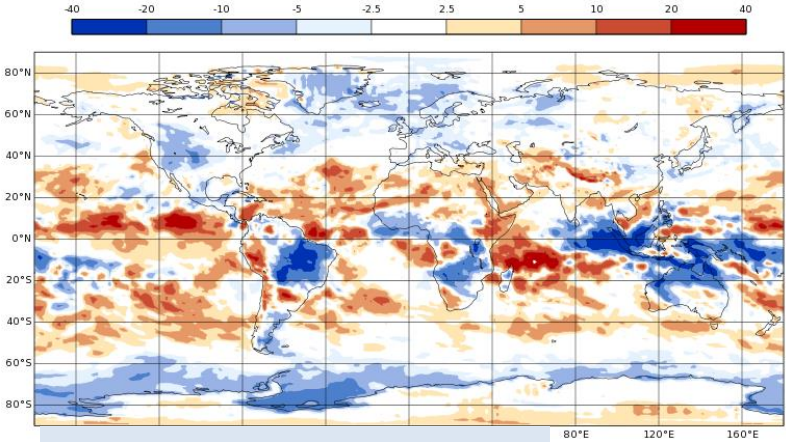
Error in global ICON 24h forecasts (Jan. 2018)

bias: 1.47 W/m²



top net **solar** ICON-RRTM - CERES

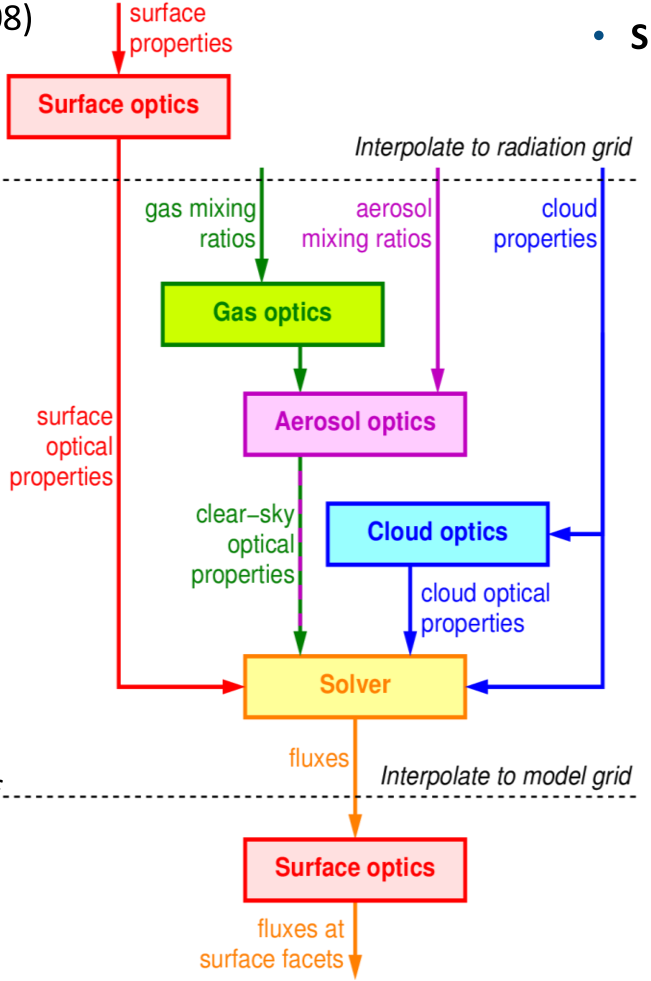
bias: 0.02 W/m²



top **thermal** ICON-RRTM - CERES

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

- **Gas optics:** RRTMG (Iacono et al. 2008)
  - *Plan to develop new scheme with fewer spectral intervals*
- **Aerosol optics:** variable species number and properties (set at run-time)
- **Cloud optics:**
  - **liquid:** SOCRATES (MetOffice), Slingo (1989)
  - **ice:** Fu 1996, 1998 (default) , Yi et al. 2013 or Baran et al. 2014
- *Surface (under development) Rigorous and consistent treatment of urban and forest canopies*

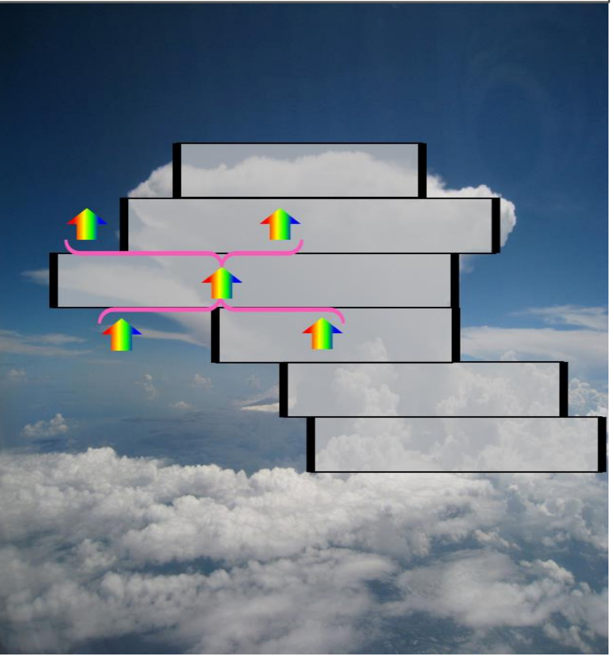


- **Solvers** for radiative transfer equations:
  - **McICA** (Pincus et al. 2005), **Tripleclouds** (Shonk & Hogan, 2008) or **SPARTACUS** (Schäfer et al. 2016, Hogan et al. 2016)
  - SPARTACUS makes ecRad the only global radiation scheme that can do **3D** radiative effects
  - Longwave scattering optional
  - Can configure **cloud overlap**
  - **Cloud inhomogeneity**: can configure width and shape of PDF

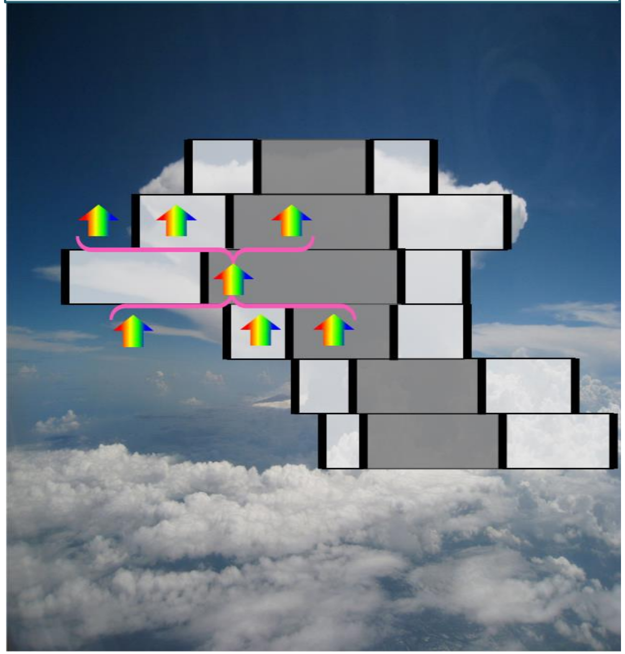
Radiation solvers

All solvers for global models **simplify** by treating **only vertical** dimension explicitly.

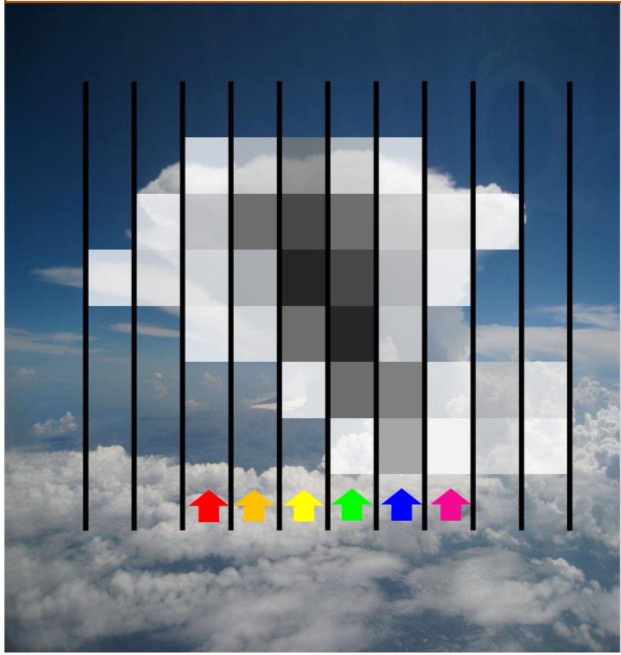
Two-stream solver: solve in **cloudy / clear regions**, partition at layer boundaries according to **overlap** (e.g. RRTM in ICON)



Tripleclouds/SPARTACUS: similar; 3 regions: **clear, thin cloud, thick cloud** → cloud **inhomogeneity**



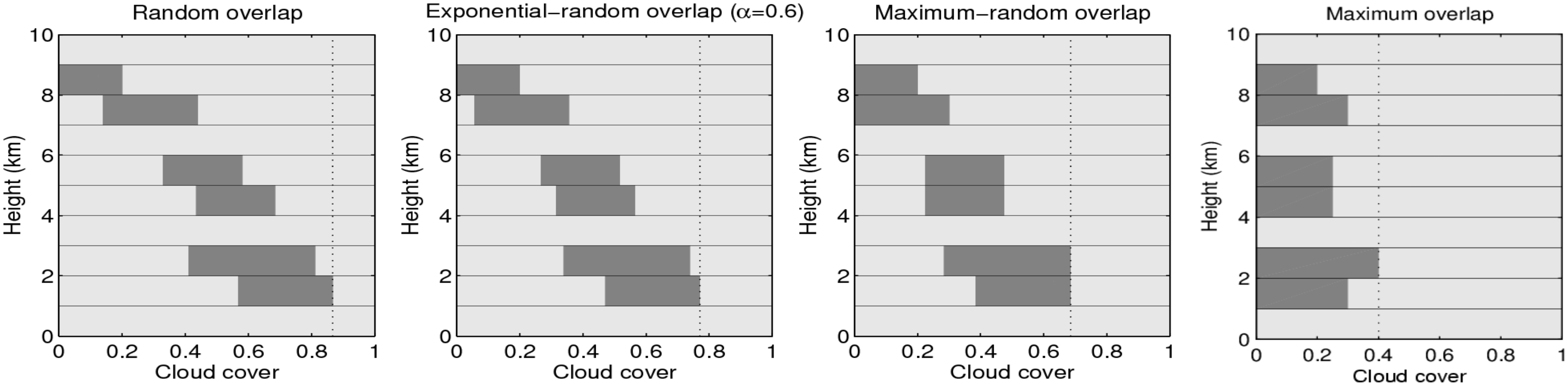
McICA: draw **random clouds in sub-columns** according to overlap + inhomogeneity; **distribute spectral intervals** in 1 sub-column each → **fast, random noise**



Plots adapted from R. Hogan

Cloud vertical overlap

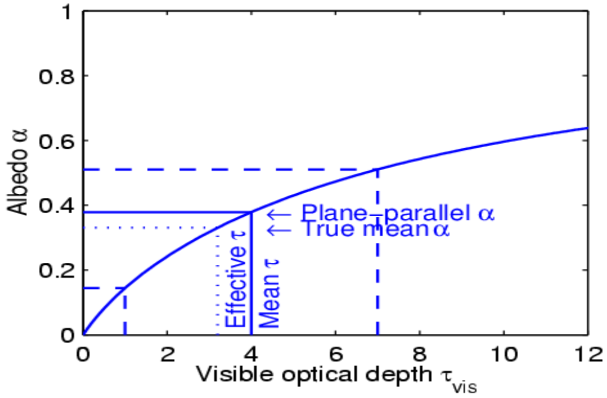
- **ICON RRTM**: different in shortwave, longwave and in total cloud cover (and bugs)
- In **ecRad**: exponential-random, maximum-random, exponential-exponential

