Uncertainties, stochastic and deterministic components in radiation modelling

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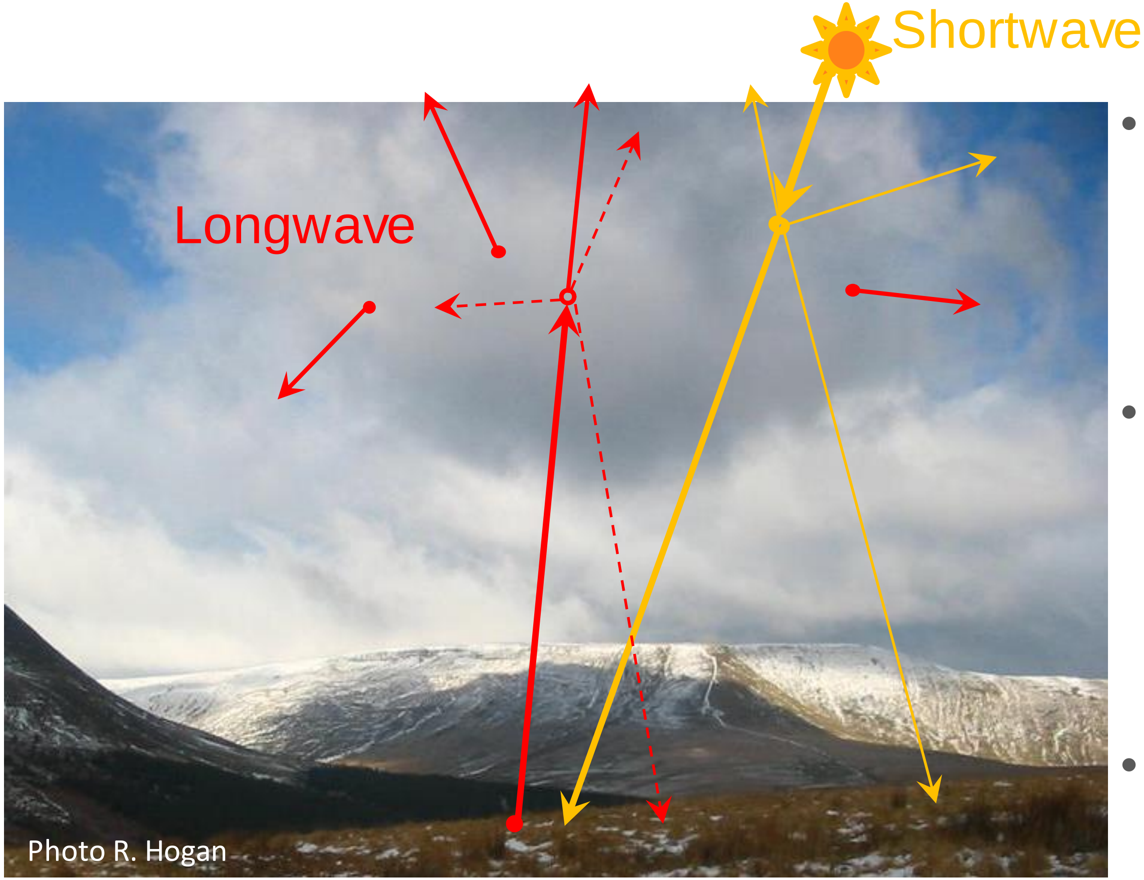
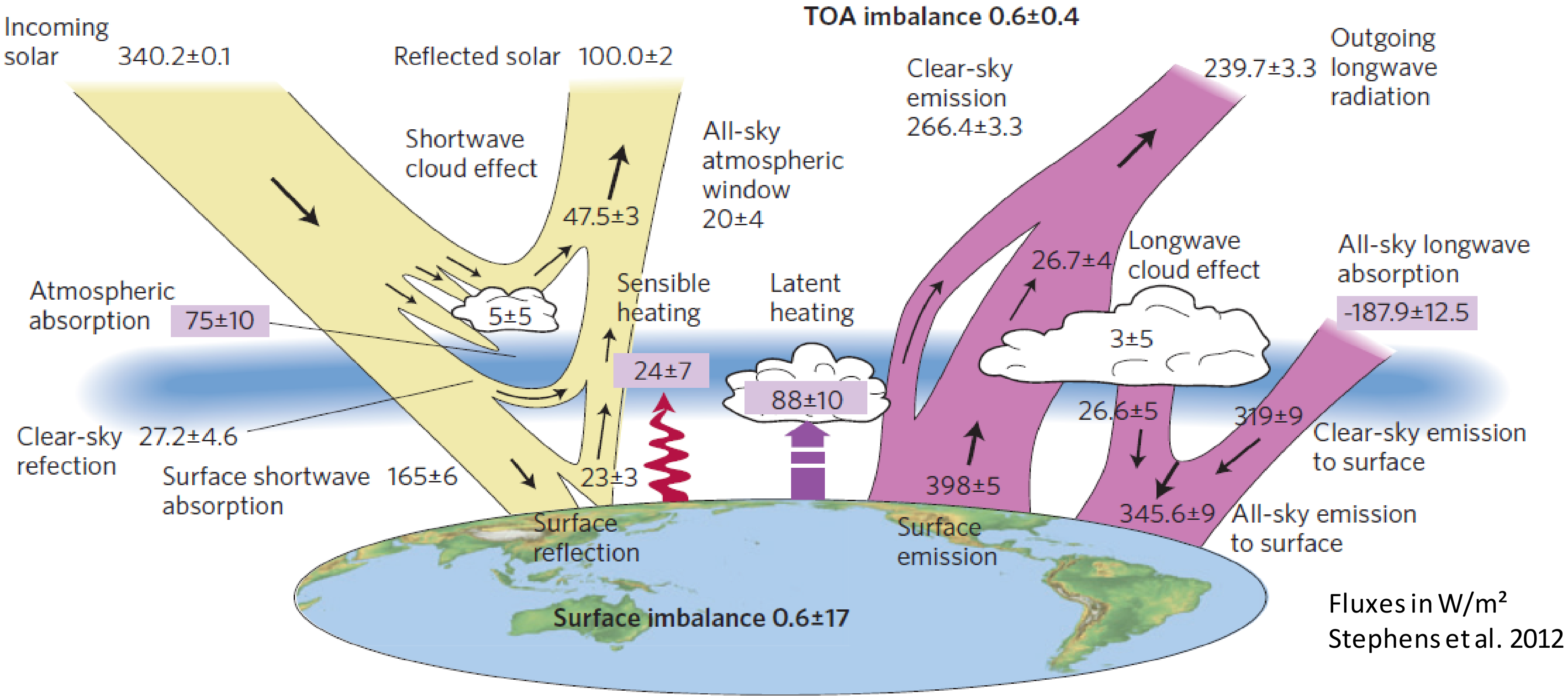
Radiation: From photons …



- Visible / thermal photons interact with surface, atmospheric gases, aerosol, cloud water or ice particles
- Described by electromagnetic **Maxwell equations** and quantum mechanics, BUT can‘t treat every photon and atmospheric particle!
- Have to capture bulk effect of each component

… to global radiation budget, weather and climate

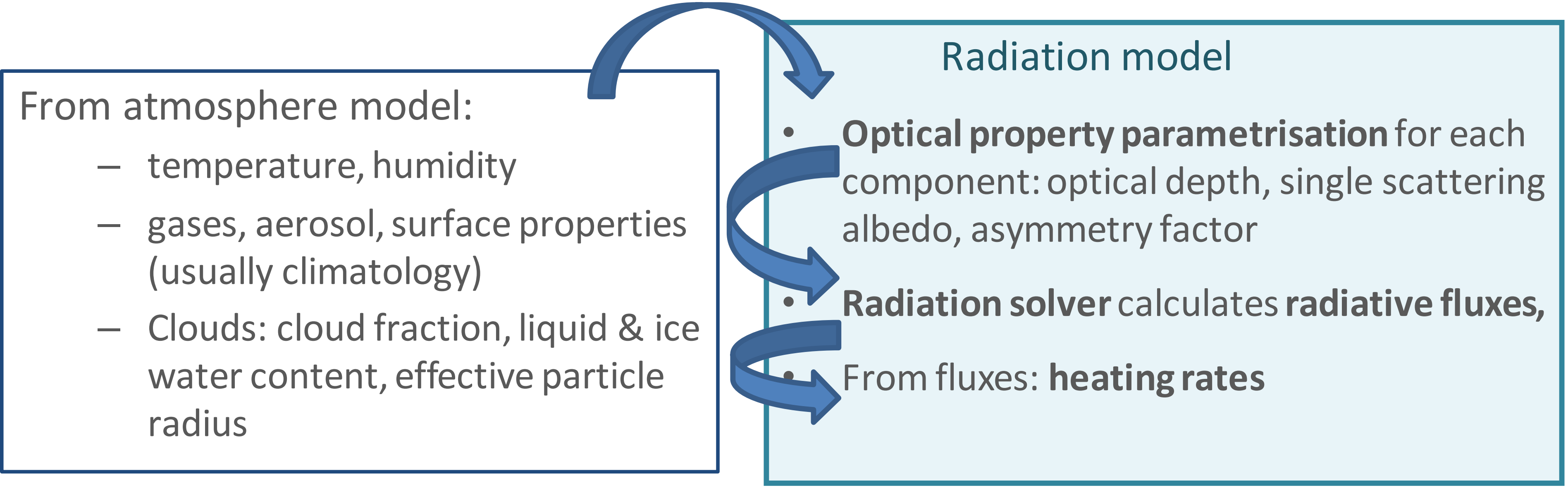


Fluxes in W/m²
Stephens et al. 2012

Radiation controls energy balance of Earth system, energy distribution throughout the atmosphere → drives weather and climate dynamics and physics

Anthropogenic climate change: 2 W/m² global radiation imbalance (Myhre et al. 2013)

Radiation scheme in global model



From atmosphere model:

- temperature, humidity
- gases, aerosol, surface properties (usually climatology)
- Clouds: cloud fraction, liquid & ice water content, effective particle radius

Radiation model

- **Optical property parametrisation** for each component: optical depth, single scattering albedo, asymmetry factor
- **Radiation solver** calculates **radiative fluxes,**
- From fluxes: **heating rates**

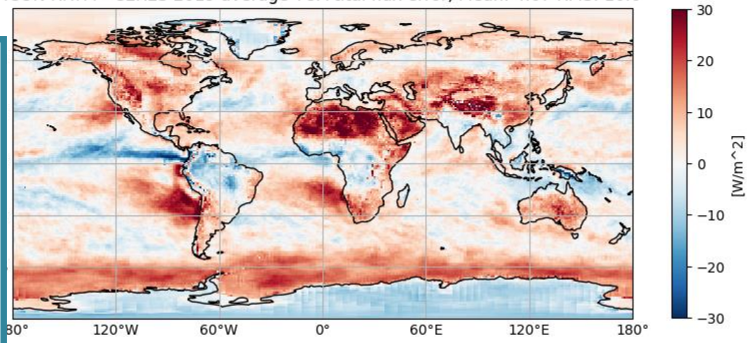
- Radiative fluxes depend on atmosphere input + radiation scheme parametrisations to make calculation practical; for efficiency use coarser radiation grid, long radiation timestep
- Model tuned to top-of-atmosphere radiative fluxes (directly observable)
- ICON: RRTM radiation scheme, from early 2021: ecRad (Hogan & Bozzo 2018)

Impact of ecRad radiation scheme, c_p/c_v-Bugfix, Tuning

Total TOA net radiation flux biases vs. CERES 2019

Routine: c_p/c_v-Bug, tuned RRTM

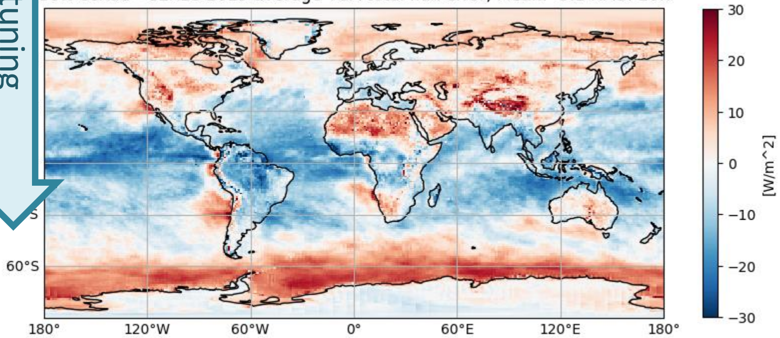
ICON RRTM - CERES 2019 average TOA tital flux error, Mean: 4.07 RMS: 10.6



