Addressing radiation, cloud, aerosol and gas uncertainties with the new radiation scheme ecRad in ICON on local to global scales

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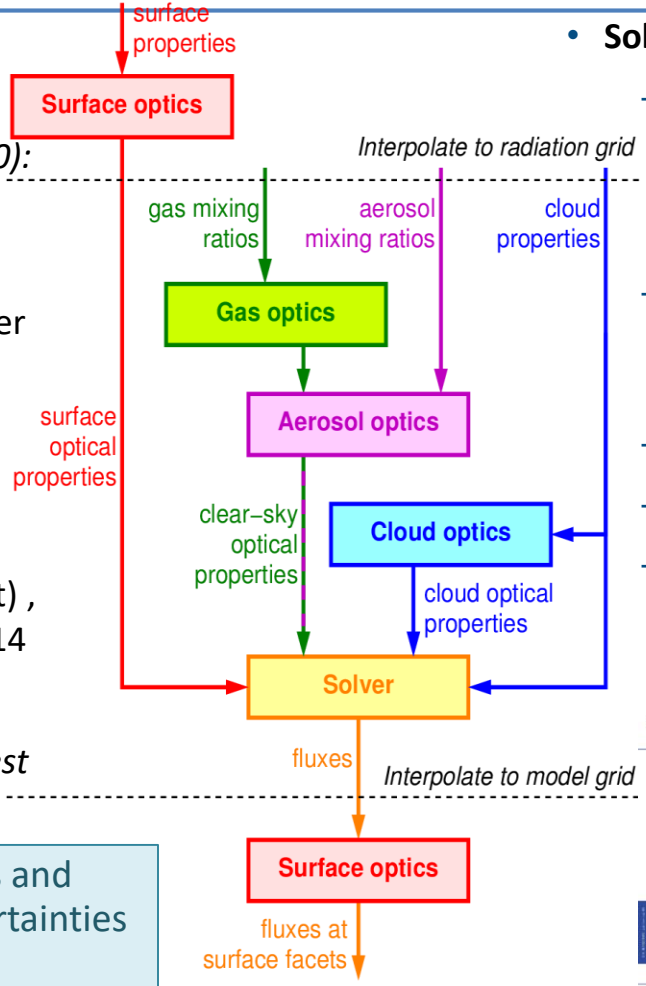
(1) Deutscher Wetterdienst, (2) Hans Ertel Centre for Weather Research, (3) European Centre for Medium-Range Weather Forecasts, (4) University of Reading, (5) Ludwig-Maximilians-University Munich, (6) Wageningen University

Overview

- Impact of new radiation scheme ecRad in ICON
- Radiation scheme uncertainties: ice optics, sub-grid cloud overlap, horizontal inhomogeneity, 3D effects
- Cloud uncertainties: cloud cover, liquid and ice water content, effective particle size
- Summary

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

- **Gas optics:**
  - RRTMG (Iacono et al. 2008)
  - *ecCKD (Hogan & Matricardi 2020): 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, 1997, 1998 (default) , Yi et al. 2013 or Baran et al. 2014
- *Surface (under development) Consistent treatment of urban and forest canopies*



- **Solvers** for radiative transfer equations:
  - **McICA** (Pincus et al. 2003), **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

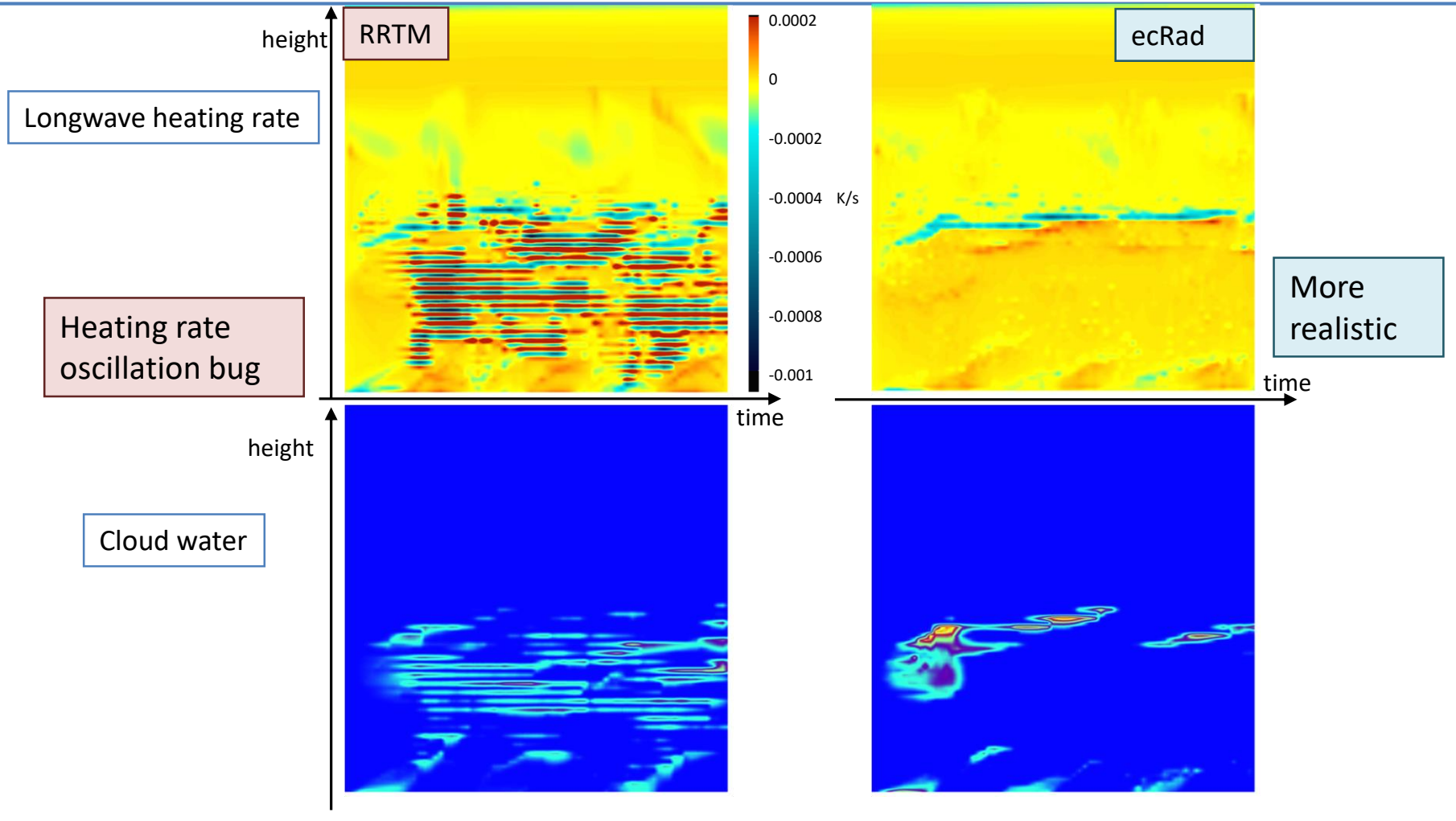
Modular: can vary optics components and solver individually to determine uncertainties

Operational in ICON: 14. April 2021



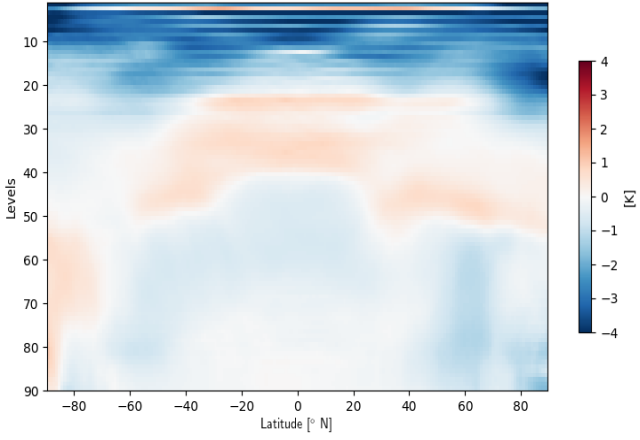
Implementation in ICON: D. Rieger, M. Köhler, R. J. Hogan, S. A. K. Schäfer, A. Seifert, A. de Lozar and G.Zängl (2019): *ecRad in ICON – Implementation Overview*, Reports on ICON

ecRad versus RRTM : ICON single column model

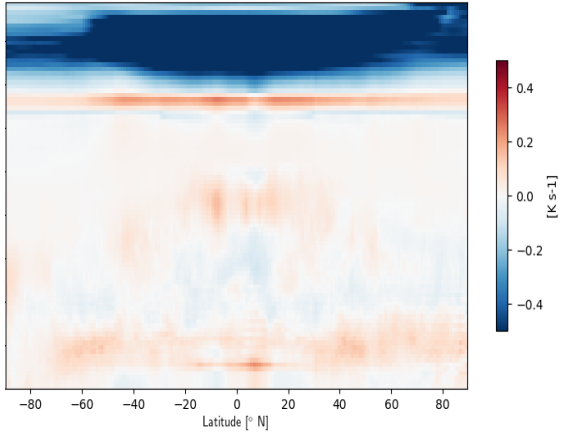


Impact of ecRad, 1 year climate runs 2019: ecRad – RRTM

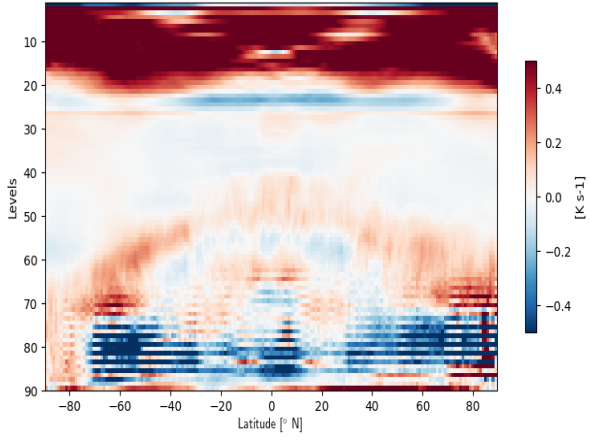
T



T SW tendency



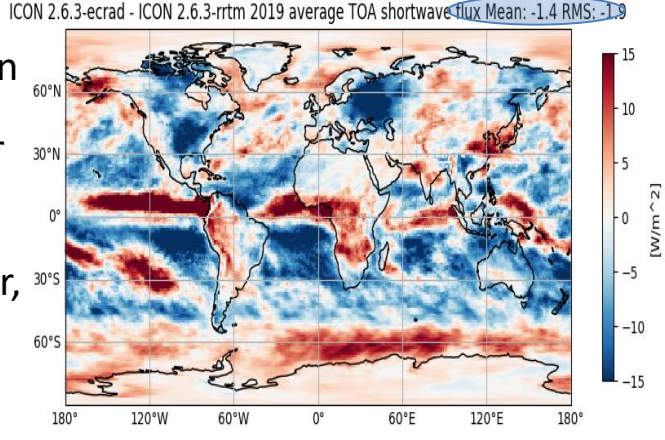
T LW tendency



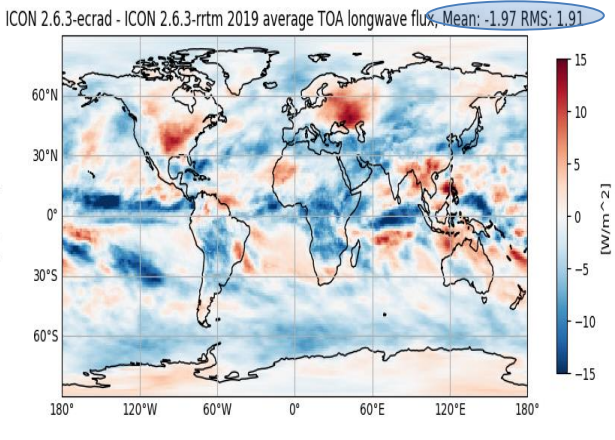
icon-2.6.3, R2B6, $\Delta x \approx 40$ km,
ecRad + tune_zvz0i = 0.85 vs.
RRTM + tune_zvz0i = 1.1

- ecRad cooler in stratosphere than RRTM (with new solar spectrum, Coddington et al. 2016), stronger cloud effects in troposphere, RRTM bug still visible!
- ITCZ, polar cloud optically thinner, ocean cumulus optically thicker
- SW effects within 24h

SW TOA net downward flux



LW TOA net downward flux

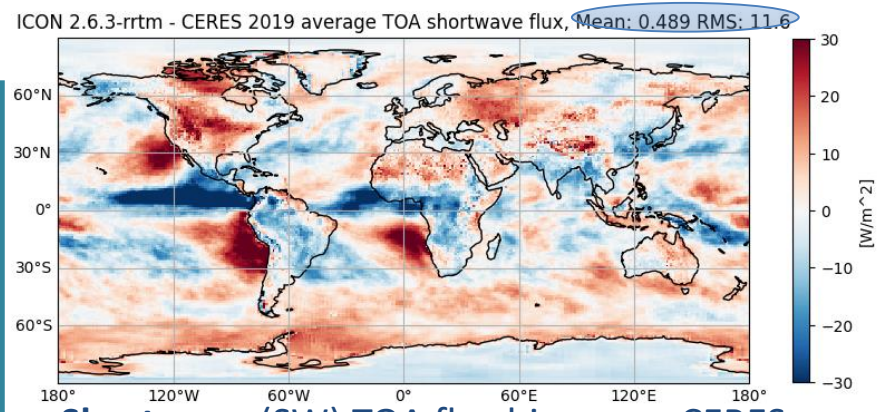


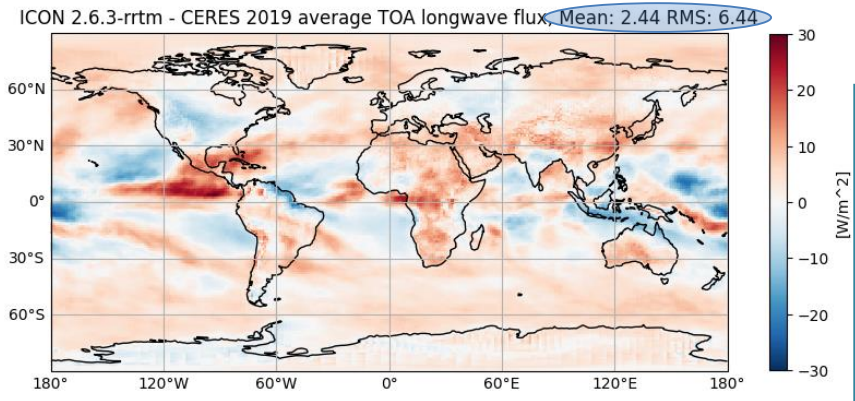
Impact of ecRad, ice fall speed tuning: Biases vs. CERES-EBAF 2019