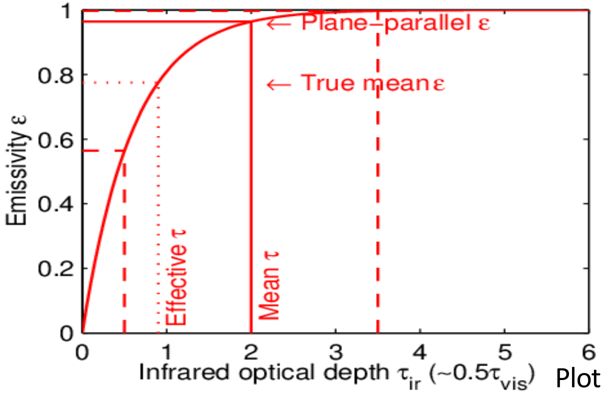


- Based on observations (Hogan & Illingworth 2000): **exponential-random overlap,** decorrelation length ca. 1.6 km; simulation studies have 100-600 m (Neggers et al. 2011, Corbetta et al., 2015)
- **McICA solver**: draws random number in each layer to decide cloudy /clear, numbers for neighbouring layers correlated according to overlap rules

Cloud inhomogeneity

- Reflectivity and longwave emissivity are **non-linear functions** of optical depth / cloud water content



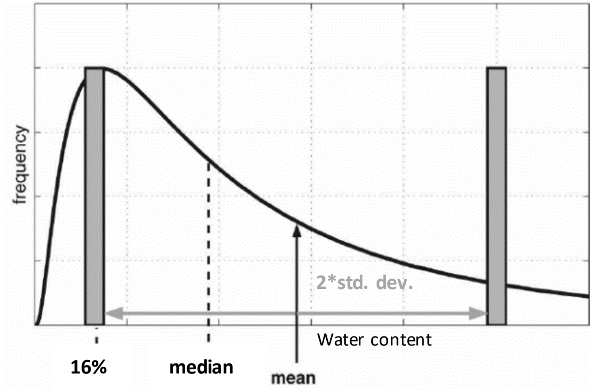


Plots by R. Hogan

- **ICON RRTM** reduces optical depth by 0.77 (liquid) or 0.8 (ice)
- COSMO reduces by 0.5

- **ecRad inhomogeneity parameters**: type of cloud water distribution (gamma / lognormal PDF),

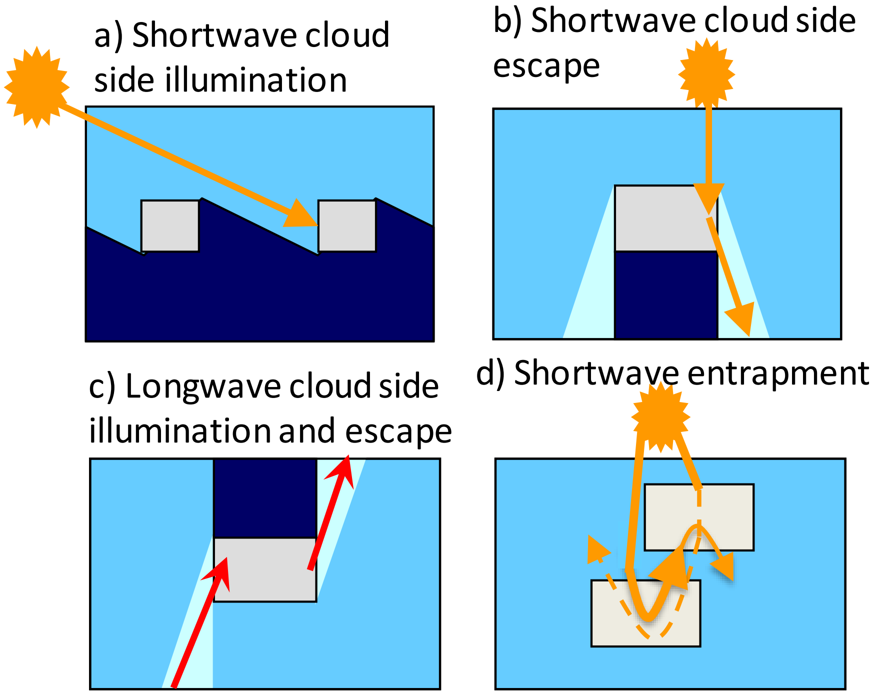
$$\textbf{fractional standard deviation} = \frac{\text{standard deviation}}{\text{mean}}$$



Adapted from Shonk & Hogan (2008)

- **Tripleclouds**: two cloudy regions (equal size, preserve standard deviation of cloud water PDF)
- **McICA**: Draw random number ∈ $[0,1]$ for each cloudy layer, correlated according to vertical inhomogeneity correlation; then scale with cloud water PDF value at this percentile

3D effects: Physical mechanisms

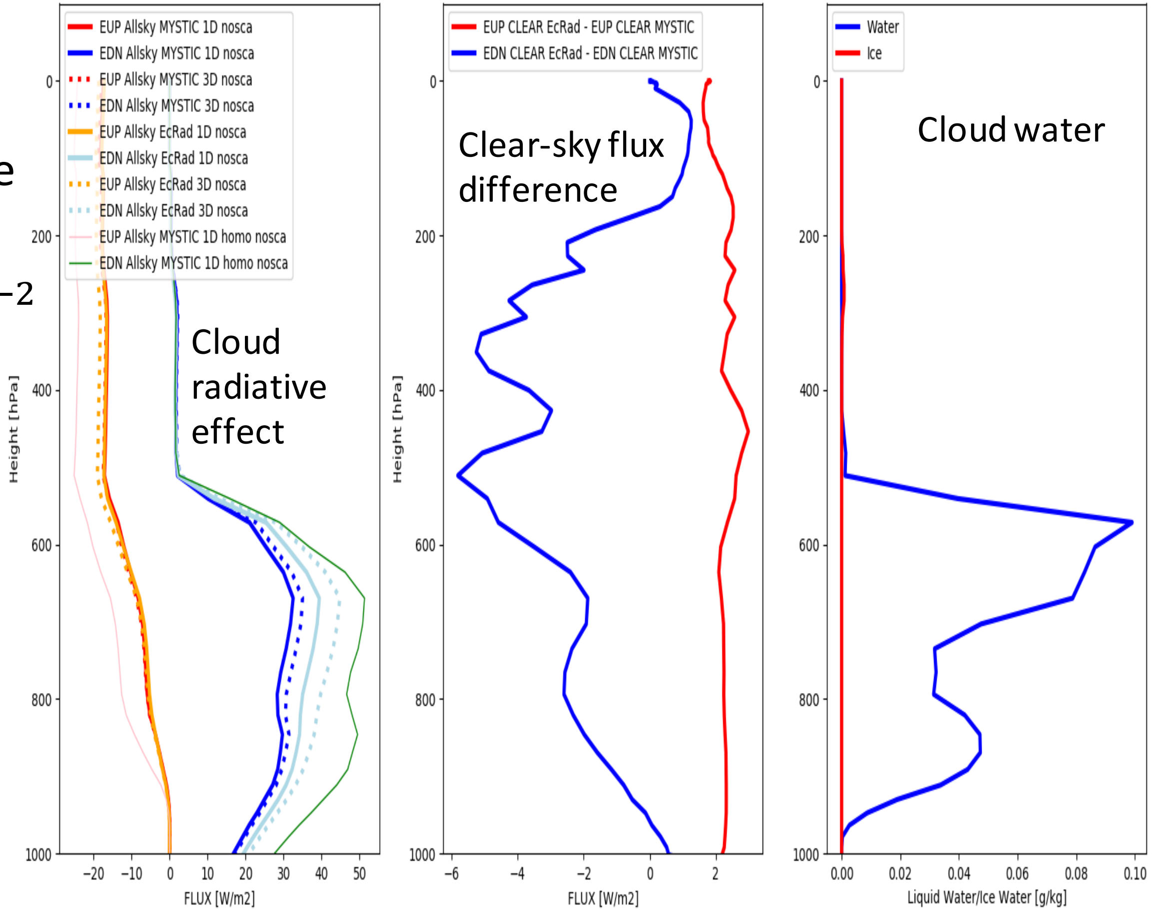


- **Shortwave cloud side illumination** increases cloud reflectivity, **cloud side escape** decreases cloud reflectivity
- **Longwave cloud side illumination and escape** increase cloud warming effect
- **Shortwave entrapment** decreases cloud reflectivity
- Similar at complex surfaces (trees, mountains, buildings)
- **Usually neglected**, **SPARTACUS** solver in ecRad can treat them for sub-grid obstacles

- **Magnitude of sub-grid cloud effects:** cloud inhomogeneity ≤ 30 W/m², 3D effects ≤ 5 W/m²

ecRad longwave evaluation (against Monte Carlo scheme)

- **Shortwave:** ecRad compares well with 3D Monte Carlo radiation (Hogan et al., 2019)
- **Longwave:** ecRad and Monte Carlo fluxes **agree well** in simple water or ice clouds, some clear-sky difference due to different gas models
- **Large uncertainty** of up to $30\ \mathrm{Wm}^{-2}$ due to **inhomogeneity**
- **3D effects** of up to 5 Wm^{-2}
- **ecRad captures effects**; somewhat **underestimates inhomogeneity**, **overestimates 3D** effects
- Inhomogeneity between water and ice can be important, not yet represented



