# ecRad: A modular radiation scheme for IFS, OpenIFS, and for offline research

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ECMWF

# Five "Grand Challenges" for radiation in NWP models

Solar spectrum

Water vapour biases

**Middle atmosphere**

Ozone

Code optimization

GPUs

**Efficiency**


Spatial/temporal/spectral resolution

**Clouds**

Overlap

Sub-grid heterogeneity

3D effects

Particle size

Optical properties

Longwave scattering

Water vapour continuum

**Clear-sky absorption**

Aerosols

Sea emissivity

Snow albedo

Forests

Urban areas

Orography

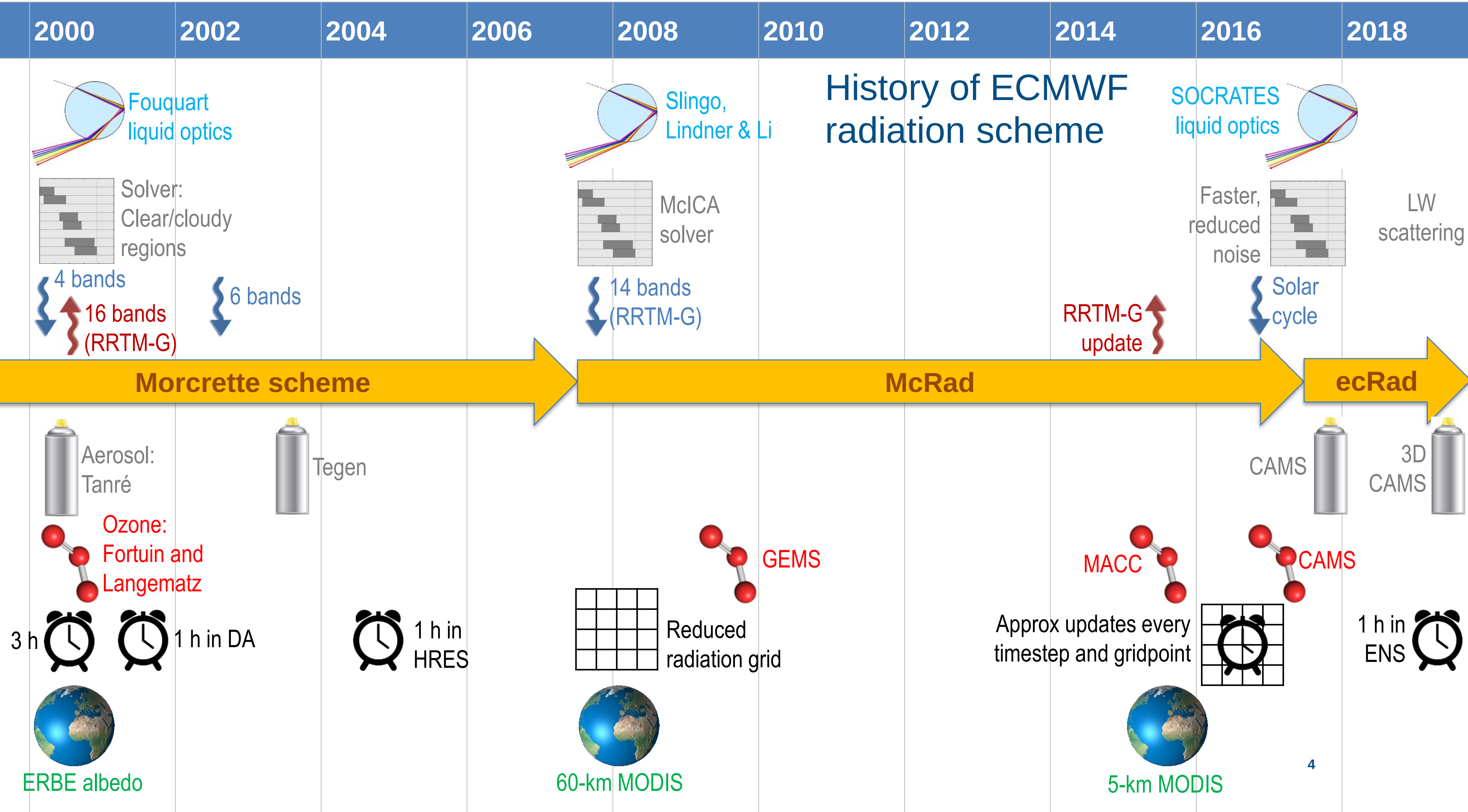
Land albedo datasets

**Surface**

Coastlines

# Overview of talk

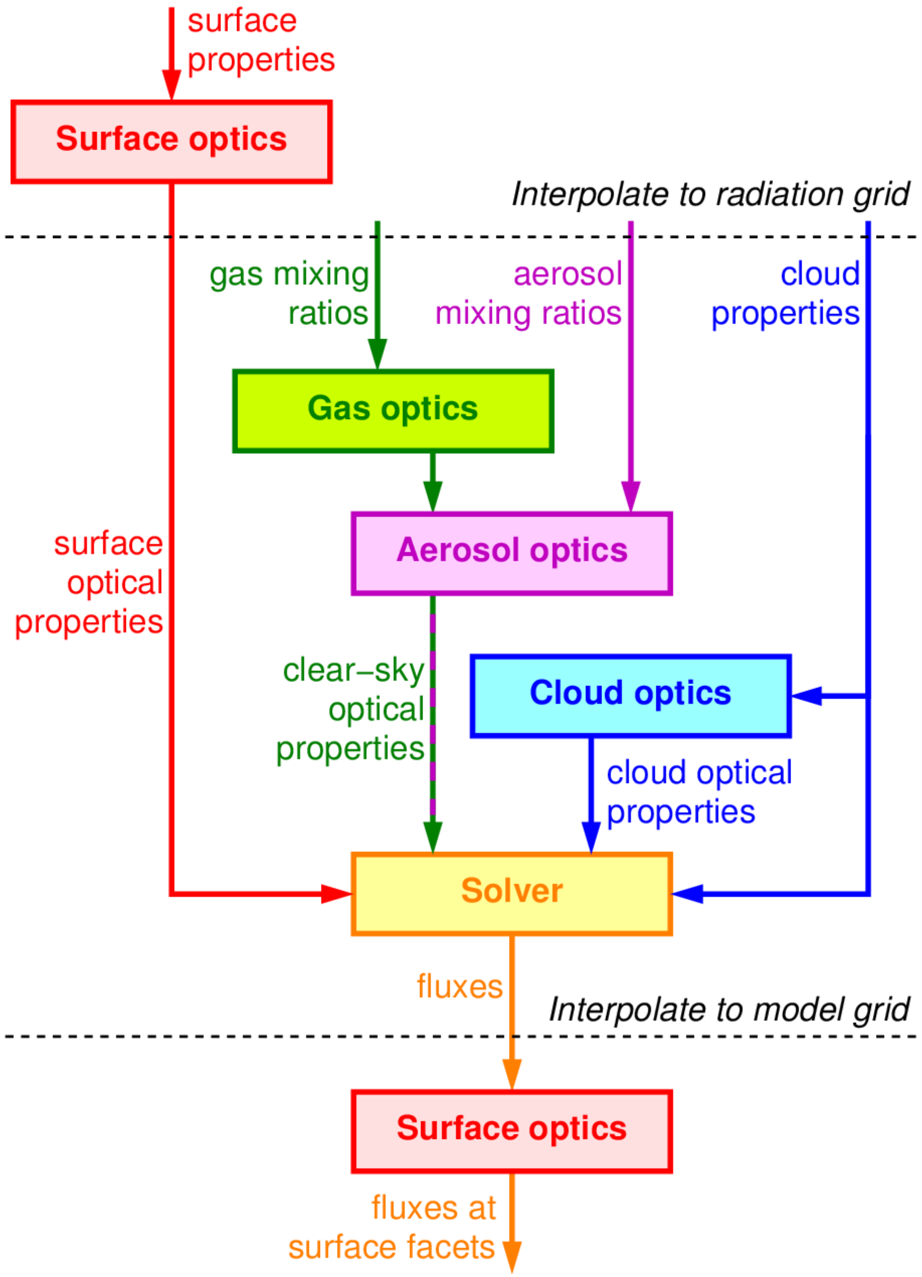
- Brief history of the ECMWF radiation scheme
- ecRad: a new radiation scheme and impact on forecast skill
- Recent changes to aerosols and the stratosphere
- Using offline and online ecRad to understand 3D cloud radiative effects
- Plans for detailed representation of vegetation and urban areas
- Plans for a faster gas optics scheme



History of ECMWF radiation scheme
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
Fouquart liquid optics
Slingo, Lindner & Li
SOCRATES liquid optics
Solver: Clear/cloudy regions
McICA solver
Faster, reduced noise
LW scattering
4 bands
16 bands (RRTM-G)
6 bands
14 bands (RRTM-G)
RRTM-G update
Solar cycle
Morcrette scheme
McRad
ecRad
Aerosol: Tanré
Tegen
CAMS
3D CAMS
Ozone: Fortuin and Langematz
GEMS
MACC
CAMS
3 h
1 h in DA
1 h in HRES
Reduced radiation grid
Approx updates every timestep and gridpoint
1 h in ENS
ERBE albedo
60-km MODIS
5-km MODIS

# Modular radiation scheme for ECMWF: ecRad

- Gas optics
  - RRTM-G (as before)
  - *Plan to develop new scheme with fewer spectral intervals*
- Aerosol optics
  - Number of species and optical properties set at run time
  - Supports prognostic & diagnostic aerosol
- Cloud optics
  - Liquid clouds: more accurate SOCRATES scheme
  - Ice clouds: Fu by default, Baran and Yi available




- Solver
  - McICA, Tripleclouds or SPARTACUS solvers
  - SPARTACUS makes the IFS the only global model that can do 3D radiative effects
  - Better solution to longwave equations improves tropopause & stratopause
  - Longwave scattering optional
  - Can configure cloud overlap, width and shape of PDF
- *Surface (under development)*
  - *Rigorous and consistent treatment of radiative transfer in urban and forest canopies*
- Offline version available for non-commercial use under OpenIFS license

# How do the three solvers compute how clouds interact with radiation?

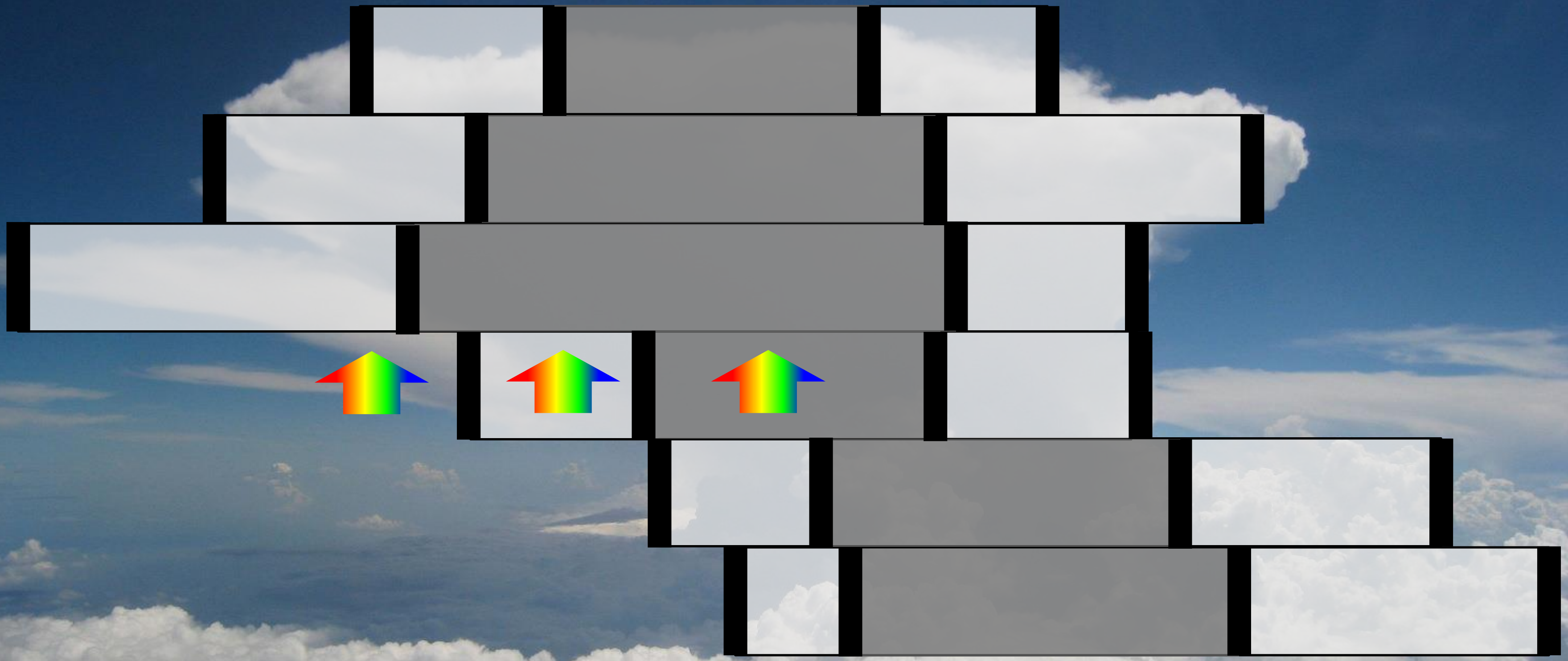
# Monte-Carlo Independent Column Approximation (McICA, Pincus et al. 2005)

