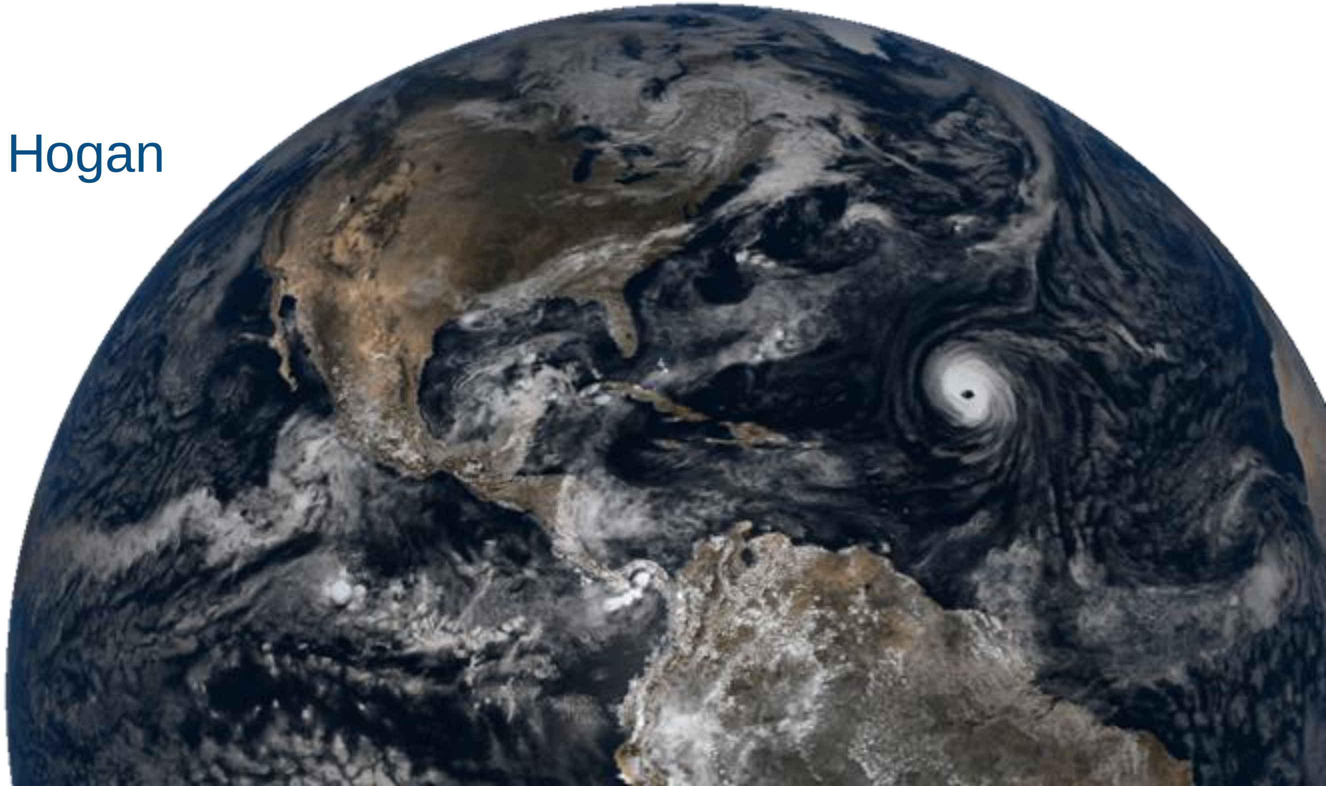
# The ECMWF radiation scheme

Peter Hill, Mark Fielding & Robin Hogan

peter.hill@ecmwf.int



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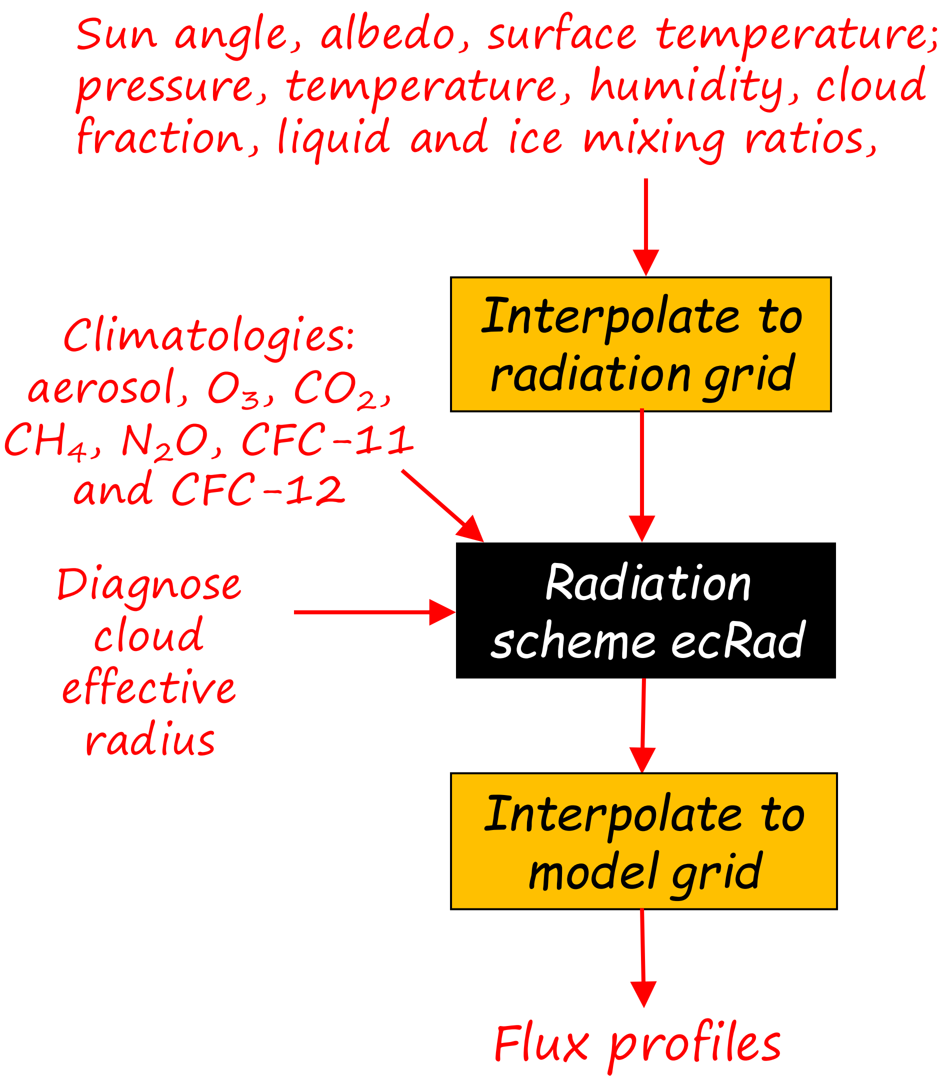
# Outline