ICON 2.6.3, **RRTM**, tune_zvz0i = 1.1

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

ICON 2.6.3, **RRTM**, tune_zvz0i = 1.1



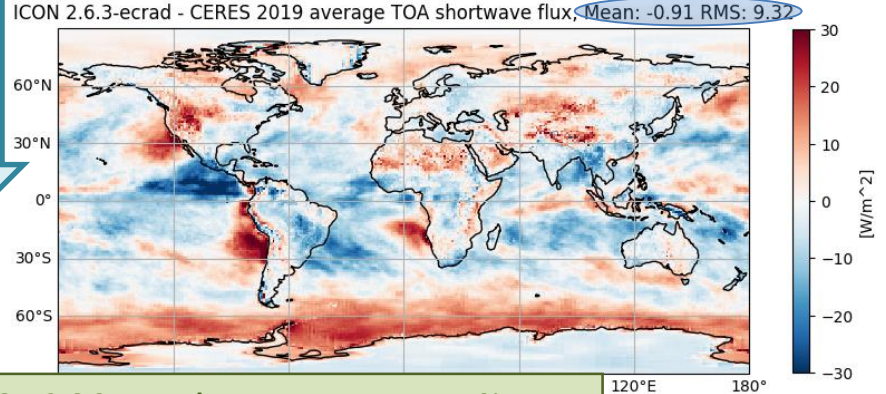


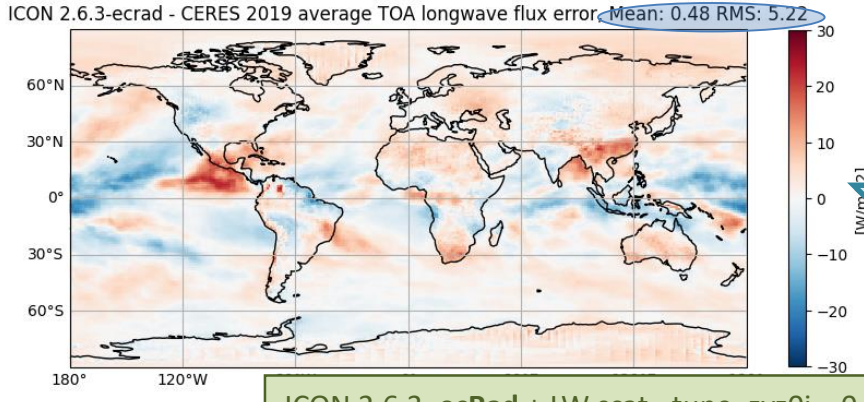
Shortwave (SW) TOA flux biases vs. CERES:
Mid-latitude ocean clouds more reflective
Similar pattern to IFS

Longwave (LW) TOA flux biases vs. CERES

ecRad, removed fall speed tuning

ecRad, removed fall speed tuning





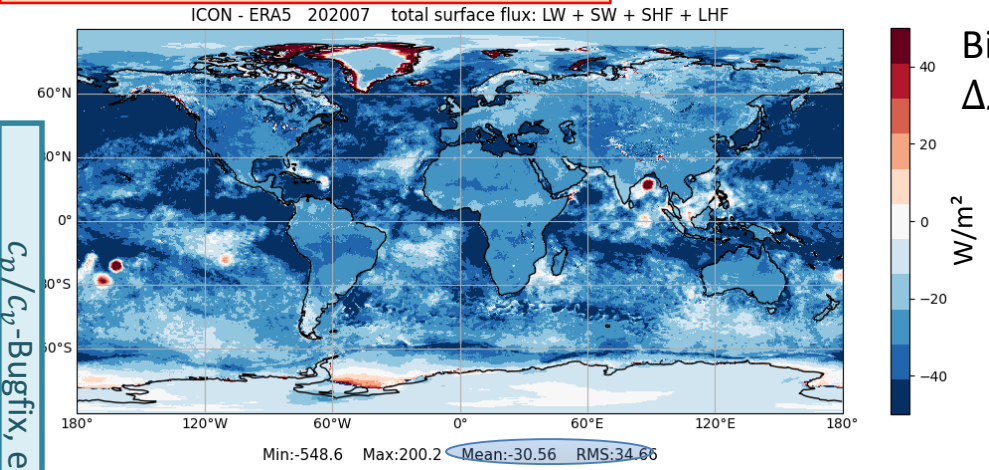
ICON 2.6.3, **ecRad** + LW scat., tune_zvz0i = 0.85

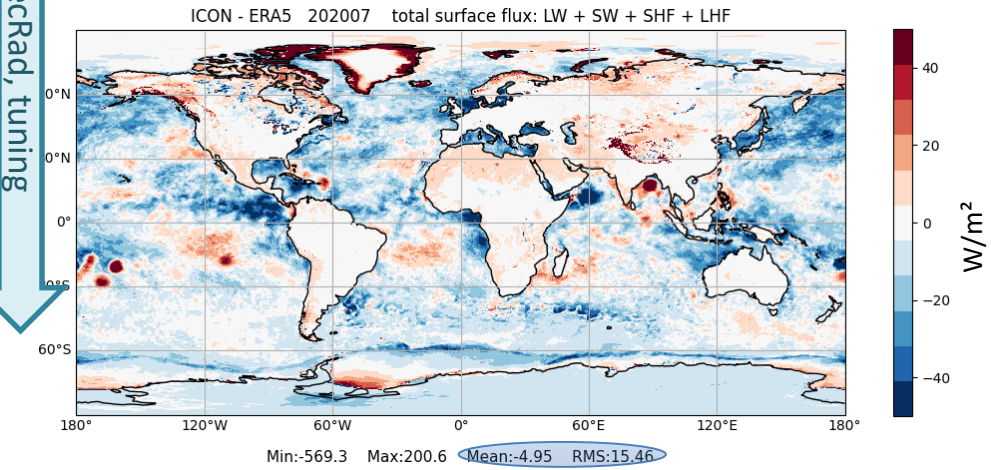
ICON 2.6.3, **ecRad** + LW scat., tune_zvz0i = 0.85

CERES-EBAF: Loeb et al. (2018)

Impact of ecRad + c_p/c_v-Bugfix: Surface fluxes

Old routine: c_p/c_v-Bug, tuned RRTM





c_p/c_v-Bugfix, ecRad, tuning

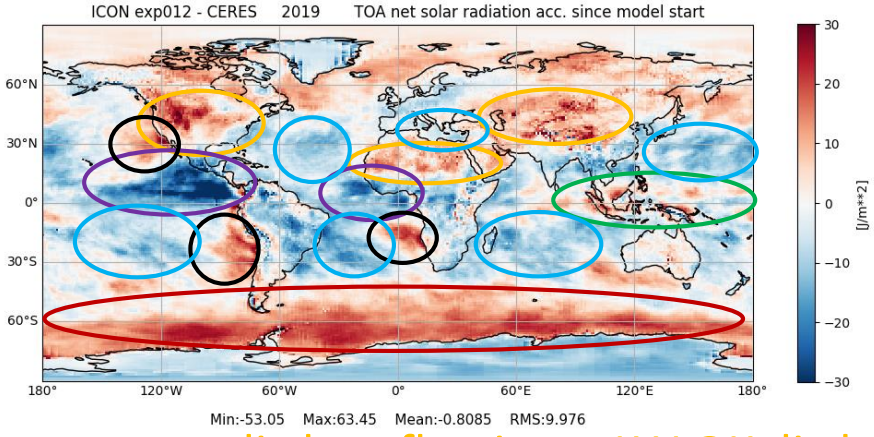
Bias of ICON total surface flux July 2020 vs. Era5, $\Delta x \approx 13$ km, plots by M. Köhler

- With ecRad: surface radiation flux bias reduced by 20 W/m², overall surface flux bias reduced by 26 W/m²
- Enables coupled climate runs

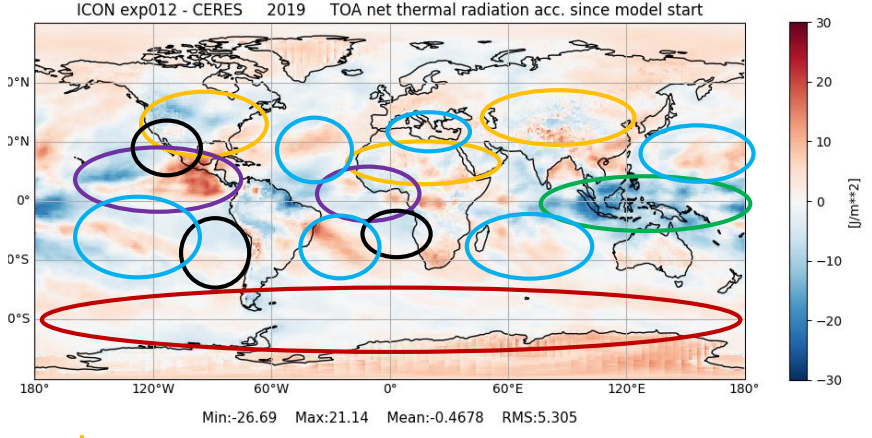
New routine: c_p/c_v-Bugfix, ecRad + LW scat., new CAMEL emissivity

Remaining regional biases – clouds major source of uncertainty

TOA SW bias vs. CERES

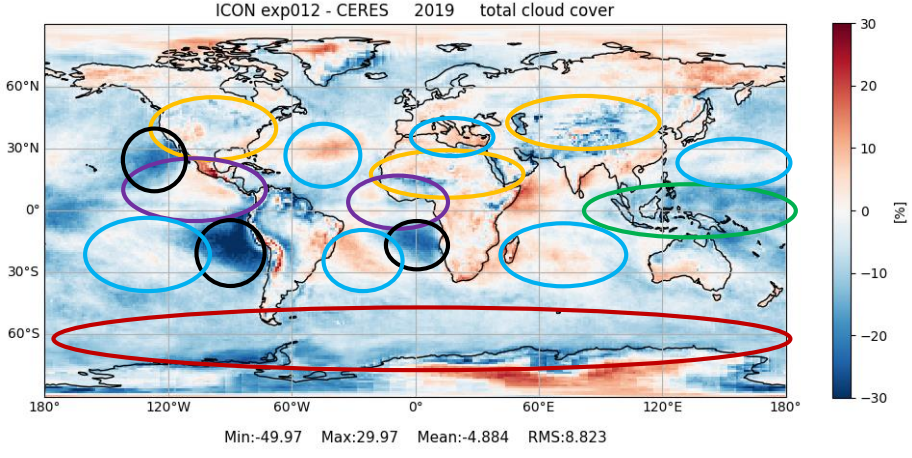


TOA LW bias vs. CERES



1. Deserts too little reflection – LW OK, little cloud
2. ITCZ eastern oceans too optically thick
3. West Pacific too little cloud
4. Too little stratocumulus (low cloud, LW OK)
5. Southern Ocean too little reflection
6. Extratropical oceans too much cloud (incl. Mediterranean)

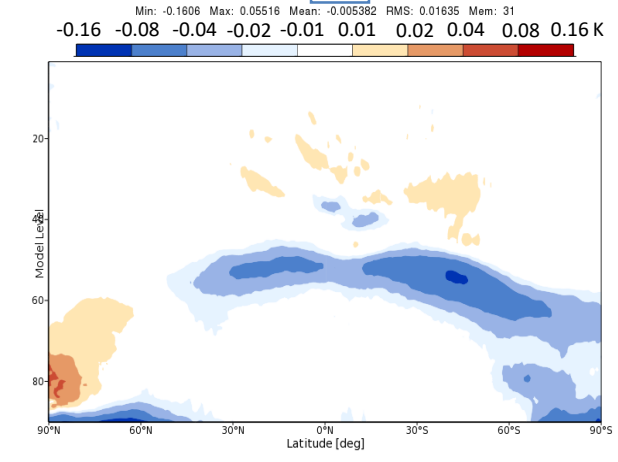
Cloud cover bias vs. CERES



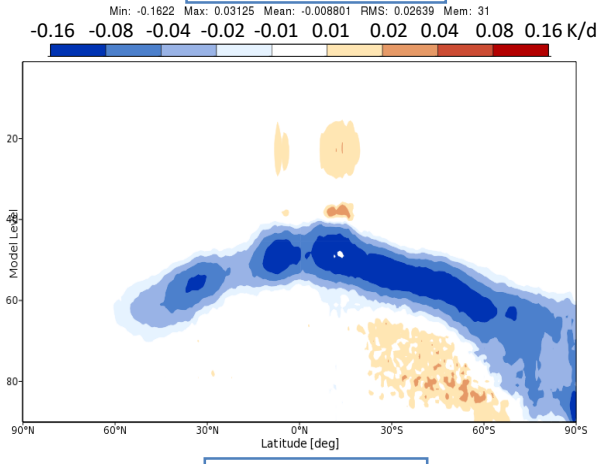
Uncertainties in radiation model and inputs