c_p/c_v-Bugfix, ecRad, tuning

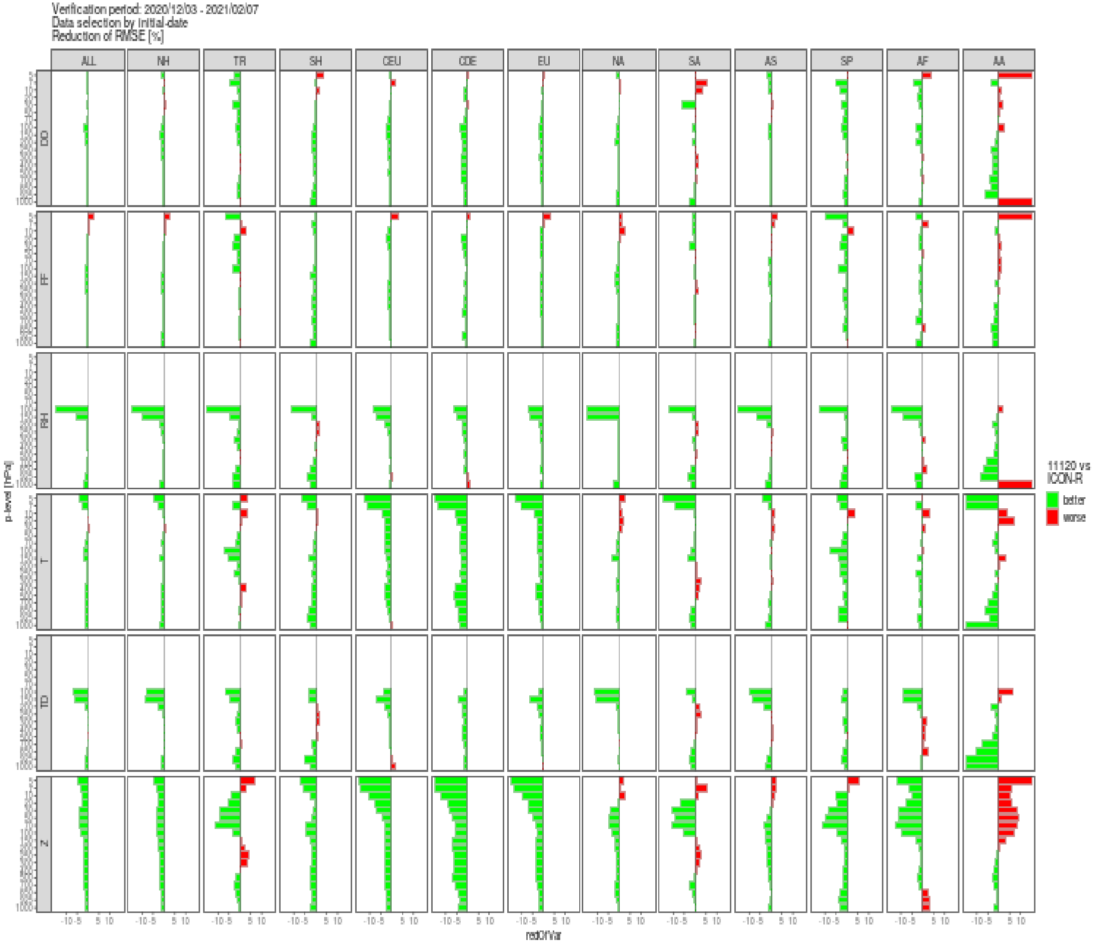
Total flux bias change:
7 W/m² global

CON ecRad - CERES 2019 average TOA total flux error, Mean: -3.1 RMS: 10.7



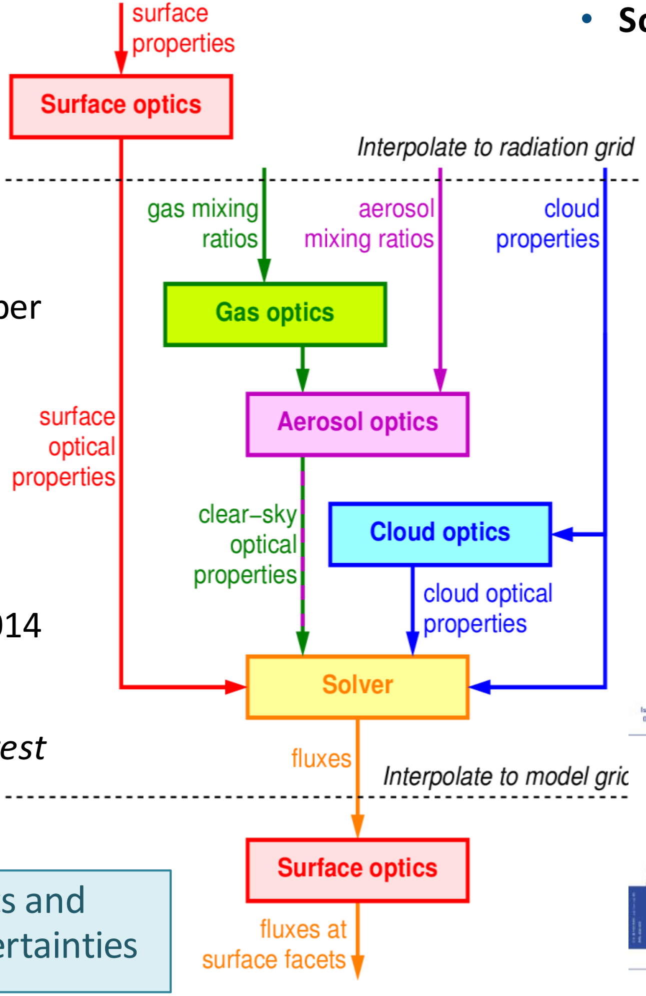
Parallel routine: c_p/c_v-Bugfix, ecRad+LW scat., new emissivity

Upper air verification (2021, G. Zängl): Parallel routine significant improvement in most variables and regions



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

- **Gas optics:**
  - RRTMG (Iacono et al. 2008)
  - *ecCKD (Hogan 2010 JAS, under development): Fewer spectral intervals but similar precision*
- **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) Consistent treatment of urban and forest canopies*



surface properties

Surface optics

Interpolate to radiation grid

gas mixing ratios

aerosol mixing ratios

cloud properties

Gas optics

Aerosol optics

surface optical properties

clear–sky optical properties

Cloud optics

cloud optical properties

Solver

fluxes

Interpolate to model gric

Surface optics

fluxes at surface facets

- **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 sub-grid **3D** radiative effects
  - Longwave scattering optional
  - Can configure **cloud overlap**
  - **Cloud inhomogeneity**: can configure width and shape of PDF

Issue 004

Reports on ICON

ecRad in ICON Implementation Overview

Daniel Rieger

November 2019

Implementation in ICON:

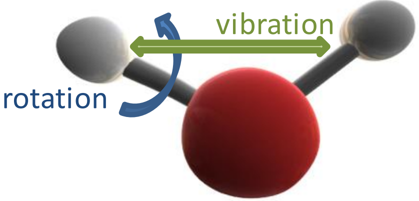
D. Rieger, M. Köhler, R. J. Hogan, S. A. K. Schäfer, A. Seifert, A. de Lozar and G.Zängl (2019): *ecRad in ICON – Implementation Overview*, Reports on ICON

> Modular: can vary optics components and solver individually to determine uncertainties

Radiation spectra and atmospheric gases

- Molecules have different modes (vibration, rotation)

Water molecule:



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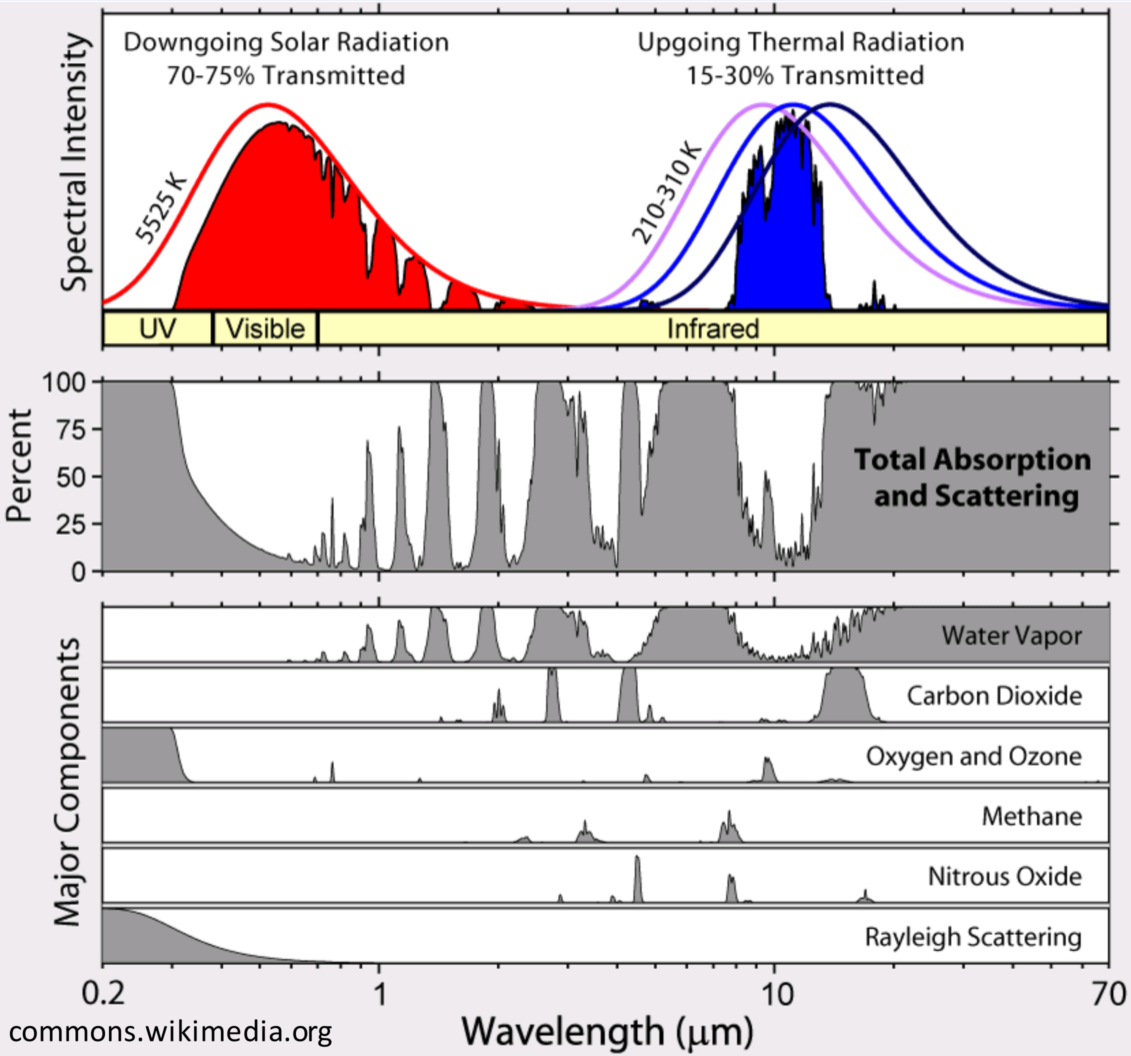
- Absorption / emission: distinct lines at energy steps → need high spectral resolution
- Divide spectrum into bands with similar Planck function, sub-divide and re-order into g-points to approximate gas absorption
- ICON uses RRTMG (Mlawer et al. 1997, Iacono et al. 2008): 14 bands in shortwave, 16 in longwave, ~200 g-points



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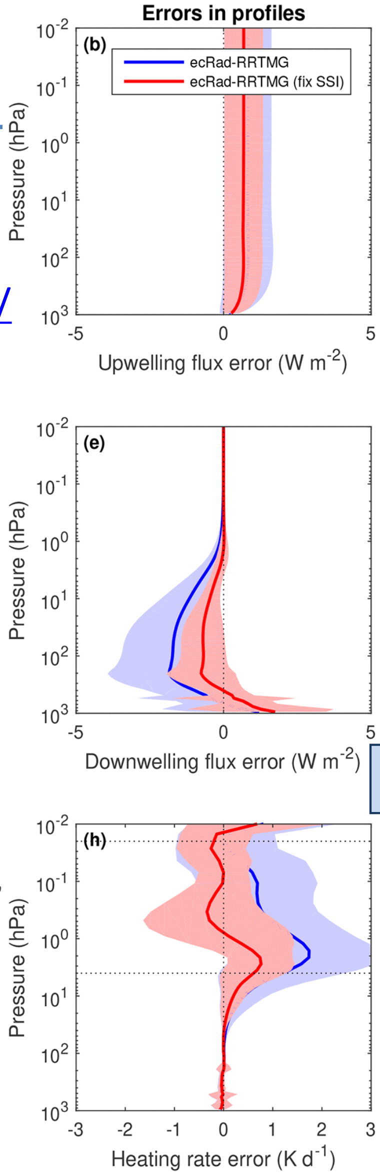
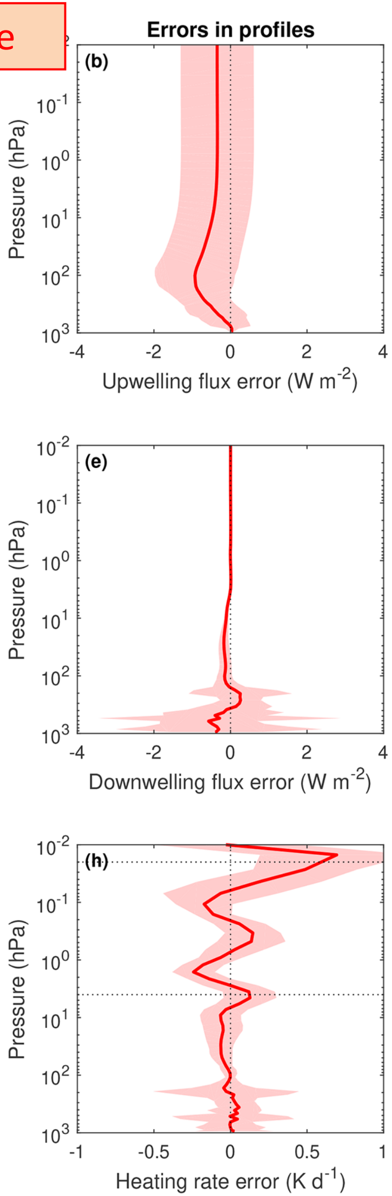
Gas model uncertainty

- CKDMIP project: evaluate against exact line-by-line calculations for 50 profiles (Hogan and Matricardi 2020, https://confluence.ecmwf.int/display/CKDMIP/)
- Shortwave: outdated band spectrum of solar incoming flux in RRTMG v.3.9 (2013) (blue lines) Scaling solar spectrum to Coddington et al. (2016) data (more visible, less UV) reduces ecRad-RRTMG biases (red lines) to 0 to 2 W/m²
- New whole-spectrum gas model ecCKD (R. Hogan): Up to 60% faster, lower biases, can be optimised for each application (weather, climate,…), could include several vesions in ensemble



Longwave

Scenario: Present-day (2020)
CKD model: ecRad-RRTMG
Bias TOA upwelling: -0.35 W m^{-2}
Bias surface downwelling: -0.40 W m^{-2}
RMSE TOA upwelling: 0.59 W m^{-2}
RMSE surface downwelling: 0.73 W m^{-2}
RMSE heating rate (0.02-4 hPa): 0.194 K d^{-1}
RMSE heating rate (4-1100 hPa): 0.106 K d^{-}