*Each wavelength sees a different cloud realization (OPERATIONAL)*

- Use prognostic cloud fraction and assumed standard deviation of cloud water
- Stochastic cloud generator is fast but leads to some noise in fluxes
- McICA now used in many (most?) global weather and climate models

# Tripleclouds (Shonk & Hogan 2008)

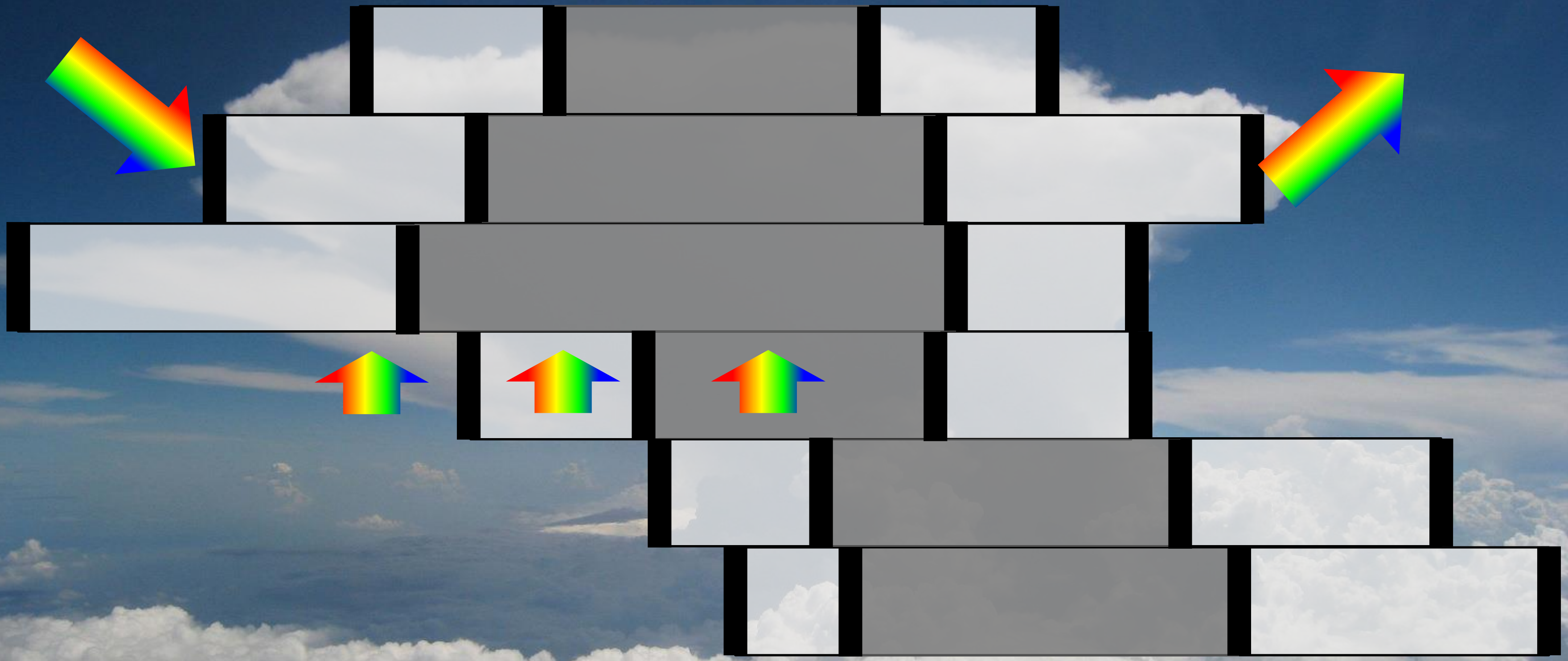
***Approximate cloud variability by three regions: one clear and two cloudy***



- Cloud overlap rules govern how radiation enters different regions at layer interfaces
- Fluxes and heating rates are noise-free, but this solver is slower than McICA

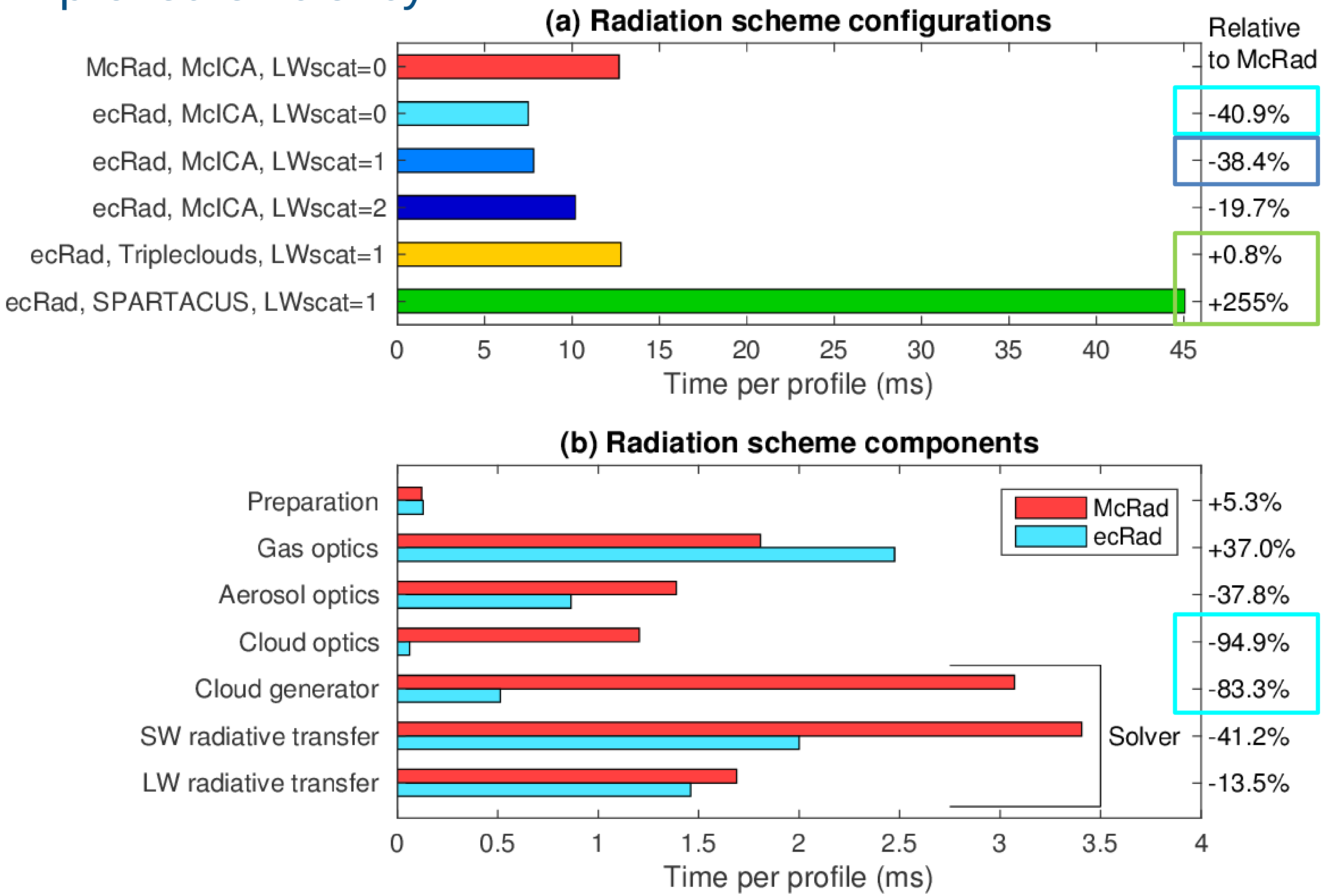
# SPARTACUS (Hogan et al., Schäfer et al. 2016)

*Tripleclouds with lateral radiation exchange between regions*



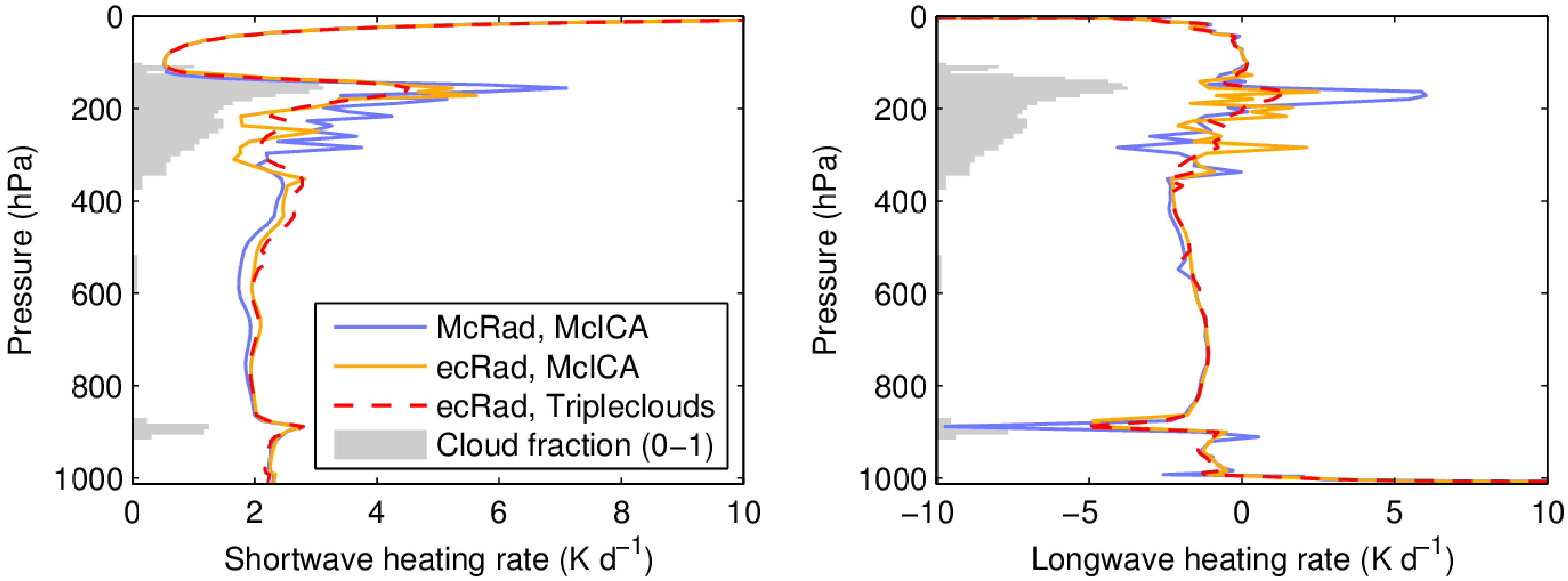
- SPARTACUS makes ecRad the first GCM radiation scheme that can simulate 3D radiative effects
- Slower than Tripleclouds, and still under development and evaluation