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

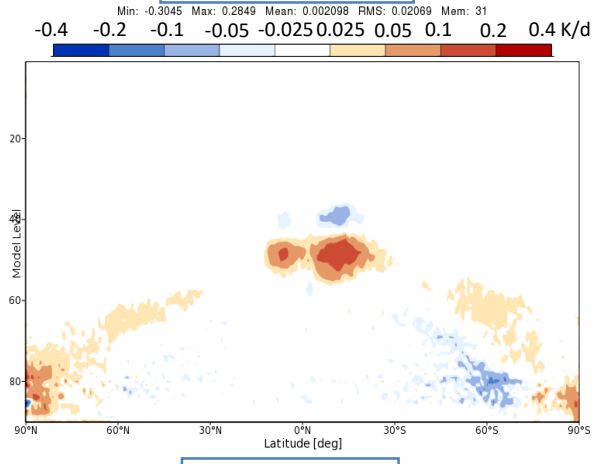
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T SW tendency

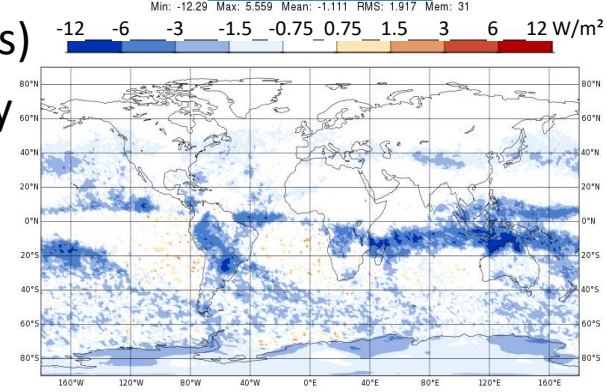


T LW tendency

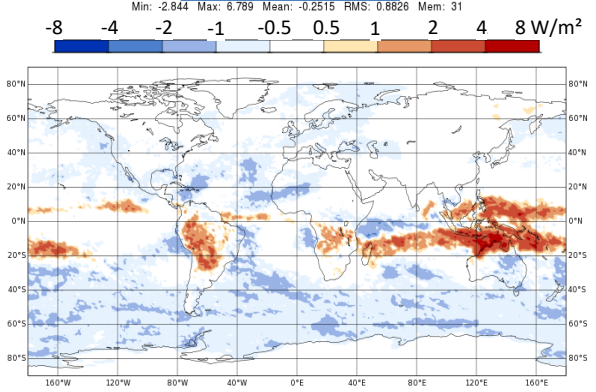


- Have to assume particle size + shape distribution (no spheres)
- Uncertainty 1.5 W/m² globally
- **Liquid optics** uncertainty 0.5W/m² (spheres)
- **Gas optics**: up to 2 W/m²
  New ecckd gas optics: similar precision with 1/3 intervals

SW TOA flux



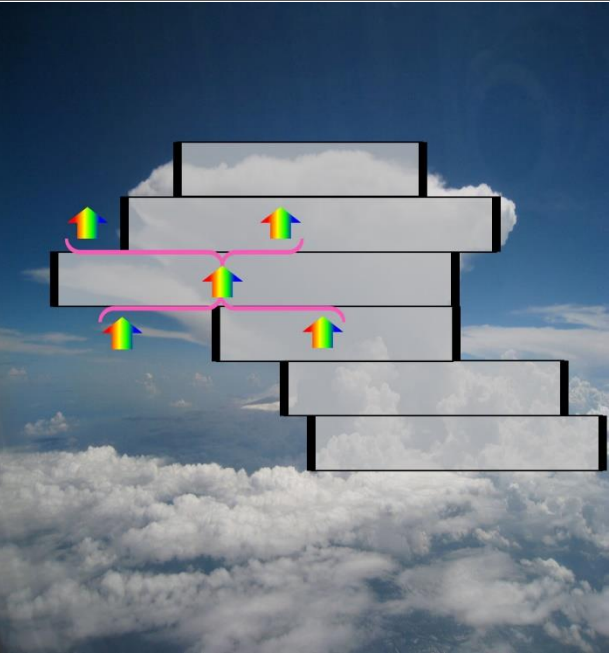
LW TOA flux



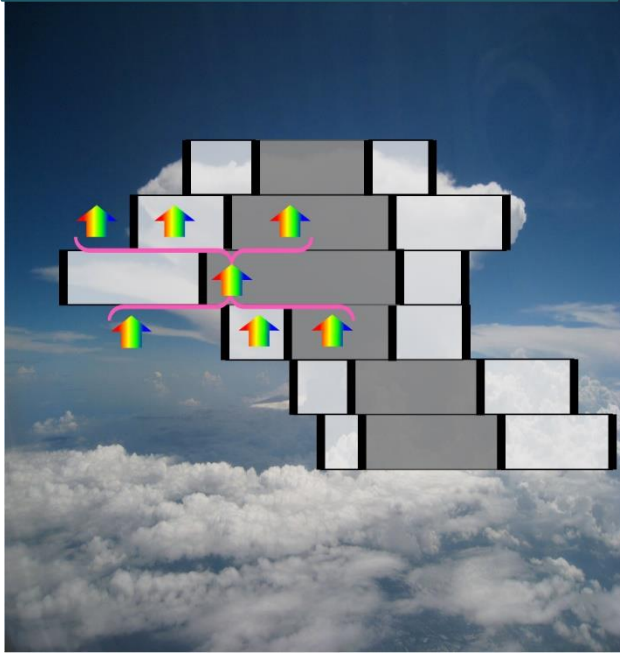
Radiation solvers: Cloud geometry treatment

Solvers for global models **simplify, treat only vertical** dimension explicitly. **Global solver uncertainty:** 2 W/m²

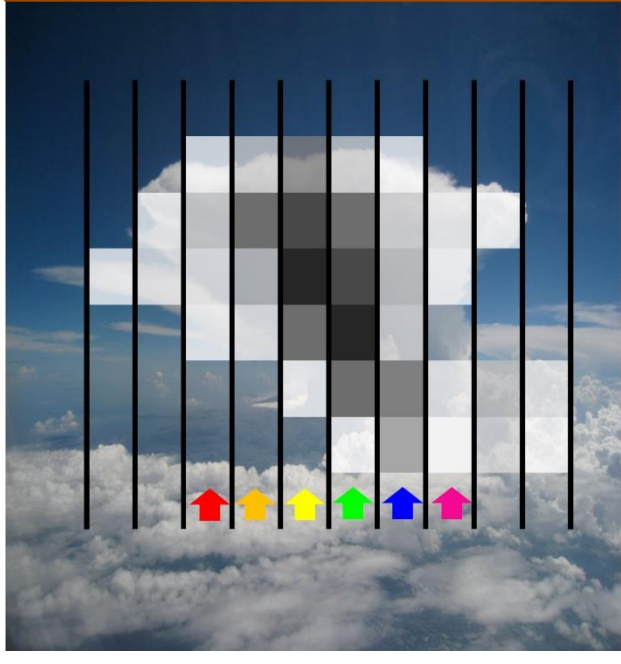
Two-stream solver: solve in **cloudy / clear regions**, partition at layer boundaries according to **overlap** (e.g. RRTM in ICON)



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

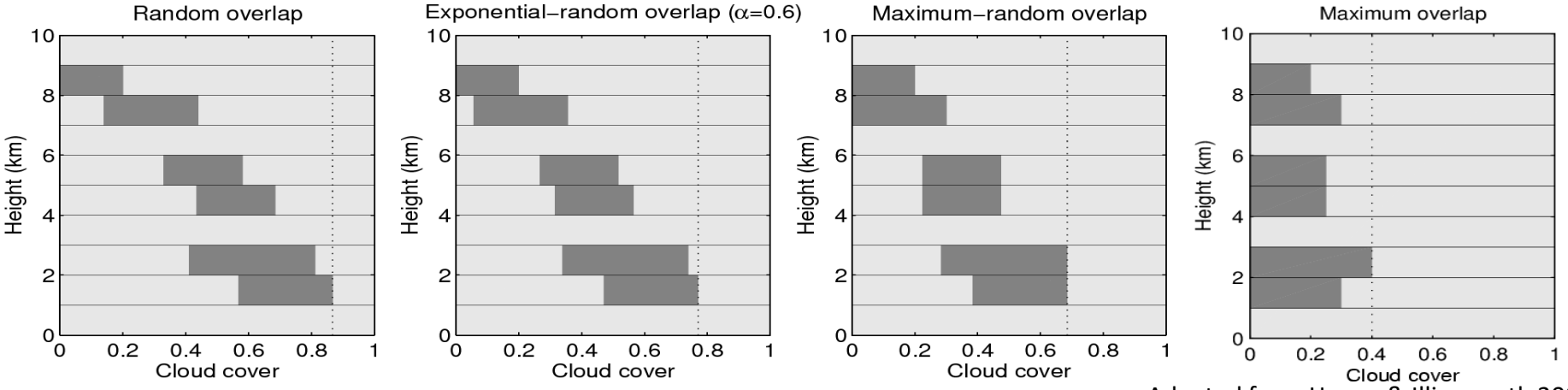


McICA: draw **random clouds in sub-columns** according to overlap + inhomogeneity; **distribute spectral intervals** in 1 sub-column each → **fast, random noise**



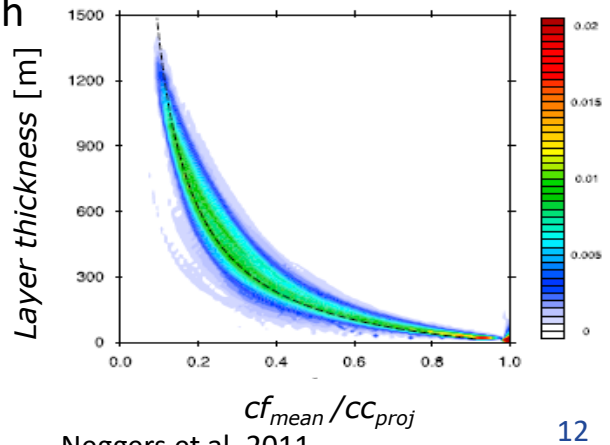
Plots adapted from R. Hogan

Cloud vertical overlap and horizontal inhomogeneity



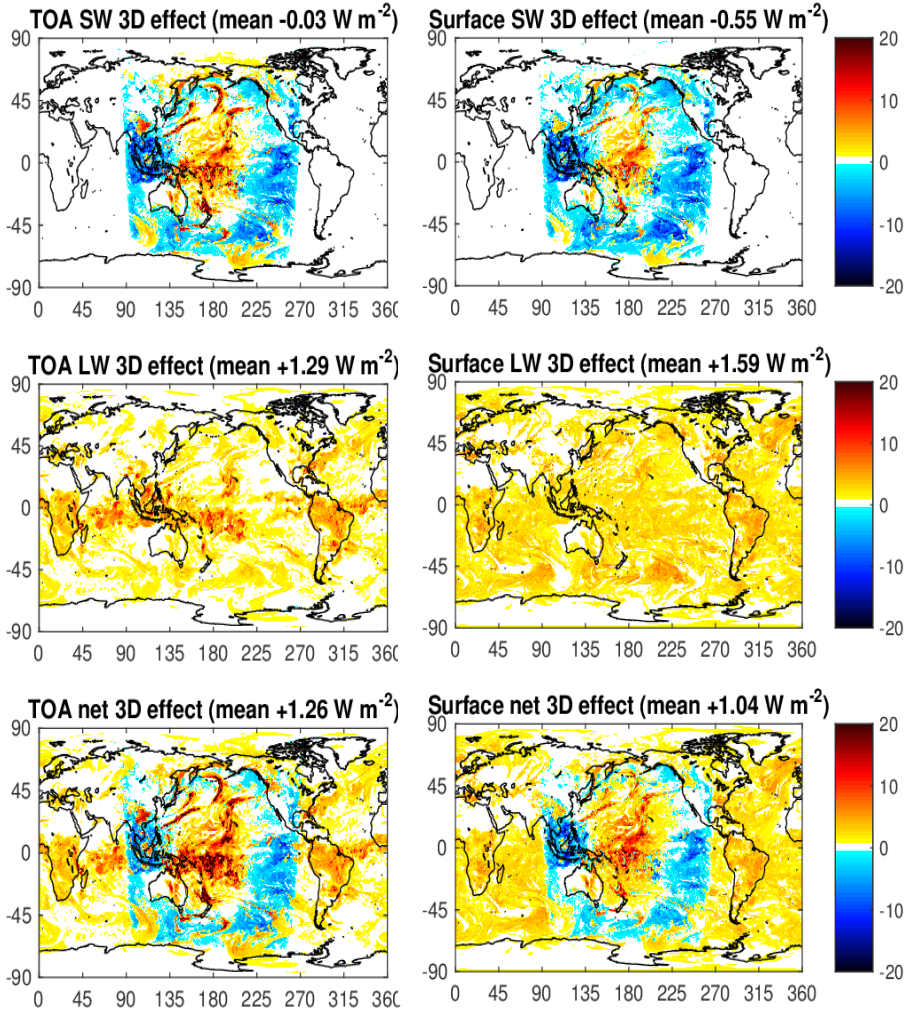
Adapted from Hogan & Illingworth 2000

- For given layer clouds, **cloud overlap** decides total cloud cover
- Observations: **exponential-random overlap,** decorrelation length 2 km (Hogan & Illingworth 2000) to 100-600 m (Neggers et al. 2011) - **Should depend** on cloud type (Sulak et al 2020)
- **Uncertainty due to overlap:** 1 W/m² in global flux
- Reflectivity and longwave emissivity **non-linear functions** of optical depth: also need **horizontal cloud variability** – uncertainty 1 W/m² in global flux