1. Overview of the current scheme: ecRad
   – Treatment of gases, aerosols and clouds
2. Optimization considerations (spectral vs spatial vs temporal)
   – Evaluating the impact of choices on forecast skill
3. Using radiation observations for forecast verification
4. Remaining challenges

# ecRad in the context of the IFS




- Radiation currently run once per hour in forecasts
  - Changed from every 3 hours in most streams before 46r1, improving tropical 2-m temperature forecasts by around 3%
- Radiation is computed at a coarser grid
  - HRES: 3.2x3.2 times coarser = 10.24x fewer gridpoints
  - ENS: 2.5x2.5 times coarser = 6.25x fewer gridpoints
- Total cost in ENS (including interpolation) is 5.8%
- If radiation scheme was faster:
  - Could call more frequently: further ~0.5% improvement in tropical 2-m temperature
  - Reduce noise (assuming using McICA solver)?
  - Increase accuracy, e.g. with more than two streams or represent 3D effects?
- Efforts to replace ecRad with a neural network replace the call to RADIATION_SCHEME (i.e. the ‘black box’)

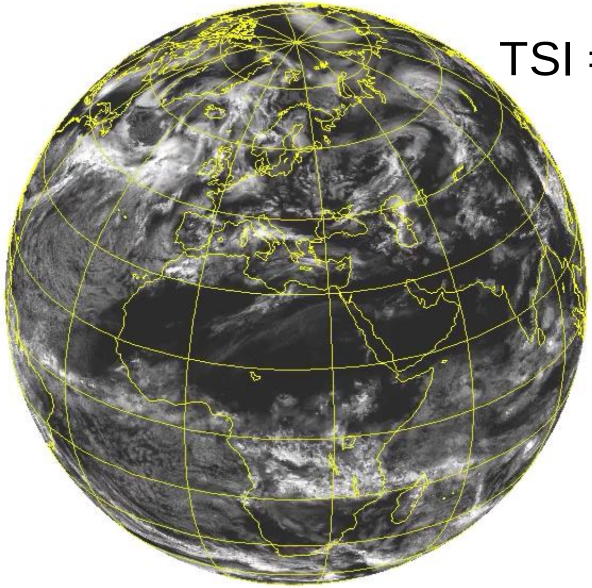
# Why should I care what's inside the black box?

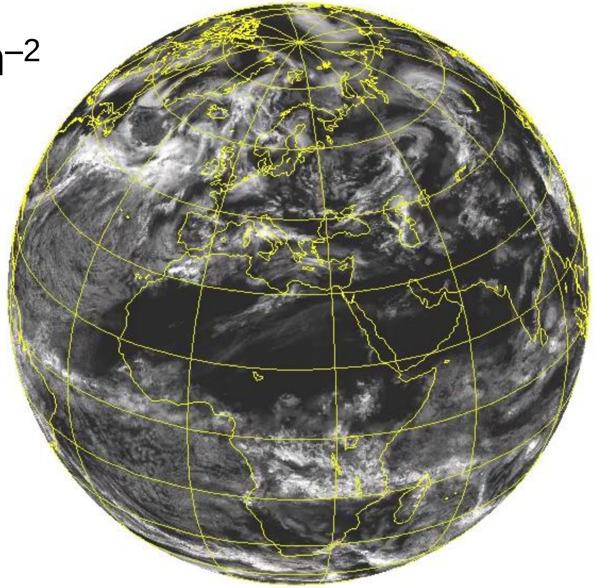
- Radiation is the driver of weather.
- All other physical parameterizations rely (directly or indirectly) on the fluxes and heating rates from the radiation scheme.
- Important to understand how changes in other schemes might affect radiation scheme.