Shortwave

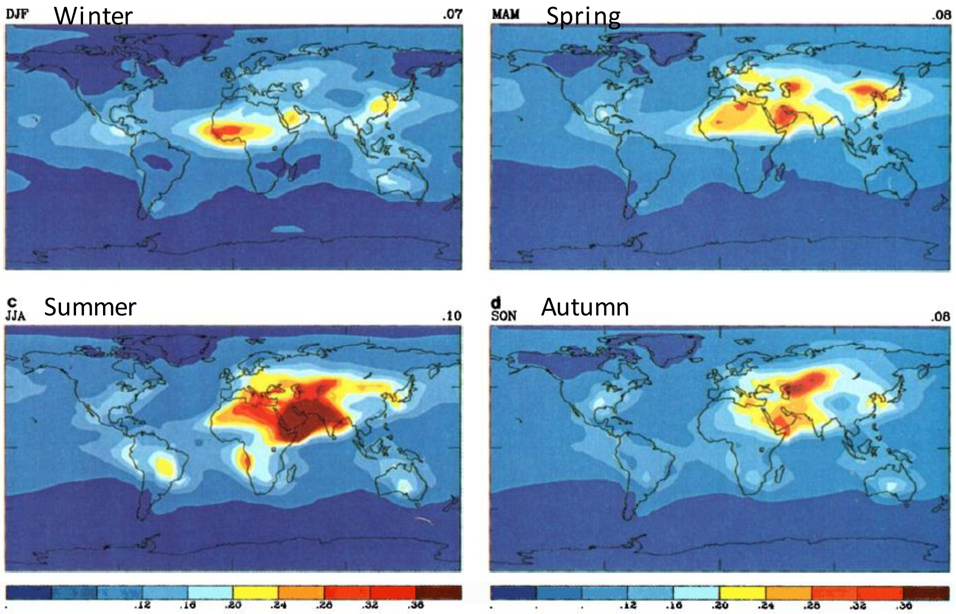
Scenario: Present-day (2020)
CKD model: ecRad-RRTMG (fix SSI)
Bias TOA upwelling: 0.68 W m^{-2}
Bias surface downwelling: 1.75 W m^{-2}
RMSE TOA upwelling: 0.76 W m^{-2}
RMSE surface downwelling: 1.96 W m^{-2}
RMSE heating rate (0.02-4 hPa): 0.660 K d^{-1}
RMSE heating rate (4-1100 hPa): 0.136 K d^{-1}

Hogan and Matricardi (2020)

Gas, Aerosol and surface input property uncertainty

- **Gases:** mixing ratio constant /profile
  some (little) variability missing

- **Aerosols:** monthly climatology of **optical properties** in external parameter file (default: Tegen et al. 1997); Alternatives: aerosol advection, ICON-ART: advection, chemistry + optical properties
  Variability missing: in IFS represented in SPP (Lang et al 2021); ICON uncertainty estimation in progress (PP CAIIR)



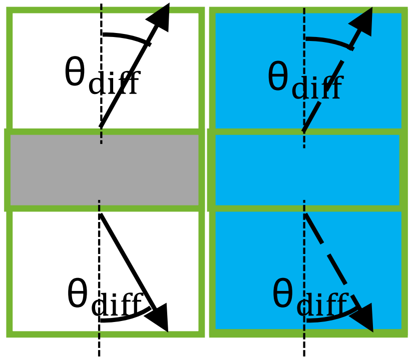
Total aerosol optical depth in Tegen et al. (1997) climatology

- **Surface** albedo and emissivity: monthly climatology, modified for soil moisture, snow, sea ice
  Surface property uncertainty: ~2W/m² globally

Radiation solver: Two-stream equations

- Simplifications (→ systematic model uncertainties)
  - ignore phase, polarisation
  - only treat up-/downward flux instead of radiances in all directions (2 streams)
  - scattering phase function described by one parameter: asymmetry factor g
  - cloudy and homogeneous clear region of gridbox (strong effects of sub-grid clouds)

- Treat direct solar radiation separately; Diffuse radiation: assume solar zenith angle θ_{diff} to approximate integral over angles



$$\frac{dF^{\downarrow}_{\text{clear}}}{dz} = \beta_{\text{ext}}\left(\boxed{\begin{array}{l}\text{Loss due to Extinction}\\ -\gamma_{1,\text{clear}}F^{\downarrow}_{\text{clear}}\end{array}} + \boxed{\begin{array}{l}\text{Gain from Scattering}\\ \gamma_{2,\text{clear}}F^{\uparrow}_{\text{clear}}\end{array}} + \boxed{\begin{array}{l}\text{Internal source}\\ S^{\downarrow}_{\text{clear}}\end{array}}\right)$$

$$-\frac{dF^{\uparrow}_{\text{clear}}}{dz} = \beta_{\text{ext}}\left(-\gamma_{1,\text{clear}}F^{\uparrow}_{\text{clear}} + \gamma_{2,\text{clear}}F^{\downarrow}_{\text{clear}} + S^{\uparrow}_{\text{clear}}\right)$$

- Multi-layer: need to know how clouds overlap vertically, also horizontal inhomogeneity
  Clouds largest uncertainty

Sub-grid cloud geometry in radiation solvers

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

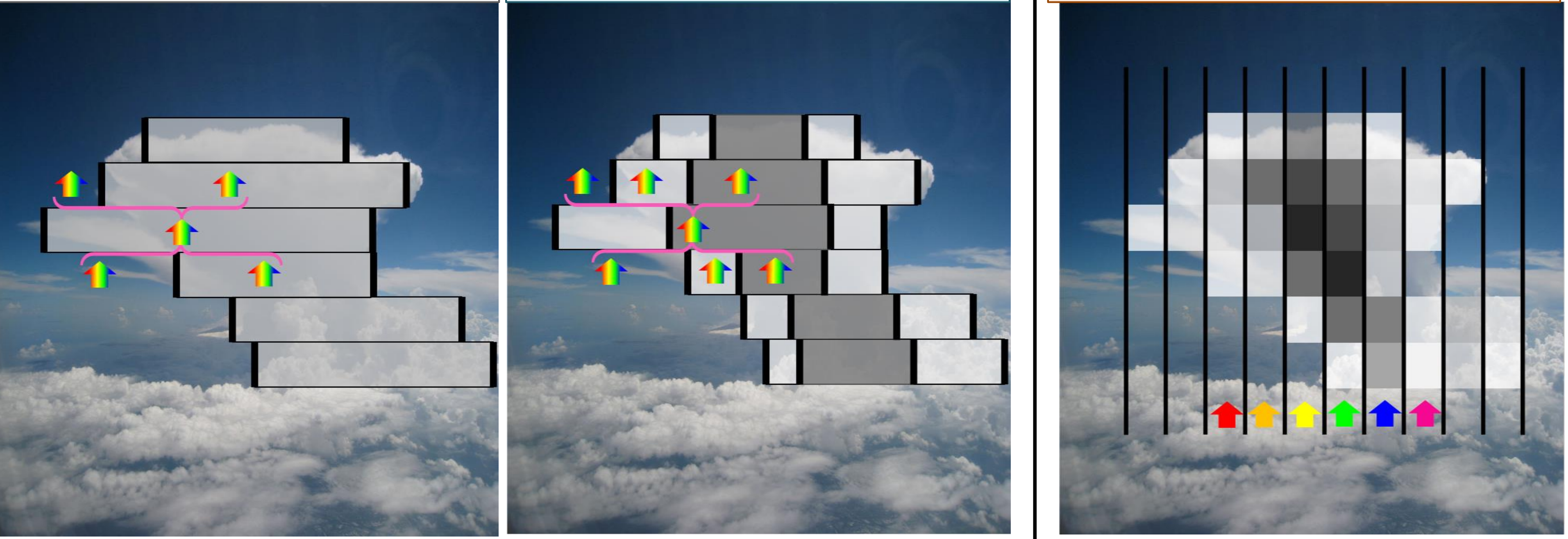
Deterministic:

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

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

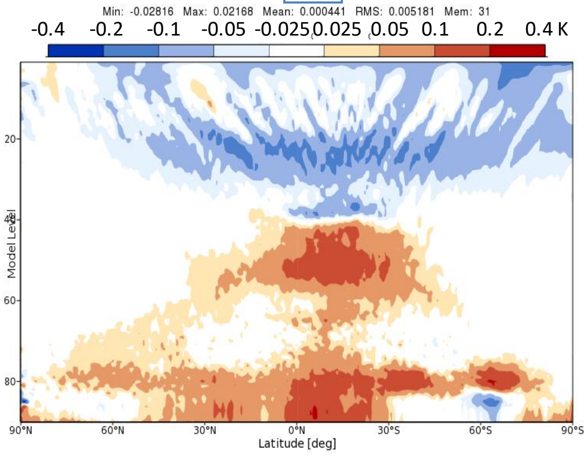
Stochastic:

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



Plots adapted from R. Hogan

Solver uncertainty in ICON+ecRad: Tripleclouds-McICA (Jan 2018, 24h runs)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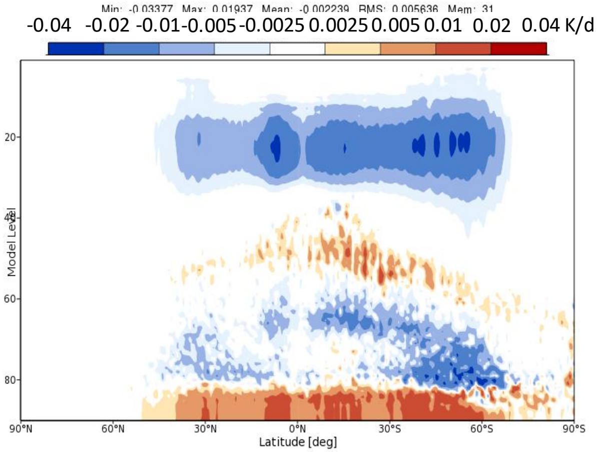
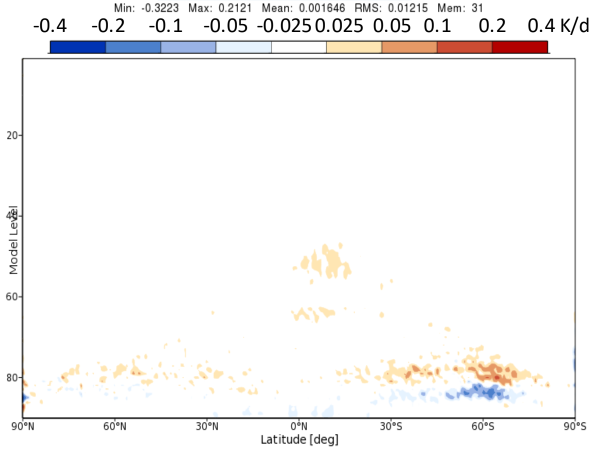
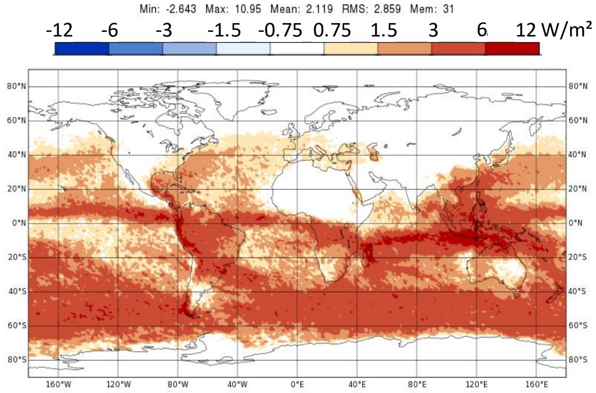
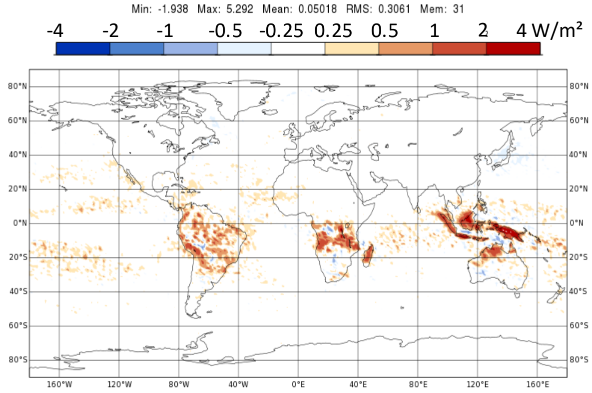

T SW tendency


T LW tendency

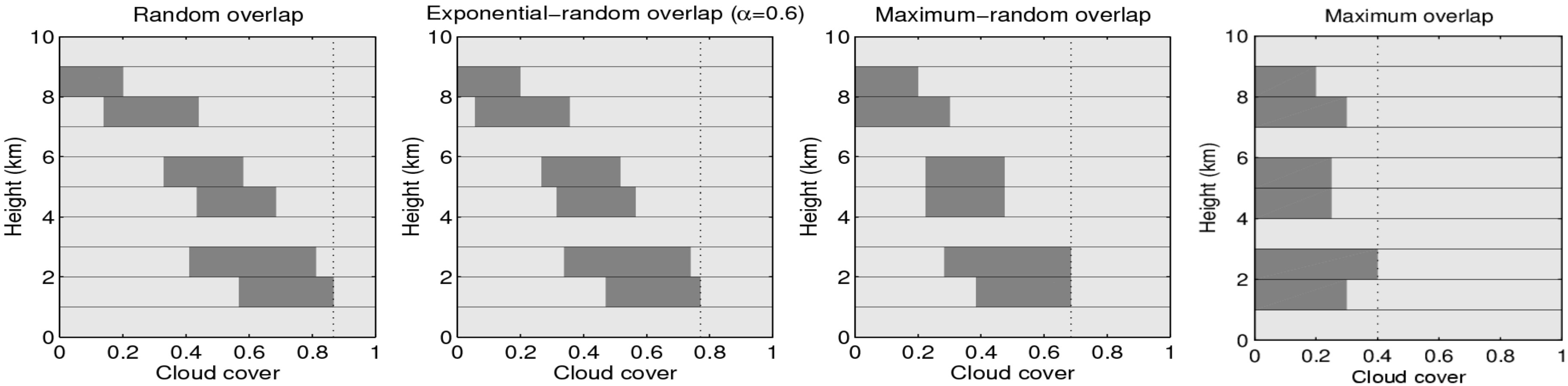
Sytematic differences (more similar settings available) + random variability in McICA