Neggers et al. 2011

Global 3D cloud and surface effects

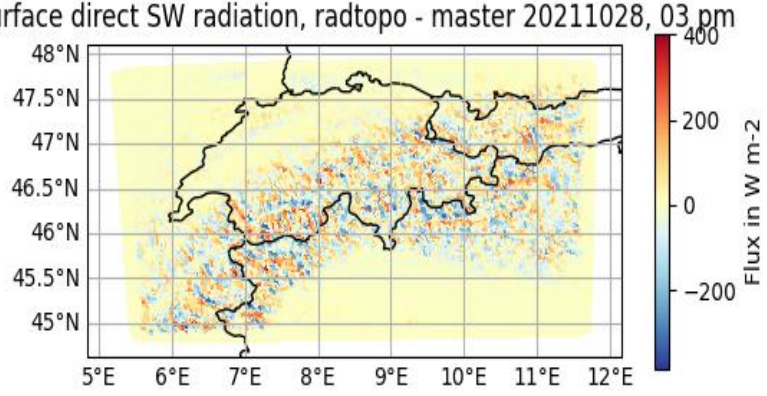


3D cloud effects:

- **Global 3D effects, surface:** Shortwave -0.6 $\mathrm{Wm^{-2}}$, Longwave 1.6 $\mathrm{Wm^{-2}}$, total 1.0 $\mathrm{Wm^{-2}}$ (Hogan et al. 2019)
- **Long-term total** +1.4 $\mathrm{Wm^{-2}}$, **warms** by ~1K (more at poles, Schäfer 2017)

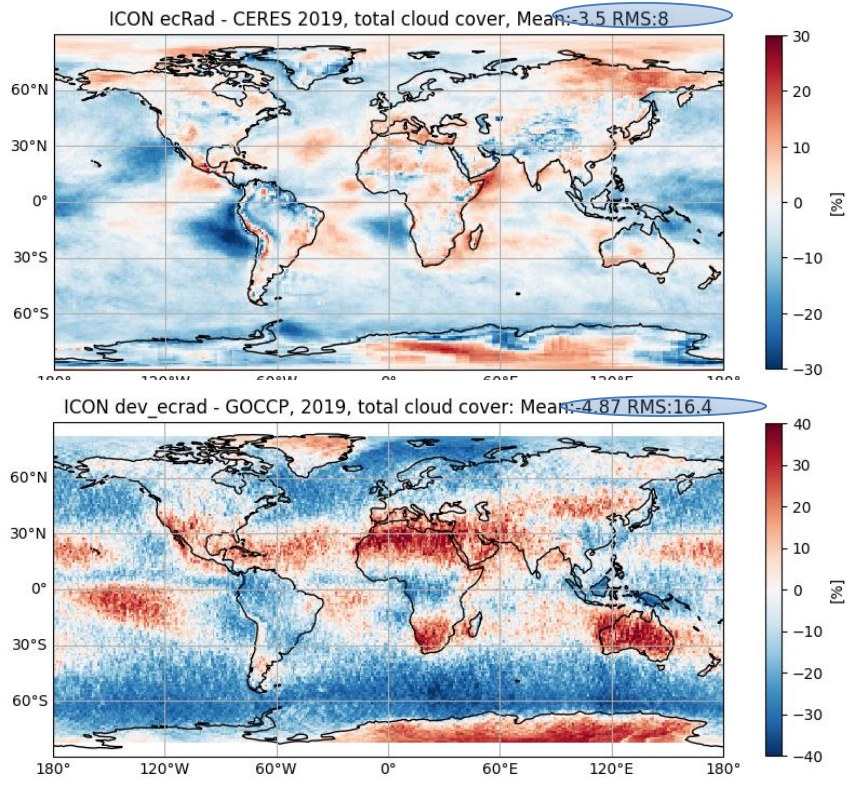
Instantaneous 3D cloud effects in Era5 field, 01.04.2000 0UTC. Plots by R. Hogan

3D orography: slope angle, shadowing, longwave skyview (with MeteoSwiss)



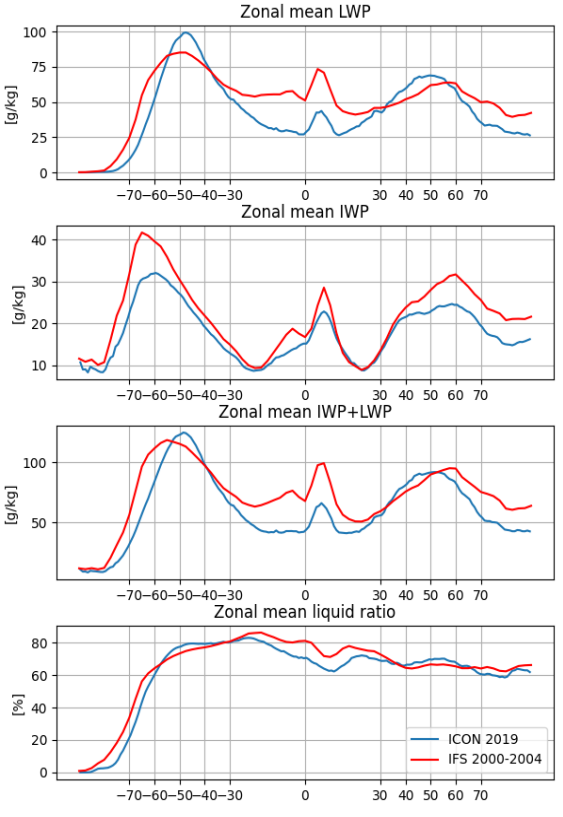
Shortwave direct effects of **including shadowing by orography** on shortwave direct flux

Cloud input uncertainty



Left: Total **cloud cover** bias vs. CERES and GOCCP, 2019

Right: Zonal mean **cloud water** in ICON 2019 and IFS 2000-2004, plots by M. Ahlgrimm, IFS data courtesy of P. Bechtold

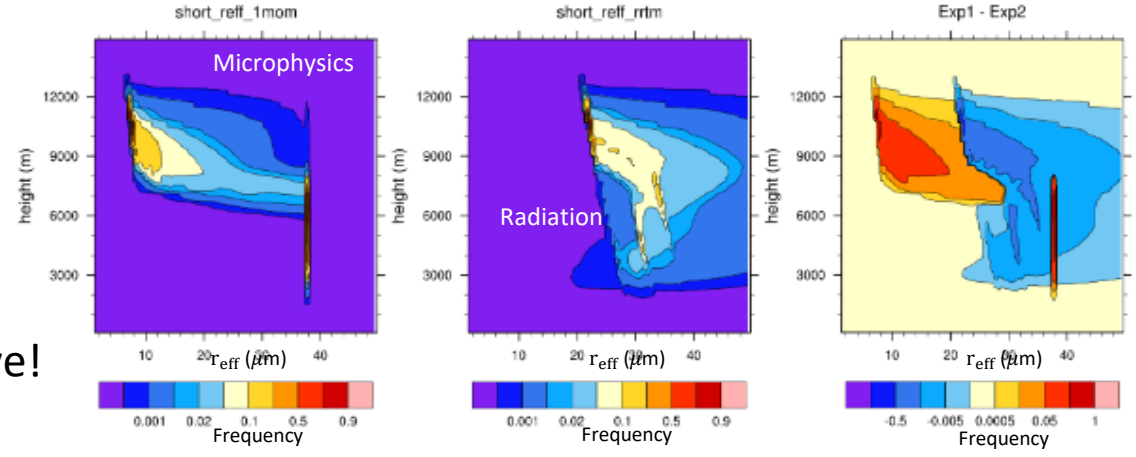


- ICON has **less cloud** cover, cloud ice and mostly less cloud water than satellite observations and ECMWF‘s IFS model, but the clouds are quite reflective – why?
- Uncertainties in retrievals, microphysics,…especially at poles

Cloud particle size parametrization, aerosols

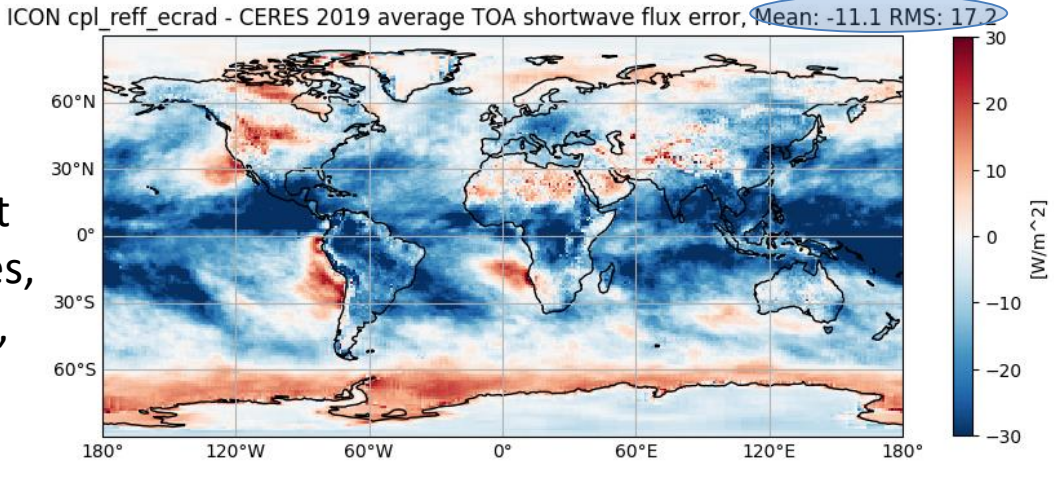
- **Currently**: ice **effective radius** in radiation **inconsistent** with microphysics
- A. de Lozar: include precipitation, effective radius consistent with microphysics – even more reflective!
- Include general particle species + large-particle optics → explicit precipitation (ongoing, with R. Hogan, COSMO PP CAIIR)

- **Aerosols:** monthly climatology (Tegen et al. 1997); Alternatives: new climatologies, aerosol advection, ICON-ART: advection, chemistry + optical properties



Plots by A. de Lozar

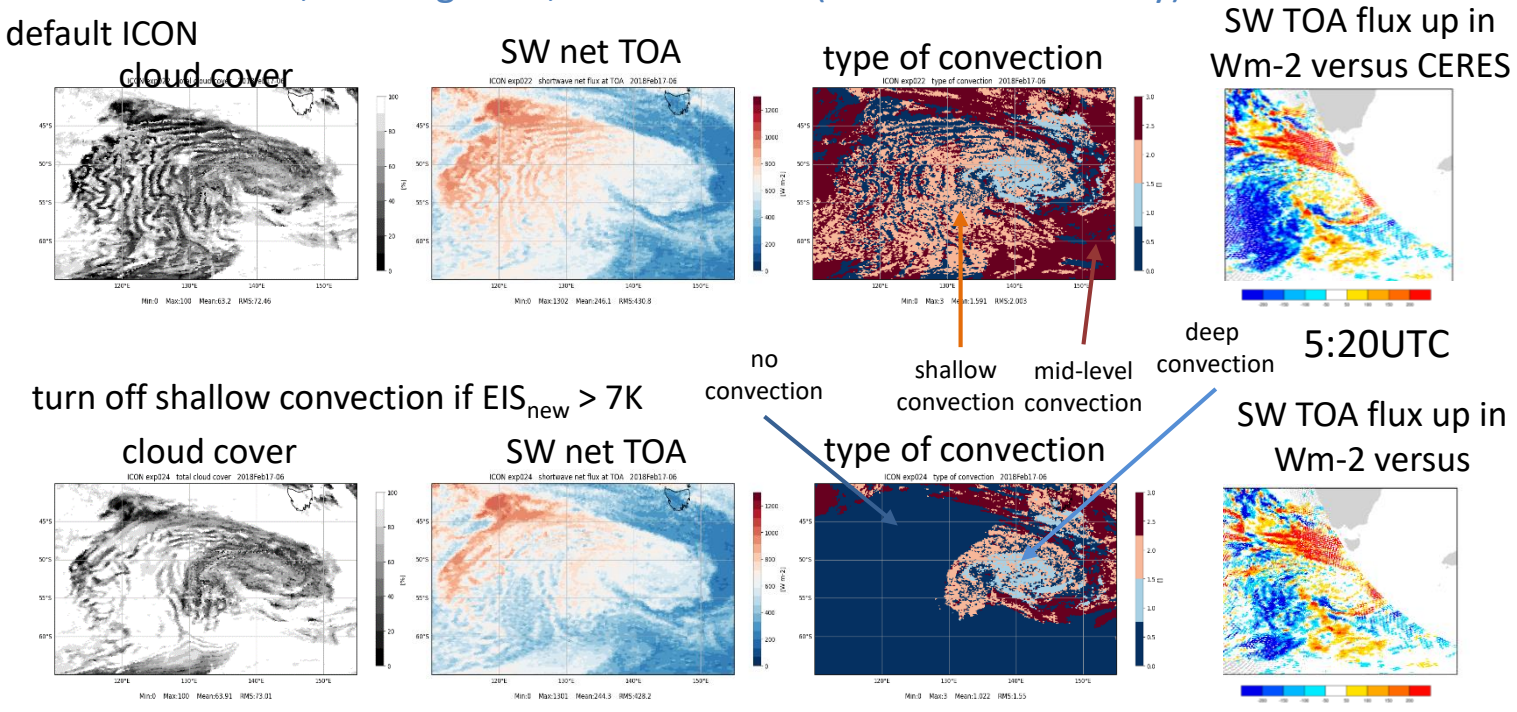
SW TOA flux bias with coupled effective radius vs. CERES, 2019



Local cloud improvement: Southern Ocean

Bias in Southern Ocean: ICON in SOCRATES region 20180217 6UTC
M. Köhler, M. Ahlgrimm, Anna Possner (Frankfurt University)

Clouds in **Southern Ocean not reflective enough**: limit shallow convection by Estimated inversion strength criterion (Marquet, Bechtold 2020) → **improved** stratiform cloud and shortwave flux



Cloud cover, Shortwave net downward TOA, convection type , shortwave flux bias vs. CERES with default ICON (above) and EIS criterion (below), Southern Ocean case

More local cloud and radiation evaluation / improvement planned, with colleagues from Wageningen University (FESSTVaL campaign Germany), Frankfurt University, Israel Meteorological Service, MeteoSwiss, TeamX campaign

Summary

- **ICON: ecRad operational** since April 2021: fast and flexible, can represent **cloud inhomogeneity** and sub-grid **3D** effects; parametrisation **choices** → uncertainty estimation
- **ecRad improves** cloud and radiation in ICON, global flux balance and general model state
- Main **uncertainties**: **gas model, cloud-radiation interaction** (up to 2 W/m²) and **cloud input** (~10 W/m²)

Ongoing work:

- Further **code optimisation** and **evaluation and improvement of radiation together with clouds**: cloud condensate, cloud geometry, particle size and shape etc. (with colleagues at DWD, ECMWF, MeteoSwiss, COSMO project CAIIR, KIT, DLR, Frankfurt and Wageningen University, etc.)
- Implementation and evaluation of **ecckd gas model** and user-defined cloud particle species (with R. Hogan, D. Rieger, H. Muskatel)
- Aerosol evaluation, ecRad in ICON-ART (with colleagues at KIT, CAIIR and project Permastrom)
- Interactions between clouds, radiation and dynamics (with colleagues at ETH)

Thank you for your attention!