# What would happen if the sun went out?

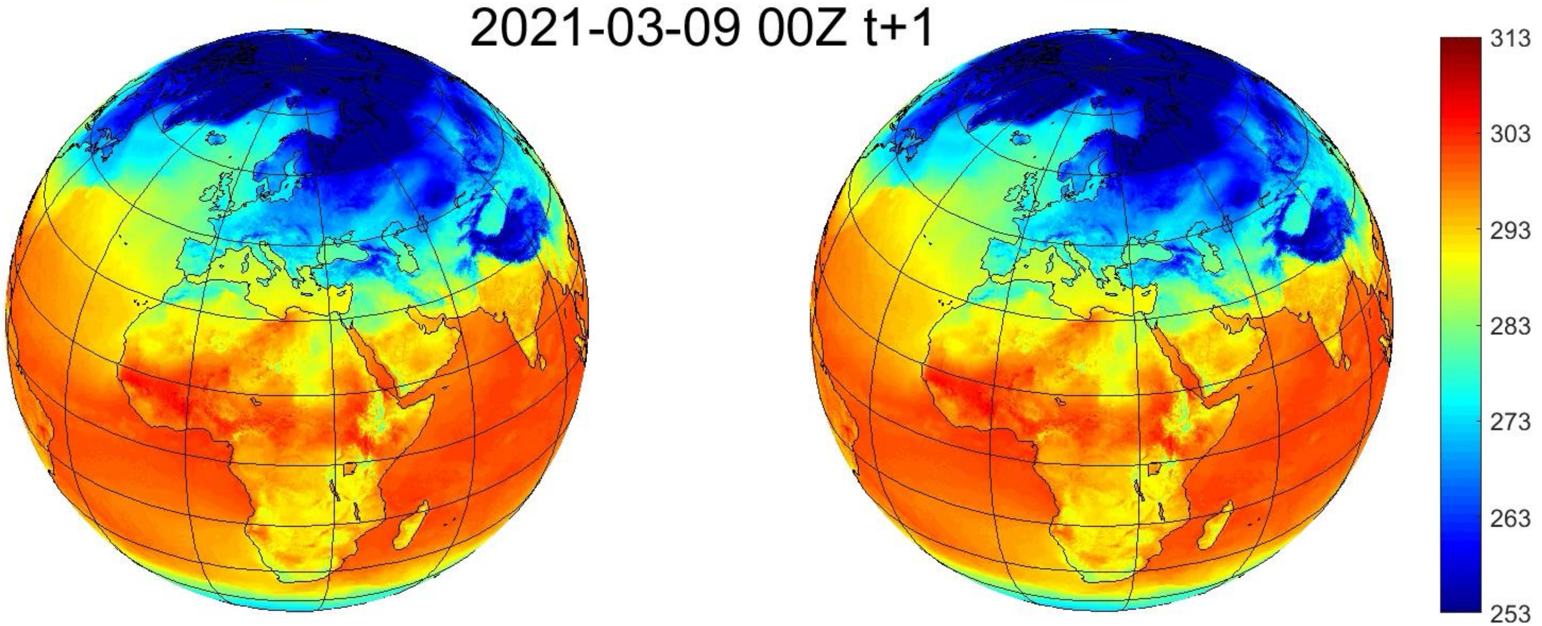
TSI = 1366 W m$^{-2}$ TSI = 0.1 W m$^{-2}$