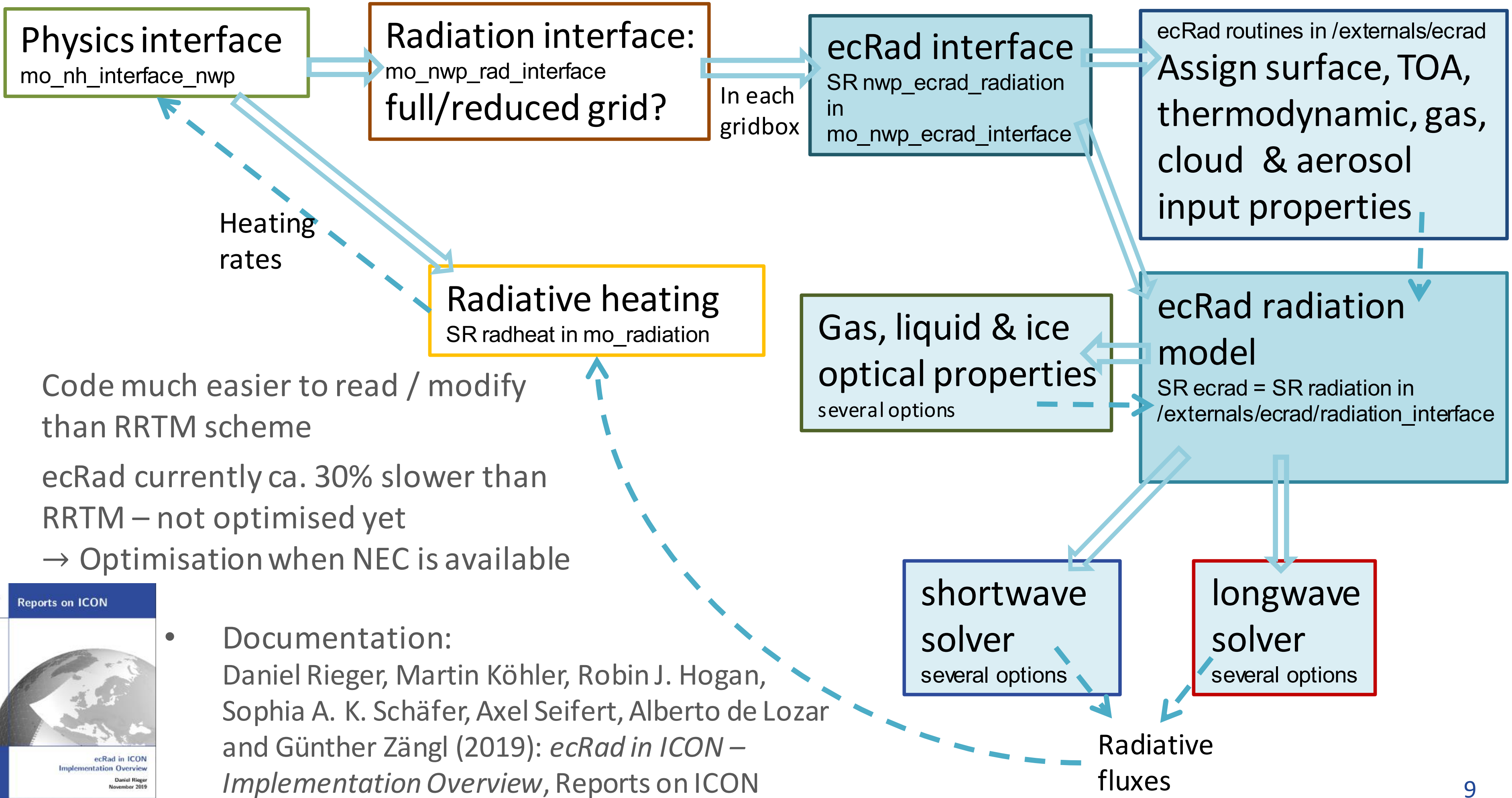
Cloud radiative effect

Clear-sky flux difference

Cloud water

Monte Carlo calculations and plots by C. Klinger

ecRad in ICON (implemented by Daniel Rieger)



Physics interface
mo_nh_interface_nwp

Radiation interface:
mo_nwp_rad_interface
full/reduced grid?

In each gridbox

ecRad interface
SR nwp_ecrad_radiation in mo_nwp_ecrad_interface

ecRad routines in /externals/ecrad
Assign surface, TOA, thermodynamic, gas, cloud & aerosol input properties

ecRad radiation model
SR ecrad = SR radiation in /externals/ecrad/radiation_interface

Gas, liquid & ice optical properties
several options

Radiative heating
SR radheat in mo_radiation

Heating rates

shortwave solver
several options

longwave solver
several options

Radiative fluxes

- Code much easier to read / modify than RRTM scheme
- ecRad currently ca. 30% slower than RRTM – not optimised yet
  → Optimisation when NEC is available

Issue 004
Reports on ICON
ecRad in ICON
Implementation Overview
Daniel Rieger
November 2019

- Documentation:
  Daniel Rieger, Martin Köhler, Robin J. Hogan, Sophia A. K. Schäfer, Axel Seifert, Alberto de Lozar and Günther Zängl (2019): *ecRad in ICON – Implementation Overview*, Reports on ICON

Namelist parameters for ecRad

To use ecRad, **need to specify** in configure: ./configure --with-ecrad
+ in ICON namelist:

&nwp_phy_nml
inwp_radiation = 4 ! 0: no radiation, 1: RRTM, 2: RG, 3: PSRAD, 4: ecRad
&radiation_nml
ecRad_data_path = ‘<ICON-directory>/externals/ecrad/data’

Can configure model behaviour:

&radiation_nml
icld_overlap=2 ! Cloud overlap (in RRTM only changes sw); 1: maximum-random, 2: exponential-random, 3: maximum, 4: random
irad_aero = 0 ! Aerosols; 0: no aerosol, 2: constant, 5:Tanre climatology, 6: Tegen climatology
iliquid_scat = 0 ! Liquid optics scheme: 0: SOCRATES, 1: Slingo (1989)
iice_scat = 0 ! Ice optics scheme: 0: Fu et al. (1996), 1: Baran et al. (2016)
llw_cloud_scat = .true. ! Do longwave cloud scattering? etc.

Additional ecRad namelist parameters set in SR setup_ecrad in mo_nwp_ecrad_init

ecrad_conf%i_solver_sw = ISolverMcICA ! Short-wave solver
ecrad_conf%i_solver_lw = ISolverMcICA ! Long-wave solver
ecrad_conf%do_3d_effect = .false. ! Do we include 3D effects?
ecrad_conf%do_lw_aerosol_scattering = .false. ! LW scattering due to aerosol etc.

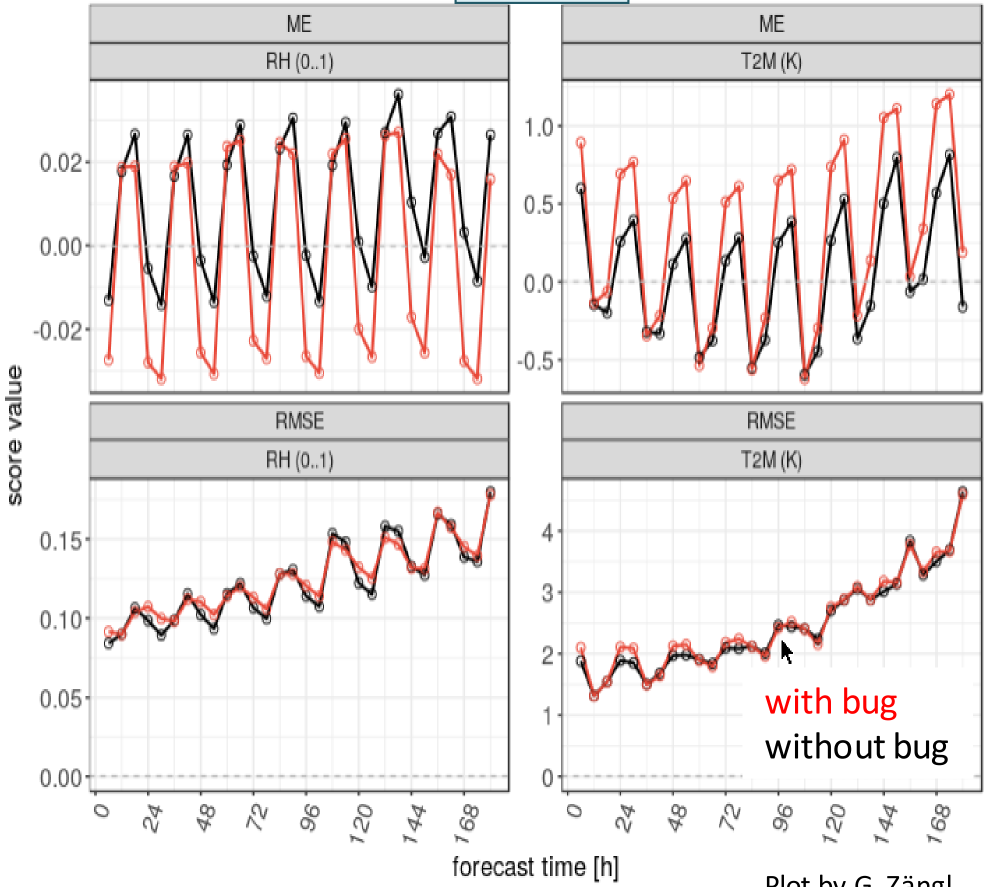
Not all combinations possible. ecRad documentation at https://confluence.ecmwf.int/display/ECRAD

Fixed bug in temperature input

- Air **temperature in lowest level** had been set to ground temperature
  → heating rate errors
  → errors in temperature, humidity, surface fluxes,…
- Bug also in RRTM (but results less sensitive)

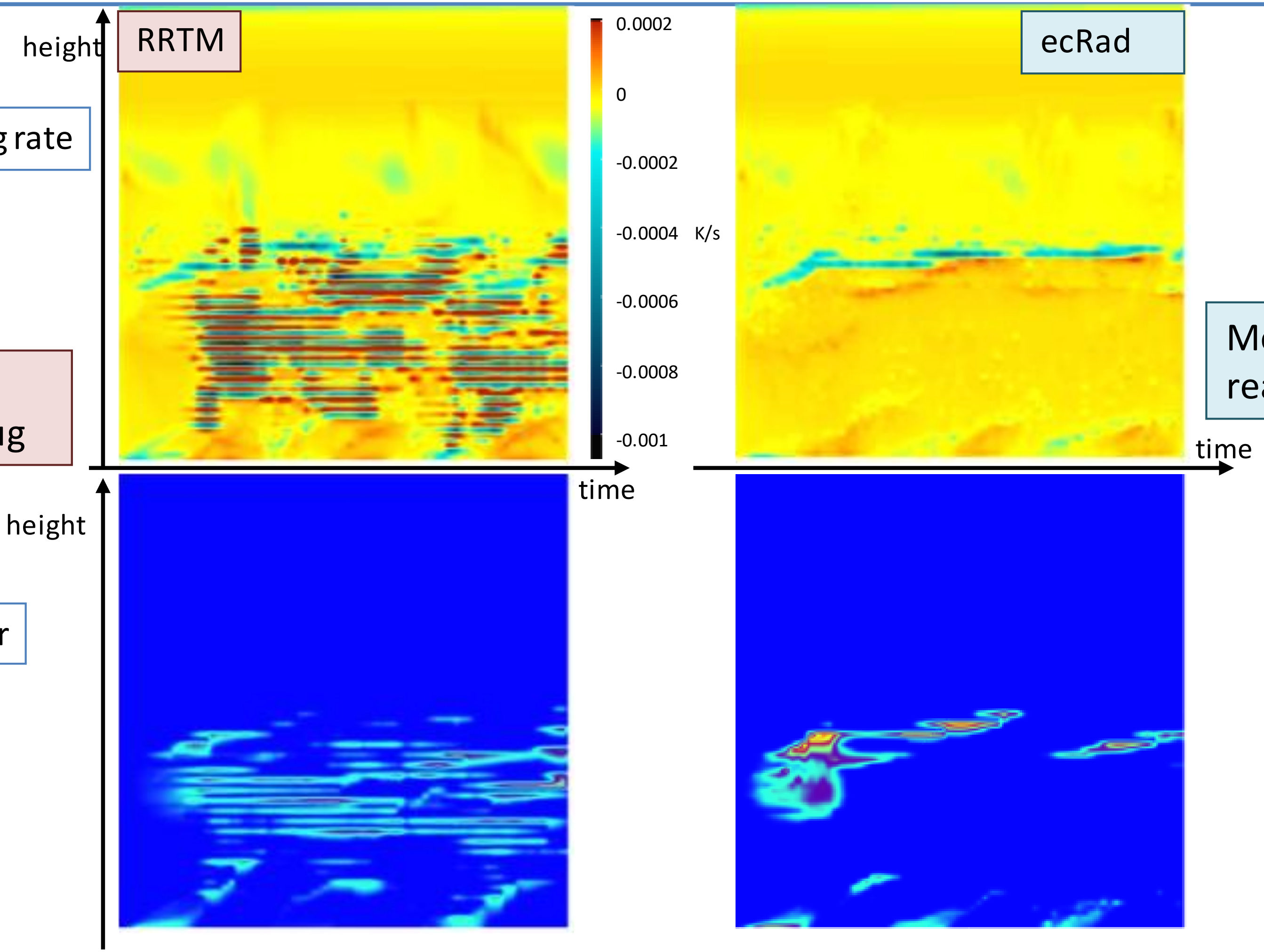
- **Now**: Heating rate, temperature,… **results improve** with both radiation schemes, **ecRad better** than RRTM