Contact: sophia.schaefer@dwd.de

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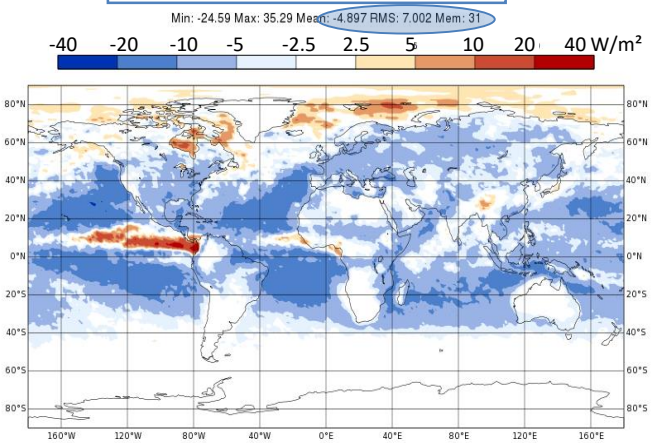
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Impact of ecRad, 24 h-forecasts, July 2020: ecRad – RRTM

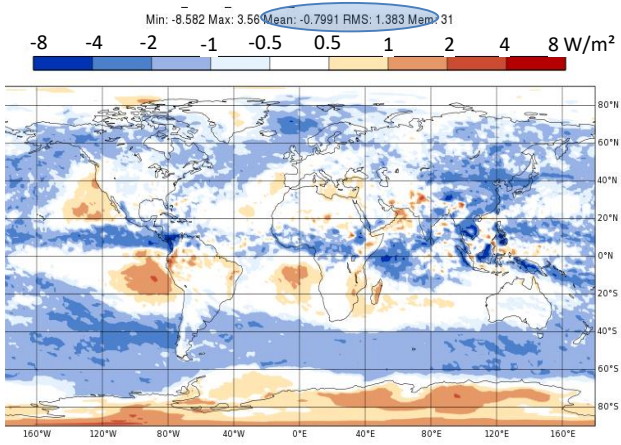
- ITCZ, polar cloud optically thinner, ocean cumulus optically thicker
- ecRad cooler in stratosphere than RRTM (with new solar spectrum scaling, Coddington et al. 2016), stronger cloud effects in tropospher

icon-2.6.3, R3B7, $\Delta x \approx 13$ km,
ecRad + tune_zvz0i = 0.85 vs.
RRTM + tune_zvz0i = 1.1

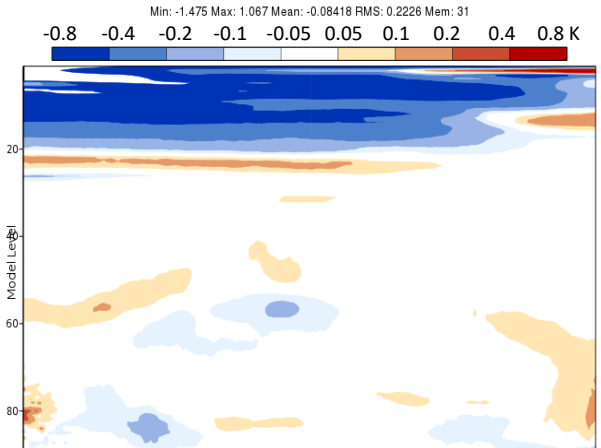
SW TOA net downward flux



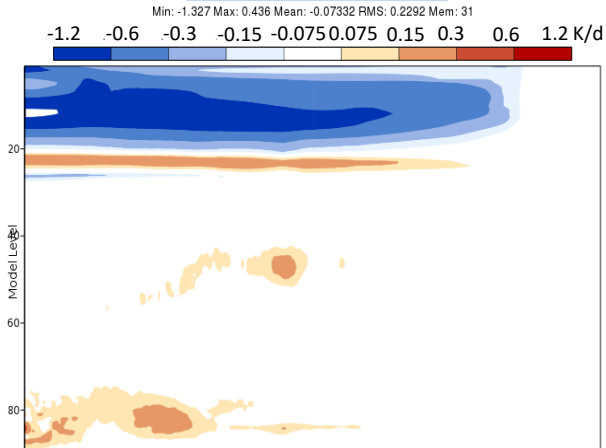
LW TOA net downward flux



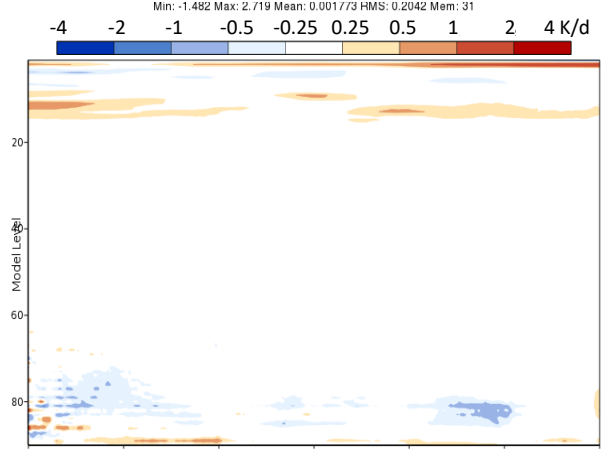
T



T SW tendency



T LW tendency

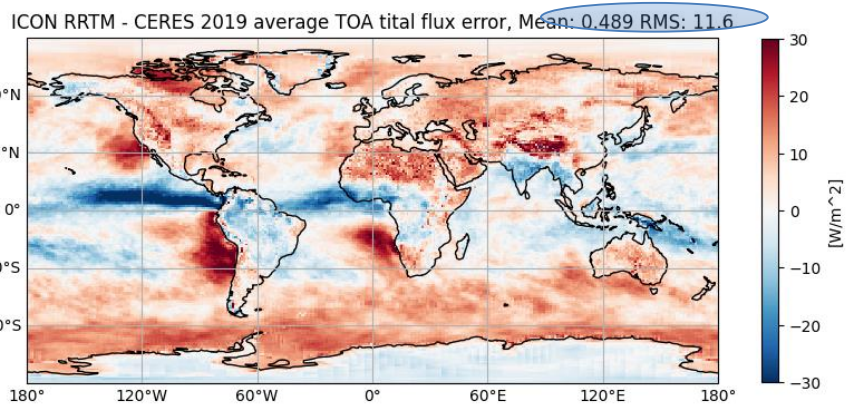


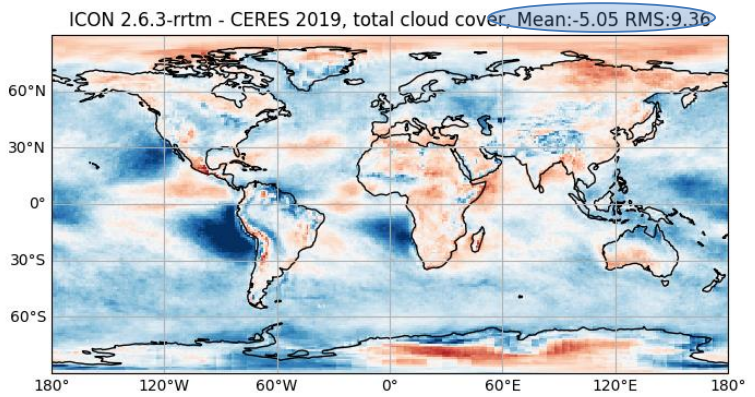
Impact of ecRad, ice fall speed tuning: Biases vs. CERES-EBAF 2019

ICON 2.6.3, **RRTM**, tune_zvz0i = 1.1

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

ICON 2.6.3, **RRTM**, tune_zvz0i = 1.1

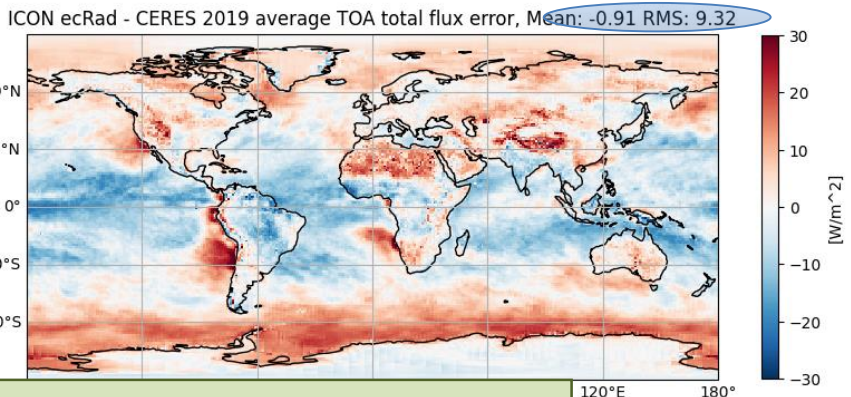


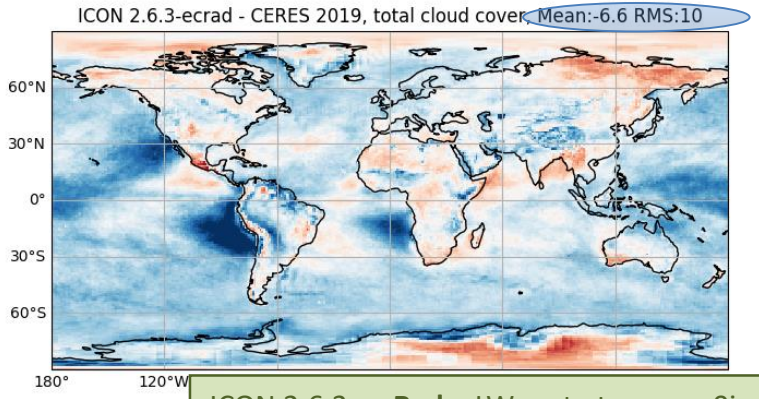


ecRad, removed fall speed tuning

Total TOA flux biases vs. CERES: **RMS decreases**
Operational model version includes more tuning

Total **cloud cover** biases vs. CERES: slightly increases





ecRad, removed fall speed tuning

ICON 2.6.3, **ecRad** + LW scat., tune_zvz0i = 0.85

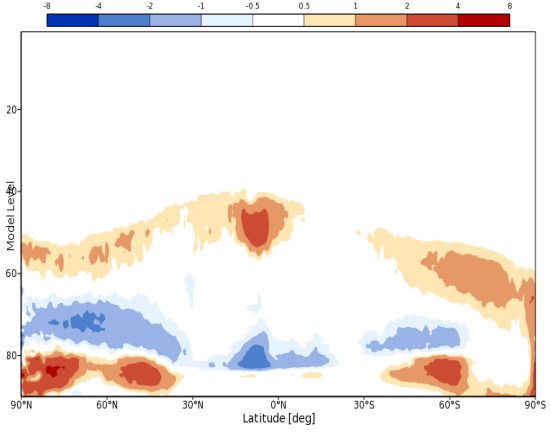
ICON 2.6.3, **ecRad** + LW scat., tune_zvz0i = 0.85

CERES-EBAF, CERES-MODIS: Loeb et al. (2018)

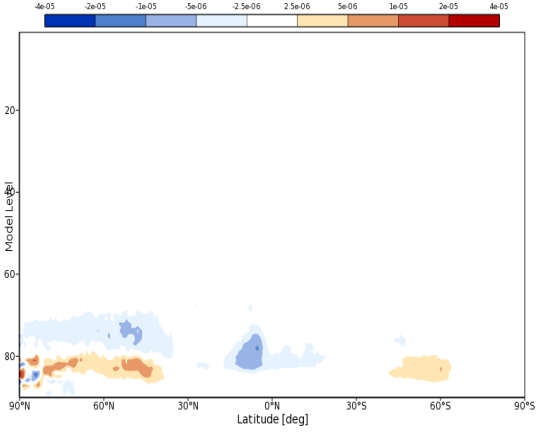
Cloud feedbacks, 24h-forecasts July 2020: ecRad – RRTM