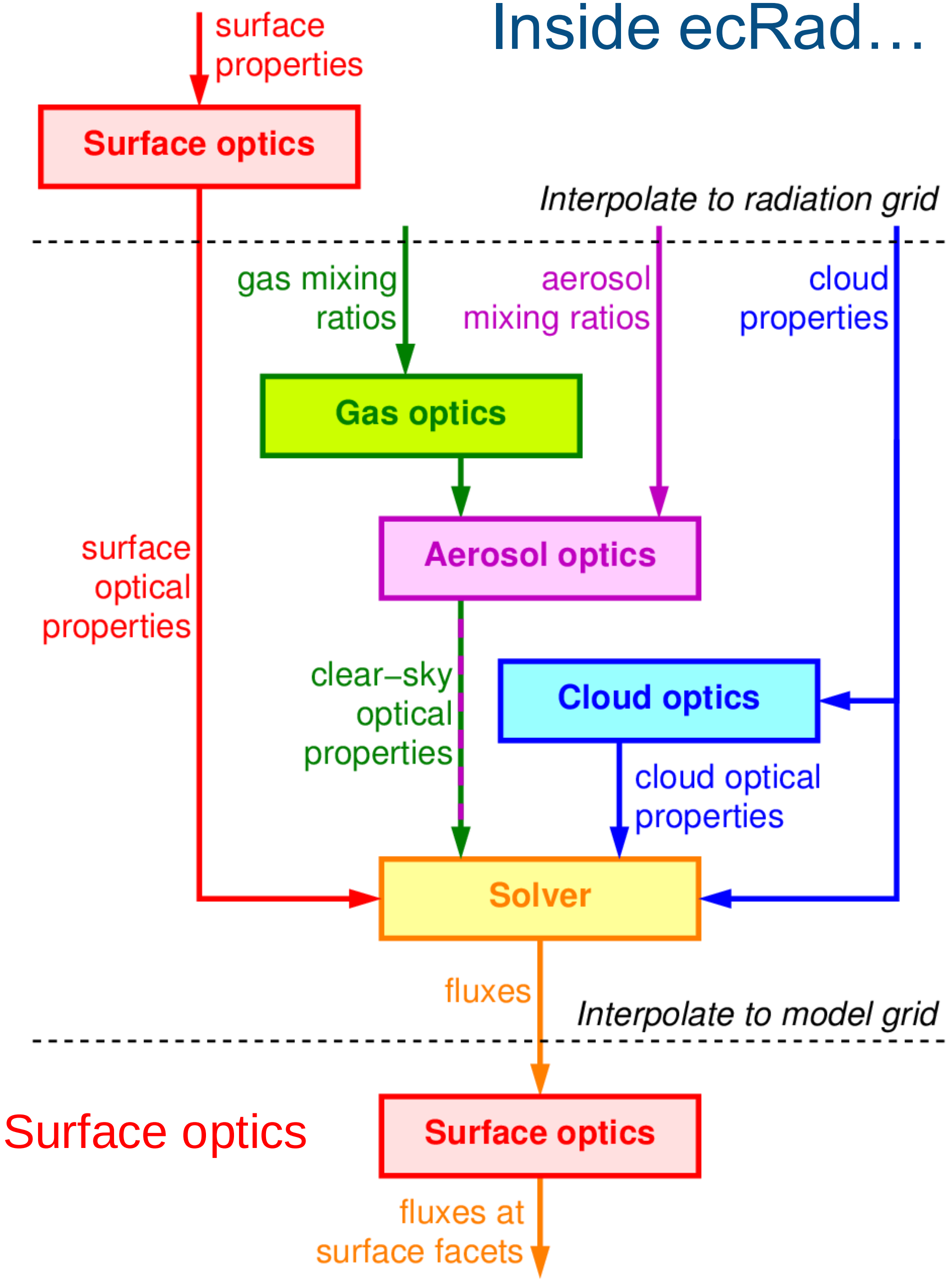
*Cloud water path*





*Two-metre temperature (K)*





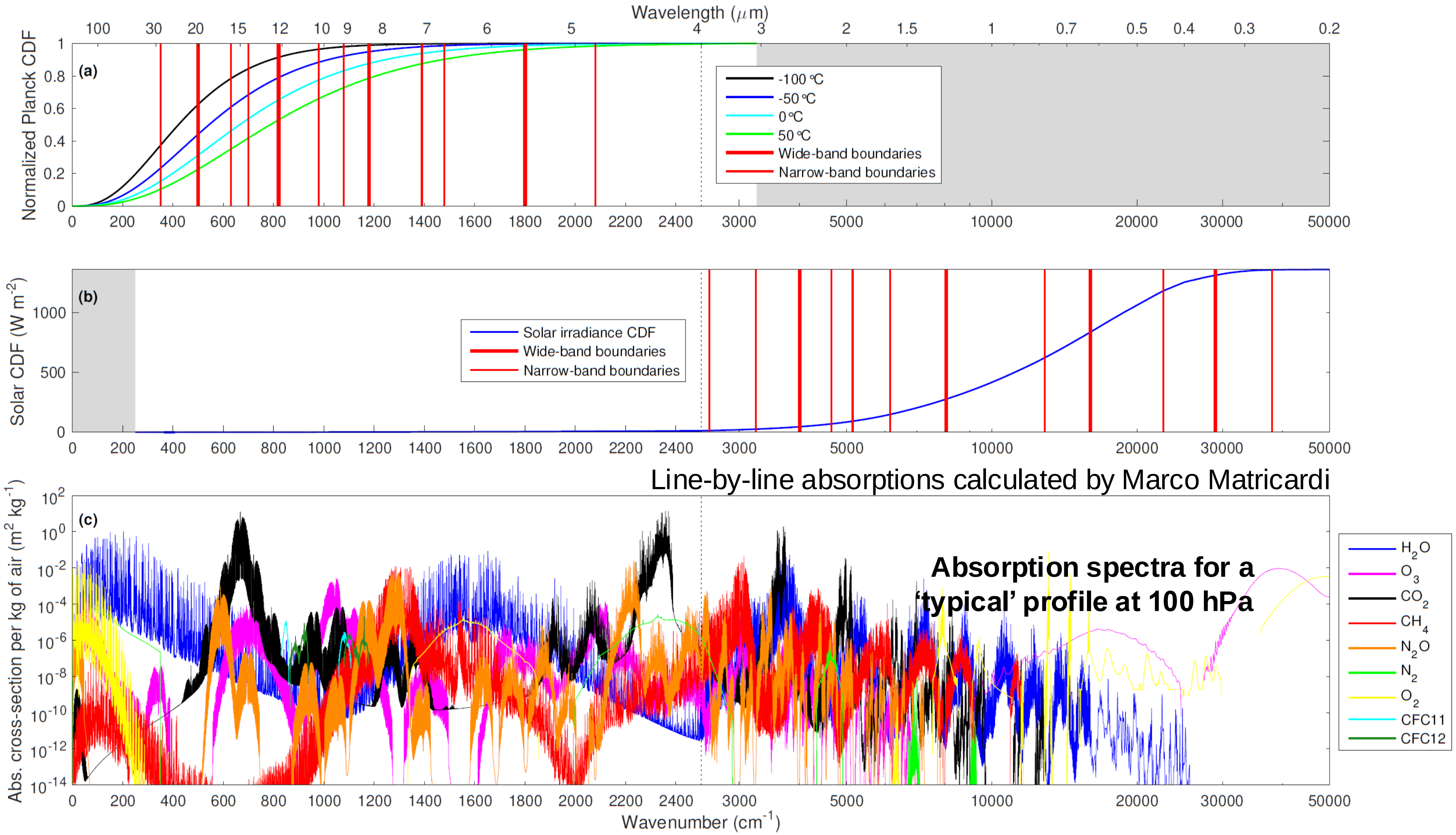

Surface optics

# Inside ecRad…

*Modular radiation scheme became operational in IFS in July 2017 (Hogan and Bozzo, 2018)*

- Gas optics
  - Provides radiative properties for atmospheric gases in a range of spectral intervals.
  - Like most current GCM radiation schemes, it uses the correlated k-distribution (CKD) method.
- Aerosol optics
  - Flexible framework for including a range of aerosol species sourced from either a climatology (e.g., Tegen) or progonostic aerosol (i.e., CAMS).
- Cloud optics
  - Parametrizations for cloud optical properties for each spectral interval, given the input cloud properties.
- Solver
  - Solves radiation equations for a number of 'bands' spanning different parts of the spectrum given the gas, aerosol and cloud optical properties.
  - ecRad includes a number of different solvers including McICA (operational), Tripleclouds and SPARTACUS