ecRad



Plot by G. Zängl

ecRad versus RRTM : ICON single column model



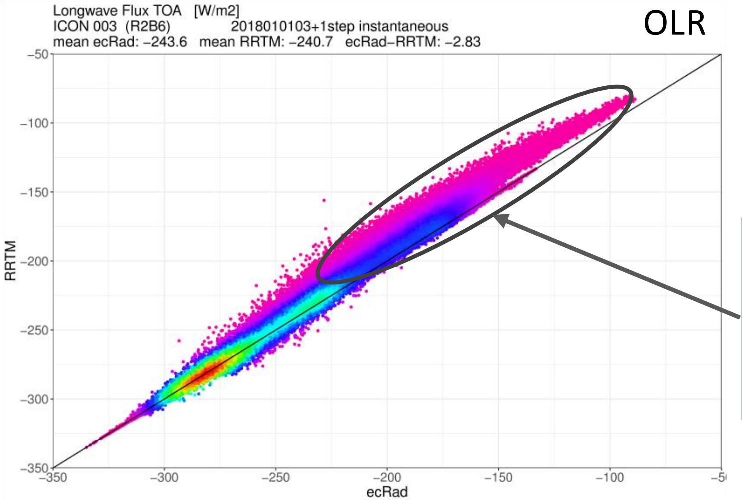
Longwave heating rate

Heating rate oscillation bug

Cloud water

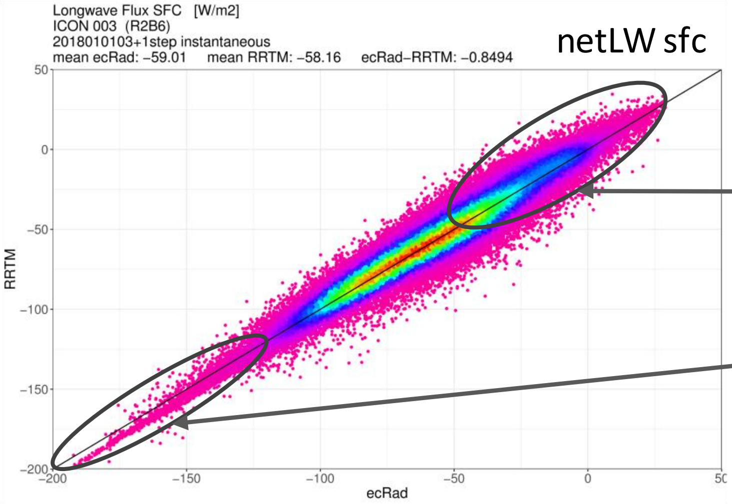
More realistic

ecRad versus RRTM: January 2018 global one step



OLR

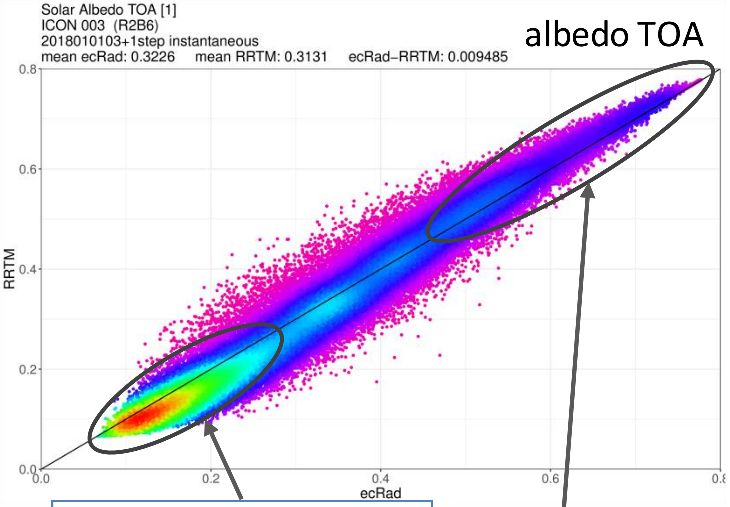
cold high clouds:
optically thinner in LW
(offset = ~15Wm^{-2})



netLW sfc

low clouds:
optically thinner (~5Wm^{-2}) in LW

clear sky:
less surface cooling (~5Wm^{-2})
opticallly thicker dry atmosphere in LW



albedo TOA

thin clouds or surface:
more reflective (~2%)

thick clouds:
less reflective (~2%)

Clear-sky results agree much closer

→ difference mainly in cloud effects

Differences: ecRad - RRTM, 24h forecasts, January 2018

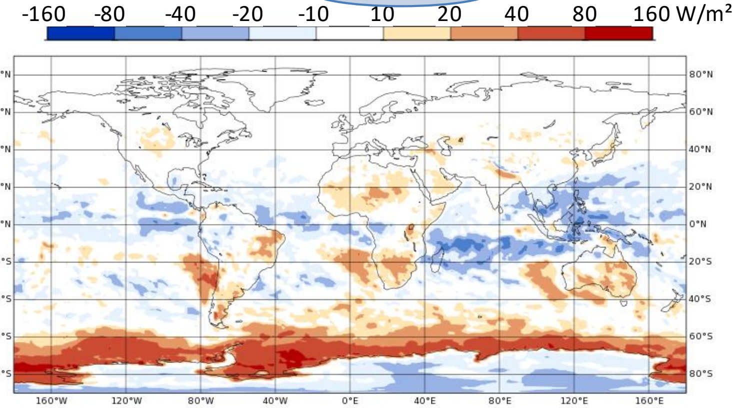
TOA solar vs. CERES

TOA thermal vs. CERES

ecRad

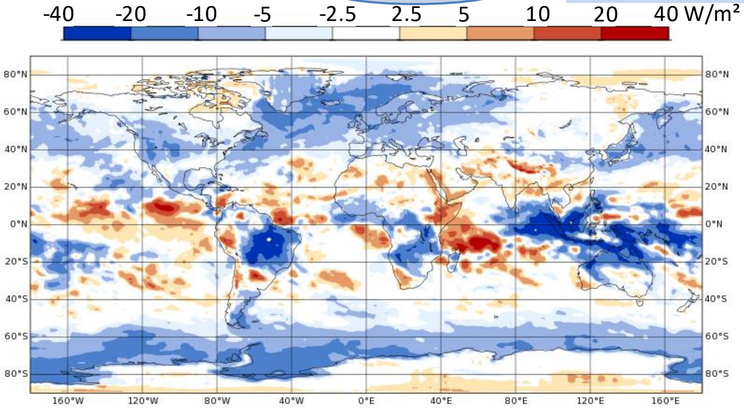
bias: -0.52 W/m²

ACCSOB_T dei2_375 - CERES 2018010100 to 2018010200
Min: -78.34 Max: 141.6 Mean: -0.5227 RMS: 17.51 Mem: 31



bias: -2.99 W/m²

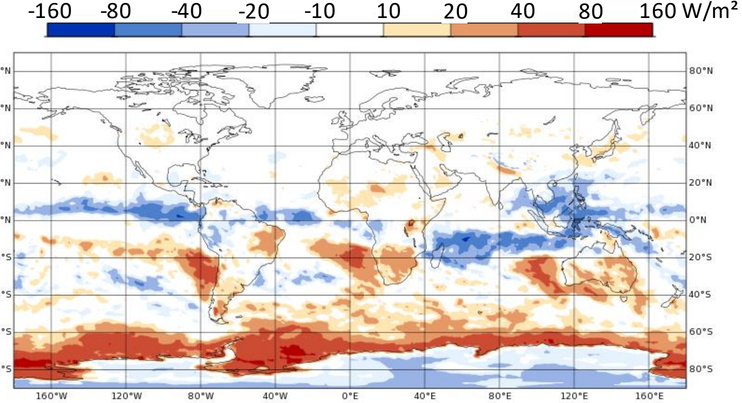
ACCTHB_T dei2_375 - CERES 2018010100 to 2018010200
Min: -44.68 Max: 34.52 Mean: -2.969 RMS: 7.822 Mem: 31



RRTM

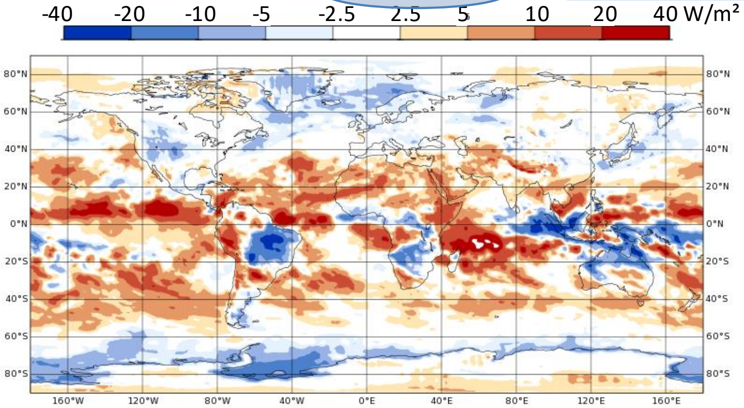
bias: 0.92 W/m²

ACCSOB_T dei2_374 - CERES 2018010100 to 2018010200
Min: -92.35 Max: 140.9 Mean: 0.9204 RMS: 19.3 Mem: 31



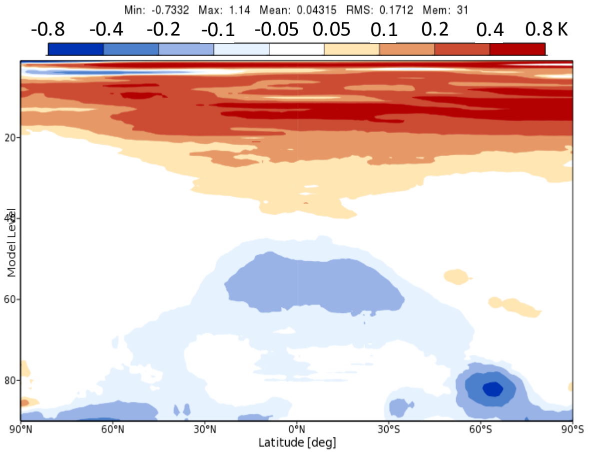
bias: 1.99 W/m²

ACCTHB_T dei2_374 - CERES 2018010100 to 2018010200
Min: -38.39 Max: 50.31 Mean: 1.999 RMS: 7.625 Mem: 31