# Improved efficiency

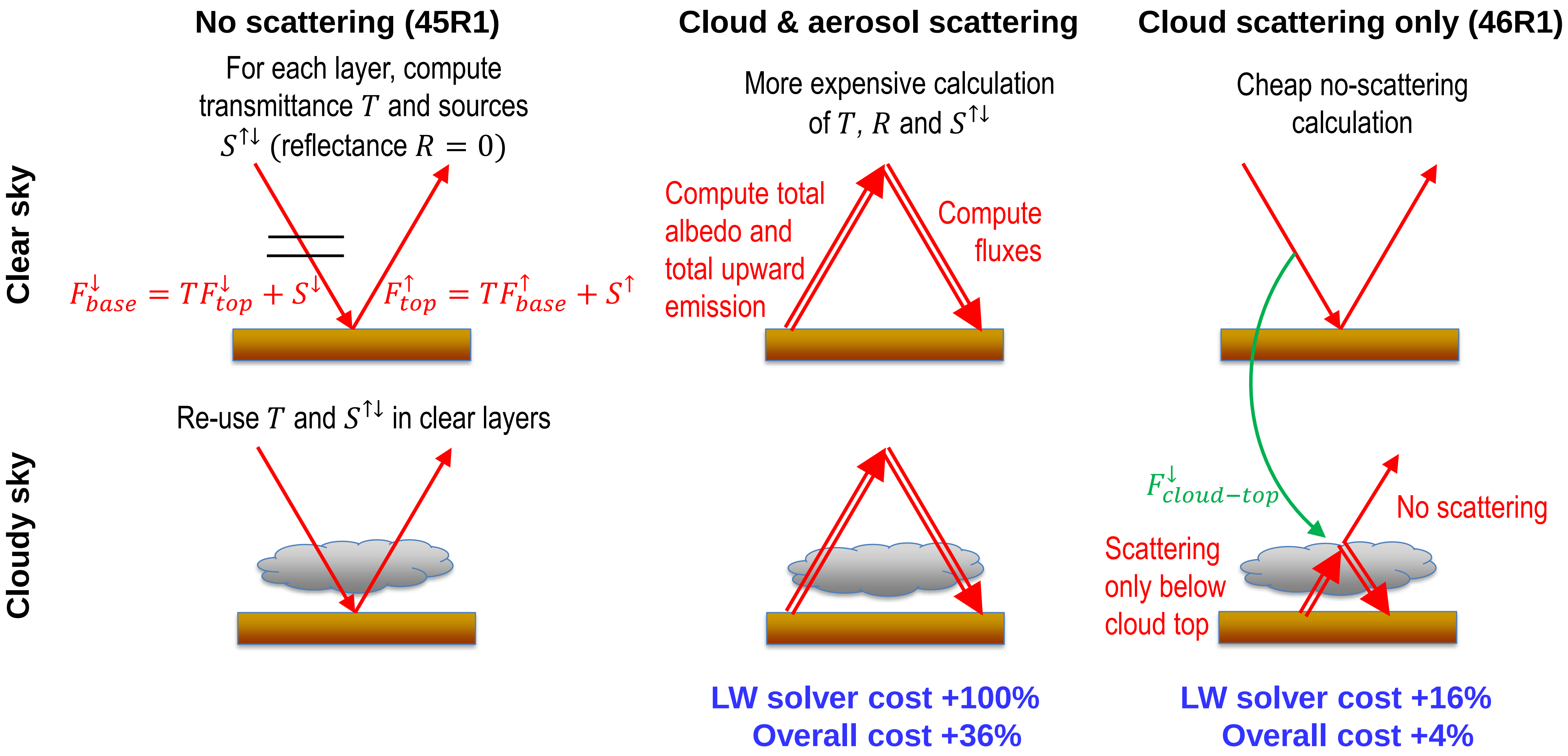



- ecRad is much faster than original McRad scheme in operational McICA configuration
- Longwave scattering introduced in 46r1 with minimal cost
- Triplecloud a bit more expensive
- 3D radiation much more expensive but feasible in research mode
- Cloud treatment is much faster

# Reduced noise in ecRad's McICA solver



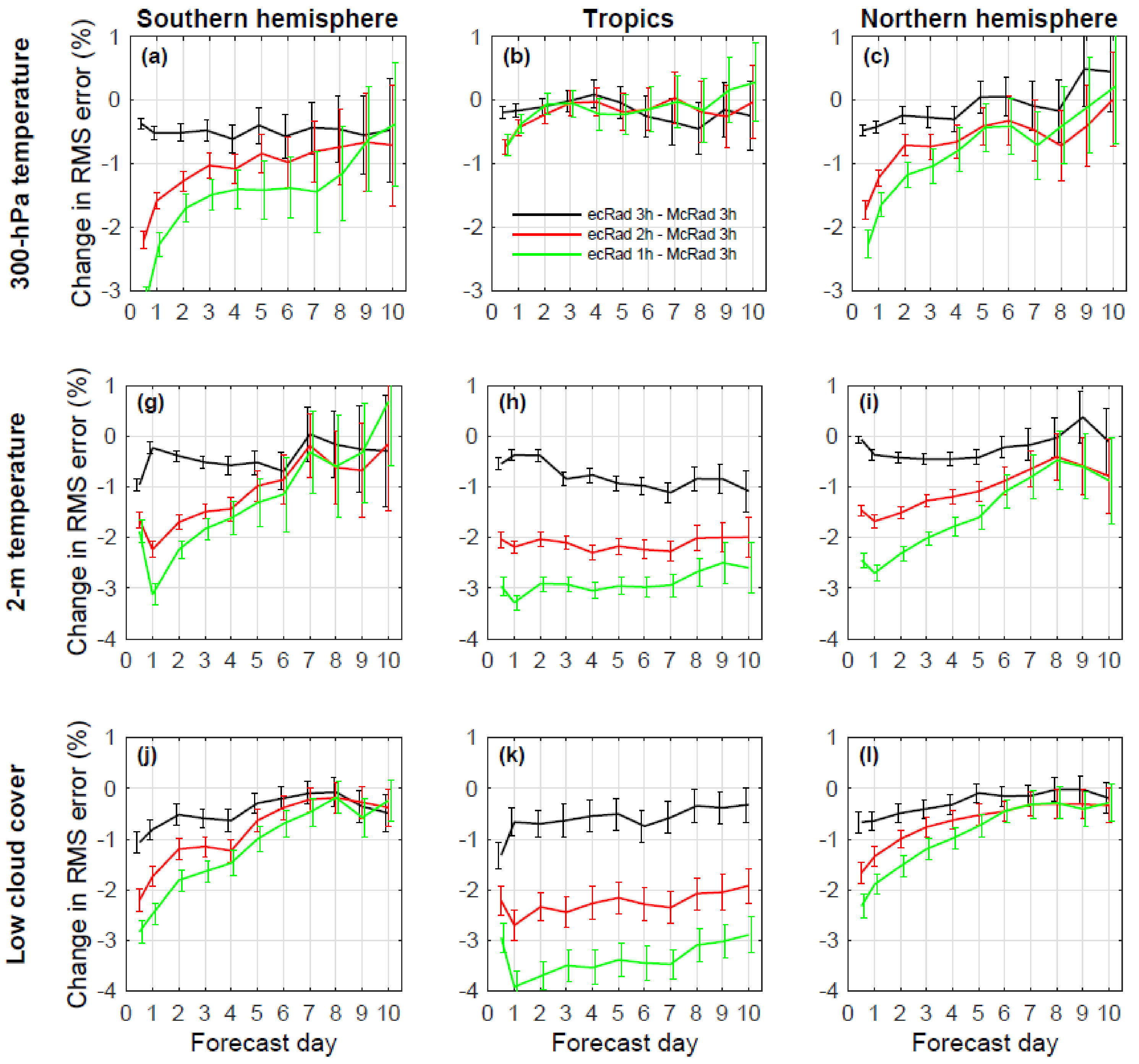
# Fast longwave scattering for clouds but not aerosols




ECMWF

# Impact on forecast skill

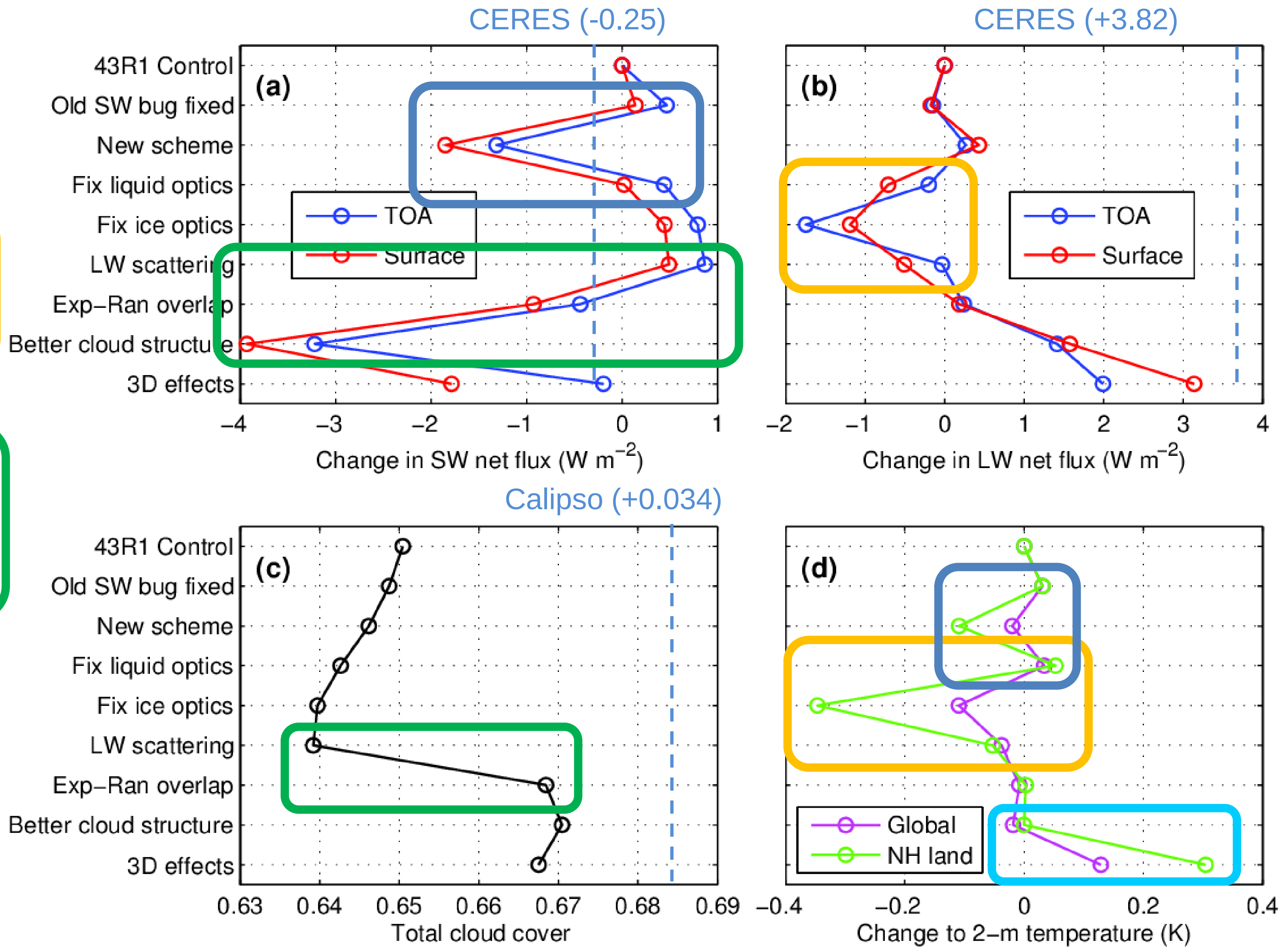
- Latest version of ecRad reduces temperature RMSE by ~0.5% compared to older McRad scheme
  - Combination of longwave scattering, reduced biases and reduced McICA noise
- Until 46R1, all model configurations except HRES call radiation every 3 h
- Reinvest 40% speed-up by calling radiation every 2 h?
  - Temperature RMSE reduced by 1-2%, associated with better low clouds especially over tropical rainforests
- Ensemble system uses 1-h radiation from operational cycle 46R1
  - Temperature RMSE down by 3%




Hogan & Bozzo (JAMES 2018)

# The fight against compensating errors…

- 43R3 introduced ecRad along with a fix for liquid cloud optics
- 46R1 introduced LW scattering and fixed an ice-optics bug that had a similar but opposite impact
- Better overlap and cloud structure improves cloud cover, but reduces shortwave at the surface, which is already too cold
- Perhaps 3D radiation would help to improve fluxes and temperature?