# Gas absorption spectra has the greatest wavelength dependence of all atmospheric components

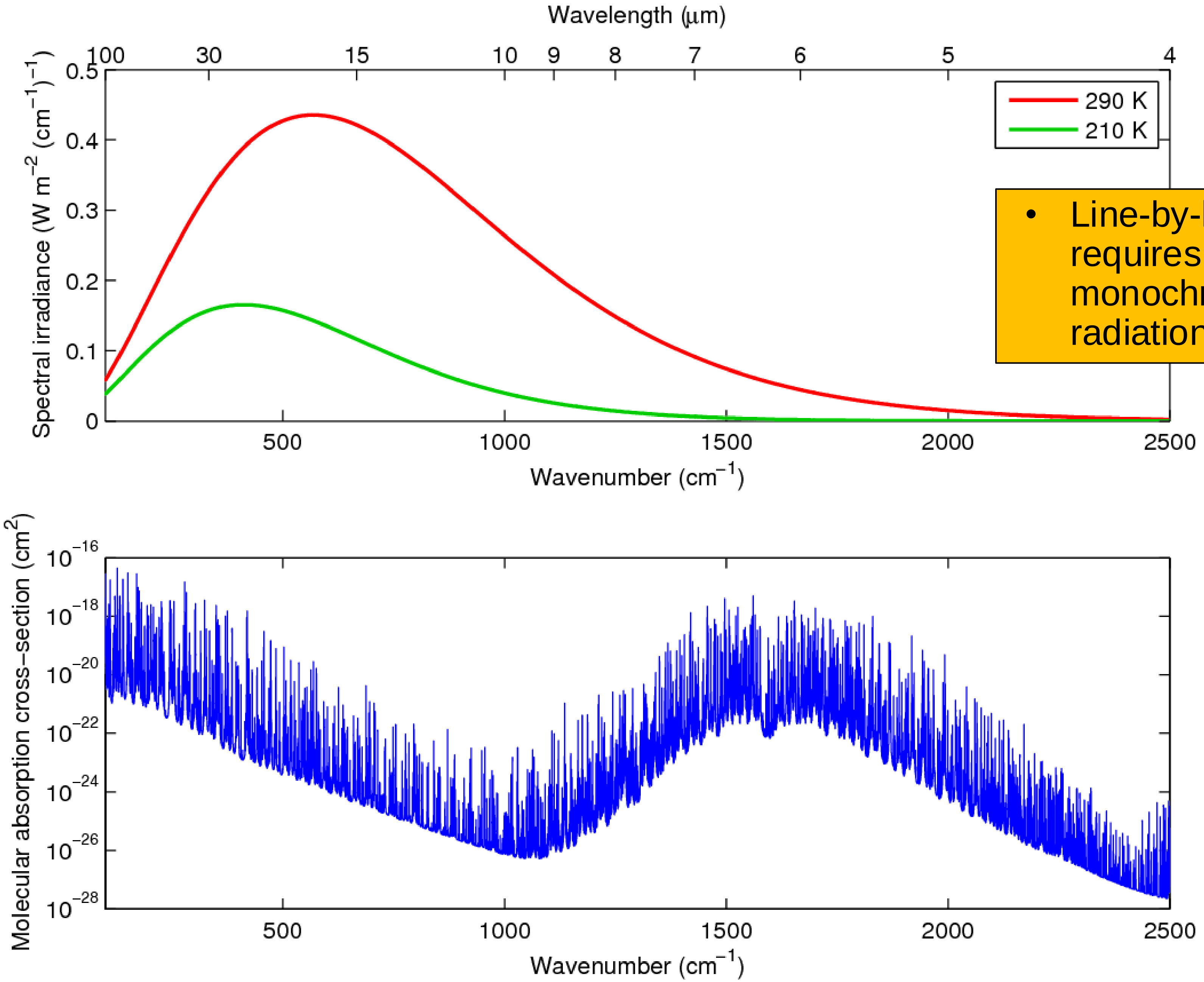



Line-by-line calculations would be too expensive, so divide spectrum into 'bands' and apply correlated-k method.