SW TOA flux


LW TOA flux

Cloud vertical overlap

- For given cloud fraction in each layer, **cloud overlap** decides total cloud cover

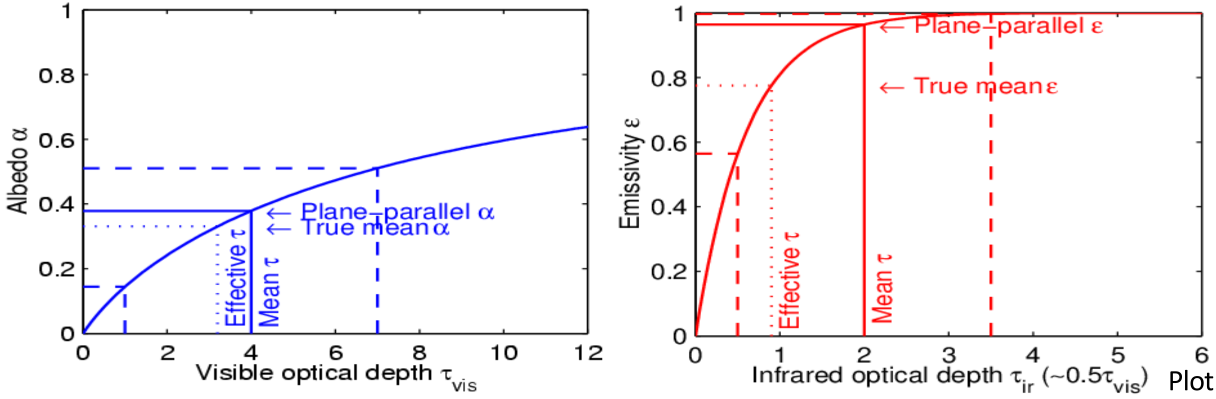


Adapted from Hogan & Illingworth 2000, QJRMS

- Based on observations (Hogan & Illingworth 2000): **exponential-random overlap,** decorrelation length ca. 2 km, small / BL cumulus: 100-600m (Neggers et al. 2011, Corbetta et al. 2015); Lang et al 2021: variation represented in SPP, mean 1 km;
- Realistically, decorrelation length should depend on situation / cloud type (Jing et al 2018, Sulak et al 2020, etc.)

Cloud inhomogeneity: fractional standard deviation

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

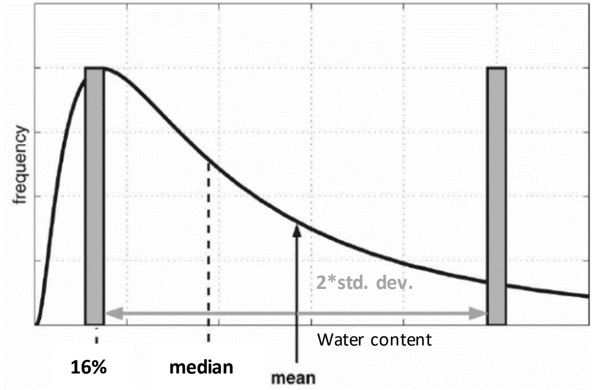


Plots by R. Hogan

- **ICON RRTM** reduces optical depth by factor 0.8 (COSMO 0.5)

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

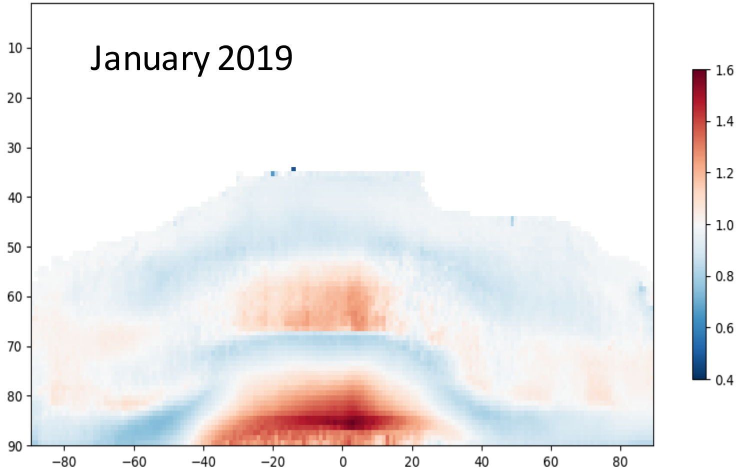
$\mathbf{fractional\ standard\ deviation} = \frac{\text{standard deviation}}{\text{mean}}$, in IFS represented in SPP (Lang et al 2021)

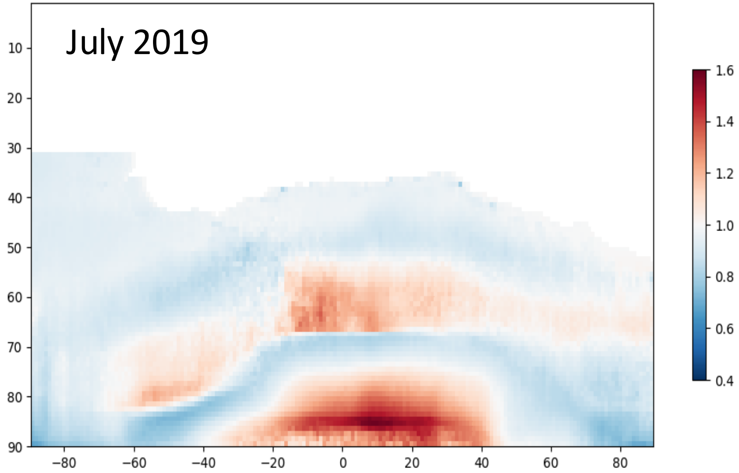


Adapted from Shonk & Hogan (2008)

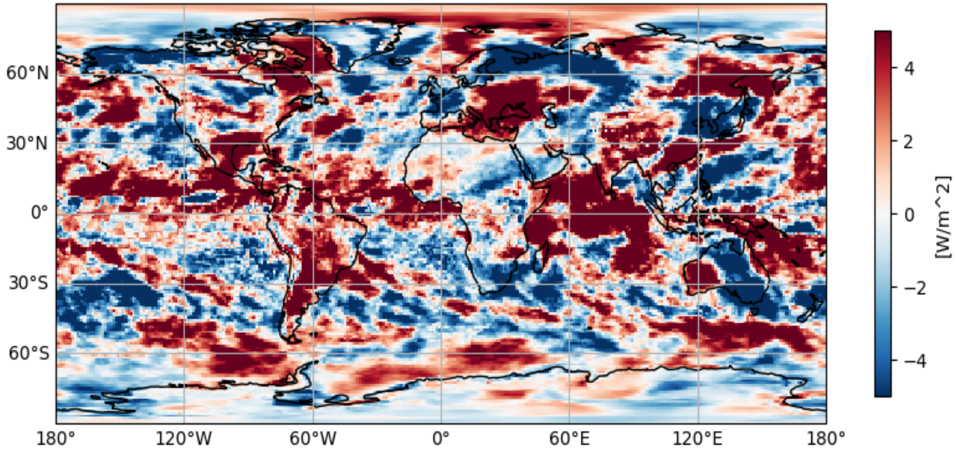
- **Tripleclouds**: two cloudy regions (equal size, preserve standard deviation of cloud water PDF)
- **McICA**: random number $\in [0,1]$ for each cloudy layer, correlated according to vertical inhomogeneity correlation; scale with cloud water PDF value at this percentile

Cloud fractional standard deviation (FSD) impact


Zonal-mean FSD, 201901 average, for gridpoints with clc>0


Zonal-mean FSD, 201907 average, for gridpoints with clc>0

Zonal mean parametrised in-cloud FSD

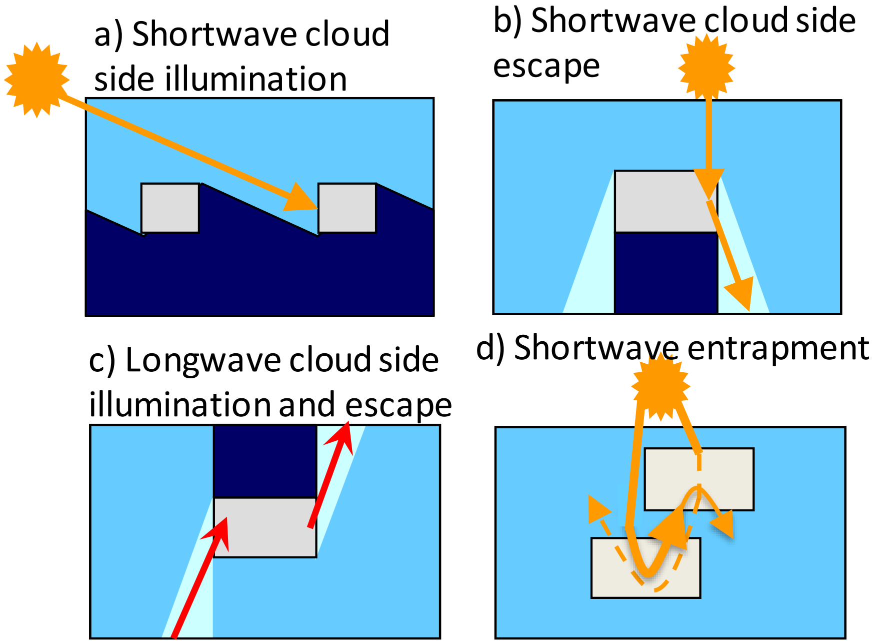

ICON fsd_ecrad - ICON fsd1_ecrad 2019 average TOA shortwave flux error, Mean: 0.778 RMS: -0.418

Change in SW TOA flux 2019: parametrised FSD vs FSD=1

FSD parametrised by cloud type (Ahlgrimm and Forbes 2016, 2017) changes SW flux by 0.8 W/m^2 globally, LW by 0.1 W/m^2, synoptic noise

→Need longer run for clearer signal

3D cloud effects



a) Shortwave cloud side illumination

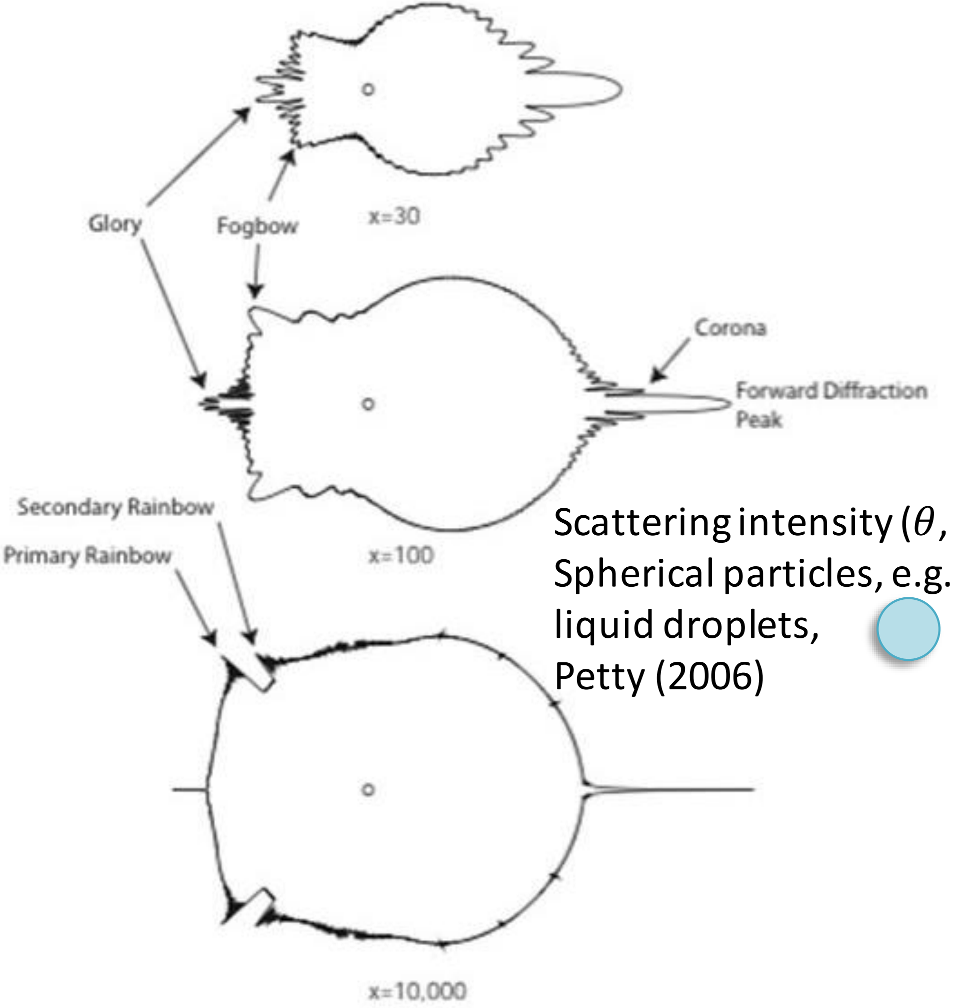
b) Shortwave cloud side escape

c) Longwave cloud side illumination and escape

d) Shortwave entrapment

- **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 effects at complex surfaces (trees / mountains / buildings)
- **Usually neglected, SPARTACUS** solver in ecRad can treat them
- **Globally**: total flux change 2 to 3 W/m^2, warms Earth by $\sim 1K$, locally higher

Cloud particle optics



Scattering intensity (θ, x)
Spherical particles, e.g.
liquid droplets,
Petty (2006)

Cloud particles: $r \sim \lambda \rightarrow$ **Mie scattering:** complex function of scattering angle

- Simplify in 3 bulk optical parameters: **optical depth** τ, **single scattering albedo** $\omega = \frac{\tau_{scat}}{\tau_{scat}+\tau_{total}}$, **asymmetry parameter** $g = \frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi} p(\theta)\cos(\theta)\, d\phi\, d\theta$