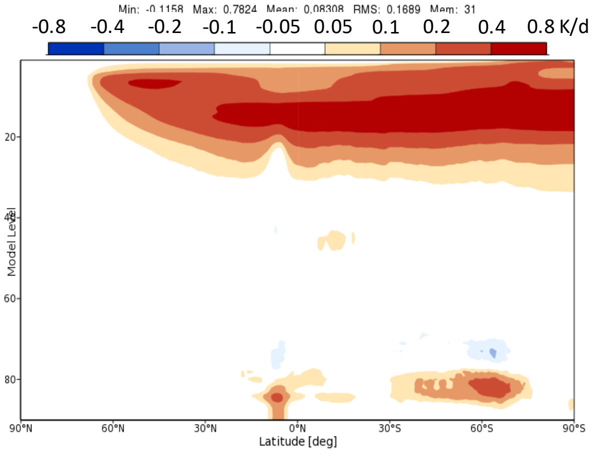


Differences: ecRad - RRTM

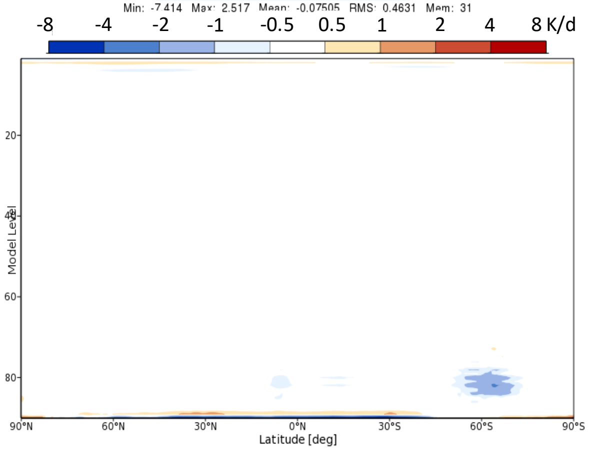
T



T SW tendency

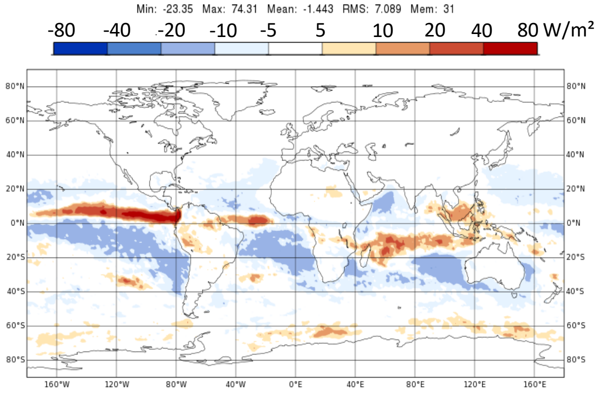


T LW tendency

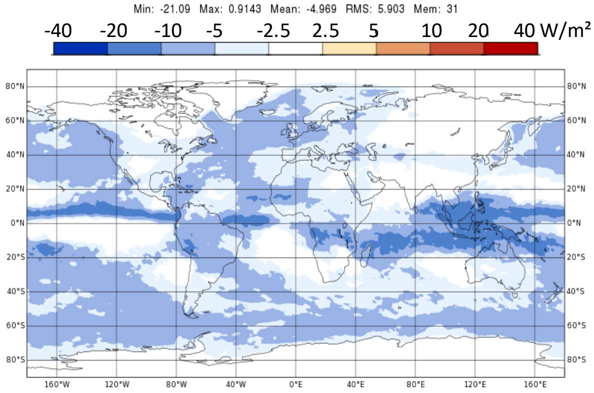


Have to check stratospheric heating – gas optics difference

SW TOA flux

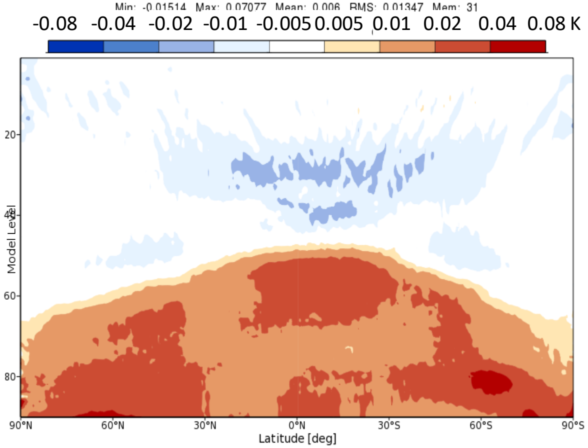


LW TOA flux

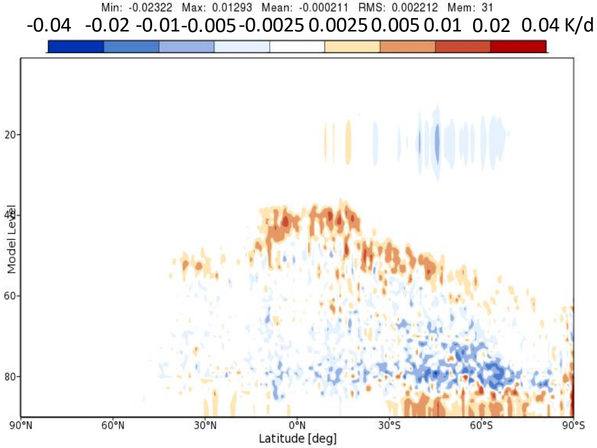


ecRad LW cloud scattering ON - OFF

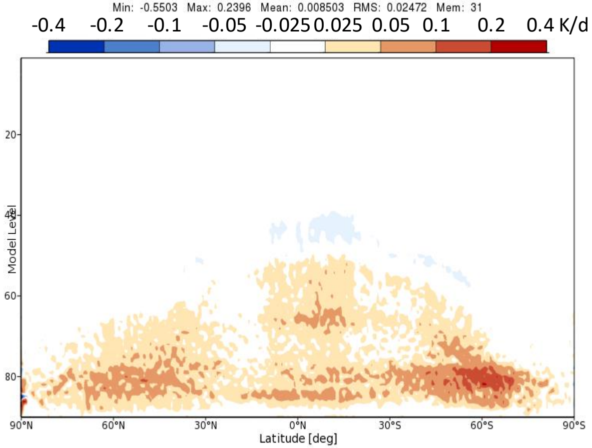
T



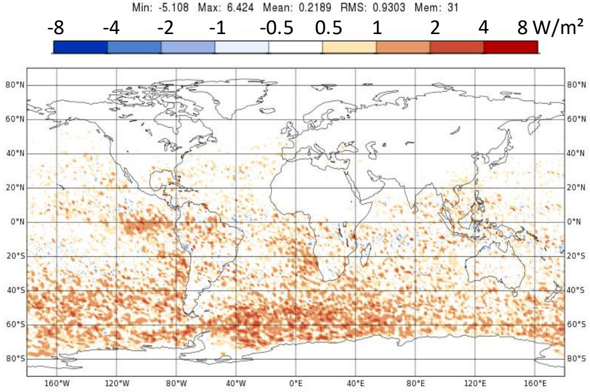
T SW tendency



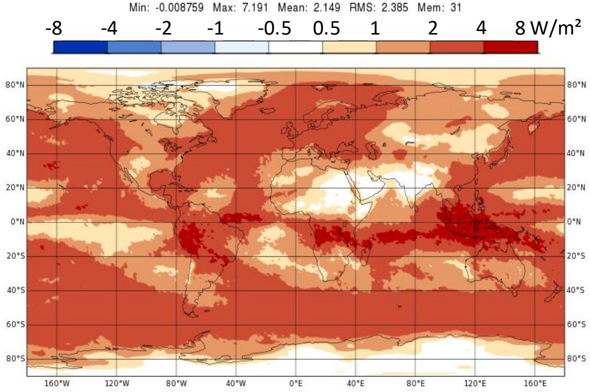
T LW tendency



SW TOA flux



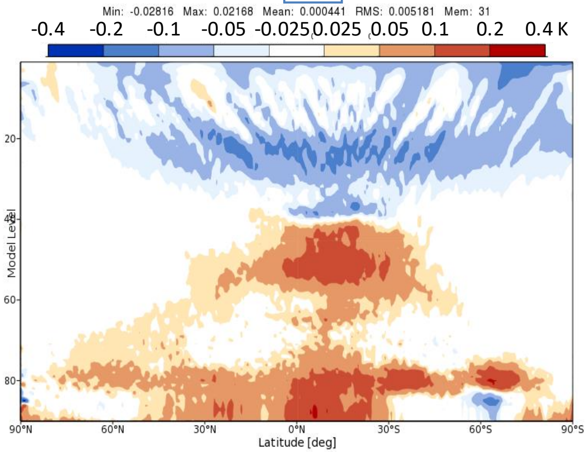
LW TOA flux



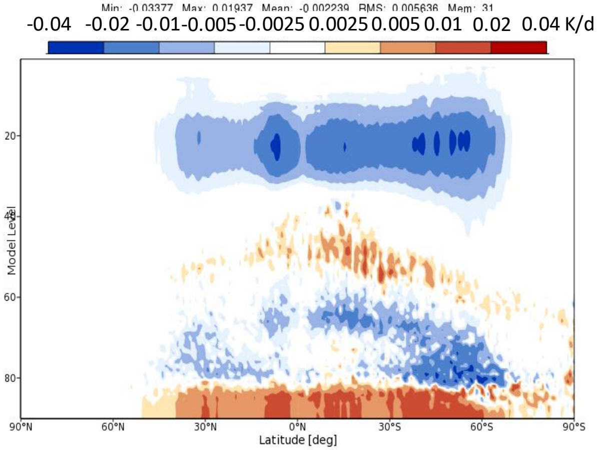
Longwave scattering slightly warms atmosphere

ecRad solver: TripleClouds - McICA

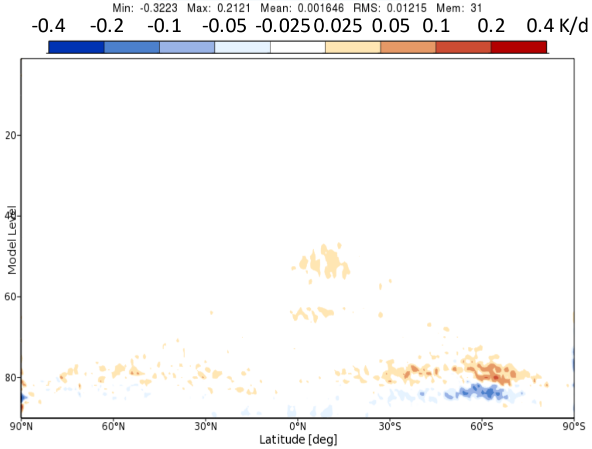
T



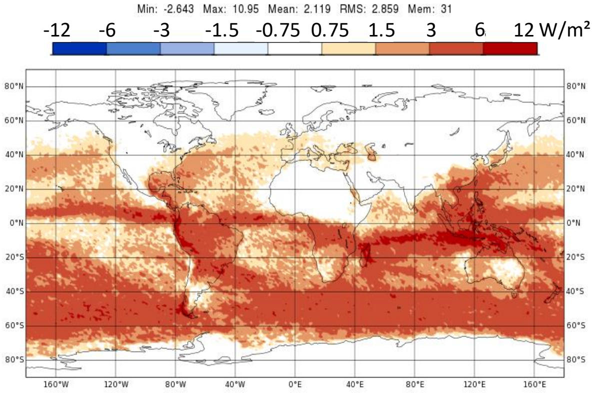
T SW tendency



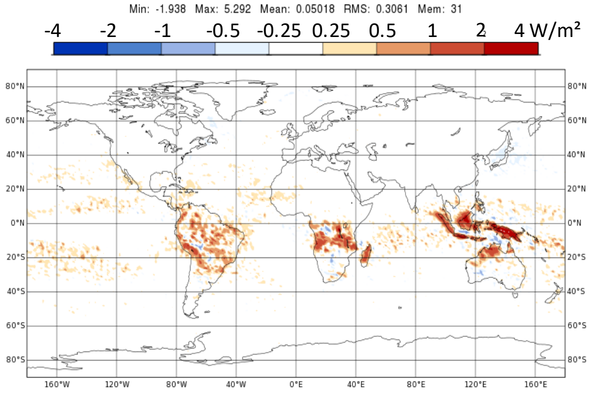
T LW tendency



SW TOA flux



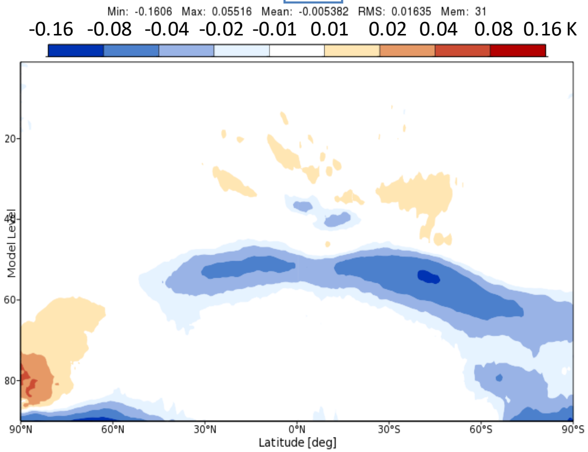
LW TOA flux



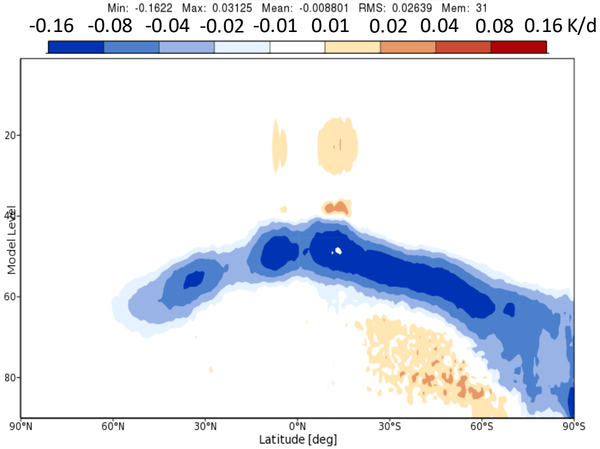
Global uncertainty
due to solver
assumptions