# What is the CKD method? 1. Consider longwave absorption spectrum ($k$)

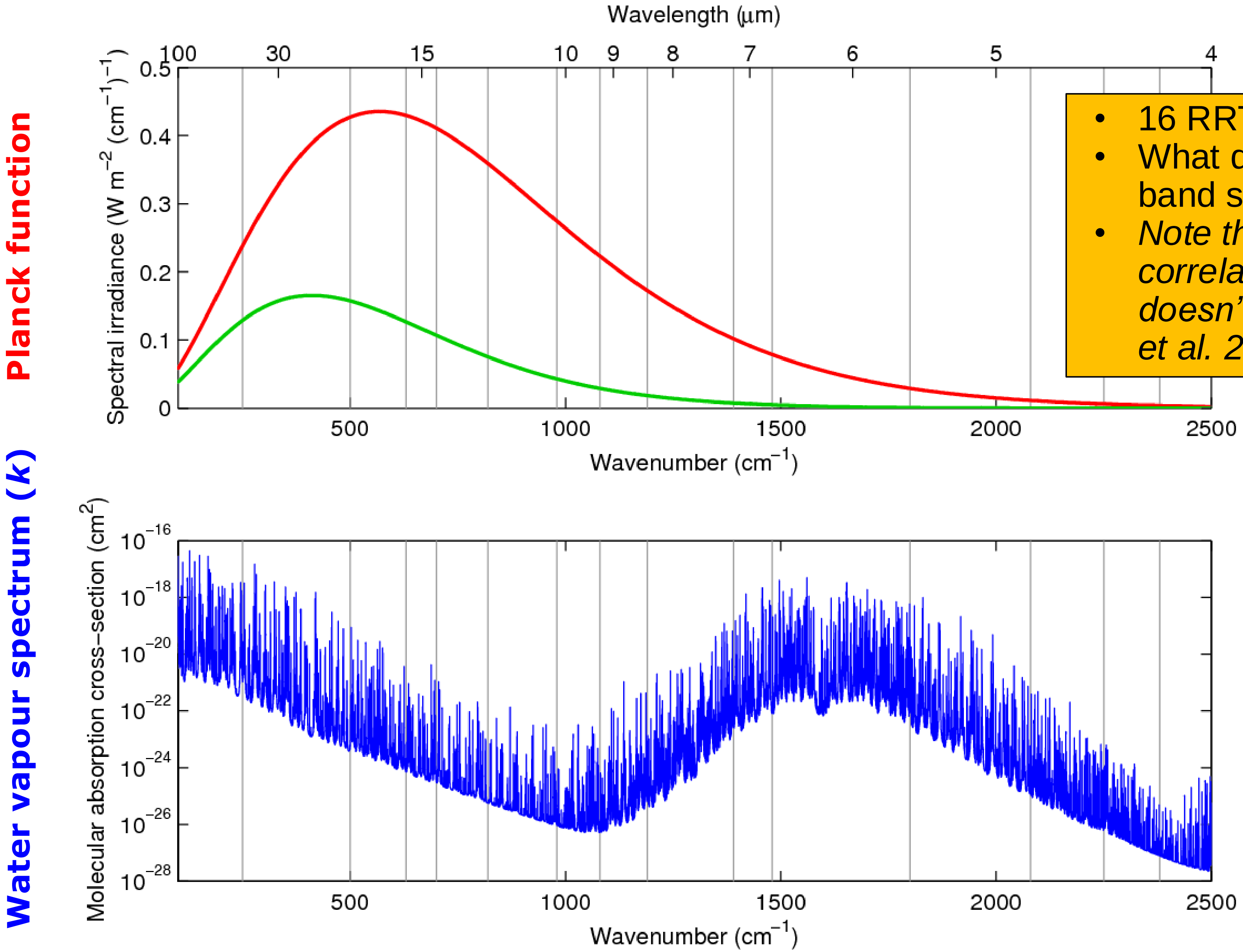
**Planck function**

**Water vapour spectrum ($k$)**



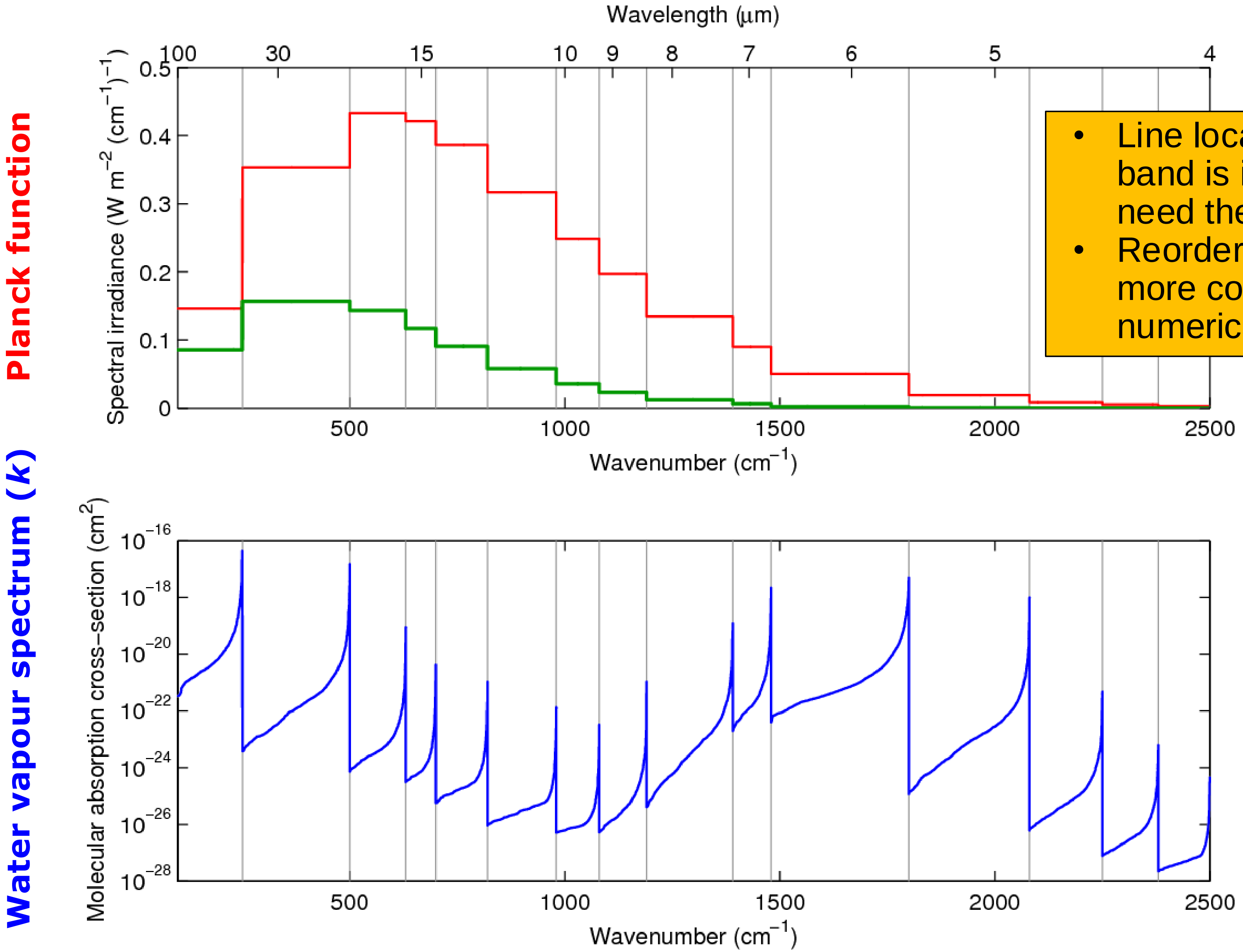

- Line-by-line reference requires $10^6$ to $10^7$ monochromatic radiation calculations