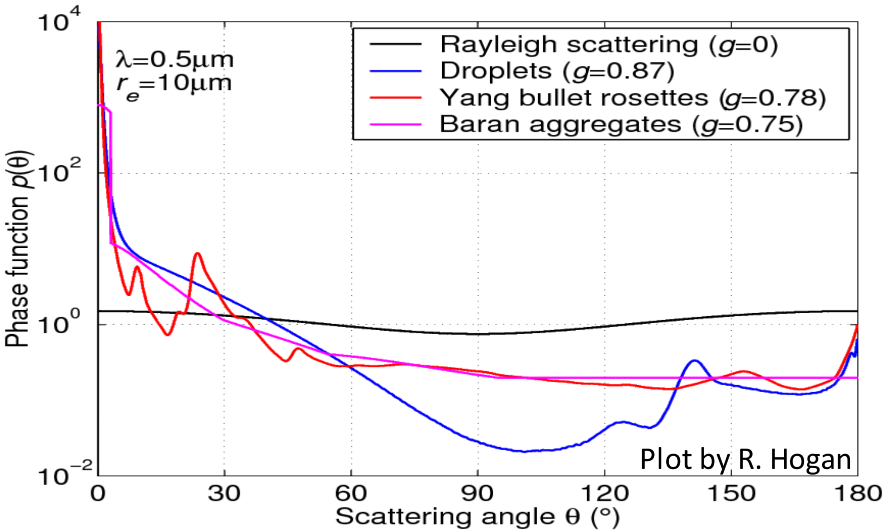
  = forward – backward scattering

- Optics look-up tables: τ, ω, g(water content, particle size)

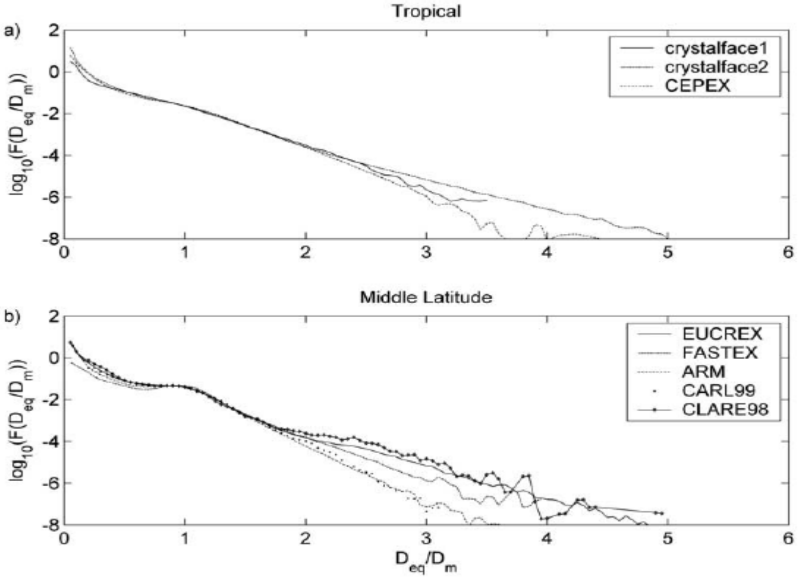
Ice particle shape and effective radius

- Complex **ice particle shapes** → shape assumptions
- Fu ice optics (Fu 1996, 1998, default in ICON): hexagonal colu

- Alternatives in ecRad: Yi ice optics (Yi et al. 2013), Baran ice optics (Baran et al. 2014): ice habit mixtures – **precipitation neglected**



Plot by R. Hogan

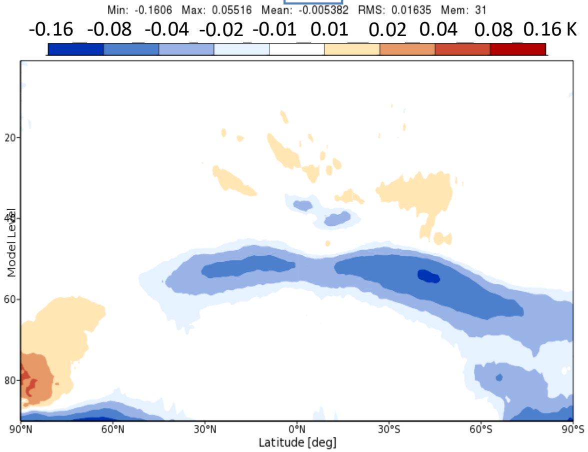


Cloud ice particle size distributions (Delanoë et al 2005)

- Mixture of particle sizes in clouds
- Parametrised input **effective radius**

  r_{eff}= mean radius weighted by number, area, scattering efficiency of each particle size
- Definition needs to agree with optics

Ice optics uncertainty in ICON+ecRad: Baran – Fu (Jan 2018, 24h runs)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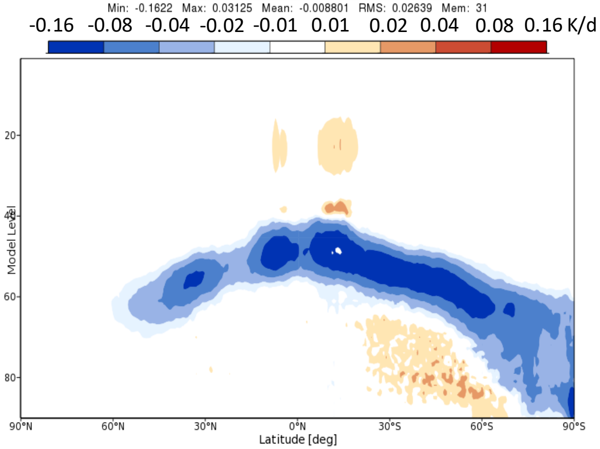
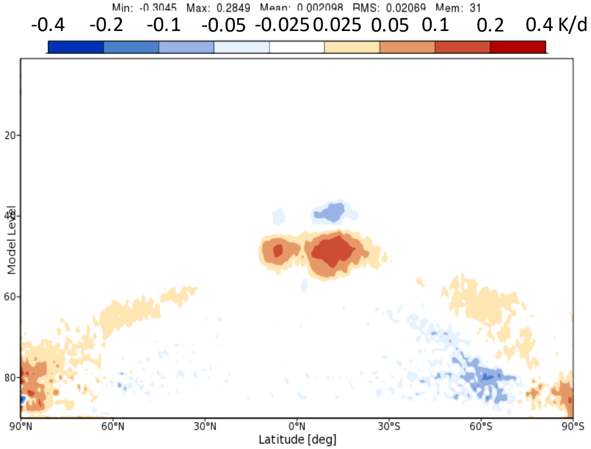
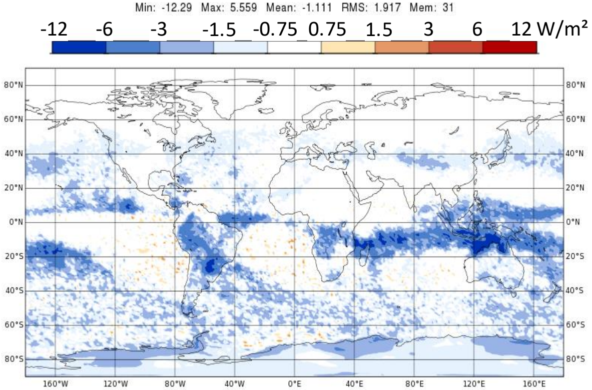
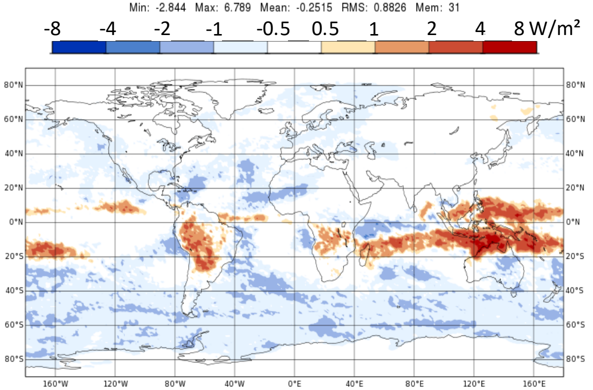

T SW tendency

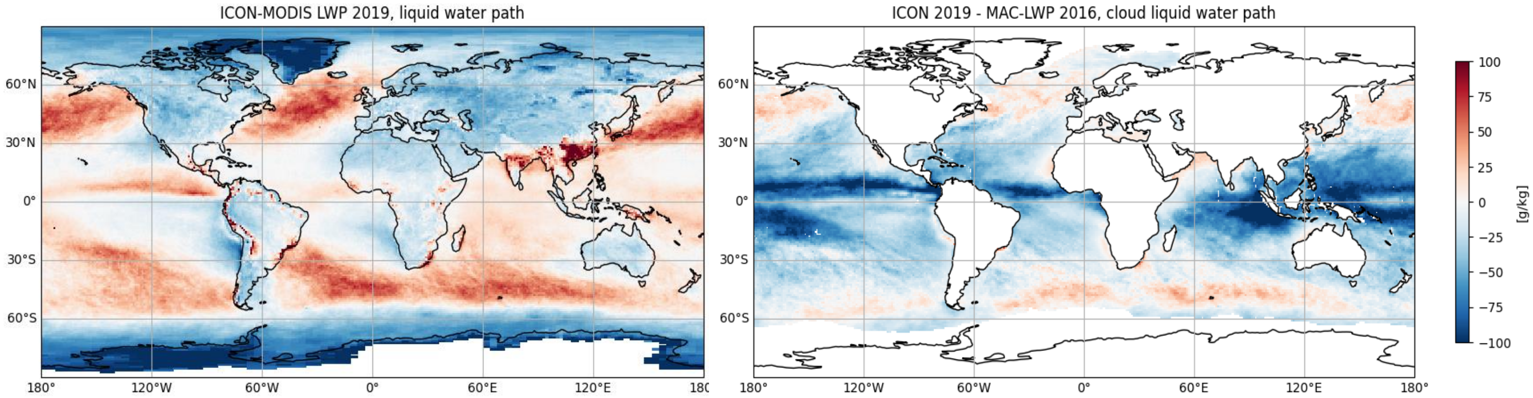

T LW tendency

- Considerable uncertainty in ice optics assumptions: ~2W/m² globally, ~10W/m² locally, not well constrained
- Need effective radius consistent with ice optics shape assumptions


SW TOA flux

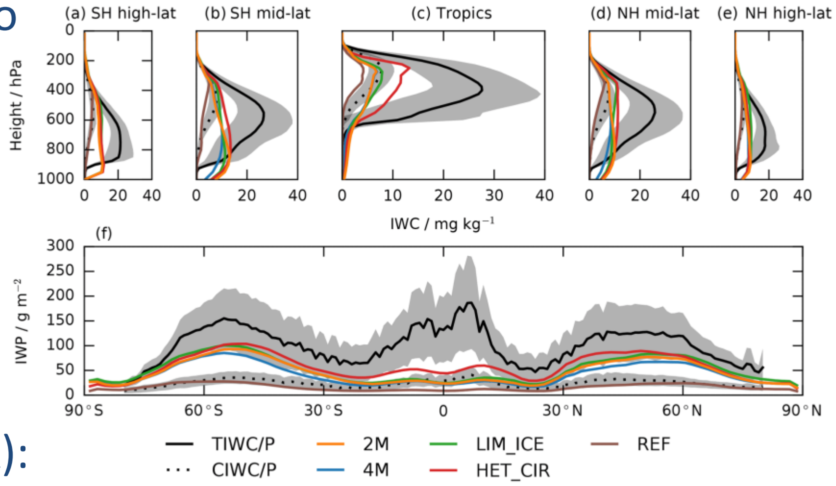

LW TOA flux

Cloud water content uncertainty



Cloud liquid water path bias in ICON 2019 compared to MODIS (left, 2019) and MAC-LWP (right, 2016-2019), by M. Ahlgrimm

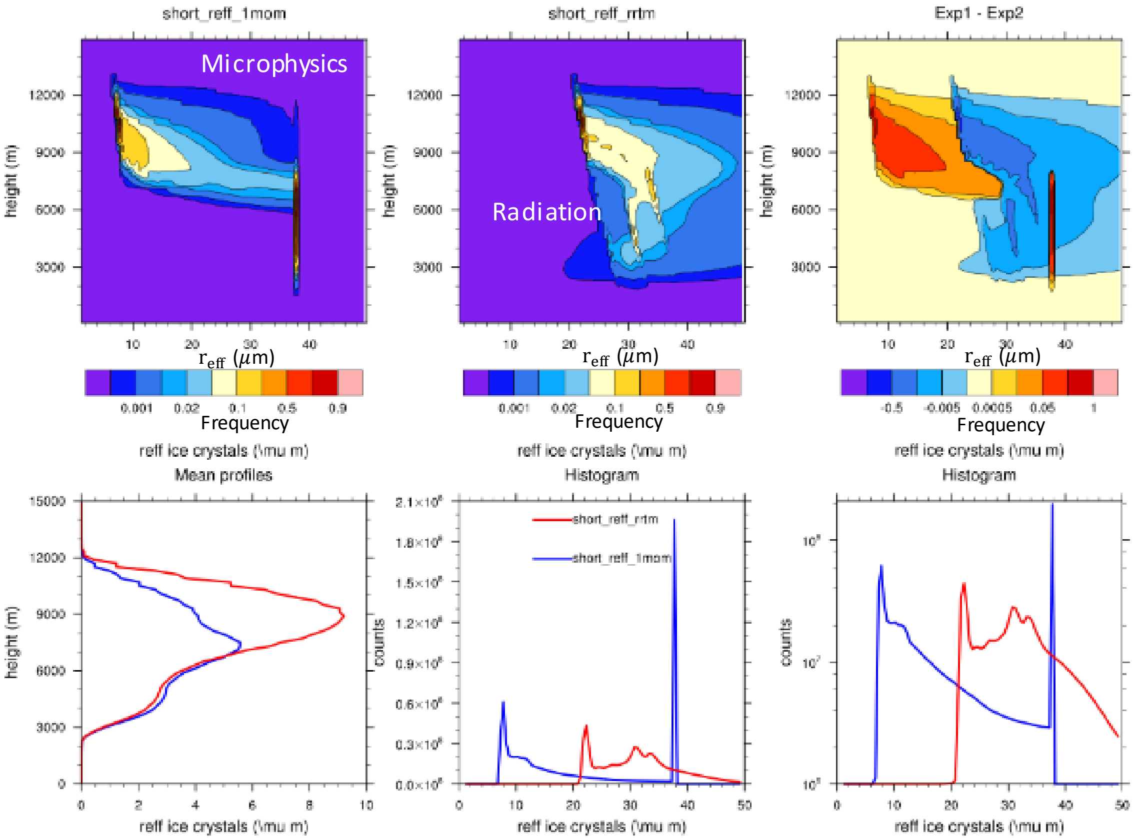
- Radiation does not consider precipitation, except to add 10% of snow to cloud ice - neglects 50 % (liquid) to 80% (ice, Li et al. 2012) of total water
- Uncertainty in retrievals and microphysics
- Models tuned to TOA radiation balance → cloud water content between observed cloud and total water content
- Ongoing work (with R. Hogan, A. de Lozar, PP CAIIR): **include** general number of particle species + optics for large particles → precipitation in ecRad