Cloud cover

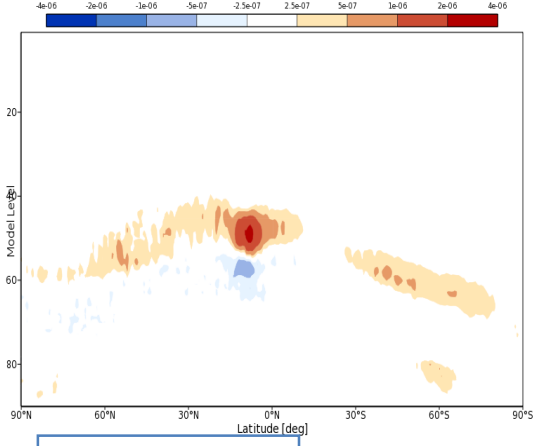
Resolution R2B6, $\Delta x \approx 40$ km



Cloud water

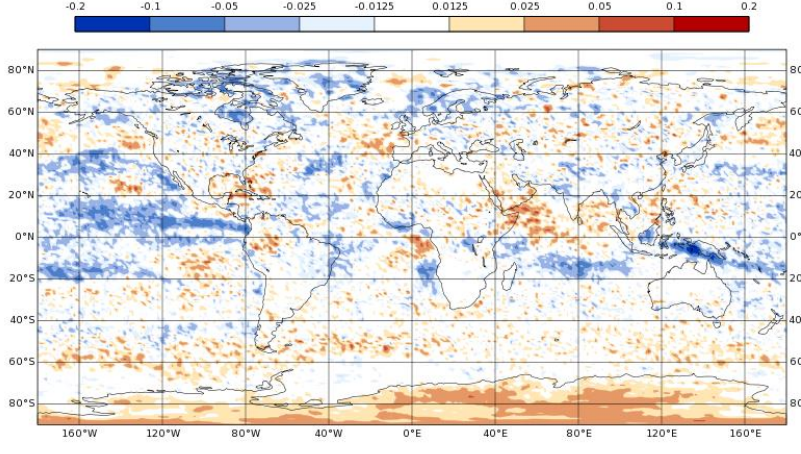


Cloud ice



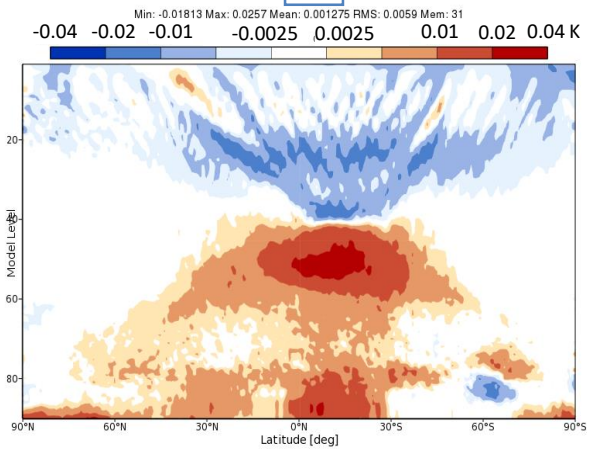
- Icon-2.6.3, R3B7, $\Delta x \approx 40$ km
- With ecRad, high and low clouds increase, mid-level clouds decrease
- Slightly less total cloud cover

Total cloud cover

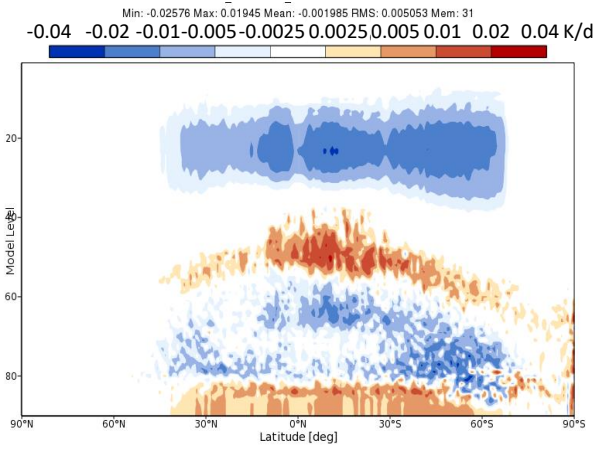


Solver uncertainty in ICON+ecRad: Tripleclouds-McICA (Jan 2020, 24h runs)

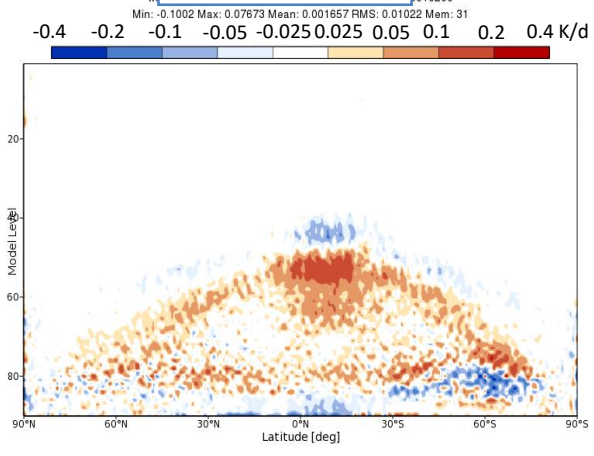
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T SW tendency

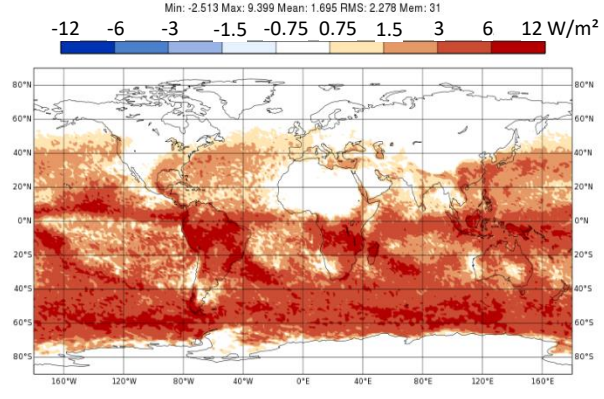


T LW tendency

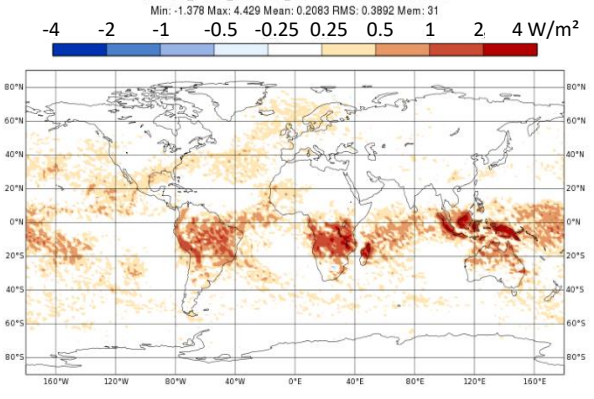


- **Uncertainty:** 2 W/m² systematic difference in global flux (similar settings available) + random variability in McICA
- Tripleclouds slightly more expensive, cheaper with ecckd gas optics

SW TOA flux



LW TOA flux



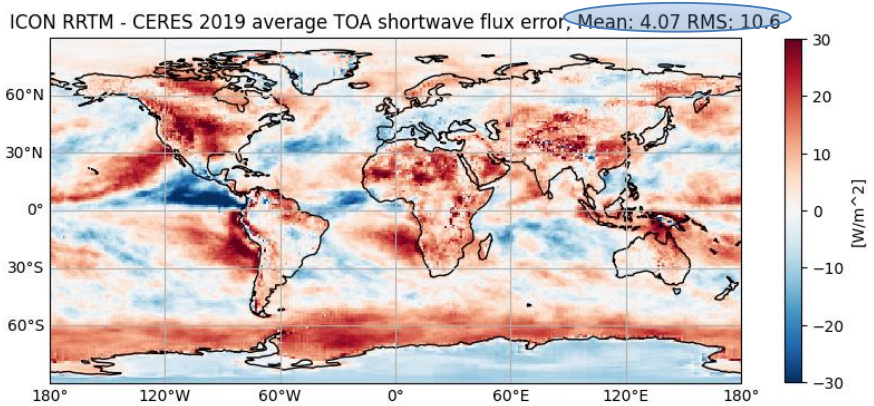
Impact of ecRad, c_p/c_v-Bugfix, tuning : Biases vs. CERES-EBAF 2019

Old routine: c_p/c_v-Bug, tuned RRTM

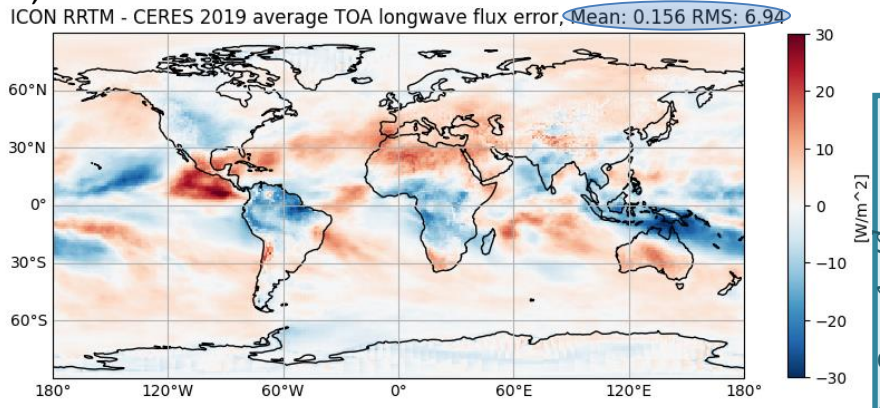
Resolution R2B6, $\Delta x \approx 40$ km

Old routine: c_p/c_v-Bug, tuned RRTM

c_p/c_v-Bugfix, ecRad, tuning

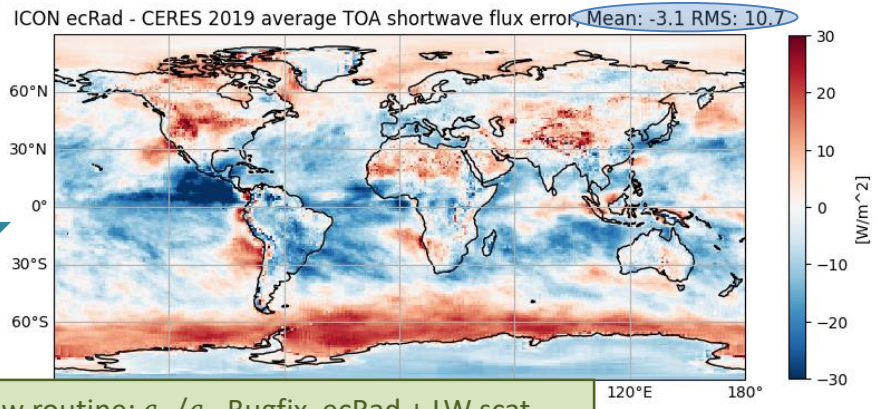


Shortwave (SW) TOA flux biases vs. CERES

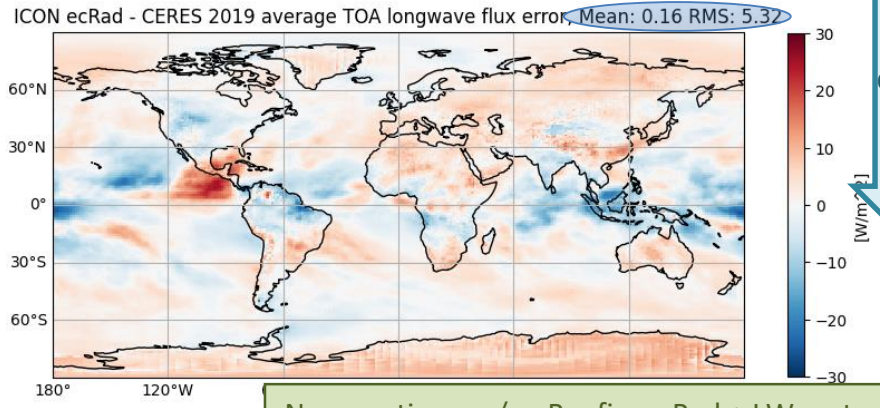


Longwave (LW) TOA flux biases vs. CERES

c_p/c_v-Bugfix, ecRad, tuning



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

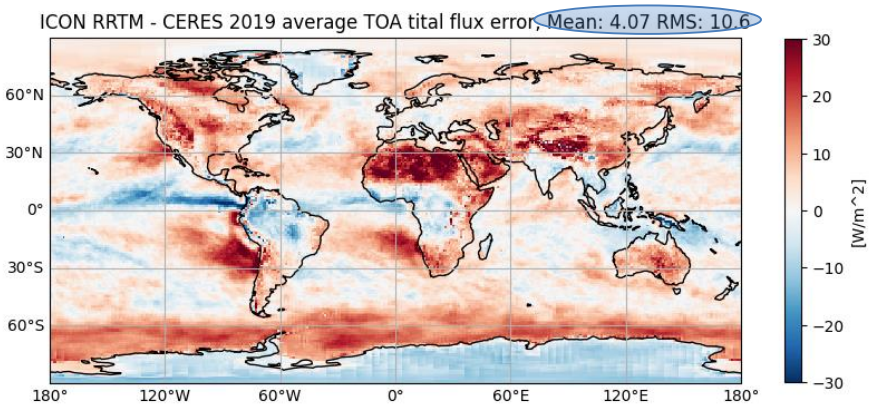


New routine: c_p/c_v-Bugfix, ecRad + LW scat., new CAMEL emissivity

CERES-EBAF: Loeb et al. (2018)