# What is the CKD method?  2. Bands



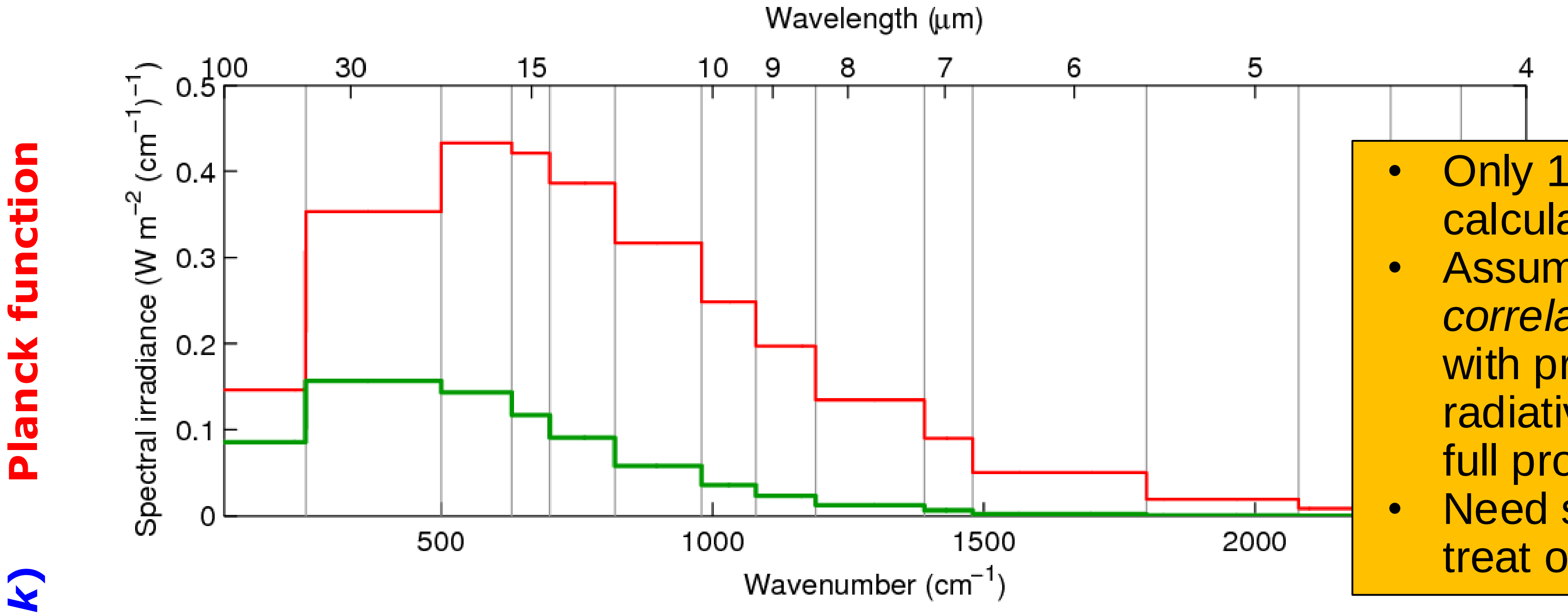

- 16 RRTMG bands
- What determines optimum band structure?
- *Note that the full-spectrum correlated-k method (FSCK) doesn't use bands (Pawlak et al. 2004, Hogan 2010)*

# What is the CKD method? 3. Reorder spectrum within each band

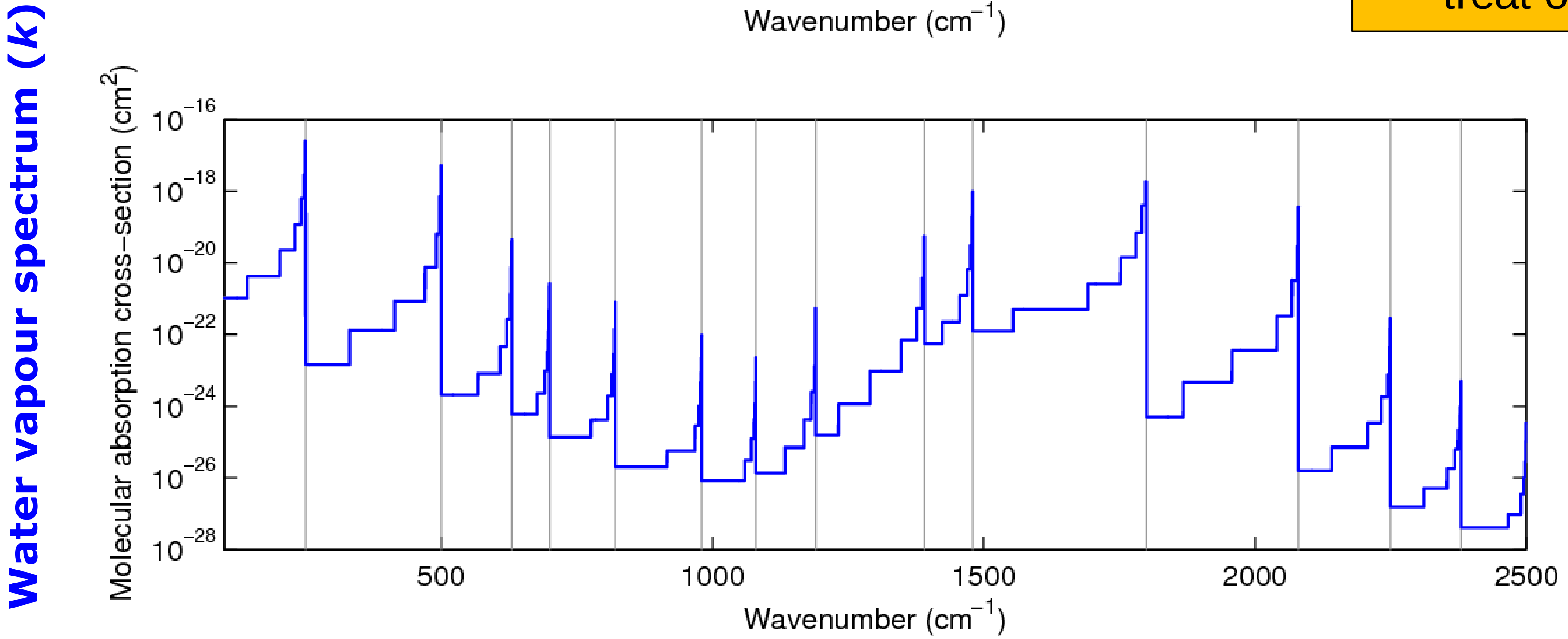



- Line location within band is irrelevant: only need the *k distribution*
- Reordered spectrum more conducive to numerical integration