ice optics: Baran - Fu

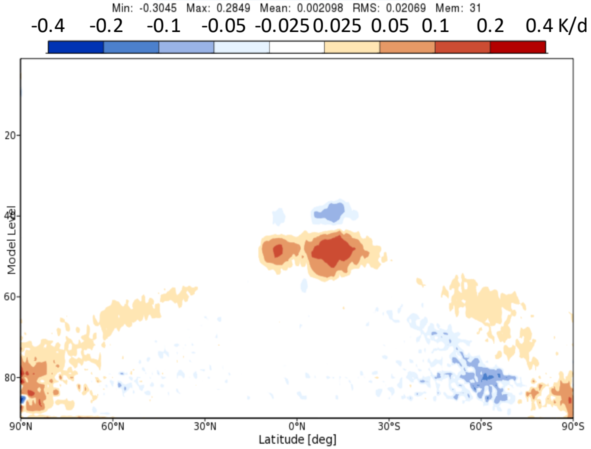
T



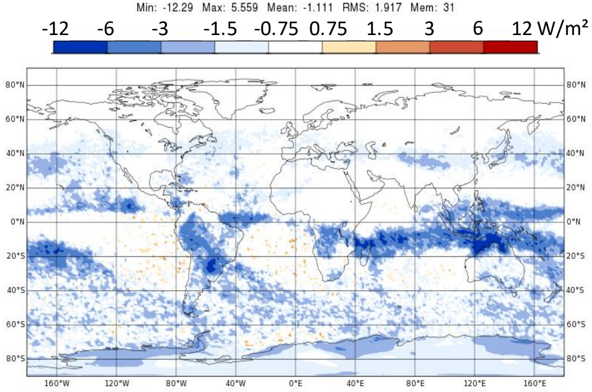
T SW tendency



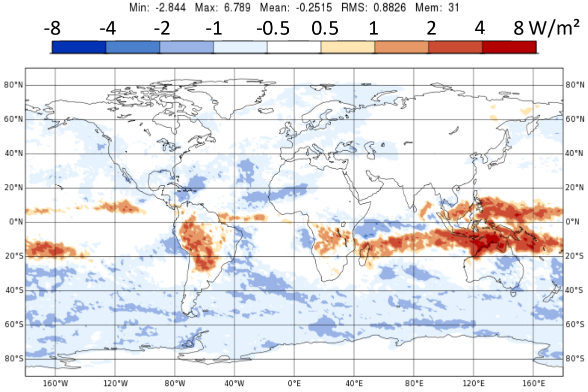
T LW tendency



SW TOA flux



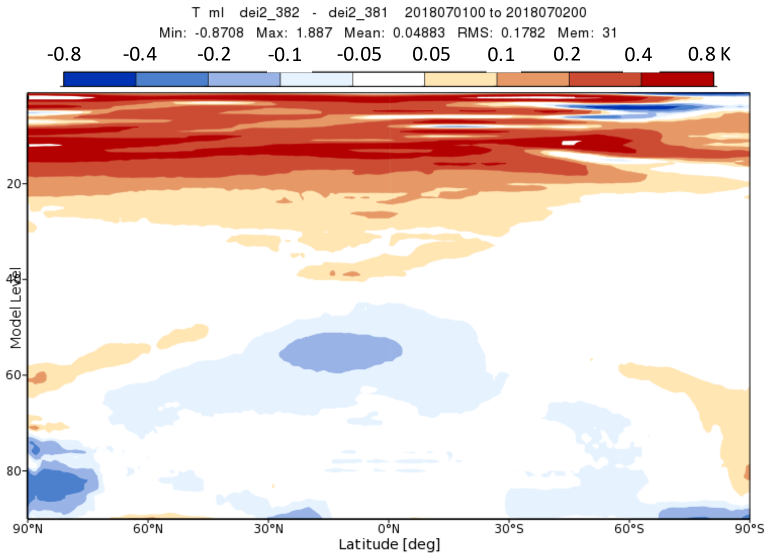
LW TOA flux



Considerable uncertainty in ice optics assumptions

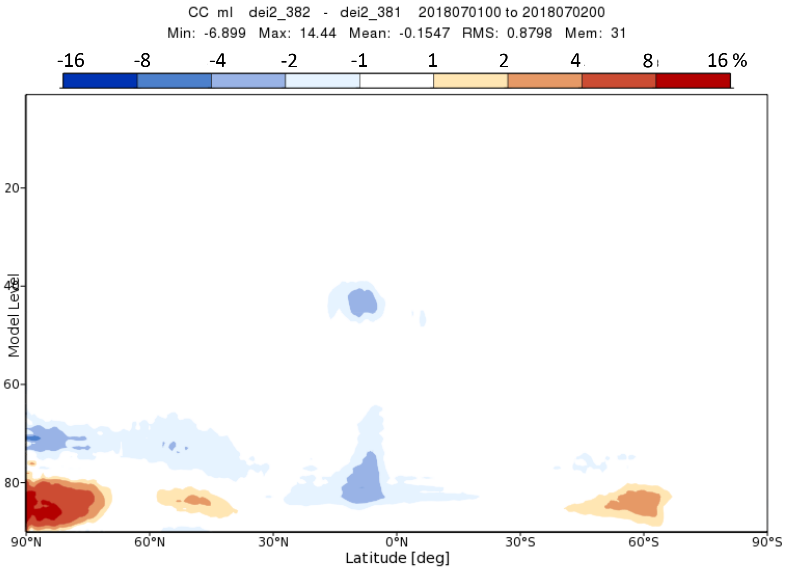
ecRad - RRTM: Full ICON run

T



T ml dei2_382 - dei2_381 2018070100 to 2018070200
Min: -0.8708 Max: 1.887 Mean: 0.04883 RMS: 0.1782 Mem: 31

Cloud cover



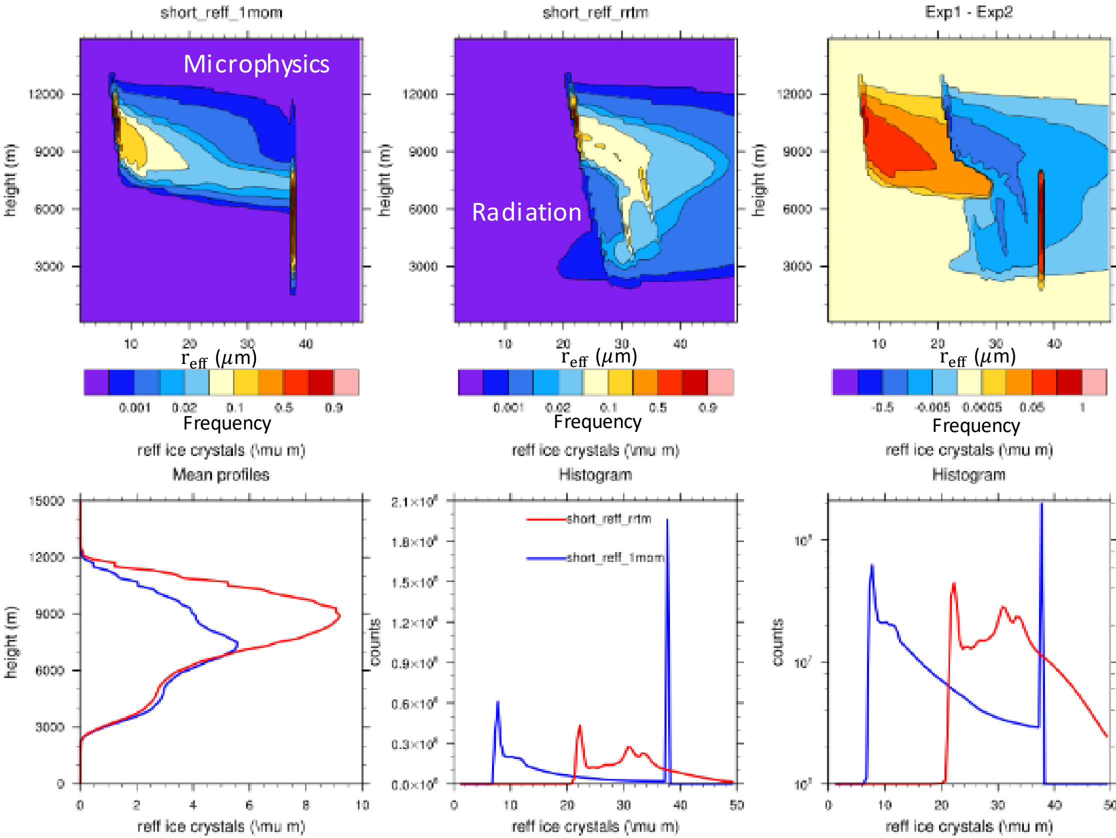
CC ml dei2_382 - dei2_381 2018070100 to 2018070200
Min: -6.899 Max: 14.44 Mean: -0.1547 RMS: 0.8798 Mem: 31

- Clouds generally optically thinner in ecRad → cooler at cloud base, warmer at cloud top
  → More cloud at base, less cloud at top
- Also less tropical convection

Input: cloud particle effective radius

- Calculated from cloud water, needs knowledge or assumptions on cloud particle size distribution and geometry

- Important for radiation (small particles dominate radiative effect)
- **Currently**: ice effective radius for radiation **inconsistent** with microphysics (liquid water better)
- Alberto de Lozar uses 1-moment- and 2-moment-microphysics assumptions to calculate effective radius for radiation
  → test radiation effect



Plots by A. de Lozar

Summary

- **ecRad implemented in ICON** (D. Rieger)
- In troposphere: **ecRad** and removal of temperature input bug **improve results** over RRTM.
- ecRad represents cloud **inhomogeneity**, SPARTACUS solver can parametrise sub-grid **3D** obstacles
- Modular scheme allows uncertainty estimation

Ongoing and future work:

- Understand cloud feedbacks, estimate uncertainties
- Evaluation of ecRad in ICON against Monte Carlo radiation calculations (with C. Klinger at LMU) and line-by-line calculations (project CKMIP at ECMWF)
- Vector optimisation for NEC@DWD
- Cloud particle effective radius parametrisation consistent with microphysics (A. de Lozar)
- Improved treatment of surface albedo and emissivity (M. Köhler, B. Fay)
- Generalise ecRad to user-defined number of cloud particle species (with R. Hogan at ECMWF)
- Extend ice optics to larger ice particles like snow or graupel (with U. Blahak and colleagues at Israel Meteorological Service)
- 3D effects of resolved (LES) clouds (with B. Mayer, C. Klinger and F. Jakub at LMU)
- Evaluation for all applications

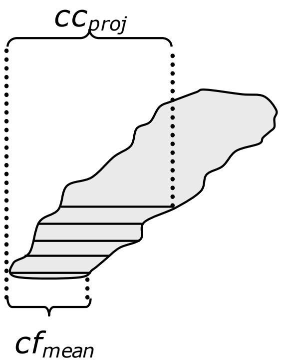
Thank you for your attention!