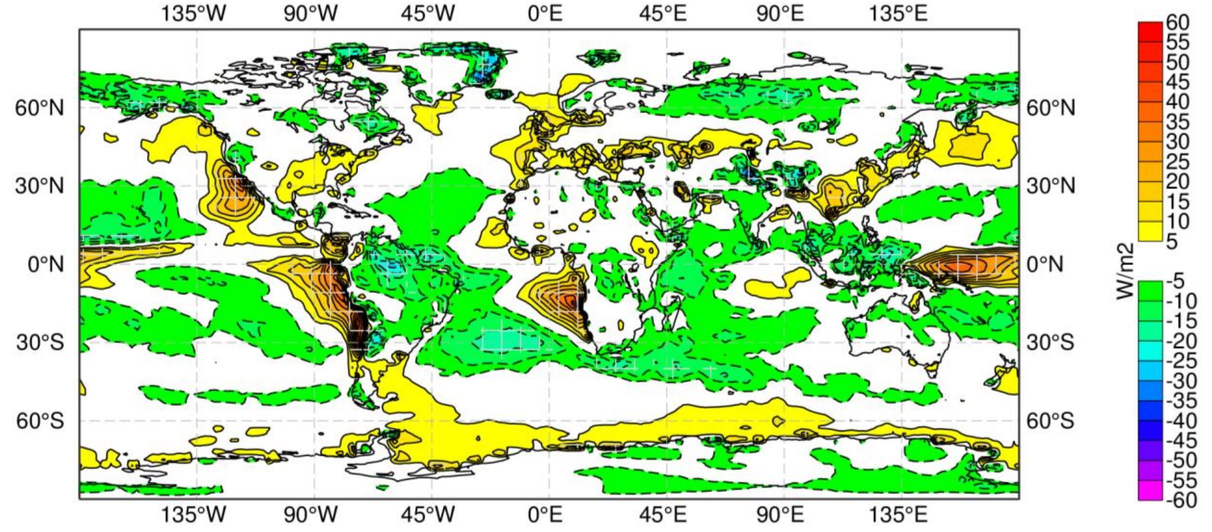

ECMWF

# IFS model climate: ***the good***…

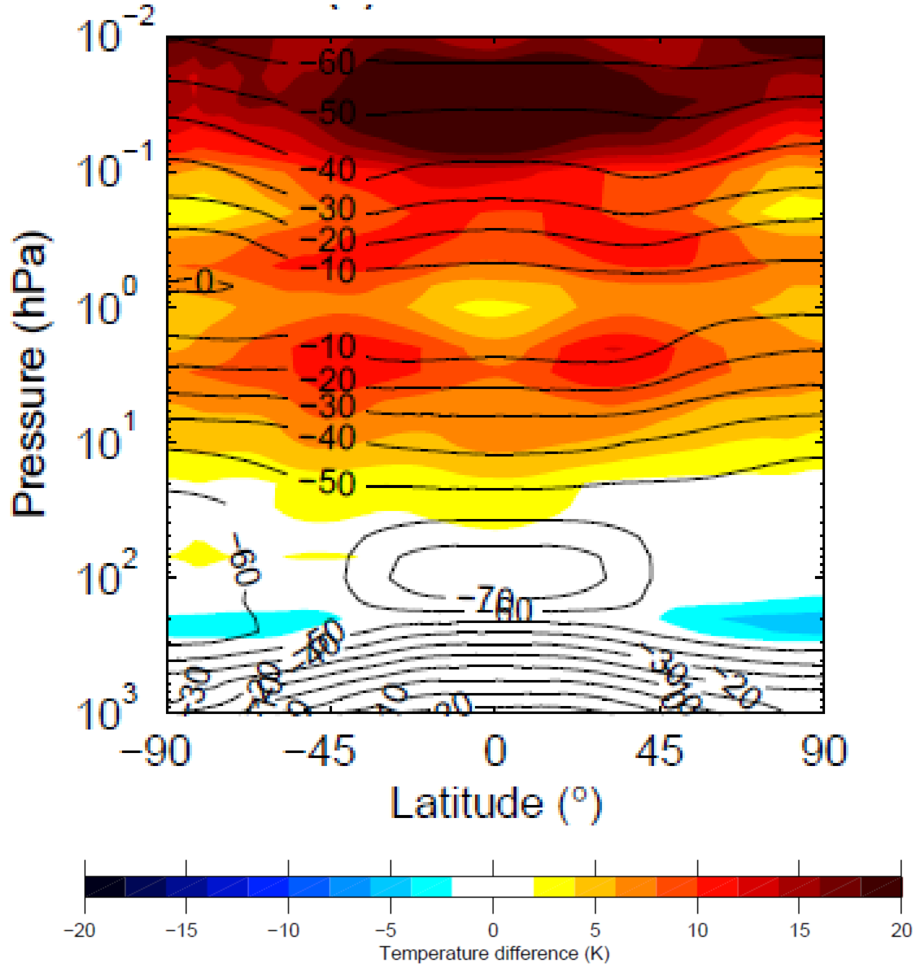
<2 ≥2 ≥4 W $m^{-2}$

| Wild et al. (2015) Surface downwelling | Global SW | Global LW | Land SW | Land LW |
|---|---|---|---|---|
| Observations | 184.7 | 341.5 | 184 | 306 |
| 43 climate models | 4 ± 5 | −2 ± 4 | 6 ± 10 | −4 ± 7 |
| ERA5 | 3.5 | −2.3 | 5.3 | −2.4 |
| Coupled IFS climate | −0.4 | −0.9 | 0.4 | 0.7 |

## *…**the bad**… (SW cloud radiative effect bias)*

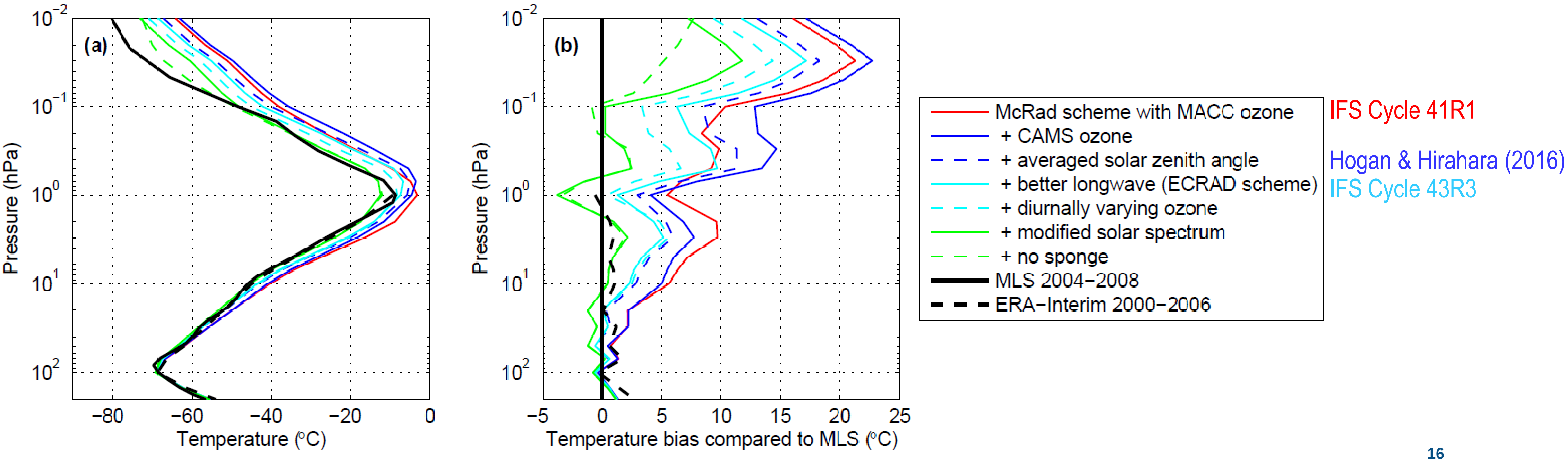



## *…**and the ugly** (middle-atmosphere temperature bias)*



# Upper stratosphere warm bias

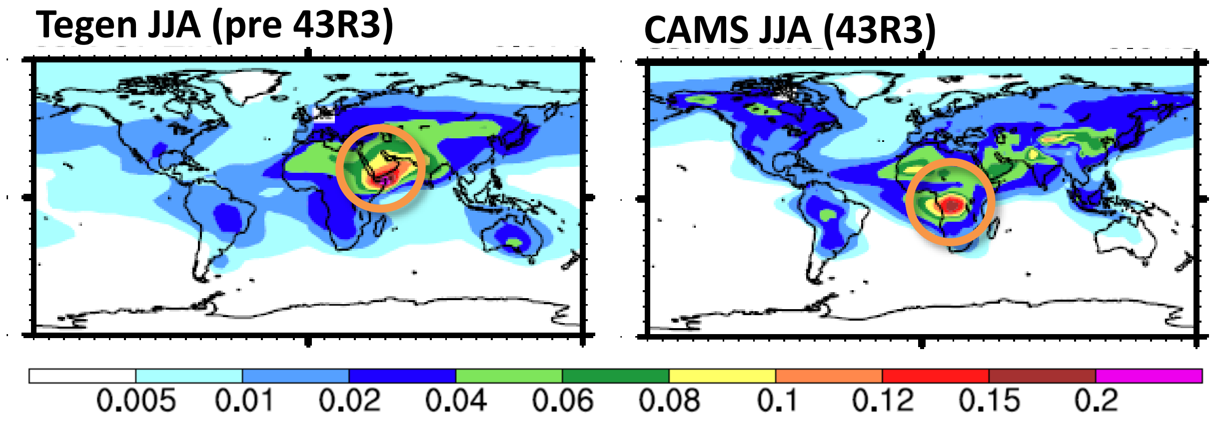
- Historically, IFS has had a huge warm bias in upper stratosphere and above
- Improved in recent cycles (better longwave in ecRad, CAMS ozone, better solar zenith averaging)
- Remaining bias could be removed in stratosphere by updating solar UV which is 7-8% too high in IFS
- Lower mesosphere could be improved with a diurnal cycle of ozone (even if approximate)
- *But resolution-dependence of lower stratosphere temperature (due to waves) needs to be addressed*



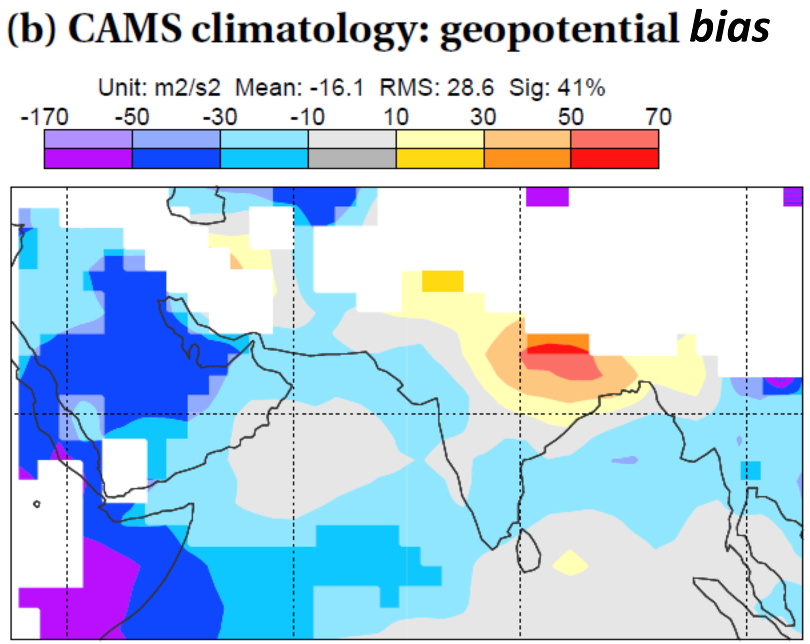
# Aerosols

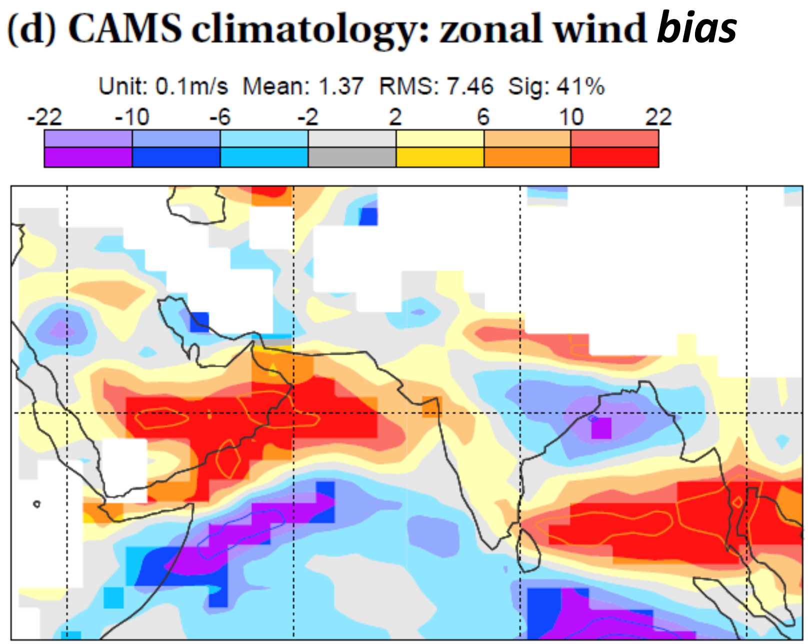
Bozzo et al. (2017)