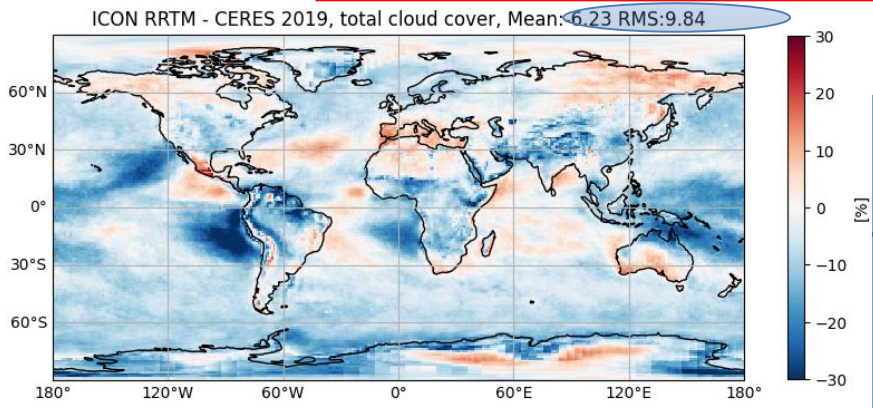
Impact of ecRad, c_p/c_v-Bugfix, tuning : Biases vs. CERES-EBAF 2019

Old routine: c_p/c_v-Bug, tuned RRTM



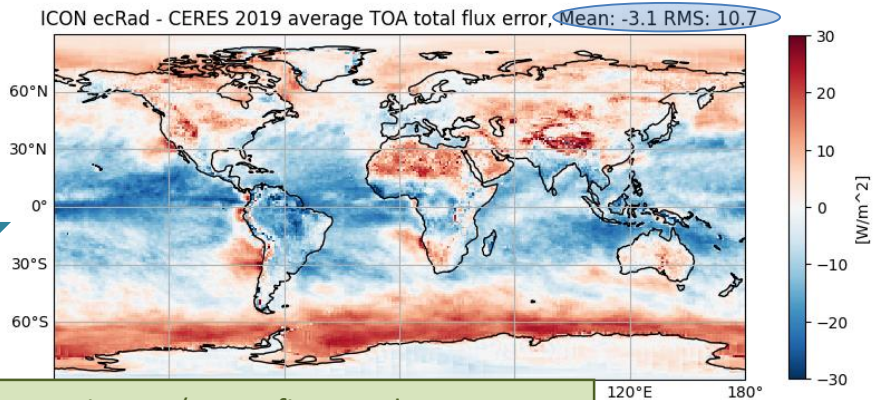
Total TOA flux biases vs. CERES

Old routine: c_p/c_v-Bug, tuned RRTM

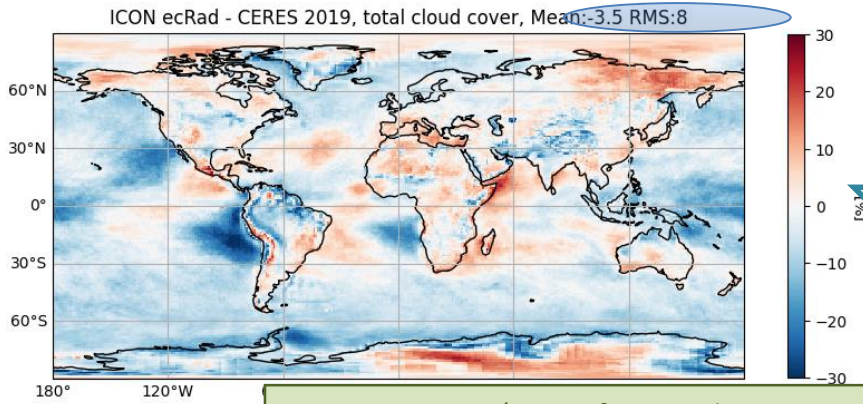


Total **cloud cover** biases vs. CERES: **decreases**

c_p/c_v-Bugfix, ecRad, tuning



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



c_p/c_v-Bugfix, ecRad, tuning

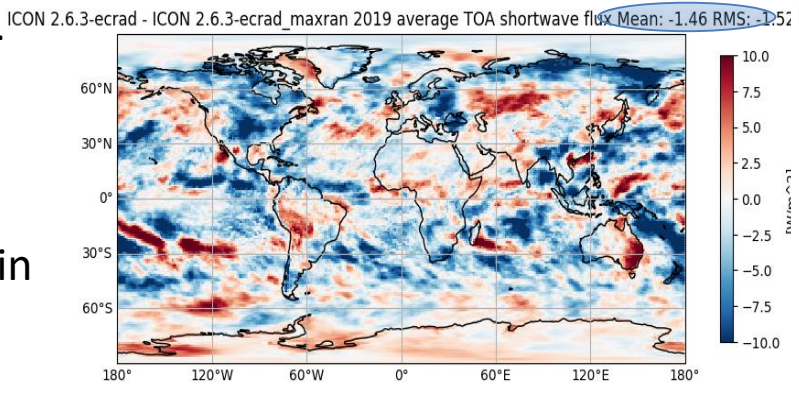
New routine: c_p/c_v-Bugfix, ecRad + LW scat., new CAMEL emissivity

CERES-EBAF, CERES-MODIS: Loeb et al. (2018)

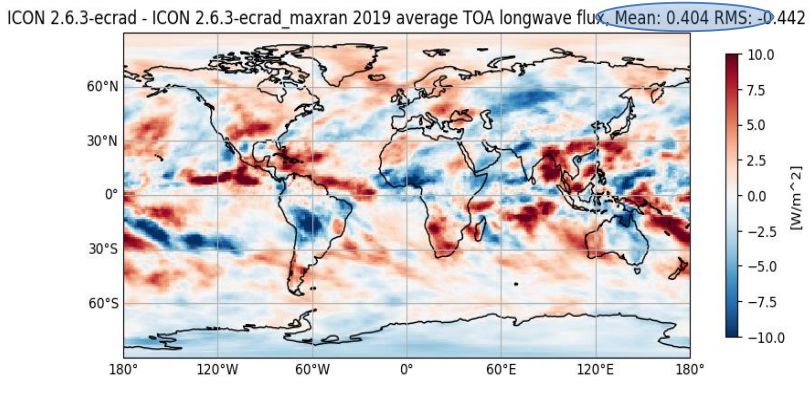
Overlap uncertainty in ICON+ecRad, 2019, 1y-run: overlap vs. exp-ran, 2km

- **Maximum-random** (RTTOV)**:** -1 W/m² difference in global flux, SW-LW opposite
- **Decorrelation length 1km:** 1 W/m² total, +2 W/m² SW

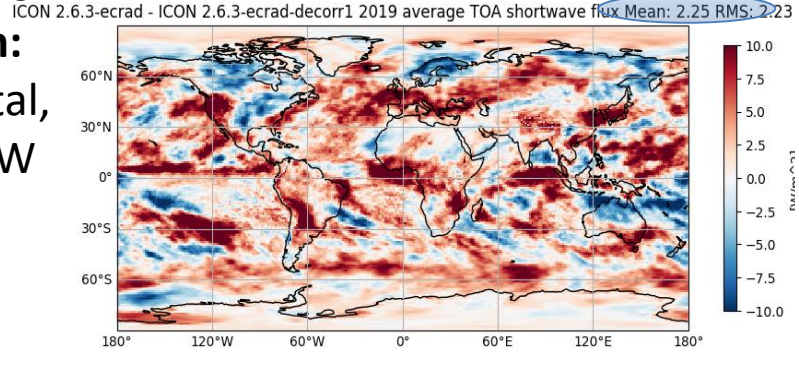
SW TOA flux



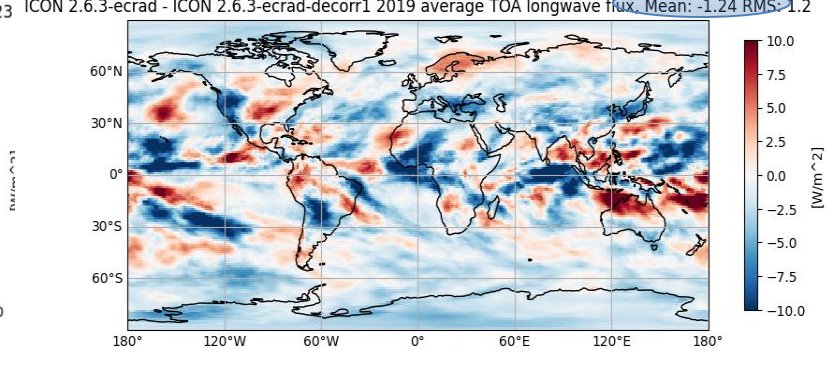
LW TOA flux



SW TOA flux

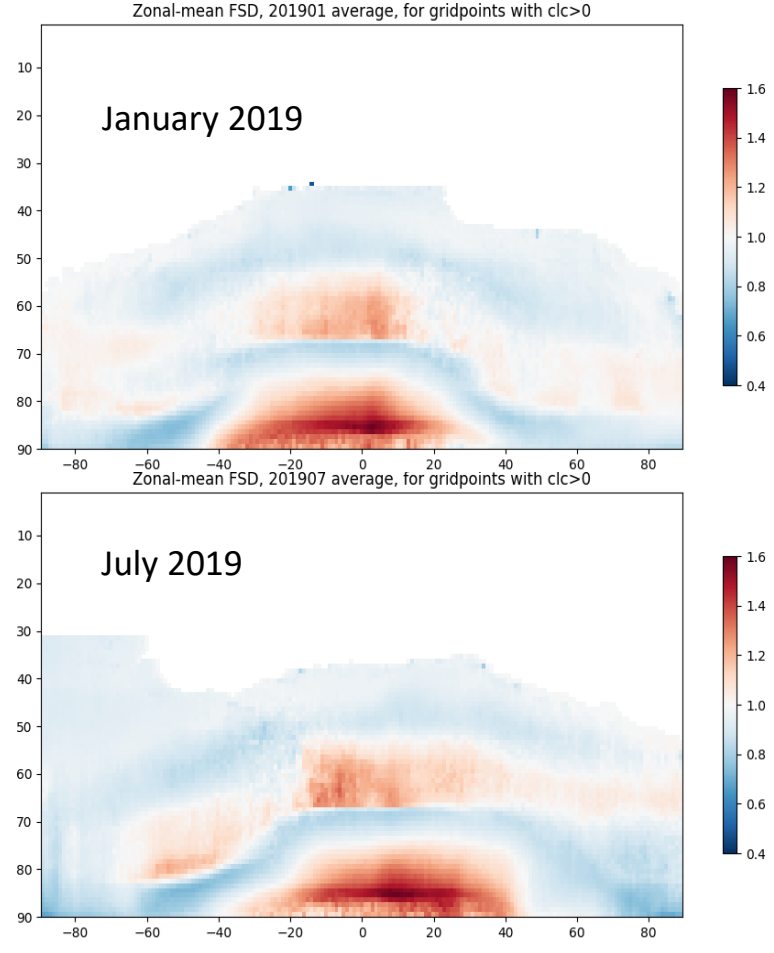


LW TOA flux



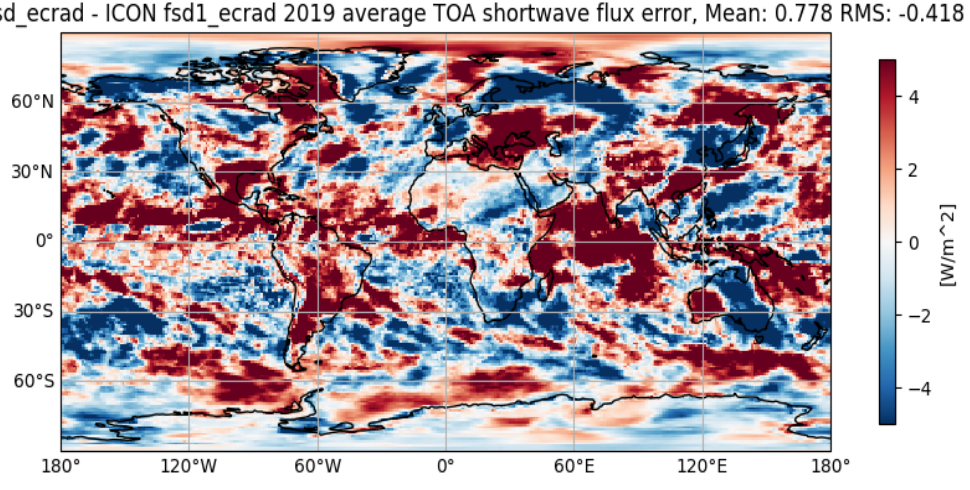
Cloud horizontal inhomogeneity

Zonal mean parametrised in-cloud FSD

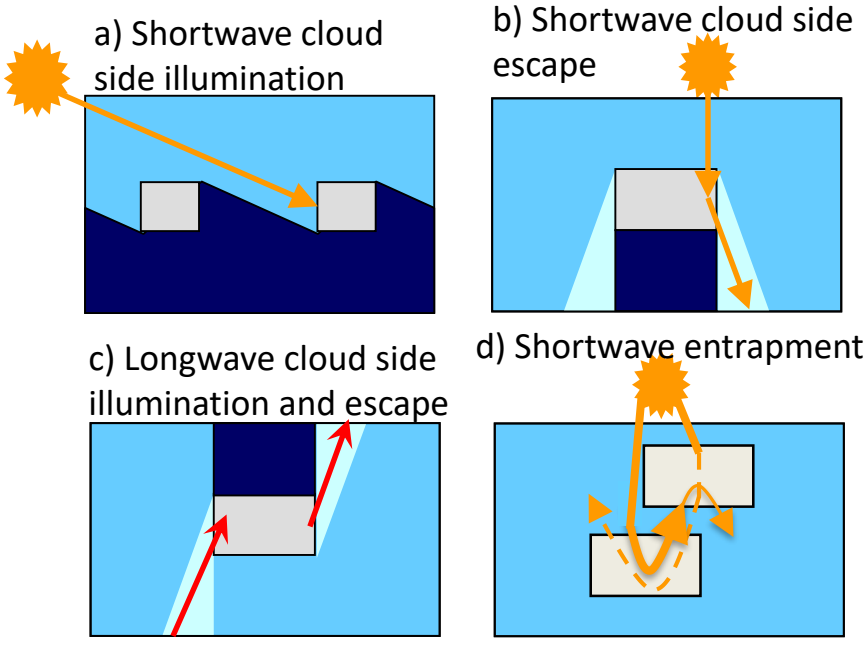


- Reflectivity and longwave emissivity **non-linear functions** of optical depth: need variability.
- Use 2 or more cloud regions, inhomogeneity parameter **fractional standard deviation** (FSD) $= \frac{\text{standard deviation}}{\text{mean}}$; default: FSD =1
- Parametrised FSD by cloud type (Ahlgrimm and Forbes 2016, 2017): global flux +0.9 W/m²