Cloud and total ice water path in ECHAM6.3 and CALIPSO-GOCCP (Dietlicher et al. 2019)

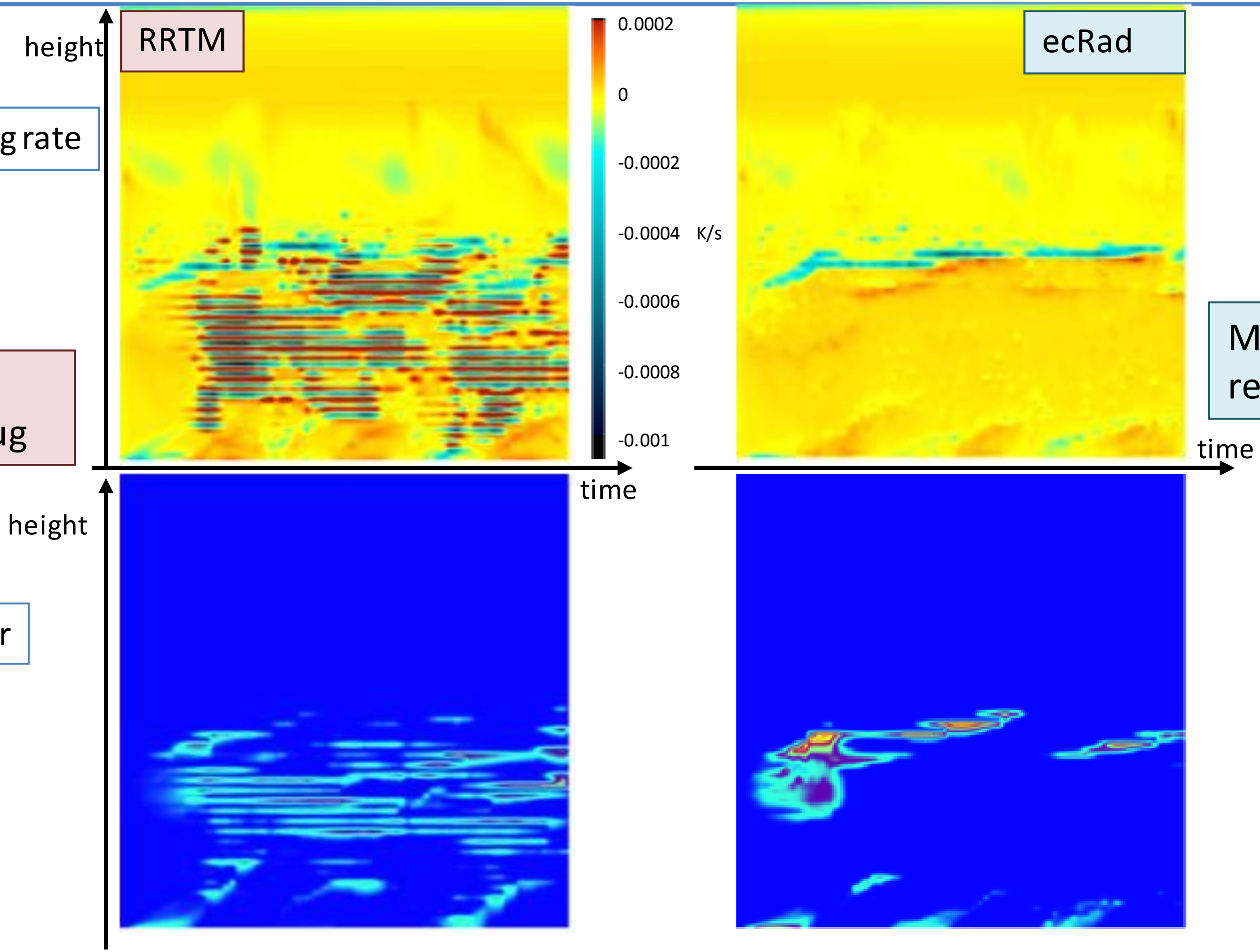
Cloud particle size parametrisation

- **Currently**: ice **effective radius** for radiation **independent** of and **inconsistent** with microphysics (liquid easier: spherical droplets)
- Ongoing work (Alberto de Lozar): effective radius for radiation consistent with 1-moment- or 2-moment-microphysics
- Could use stochastic microphysics for uncertainty (in IFS: SPP, Lang et al 2021)



Plots by A. de Lozar

Cloud feedback: ecRad versus RRTM in ICON single column model



Longwave heating rate

Heating rate oscillation bug

More realistic

Cloud water

Summary and Outlook

- Largest uncertainty in both radiation model and input: Clouds
- ecRad improves ICON, can vary optics parametrisations, solver, cloud overlap and inhomogeneity treatment → can estimate and include parameter and parametrisation uncertainty; stochastic treatment of cloud geometry
- Several components have uncertainties of 1 to 10 W/m²

Next steps:

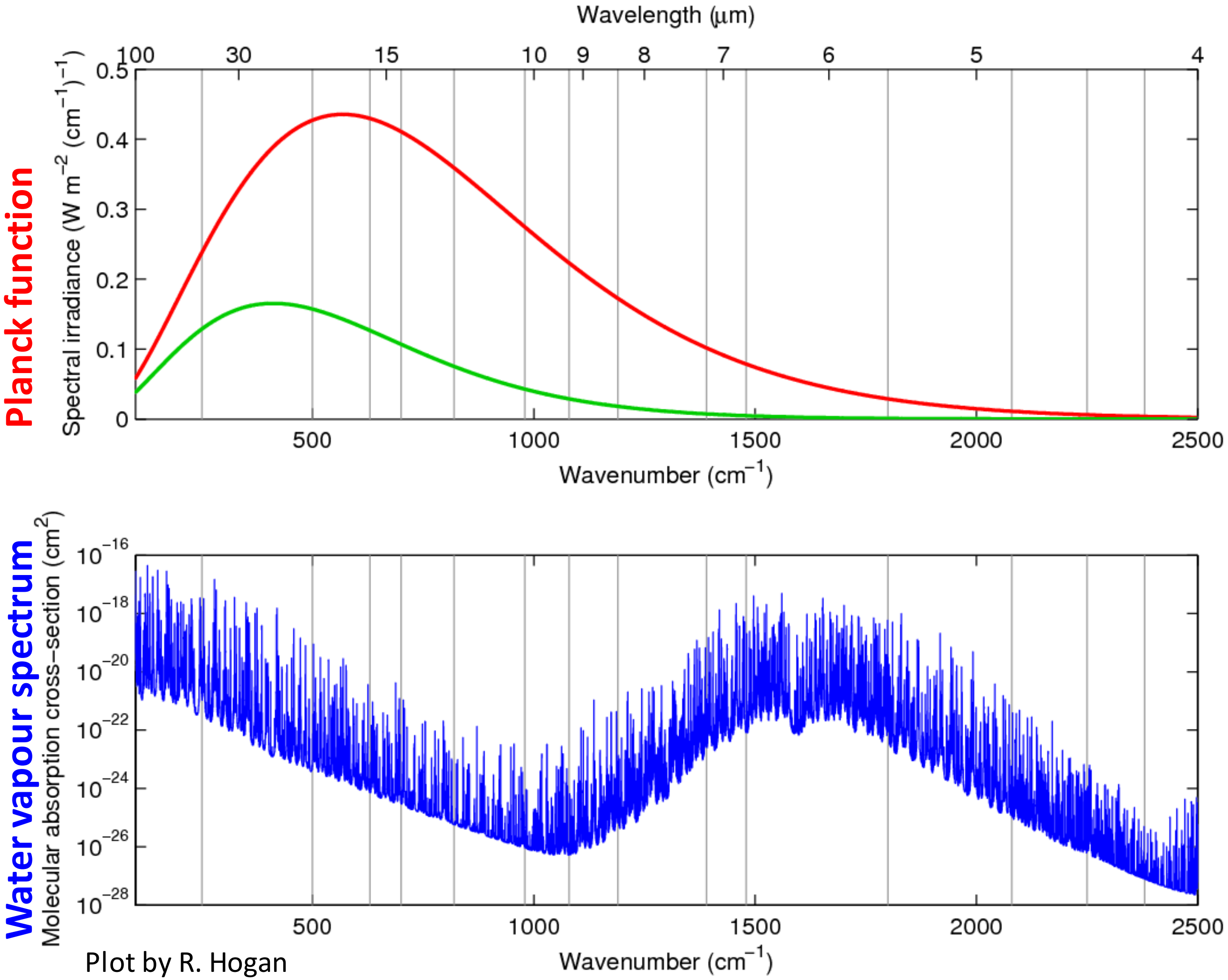
- General number of hydrometeor species → include snow, graupel, rain in radiation, evaluate and adjust water content in model
- Vary overlap and vertical decorrelation length parametrisation
- More consistent particle size and shape treatment
- Ensemble including ecRad parametrisation range?
- Ongoing model evaluation for all applications, incl. feedbacks

Thank you for your attention!

Contact: sophia.schaefer@dwd.de

Gas optics model: bands

- Divide spectrum into bands where Planck function is similar
- ICON uses RRTMG (Mlawer et al. 1997, Iacono et al. 2008): 14 bands in shortwave, 16 in longwave



Plot by R. Hogan

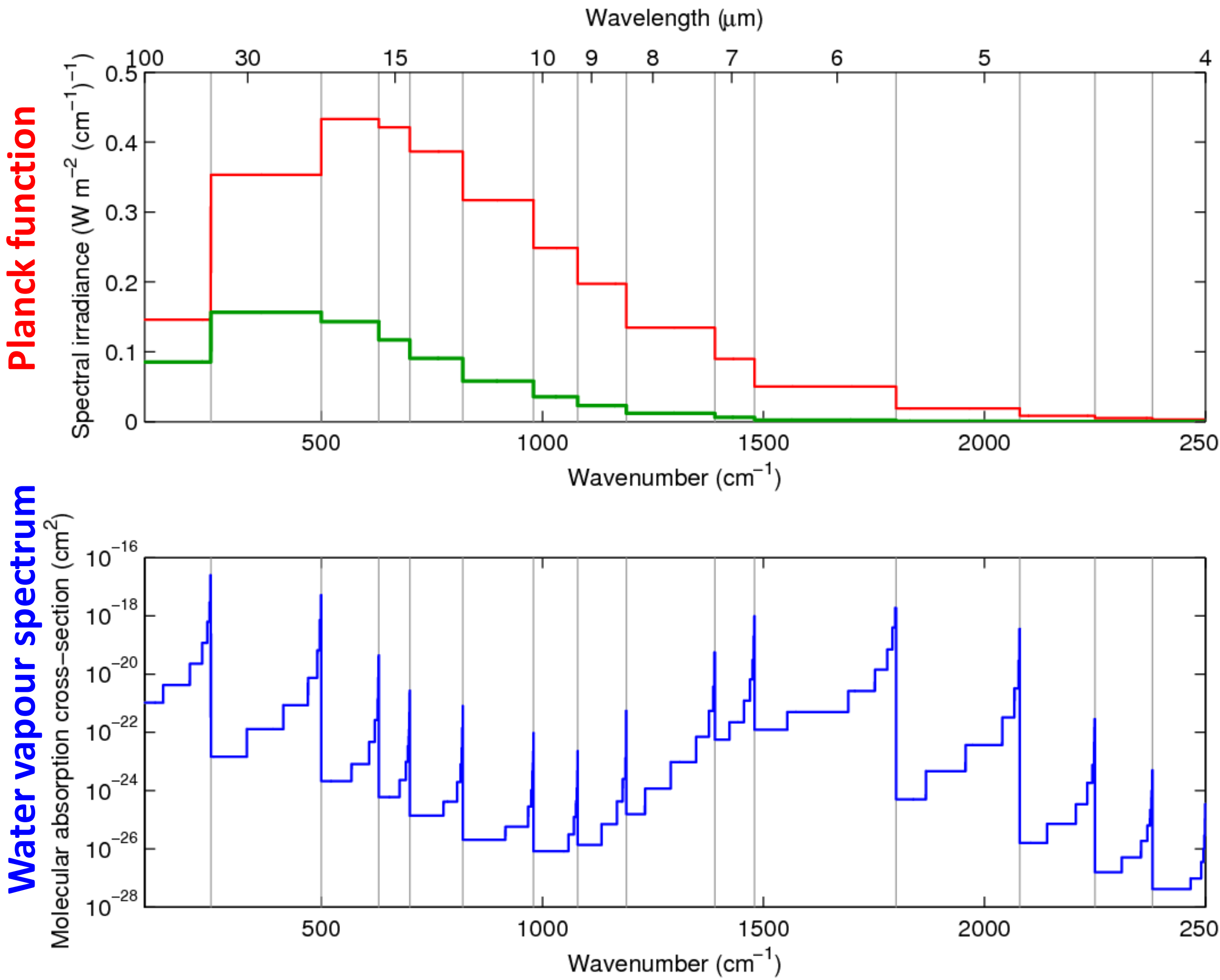
Gas optics: g-points / correlated-k-method