- Atmospheric forcing depends on *absorption* optical depth:



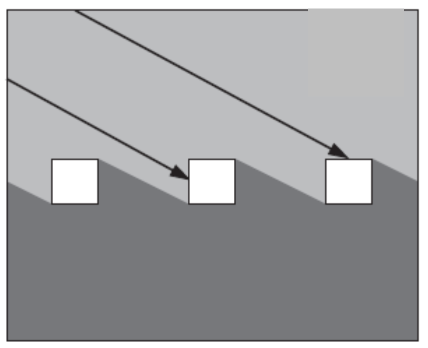

- Reduced absorption over Arabia in new CAMS climatology weakens the overactive Indian Summer Monsoon, halving the overestimate in monsoon rainfall
- Increased absorption over Africa degraded 850-hPa temperature, traced to excessive biomass burning in CAMS
- *We can measure the impact of aerosols on the tropical atmosphere more easily than the absorption optical depth itself! Use to provide information on aerosol errors?*



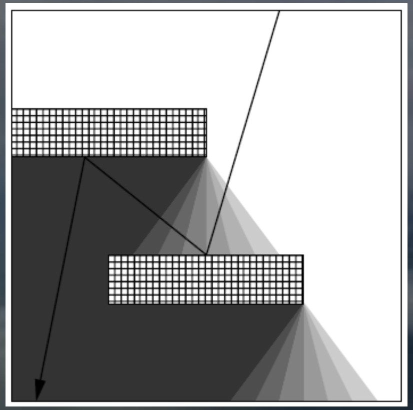



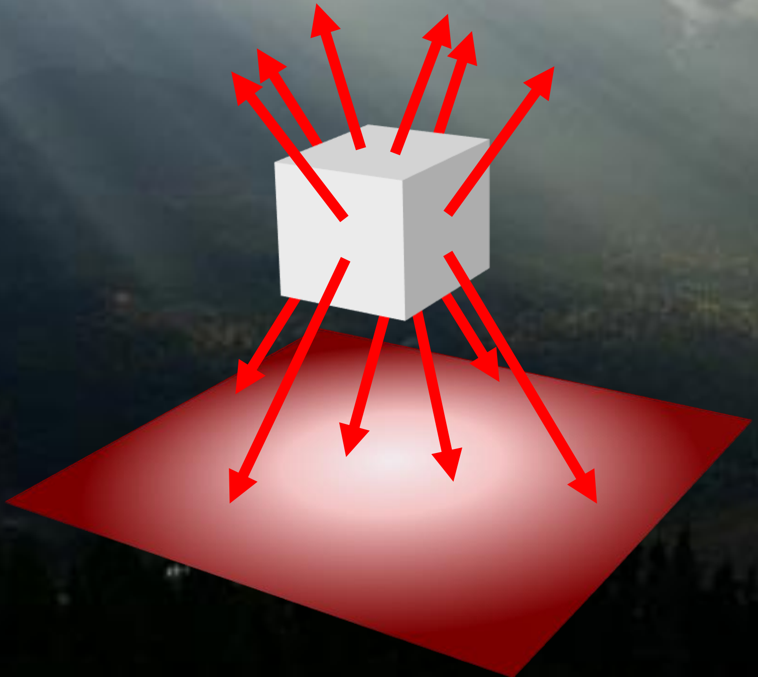
# Main mechanisms for 3D radiative effects

- **Shortwave side illumination**
  - Strongest when sun near horizon
  - Increases chance of sunlight intercepting cloud



- **Shortwave entrapment (new!)**
  - Horizontal transport beneath clouds makes reflection to space less likely

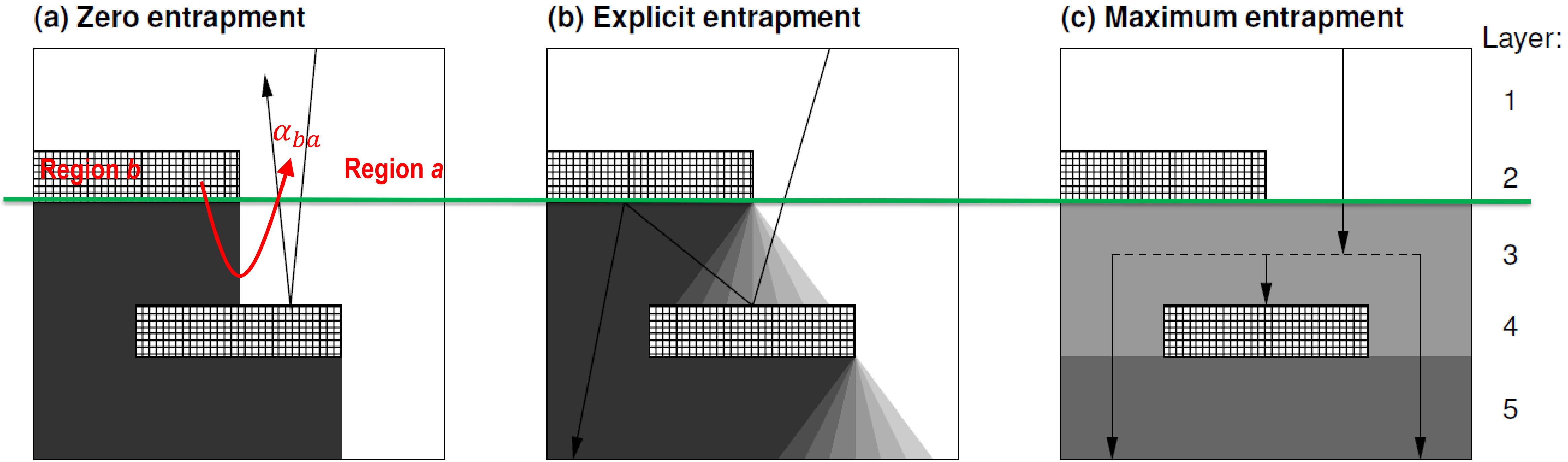




- **Longwave side emission**
  - Radiation can now be emitted from the side of a cloud
  - 3D effects can increase surface cloud radiative effect

# Representing three extremes of "entrapment" in SPARTACUS

- We need albedo matrix **A** at layer interfaces




No 3D effects requires matrix to be diagonal

$$\mathbf{A} = \begin{pmatrix} \alpha_{aa} & \alpha_{ba} \\ \alpha_{ab} & \alpha_{bb} \end{pmatrix} = \begin{pmatrix} \alpha & 0 \\ 0 & \alpha \end{pmatrix}$$

*Better approach in 46r1: compute RMS horizontal migration distance of light paths beneath cloud*

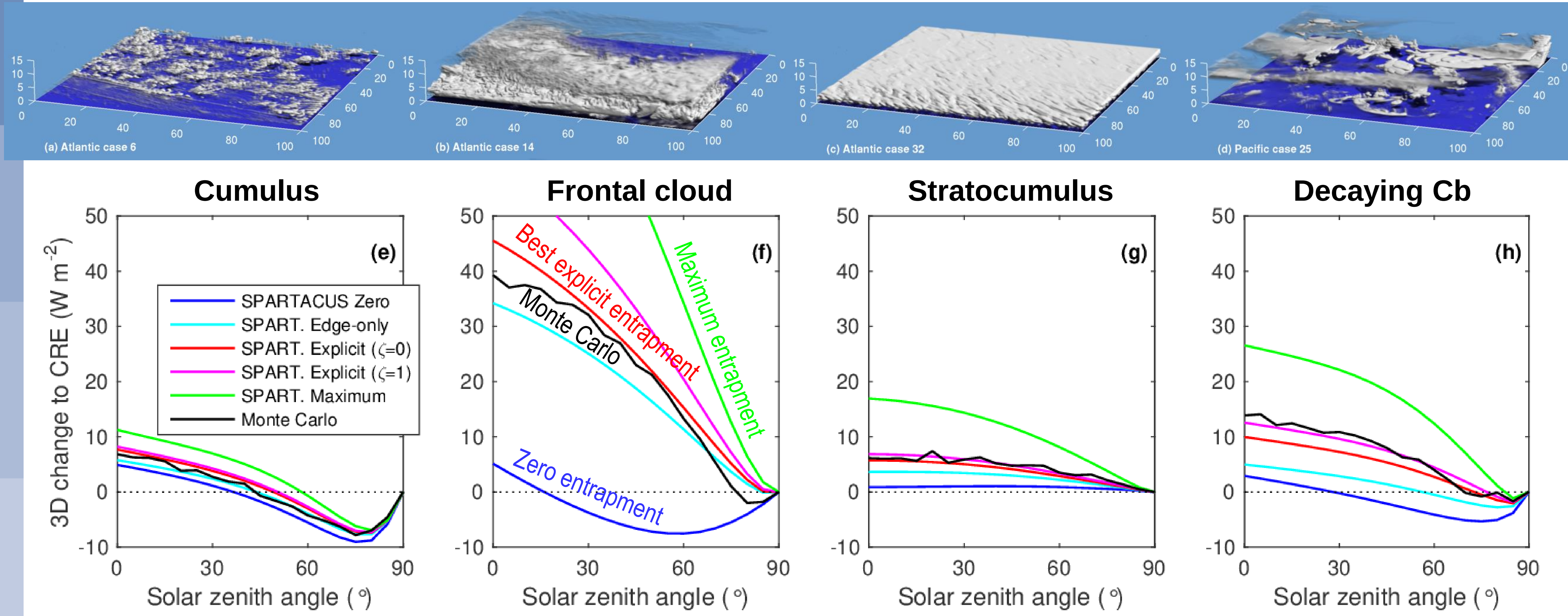
43r3 SPARTACUS: full horizontal homogenization of radiation under clouds

$$\mathbf{A} = \begin{pmatrix} \alpha/2 & \alpha/2 \\ \alpha/2 & \alpha/2 \end{pmatrix}$$