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

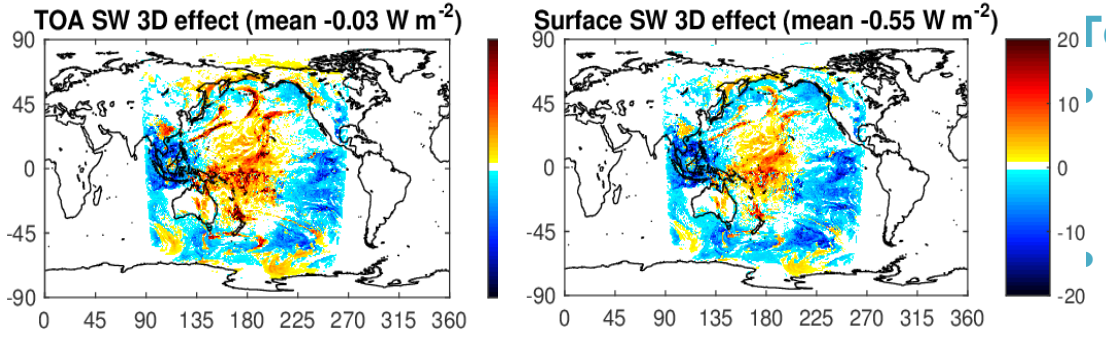


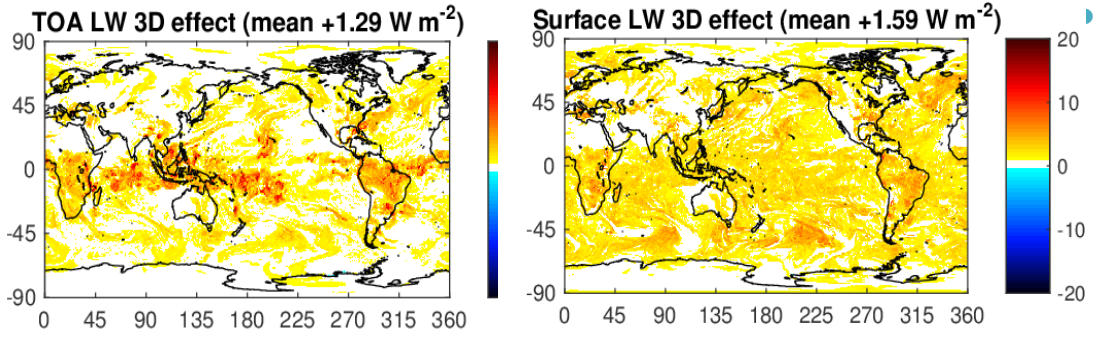
3D cloud effects

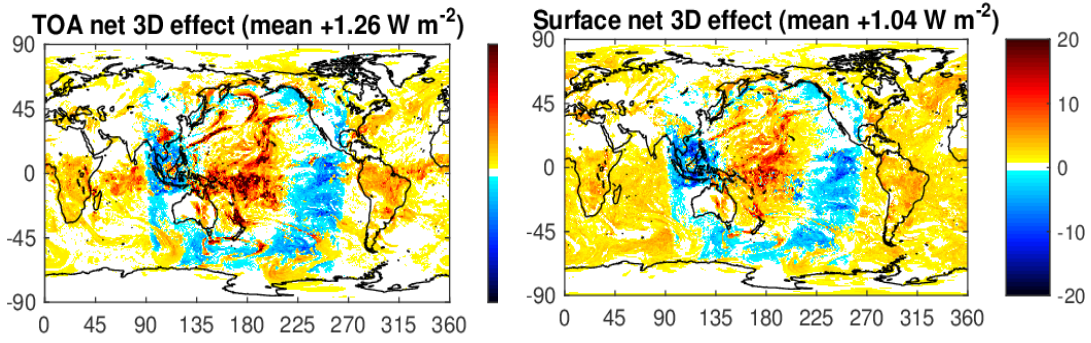


- **Shortwave cloud side illumination** increases cloud reflectivity, **cloud side escape** decreases cloud reflectivity
- **Longwave cloud side illumination and escape** increase cloud warming effect
- **Shortwave entrapment** decreases cloud reflectivity
- Similar effects at complex surfaces (trees / mountains / buildings)
- **Usually neglected, SPARTACUS** solver in ecRad can treat them (Schäfer et al. 2016, Hogan et al. 2016, 2019), cost ×4

Global 3D cloud and surface effects





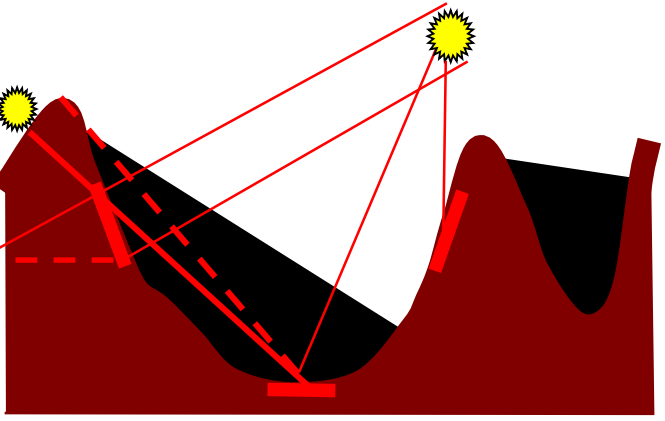


Total 3D cloud effect

- **Global 3D effects, surface:** Longwave +1.6 $\mathrm{Wm^{-2}}$, Shortwave -0.6 $\mathrm{Wm^{-2}}$
- **Long-term total** +1.4 $\mathrm{Wm^{-2}}$, **warms** by ~1K (more at poles)
- Depends on cloud geometr, solar zenith angle (Hogan et al. 2019)

Instantaneous 3D cloud effects in Era5 field, 01.04.2000 0UTC. Plots by R. Hogan

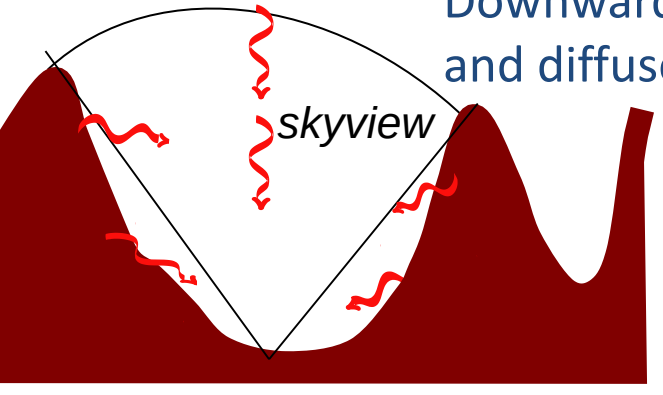
Surface: include radiation effects of orography



slope aspect
slope angle
horizon angle
sun elevation angle
sun azimuth angle

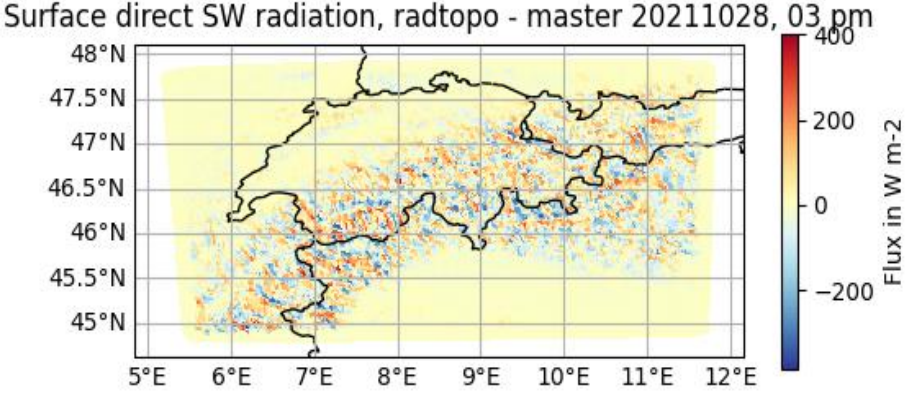
Direct shortwave downward radiation

- Some effects already in ICON (Günther Zängl)
- Additional 3D effects included by André Walser, Guy de Morsier, Remo Dietlicher (MeteoSwiss)



Downward longwave and diffuse radiation

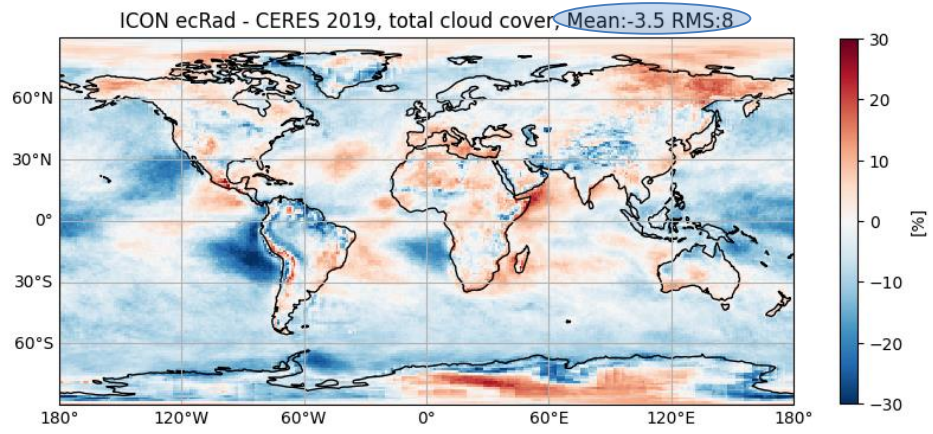
Schematics by Matteo Buzzi (2008), André Walser, MeteoSwiss

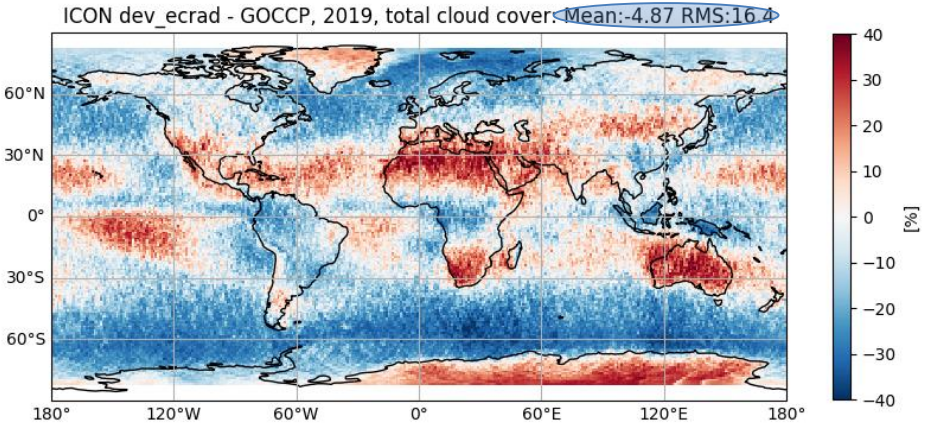


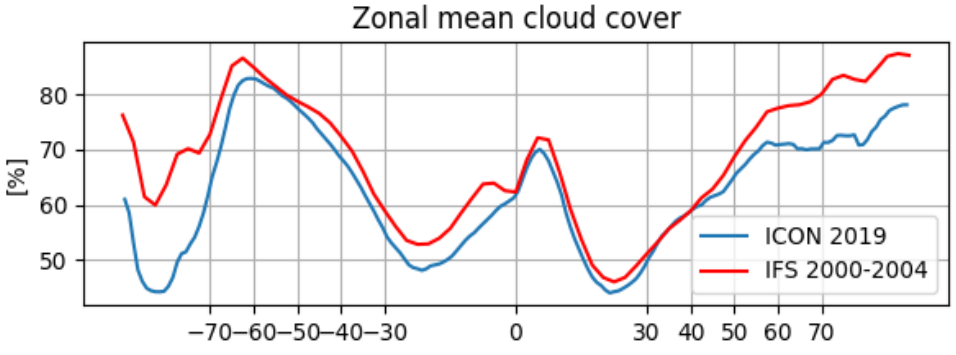
Shortwave direct effects of **improved orography treatment**

Cloud cover uncertainty

Total **cloud cover** bias vs. CERES and GOCCP, 2019







Zonal cloud cover in ICON 2019 and IFS 2000-2004,
IFS data courtesy of P. Bechtold

- Globally: 3.5% too little cloud cover vs. CERES (Loeb at al. 2018), 4.9 % vs. GOCCP; less cloud cover than IFS
- Need to consider retrievals, sensitivity and cloud cover definition, potentially evaluate in observation space
- New cloud parametrisation in ICON planned