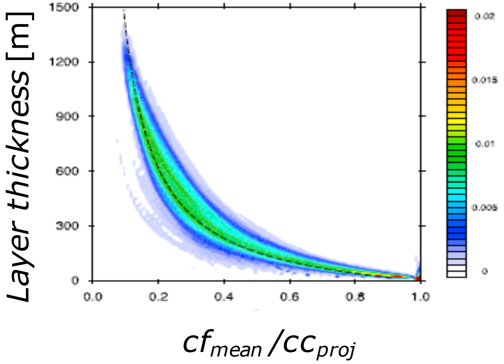
Contact: sophia.schaefer@dwd.de

vertical SGS cloud overlap (M.Köhler)

Neggers, Heus, Siebesma, 2011

Decorrelation length scale: 220m





LES simulation of BOMEX cumulus (dz=10m)

Corbetta, Orlandi, Heus, Neggers, Crewell, 2015

100-600m

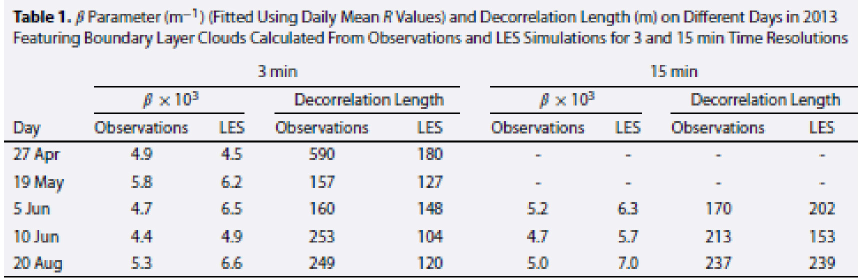


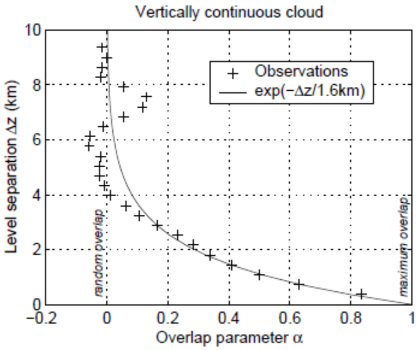
Table 1. *β* Parameter (m^{-1}) (Fitted Using Daily Mean *R* Values) and Decorrelation Length (m) on Different Days in 2013 Featuring Boundary Layer Clouds Calculated From Observations and LES Simulations for 3 and 15 min Time Resolutions

	3 min				15 min			
	$\beta \times 10^3$		Decorrelation Length		$\beta \times 10^3$		Decorrelation Length	
Day	Observations	LES	Observations	LES	Observations	LES	Observations	LES
27 Apr	4.9	4.5	590	180	-	-	-	-
19 May	5.8	6.2	157	127	-	-	-	-
5 Jun	4.7	6.5	160	148	5.2	6.3	170	202
10 Jun	4.4	4.9	253	104	4.7	5.7	213	153
20 Aug	5.3	6.6	249	120	5.0	7.0	237	239

Jülich cases LES forced by ECMWF (dz=40m)

Hogan, Illingworth, 2000

Decorrelation length scale: 1600m



Chilbolton, radar, dz=360m, dt=1h

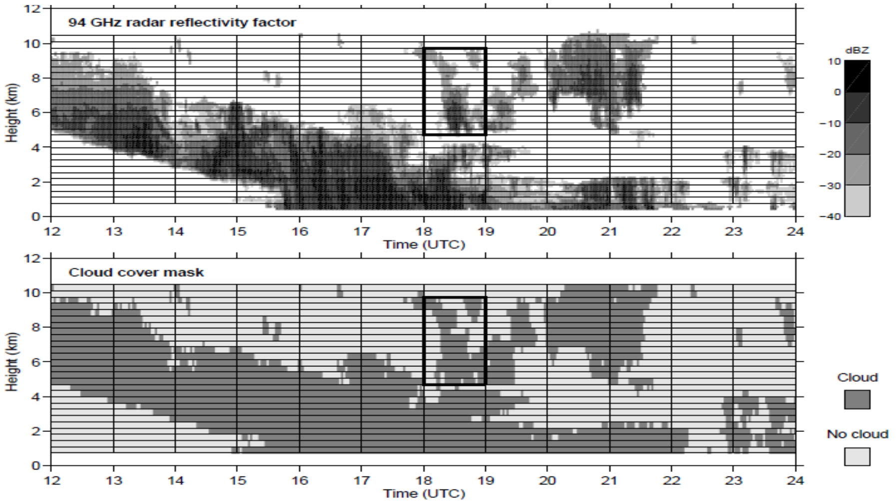
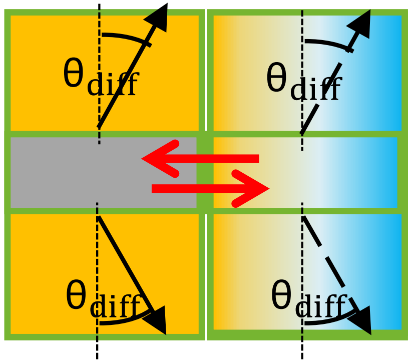


Figure 2. An example of cloud radar data used to derive the cloud cover mask, from 11 December 1998. Intermittent light drizzle was measured at the ground between 17 and 19 UTC. The resolution of the grid is 360 m and 1 hour.

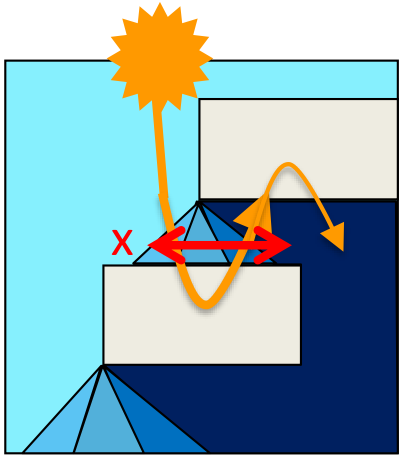
SPARTACUS: Incorporating 3D effects in a rapid radiation scheme

SPARTACUS radiation solver (SPeedy Algorithm for Radiative TrAnsfer through CloUd Sides, Schäfer et al., 2016, Hogan et al, 2016): cloud treatment based on 1D Tripleclouds solver, but includes 3D effects.

- Incorporate **3D cloud side effects** as additional terms in 2-stream calculation representing transfer between clear / cloudy regions ∝ cloud side area.



SPARTACUS treatment of cloud side transfer (left) and entrapment (right).



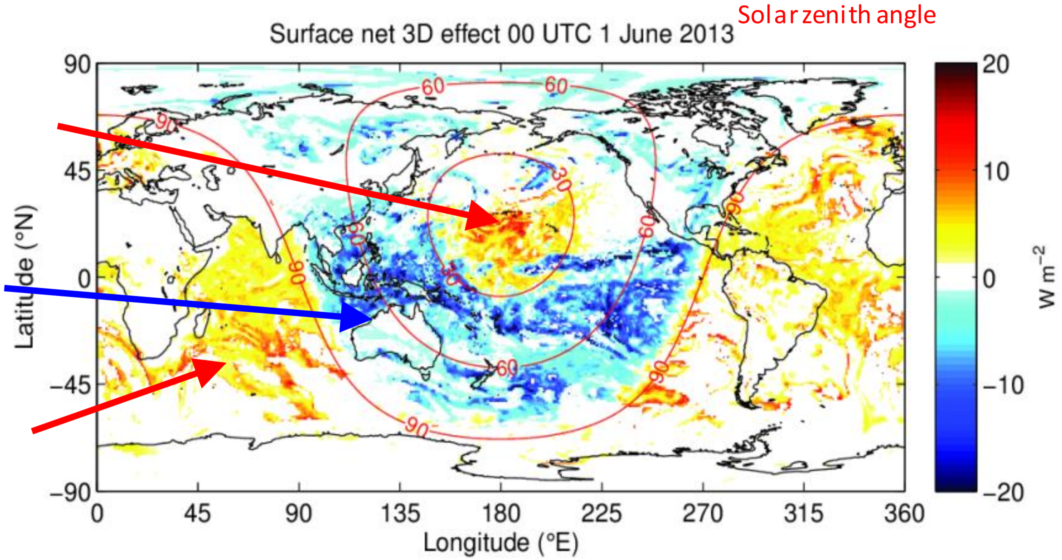
- **Entrapment**: Estimate mean horizontal path travelled x.

- SPARTACUS $10^4 - 10^7 \times$ cheaper than 3D Monte Carlo, suitable for global model.

Global 3D cloud side effects

Cloud side effects (instantaneous)