# Evaluating offline ecRad using Monte Carlo calculations on 100x100km scenes

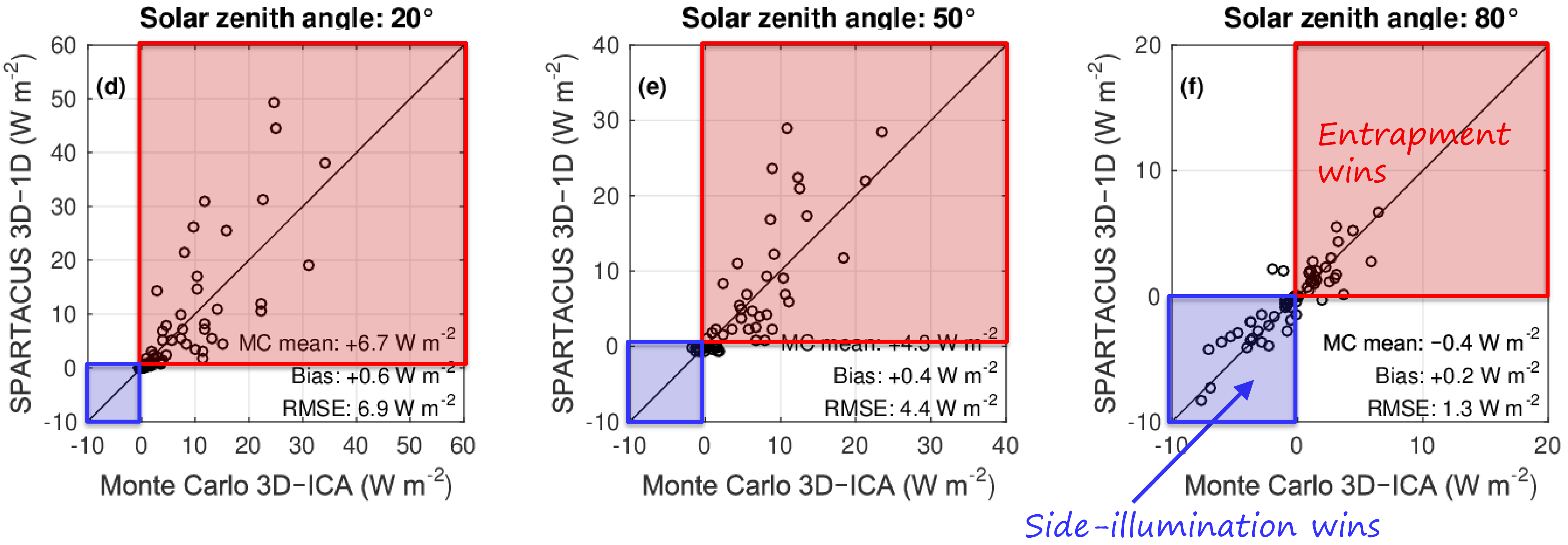
- SPARTACUS with **explicit entrapment** matches **Monte Carlo** well, on average
- Huge difference between **maximum entrapment** and **zero entrapment**

Monte Carlo calculations by Howard Barker



# Evaluating fluxes using all 65 scenes

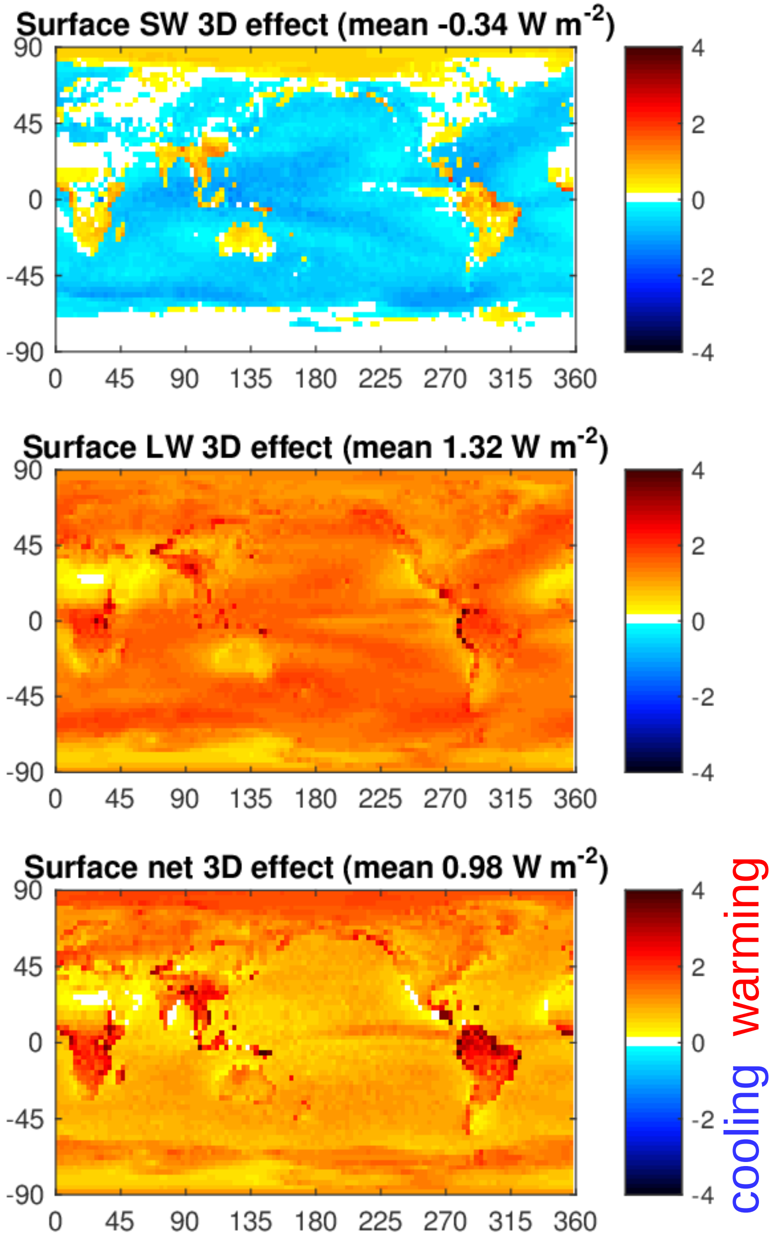
- 3D radiative effect predicted by SPARTACUS agrees quite well with Monte Carlo



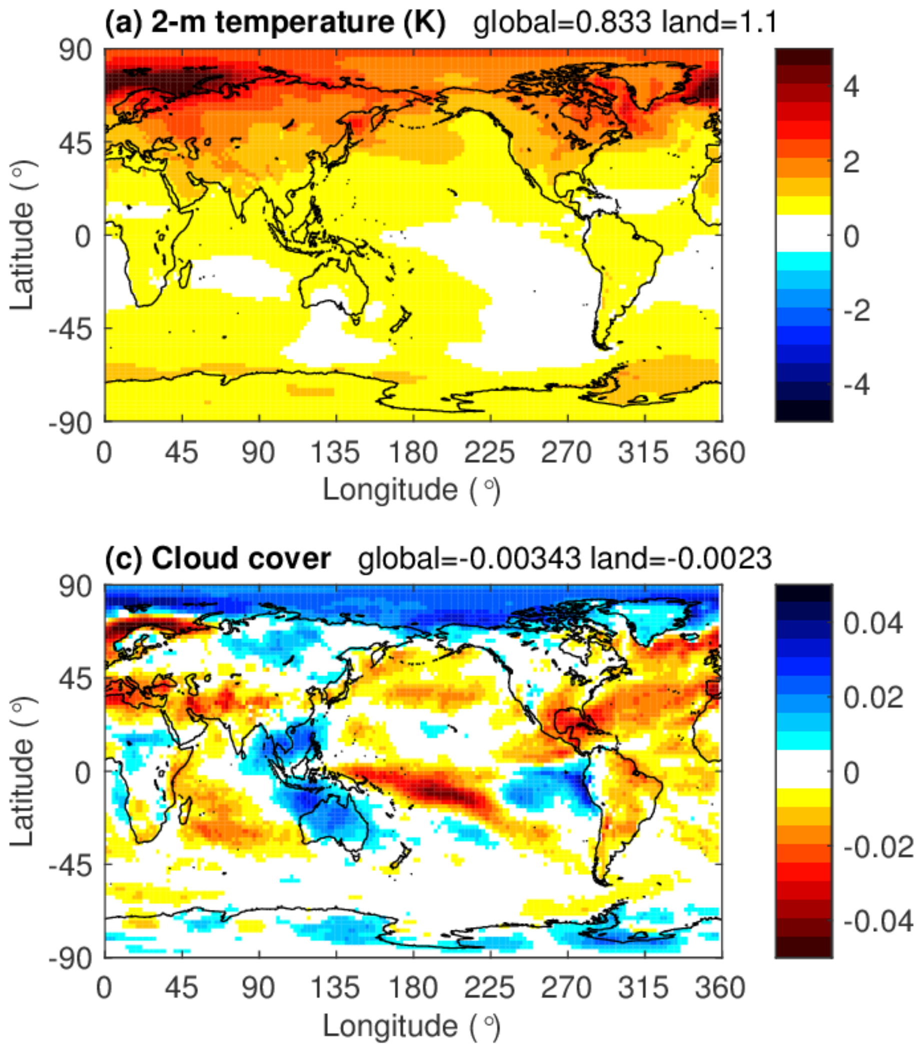

- The entrapment mechanism appears to win over side-illumination, implying shortwave 3D effects warm the climate system
- Very dependent on *cloud size*, which might not be realistic for these CRM scenes but needs to be parameterized in any global simulation

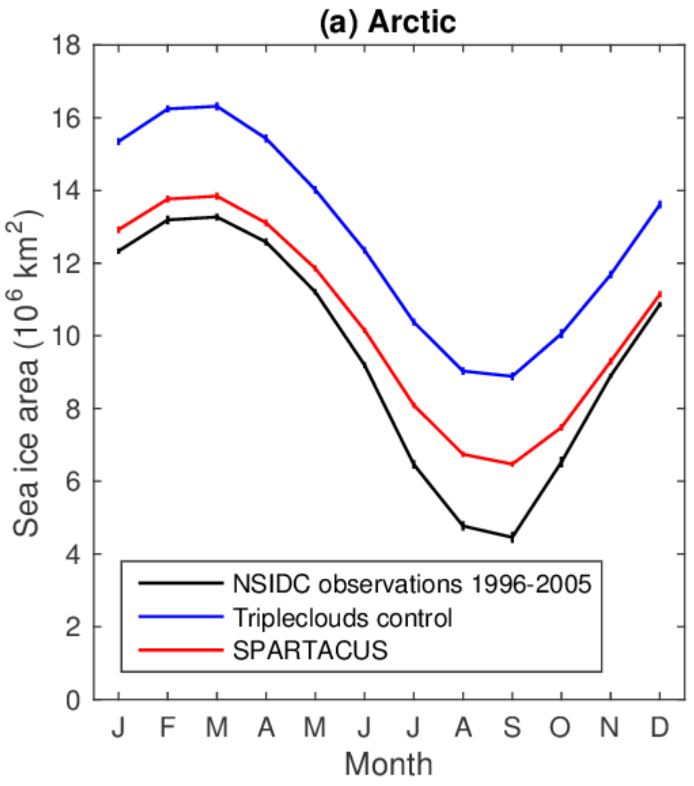
ECMWF

# Offline 3D radiative effect… …online impact in a climate simulation




- 25-year free-running coupled simulation of the IFS
- Positive feedback in the Arctic associated with clouds and sea ice