- In each band:
  - Approximate Planck function
  - Re-order by gas absorption, approximate in 6-21 g-points

  (Lacis, Oinas 1991)

- RRTMG: ~200 g-points

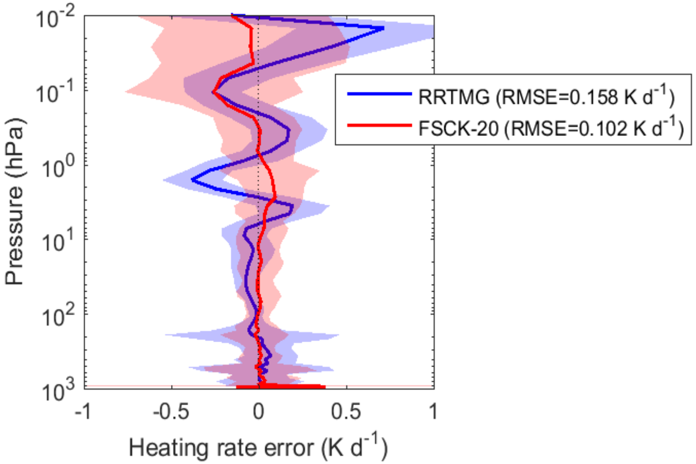
- Could reduce cost by re-ordering full spectrum (Hogan 2010 JAS)



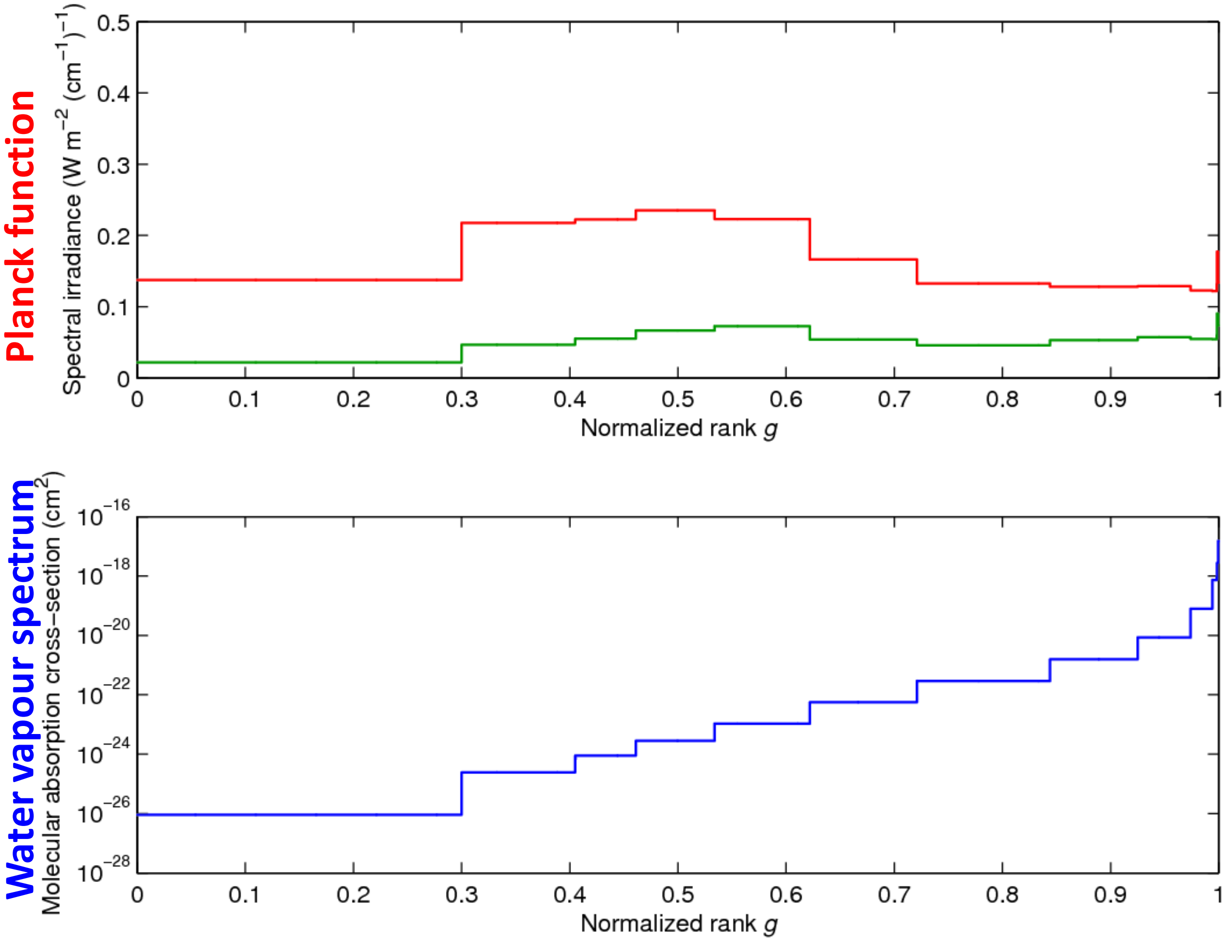
Plot by R. Hogan

Alternative gas optics: full-spectrum correlated-k-method

- Re-order whole spectrum, average Planck emission for wavelengths in each g-point (Hogan 2010, JAS)
- With 40 g-points: cheaper, more precise that RRTMG - future in ICON?



ecRad longwave heating rate error on 50 test profiles, RRTMG and ecCKD gas optics

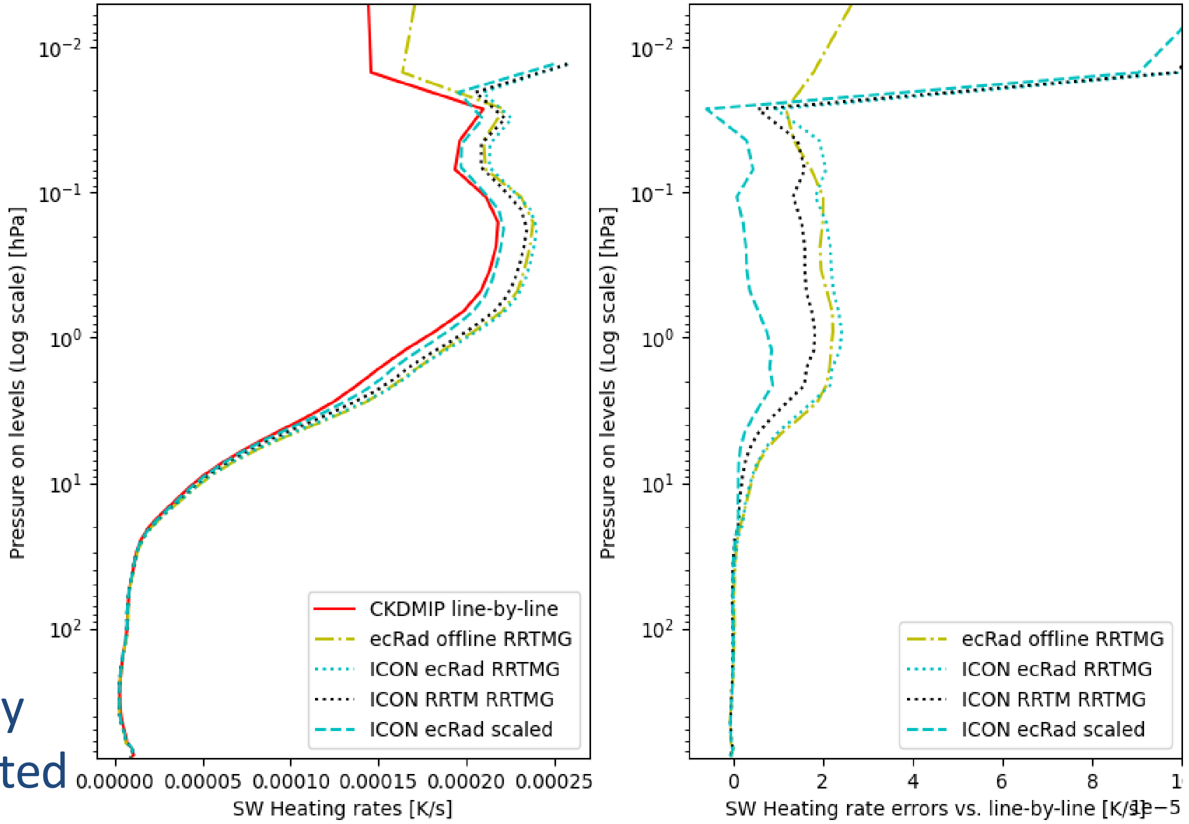


Plots by R. Hogan

ecRad in ICON with new solar spectrum

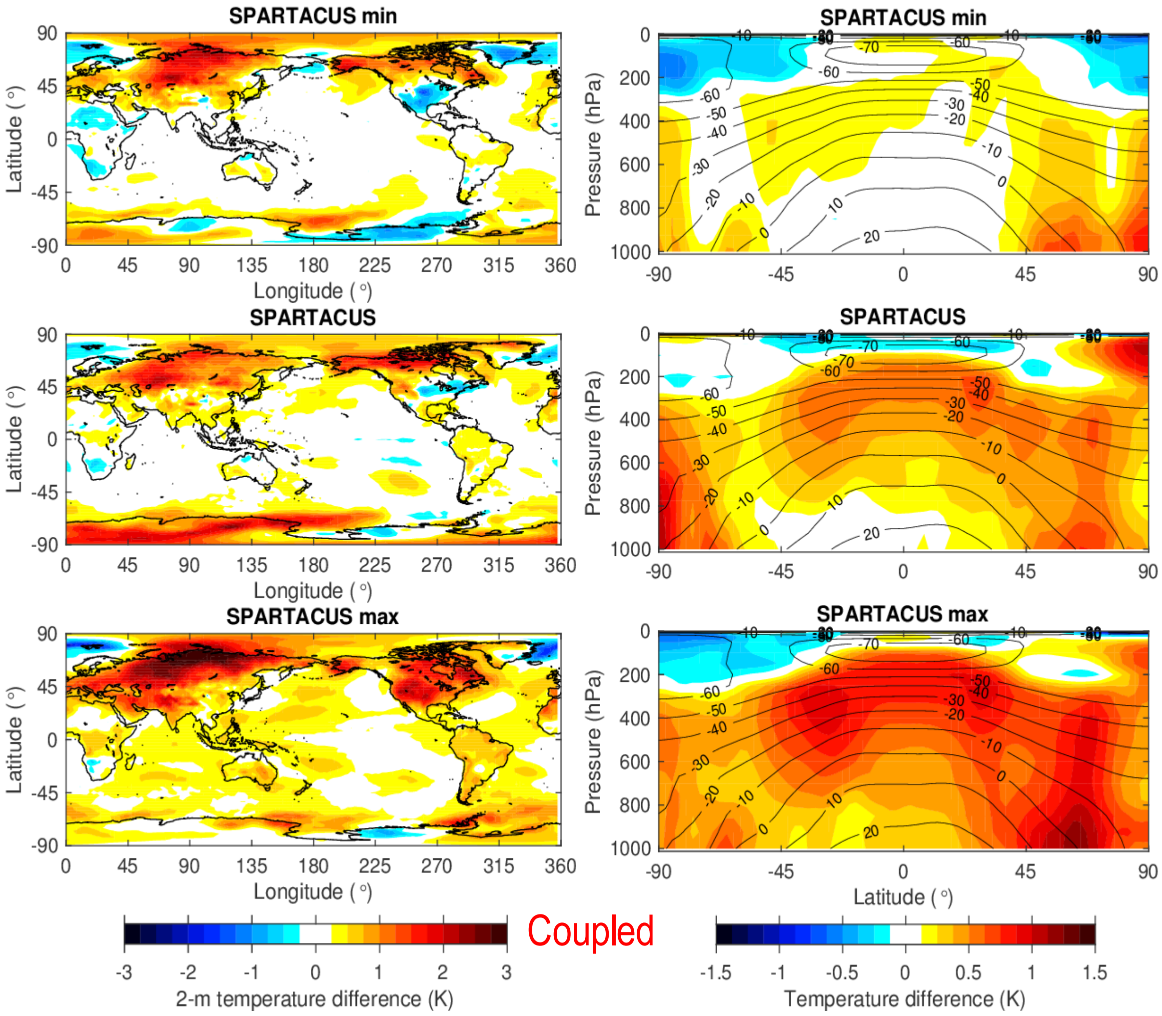
- Scaling improves agreement with line-by-line calculations, removes spurious stratospheric heating
- With new spectral scaling, ecRad improves ICON results in both troposphere and stratosphere vs. RRTM radiation scheme
- RRTM also uses RRTMG gas model – less sensitive

Gas model /spectrum uncertainty up to 2 W/m², not now represented



Future ecCKD gas model: less uncertainty, cheaper, could use different versions in ensemble

Global total 3D cloud effects



Total 3D effect on climate

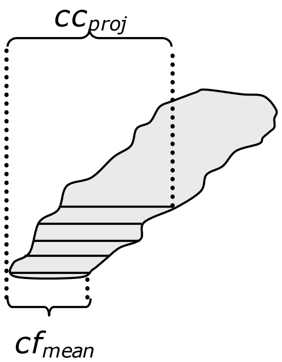
- **Global fluxes (net down, surface):** Longwave +1.6 Wm^{-2}, Shortwave +0.8 Wm^{-2}, Total +2.4 Wm^{-2}
- **Temperature increases** by around 1K.
- Depends on entrapment and cloud geometry (Schäfer et al., in prep.)

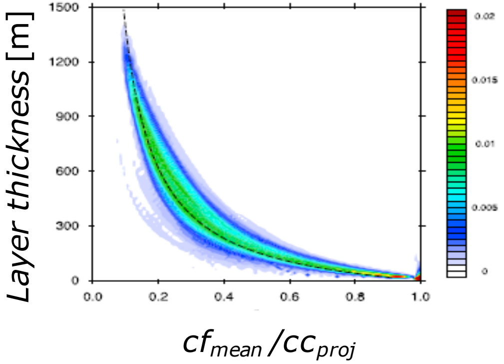
Mean 3D effect on temperature in four 1-year simulations with coupled ocean, with minimum (top) / calculated (middle) / maximum (base) entrapment.