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



High sun:
positive SW escape

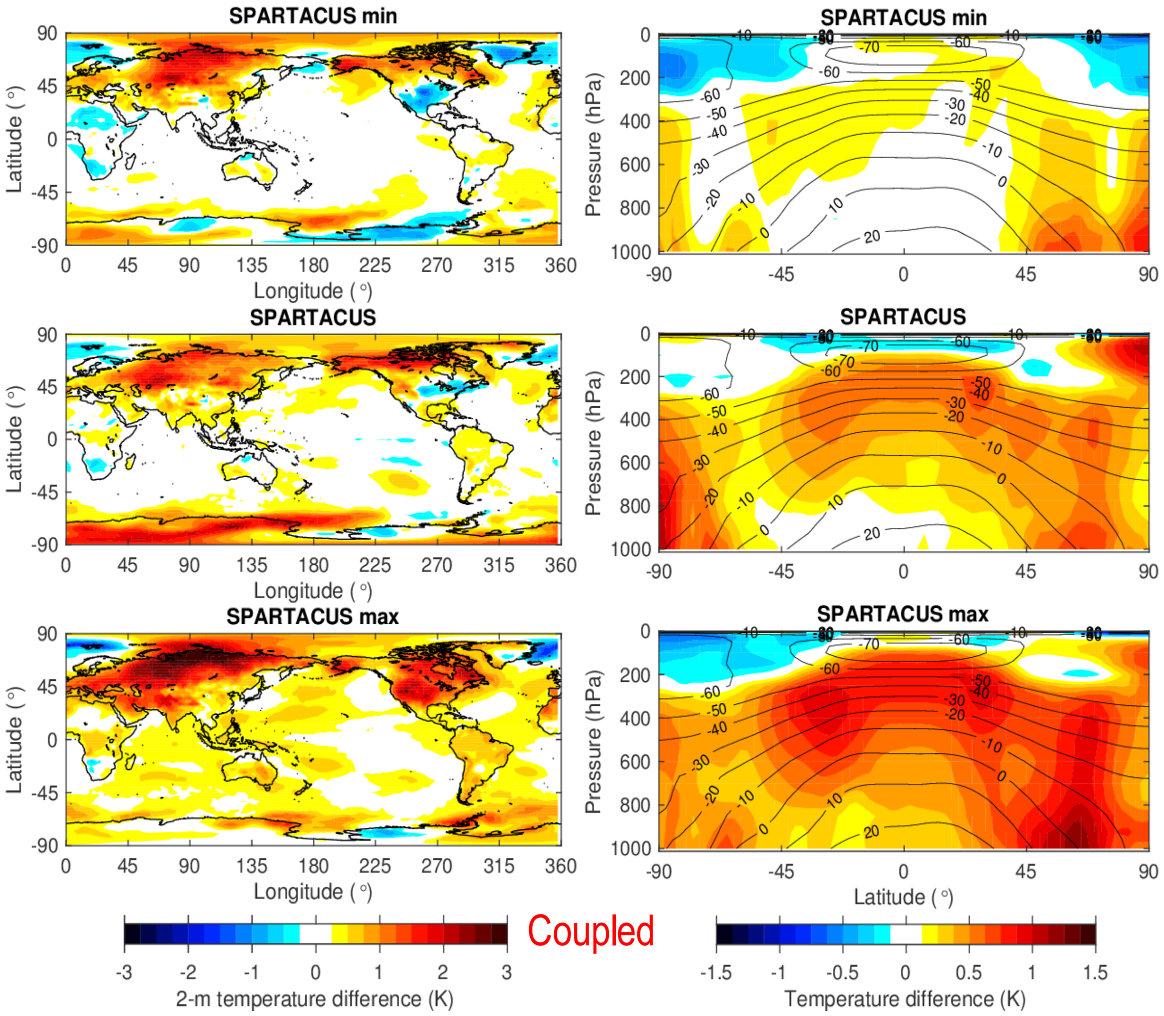
Low sun:
negative SW
interception

Night-time:
positive LW effect

Cloud side effects on net downward surface flux in ERA-Interim scene

Plot by R. Hogan

Global total 3D cloud effects



Total 3D effect on climate

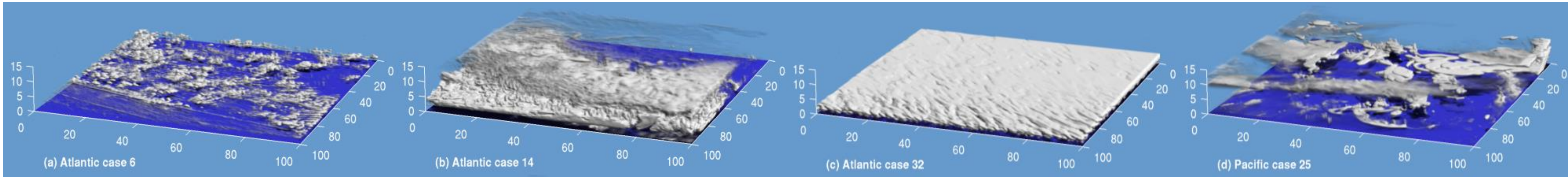
- **Global fluxes (net down, surface):**
  Longwave +1.6 Wm^{-2},
  Shortwave +0.8 Wm^{-2},
  Total +2.4 Wm^{-2}
- **Temperature increases** by around 1K.
- Depends on entrapment and cloud geometry (Schäfer et al., in prep.)

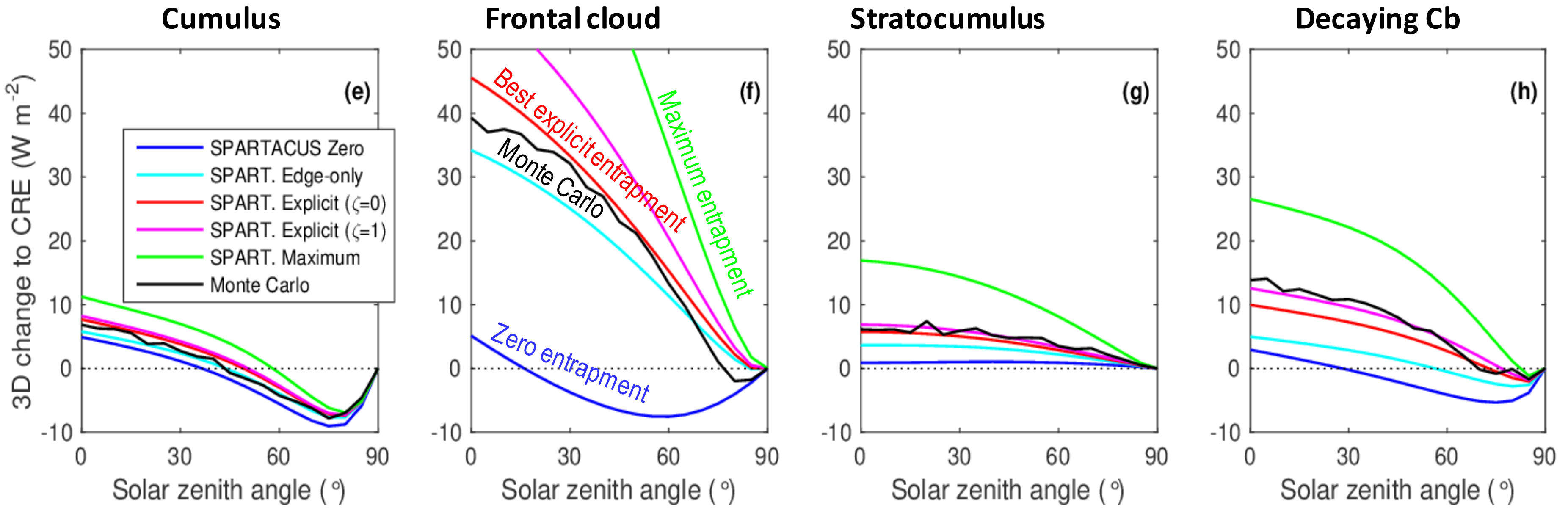
Mean 3D effect on temperature in four 1-year simulations with coupled ocean, with minimum (top) / calculated (middle) / maximum (base) entrapment.

Plots by R. Hogan

Shortwave 3D evaluation (Hogan et al., 2019, JAS)

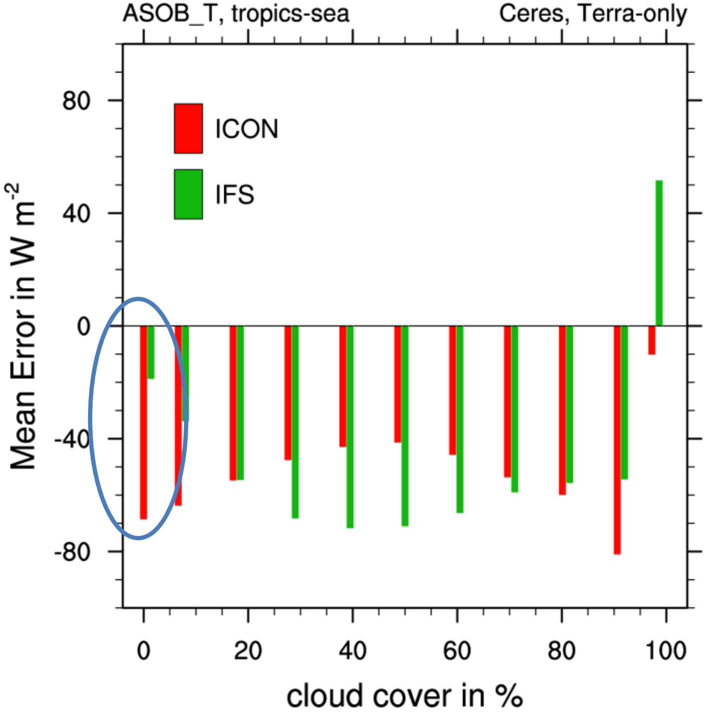
- SPARTACUS with **explicit entrapment** matches **Monte Carlo** well on average on 100 km x 100 km scenes
- Huge difference between **maximum entrapment** and **zero entrapment**

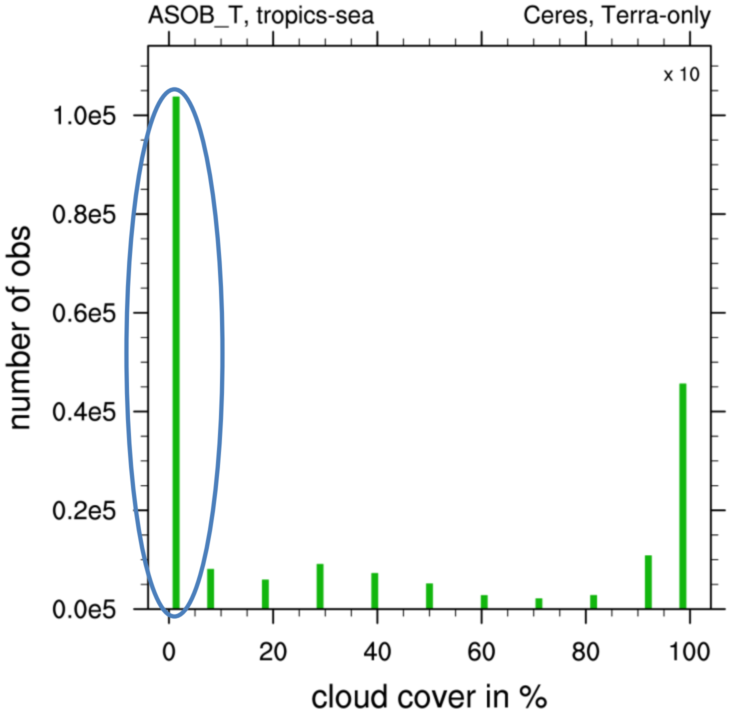




Plots by R. Hogan

ocean direct albedo



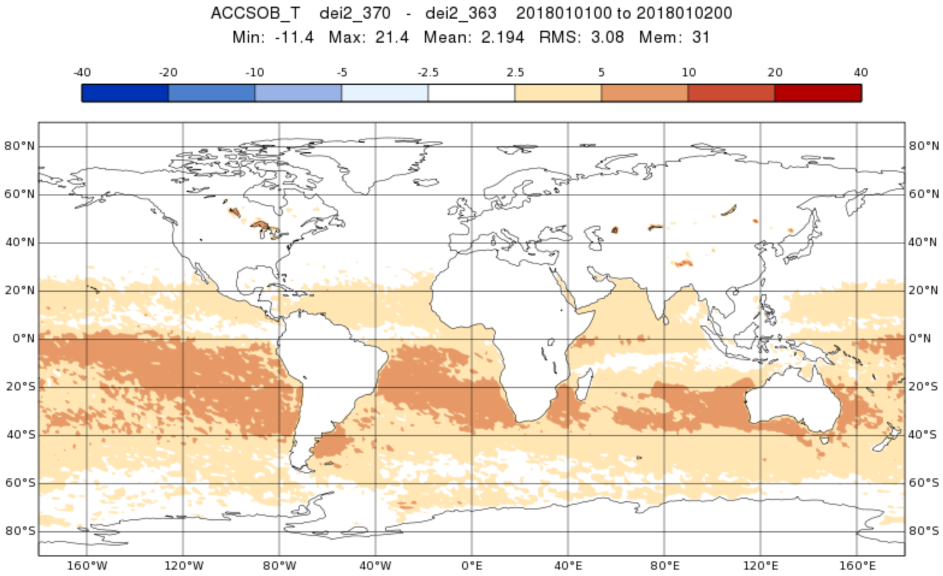


- ICON oper (13km)
- CERES TERRA (10:30am/pm at equator)
- compared colacated for consistent 25km grid

Axel Seifert, DWD

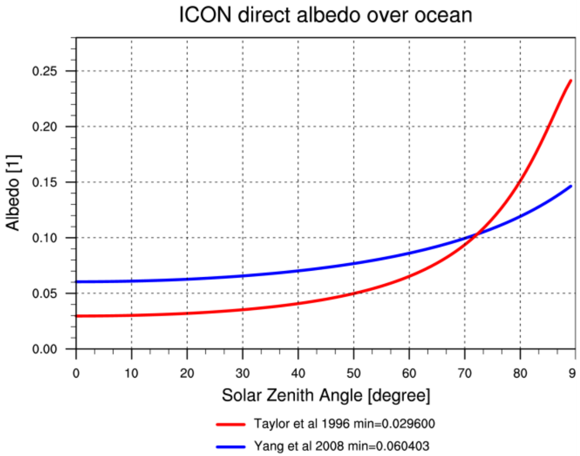
ocean direct albedo (M. Köhler)

difference IFS-ICON ocean direct albedo



mean difference: 2.194 W/m^2
ICON (40km), January 2018, 31 forecasts of 24h

- ICON: Yang et al. (2008)
- IFS: Taylor et al. (1996)



Try other parametrisations (potentially also for waves / whitecaps)