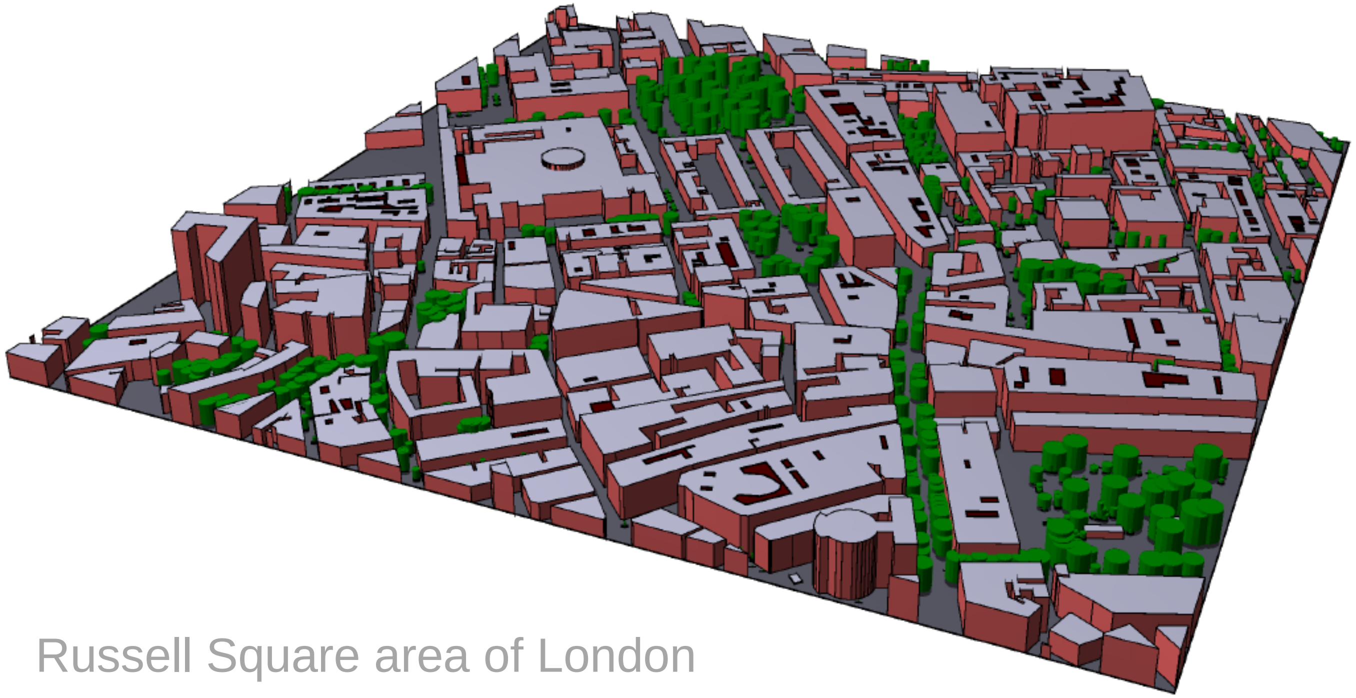


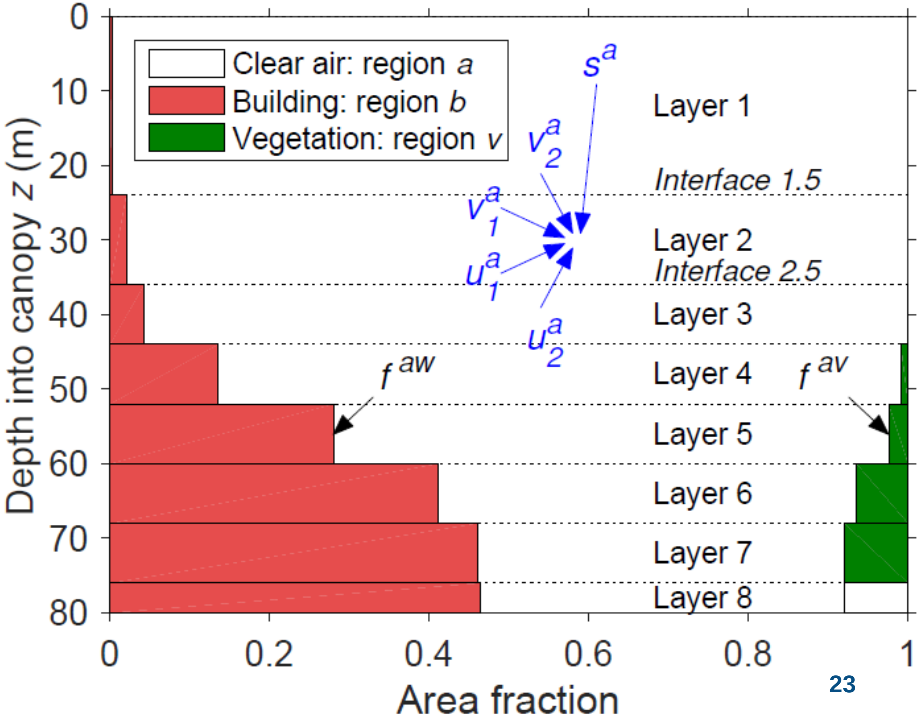

Better agreement with annual cycle of observed sea ice

# Towards "SPARTACUS-Surface"

- SPARTACUS technique to represent 3D interaction of radiation with clouds can be applied to trees (Hogan et al., GMD 2018) and buildings (Hogan, BLM 2019)
- Currently testing offline, but could be used to improve representation of forests and cities in IFS / OpenIFS in future

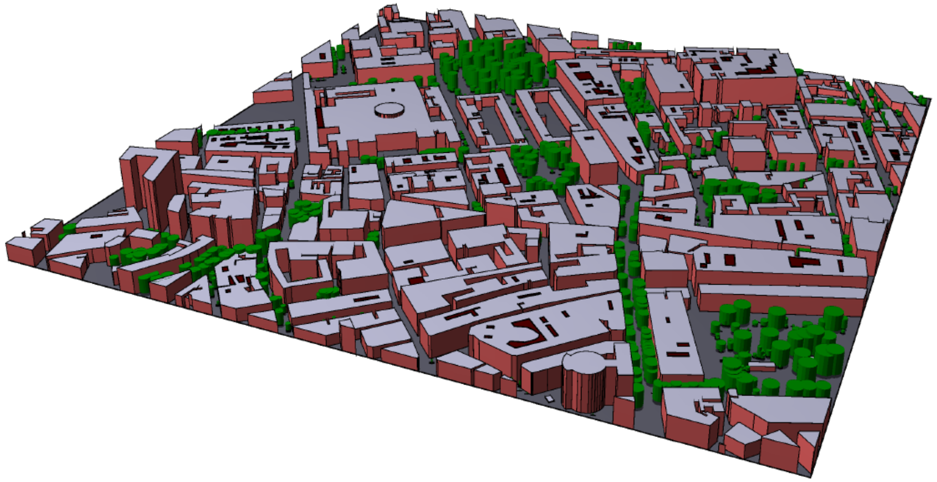


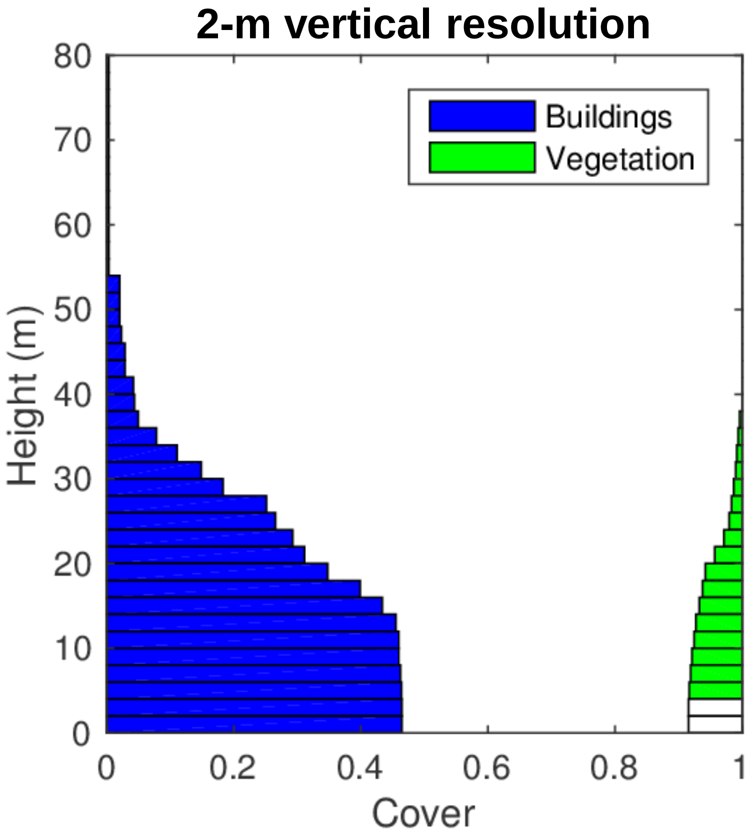
Russell Square area of London

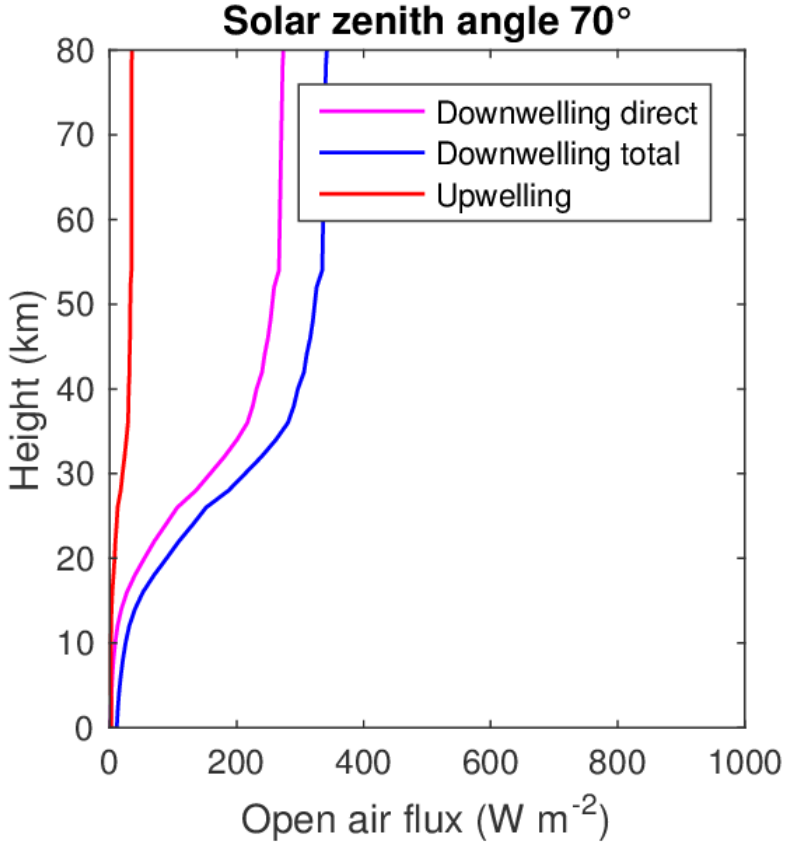


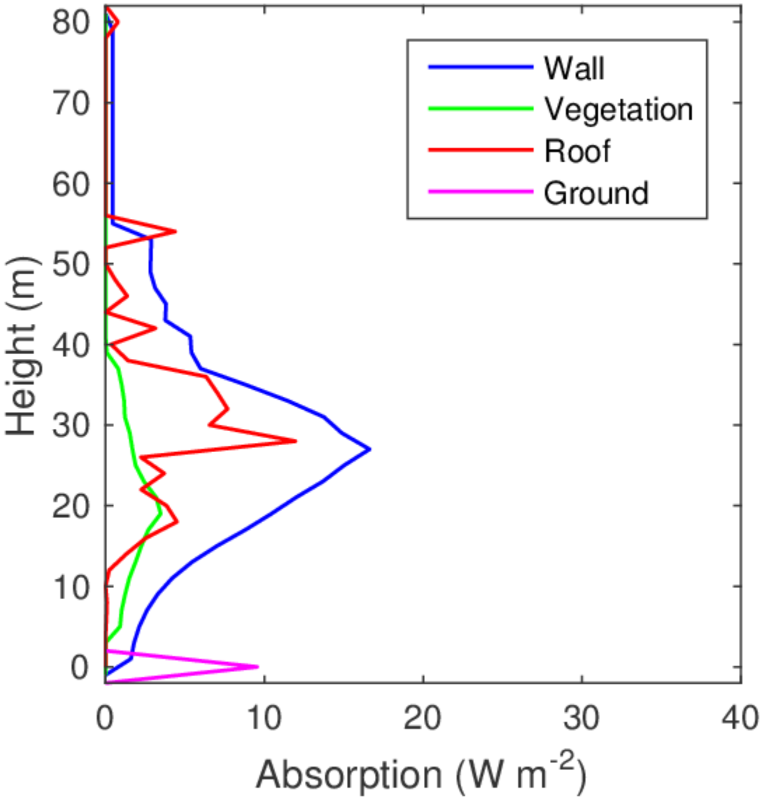
# Example profiles of flux and net absorption

- *Meg Stretton's PhD project:* compare profiles to explicit calculations using DART model
- Which details of an urban scene really matter which can be safely ignored? What level of detail can be justified in a weather or climate model?