Vertical cloud overlap uncertainty

Neggers, Heus, Siebesma, 2011

Decorrelation length scale:
220m





LES simulation of BOMEX cumulus (dz=10m)

Corbetta, Orlandi, Heus, Neggers, Crewell, 2015

100-600m

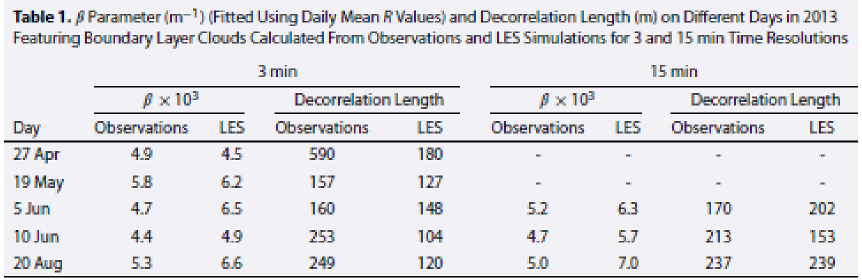


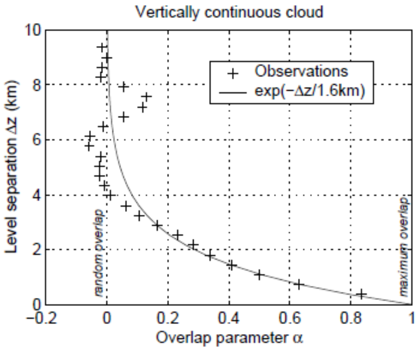
Table 1. β Parameter (m^{-1}) (Fitted Using Daily Mean R Values) and Decorrelation Length (m) on Different Days in 2013 Featuring Boundary Layer Clouds Calculated From Observations and LES Simulations for 3 and 15 min Time Resolutions

	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

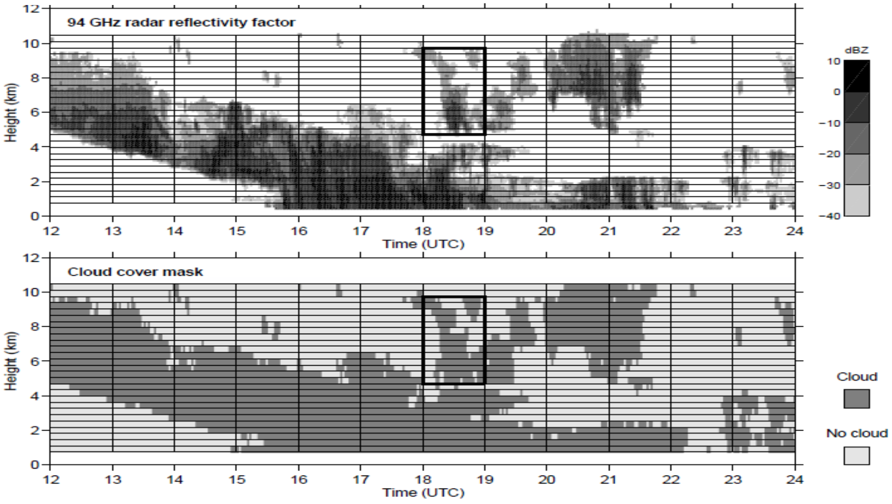
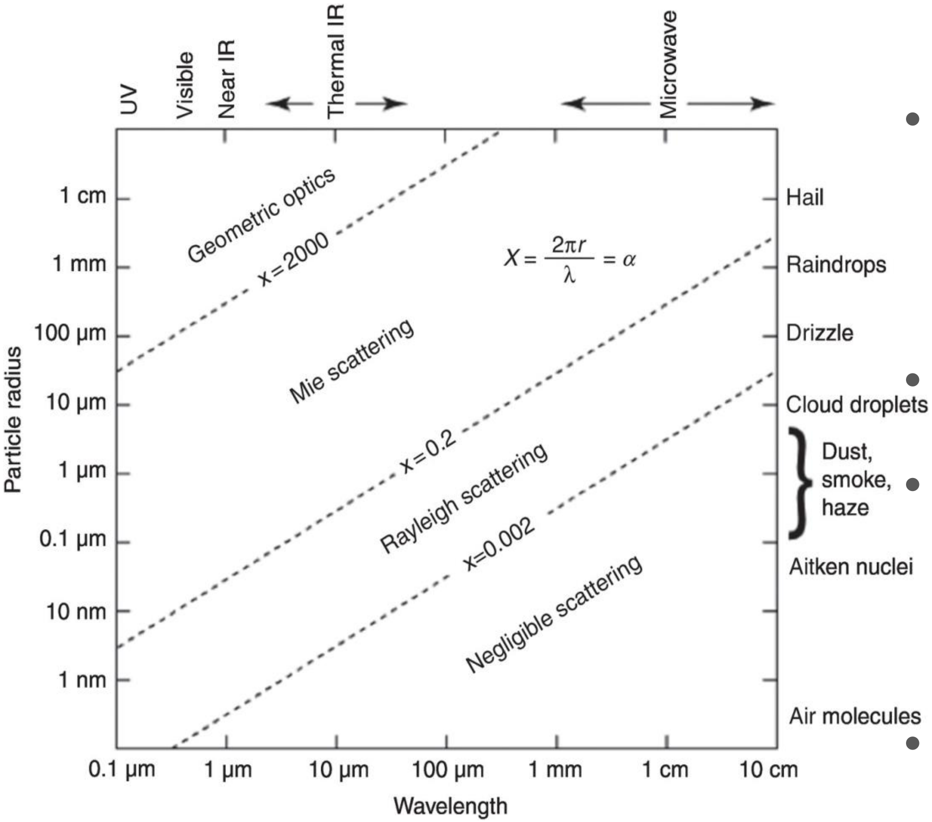
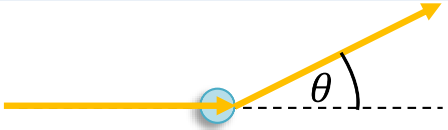


Figure 2. An example of cloud radar data used to derive the cloud cover mask, from 11 December 1998. Intermittent light drizzle was measured at the ground between 17 and 19 UTC. The resolution of the grid is 360 m and 1 hour.

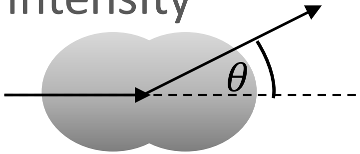
Scattering by particles



Petty (2006)



- Scattering intensity at scattering angle θ depends on size parameter $x = \frac{2\pi r}{\lambda}$: ratio of particle radius r and wavelength λ
- $r \gg \lambda$: Geometric optics
- $r \ll \lambda$: Rayleigh scattering: particle acts as electric dipole, scattering intensity $p(\theta) = \frac{3}{4}(1 + (\cos\theta)^2)$



- Rayleigh **scattering efficiency** $Q_s \propto x^4$ (measures scattering per particle area)

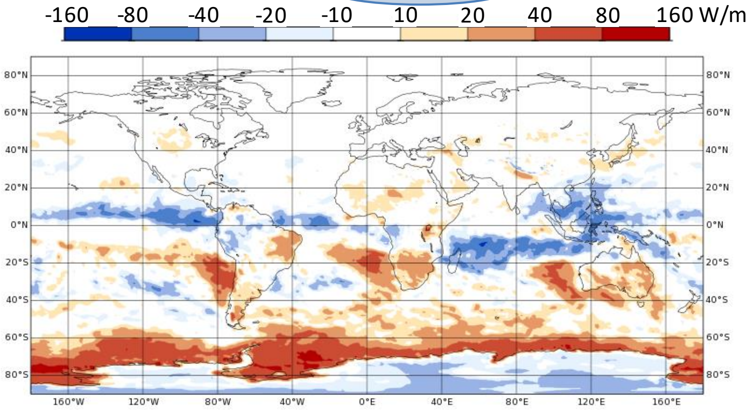
Evaluation (CERES): RRTM and first ecRad, 24h forecasts, Jan. 2018

TOA solar vs. CERES

TOA thermal vs. CERES

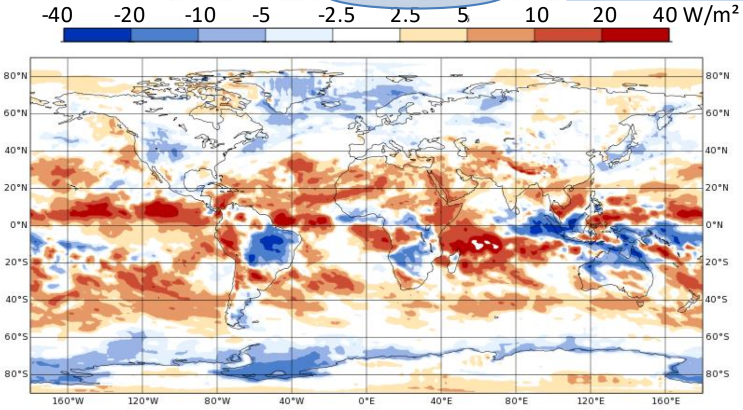
ACCSOB_T dei2_374 - CERES 2018010100 to 2018010200
Min: -92.35 Max: 140.9 Mean: 0.9204 RMS: 19.3 Mem: 31

bias: 0.92 W/m²



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

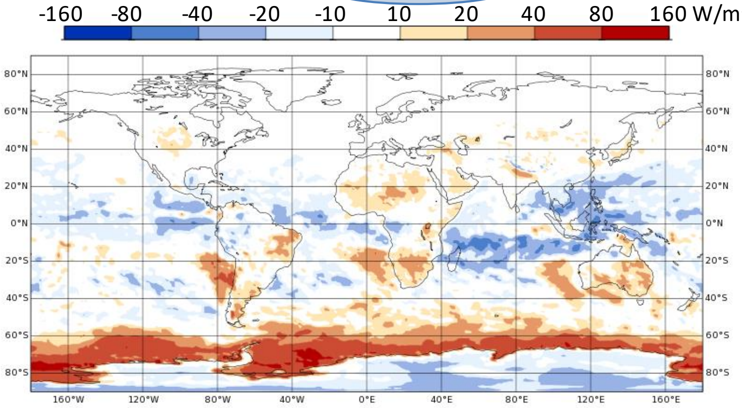
bias: 1.99 W/m²



RRTM

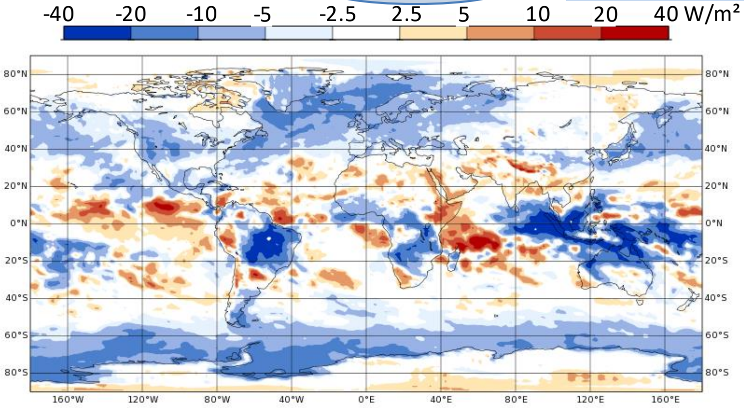
ACCSOB_T dei2_375 - CERES 2018010100 to 2018010200
Min: -78.34 Max: 141.6 Mean: -0.5227 RMS: 17.51 Mem: 31

bias: -0.52 W/m²



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

bias: -2.99 W/m²



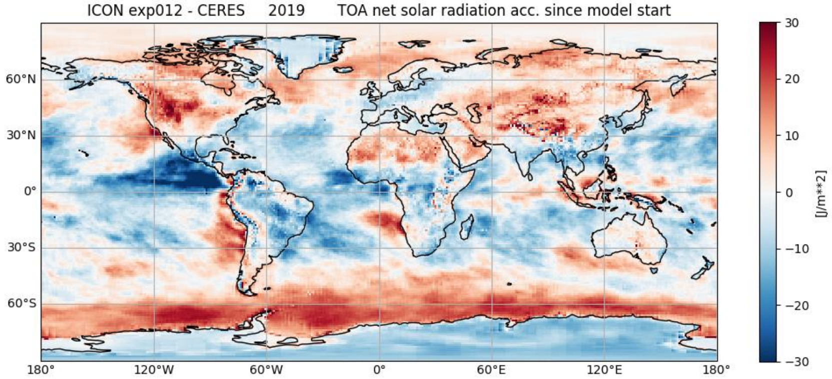
ecRad
first version
- not tuned

Evaluation vs. CERES 2019 all year: Energy bugfix + ecRad + LW scat.

Energy bugfix+ecRad
+ cloud LW scattering

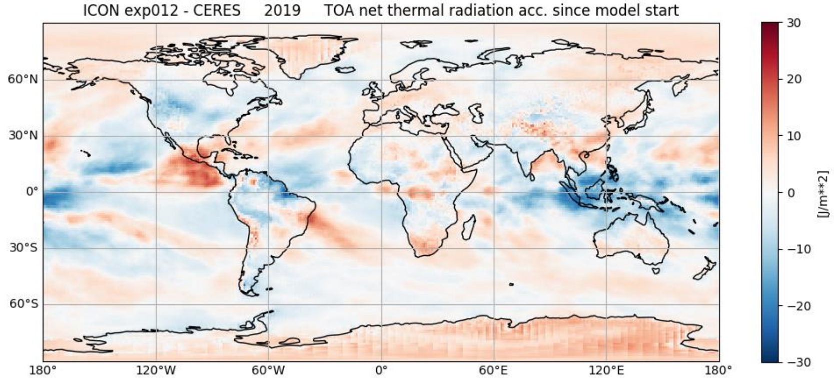
TOA solar vs. CERES

bias: -0.81 W/m^2



TOA thermal vs. CERES

bias: -0.47 W/m^2



Resolution R2B6, $\Delta x \approx 40$ km