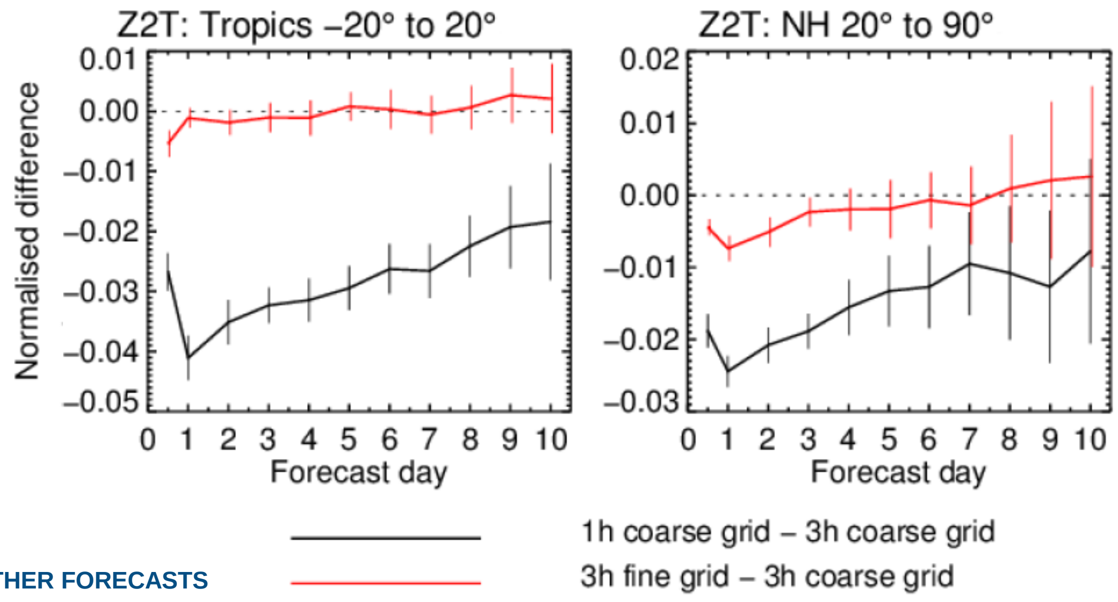



# Efficiency: temporal versus spatial resolution

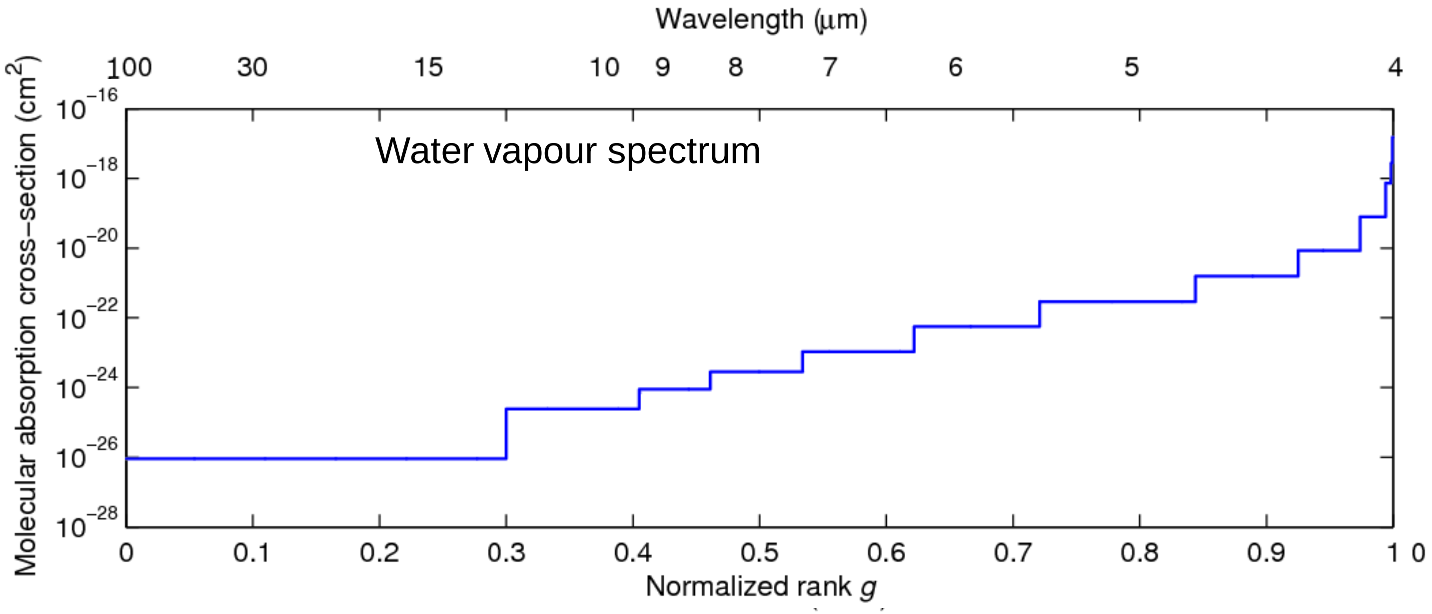
- Radiation is now 5% of high-resolution (HRES) model time, compared to 19% a decade ago
- Cost of radiation is a trade-off between temporal/spatial/spectral resolution and physical sophistication, and compared to other global NWP centres, ECMWF *has lowest temporal/spatial resolution* and *highest spectral resolution* (Met Office uses 3.7 times fewer spectral intervals!)
- Spatial coarsening is severe, but thanks to approximate radiation updates, **6.25x more spatial resolution** (and cost) gives only marginal improvement in 2-m temperature, whereas **reducing radiation timestep from 3h to 1h** improves forecasts by 2-4%
- *How can we afford even more frequent radiation and more physical sophistication (e.g. 3D effects)?*

| Centre | Radiation timestep (h) | | Horiz. coarsening | | Spectral intervals | |
|---|---|---|---|---|---|---|
| | HRES | ENS | HRES | ENS | SW | LW |
| ECMWF | 1 | 3 | 10.24 | 6.25 | 112 | 140 |
| NCEP | 1 | 1 | 1 | 1 | 112 | 140 |
| DWD | 0.4 | 0.6 | 4 | 4 | 112 | 140 |
| Météo France | 1 | 1 | 1 | 1 | – | 140 |
| Met Office | 1 | 1 | 1 | 1 | 21 | 47 |
| CMC | 1 | 1 | 1 | 1 | 40 | 57 |
| JMA | 1 | 1 (SW), 3 (LW) | 4 | 4 | 22 | 156 |
| FSCK | – | – | – | – | ~ 15 | ~ 32 |



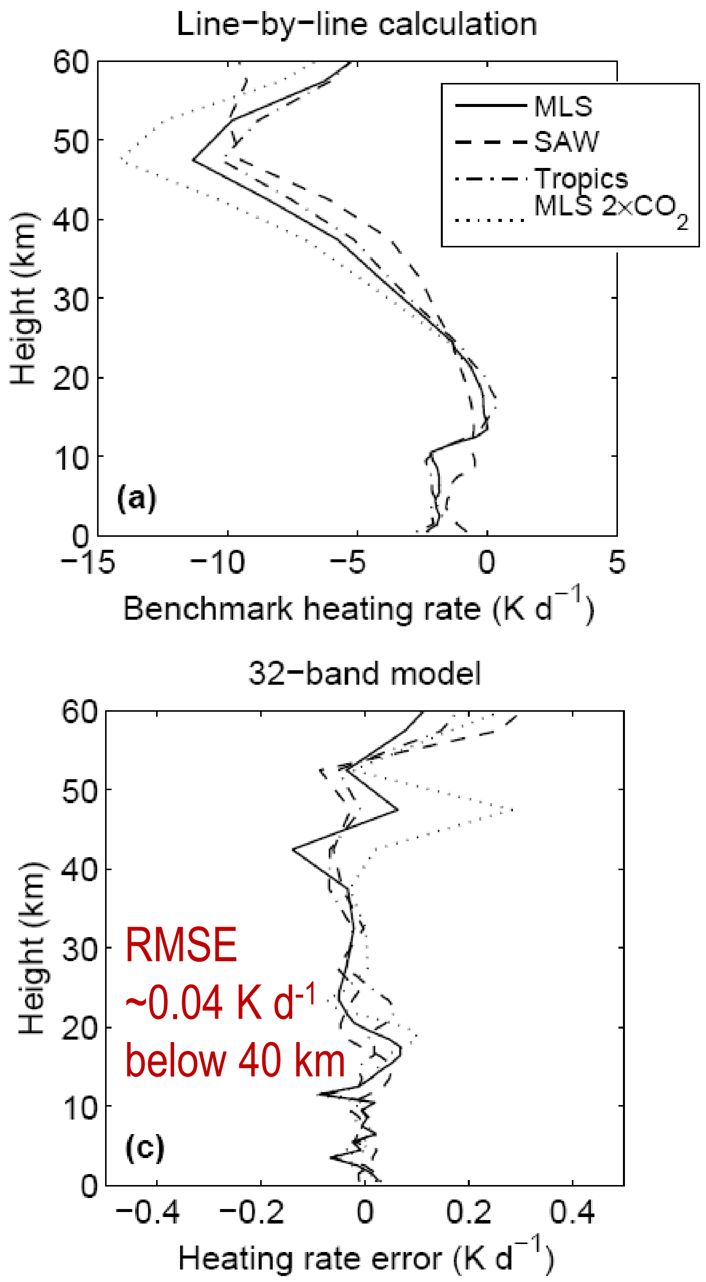
# How can we optimize the spectral integration?

- Three options under consideration:
  - RRTMGP: optimized RRTM-G from U. Colorado
  - Neural network: collaboration with NVIDIA
  - *Full-spectrum correlated-k scheme (Pawlak et al. 2014, Hogan 2010)*




RRTM-G uses 16 LW bands… reorder and discretize to 140 spectral intervals

FSCK reorders the *entire spectrum*: only 30-35 intervals required for same accuracy?




Hogan (JAS 2010)

# Summary and outlook

- Modular design of ecRad makes it well suited for research and operational use
  - We can test alternative modules (e.g. new solvers) while keeping everything else fixed
  - ecRad has been implemented in IFS, MesoNH and ICON models
- Offline version (available under an identical license to OpenIFS) helps research work
  - Offline ecRad has >20 users worldwide
  - Easier to implement and test new features offline
- Outlook for the "Grand Challenges" in the coming years
  - Overhaul surface treatment, including 3D interactions with cities and forests
  - Package of physically-based improvements to clouds
  - Role of aerosols in predictability; upgrade water vapour continuum
  - Remove middle-atmosphere temperature bias via new UV solar spectrum and ozone
  - Much more efficient gas optics and spectral integration

# Further reading

- **Radiation in NWP (ECMWF Technical memo, 2017)**
- **ecRad (JAMES 2018)**

TECHNICAL MEMO

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## Radiation in numerical weather prediction

Robin J. Hogan, Maike Ahlgrimm, Gianpaolo Balsamo, Anton Beljaars, Paul Berrisford, Alessio Bozzo, Francesca Di Giuseppe, Richard M. Forbes, Thomas Haiden, Simon Lang, Michael Mayer, Inna Polichtchouk, Irina Sandu, Frederic Vitart and Nils Wedi

Research, Forecast and Copernicus Departments

Paper to the 46th Science Advisory Committee, 9–11 October 2017

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RESEARCH ARTICLE

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## A Flexible and Efficient Radiation Scheme for the ECMWF Model

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**Key Points:**

- A new radiation scheme for the ECMWF model is described that is 41% faster than the original scheme
- We describe how longwave scattering by clouds can be represented with only a 4% increase in computational cost, improving forecast skill
- A sequence of changes have reduced the long-standing warm bias in the middle to upper stratosphere of the ECMWF model

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**Abstract** This paper describes a new radiation scheme *ecRad* for use both in the model of the European Centre for Medium-Range Weather Forecasts (ECMWF), and off-line for noncommercial research. Its modular structure allows the spectral resolution, the description of cloud and aerosol optical properties, and the solver, to be changed independently. The available solvers include the Monte Carlo Independent Column Approximation (McICA), *Tripleclouds*, and the Speedy Algorithm for Radiative Transfer through Cloud Sides (SPARTACUS), the latter which makes ECMWF the first global model capable of representing the 3-D radiative effects of clouds. The new implementation of the operational McICA solver produces less noise in atmospheric heating rates, and is 41% faster, which can yield indirect forecast skill improvements via calling the radiation scheme more frequently. We demonstrate how longwave scattering may be implemented for clouds but not aerosols, which is only 4% more computationally costly overall than neglecting longwave scattering and yields further modest forecast improvements. It is also shown how a sequence of radiation changes in the last few years has led to a substantial reduction in stratospheric temperature biases.

**Plain Language Summary** Solar and thermal infrared radiation provide the energy that drives weather systems and ultimately controls the Earth's climate. Accurately simulating these energy flows is therefore a crucial part of the computer models used for weather and climate prediction. This paper describes a flexible and efficient new software package, *ecRad*, for computing radiation exchange. It became operational in the forecast model of the European Centre for Medium-Range Weather Forecasts (ECMWF) in July 2017, and is 41% computationally faster than the previous package. This offers the possibility to update the radiation fields in the model simulations more frequently for the same overall computational cost, which we show in turn can improve the skill of weather forecasts. A unique feature for a radiation package of this kind is the ability to simulate radiation flows through the sides of clouds, not just through the base and top, making it well suited as a tool for research into atmospheric radiation exchange.

**1. Introduction**