# What is the CKD method? 4. Discretize smooth reordered spectra



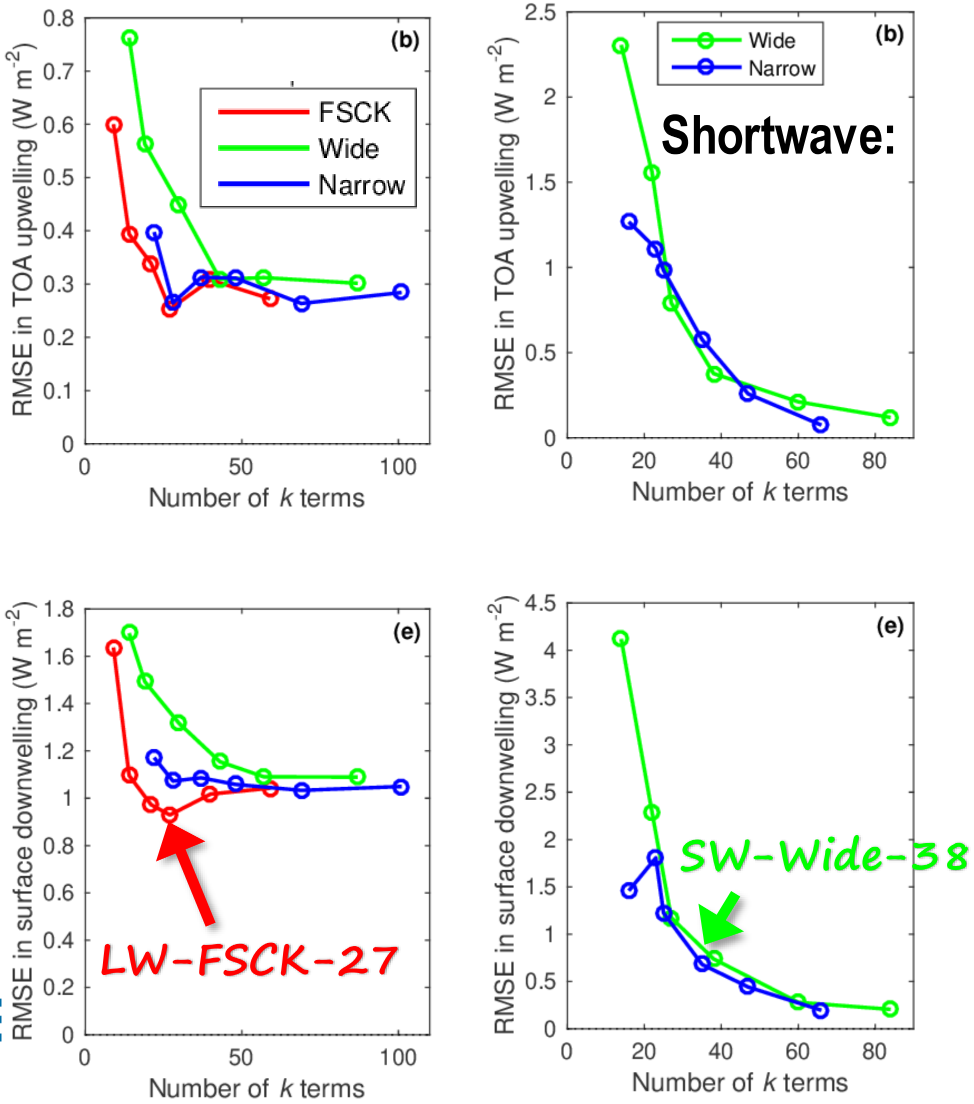

- Only $10^2$ monochromatic calculations now required!
- Assume perfect *rank correlation* of absorption with pressure when doing radiative transfer through full profile
- Need some black magic to treat overlapping gases



# New tool, ecCKD, can automatically generate CKD model to specified error tolerances

- Unsurprisingly, error decreases with number of *k* terms
- Full-spectrum correlated-k (FSCK) method works well in longwave, but not yet in shortwave

**Longwave:**

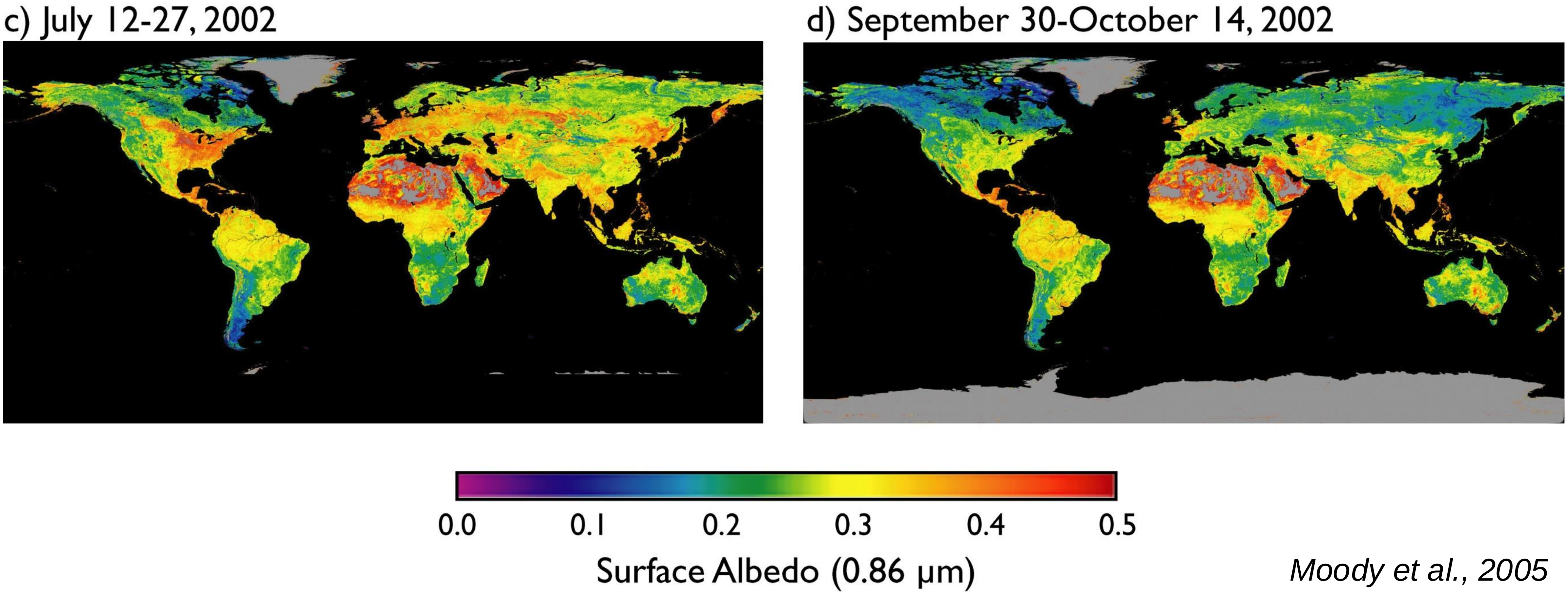



## Comparison to RRTMG for 'present-day CKDMIP scenario'

- LW-FSCK-27 with 27 *k* terms has slightly lower RMS error than LW RRTMG with 140 *k* terms
  - Entire longwave scheme 5.2x faster!
- SW-Wide-38 with 38 *k* terms has much lower RMS errors than SW RRTMG with its 112 *k* terms
  - Entire shortwave scheme 2.9x faster!

# Surface optics (currently outside ecRad)

- Surface scheme computes grid box mean skin temperature, longwave emissivity, shortwave direct and diffuse albedo in six spectral intervals.




*Moody et al., 2005*

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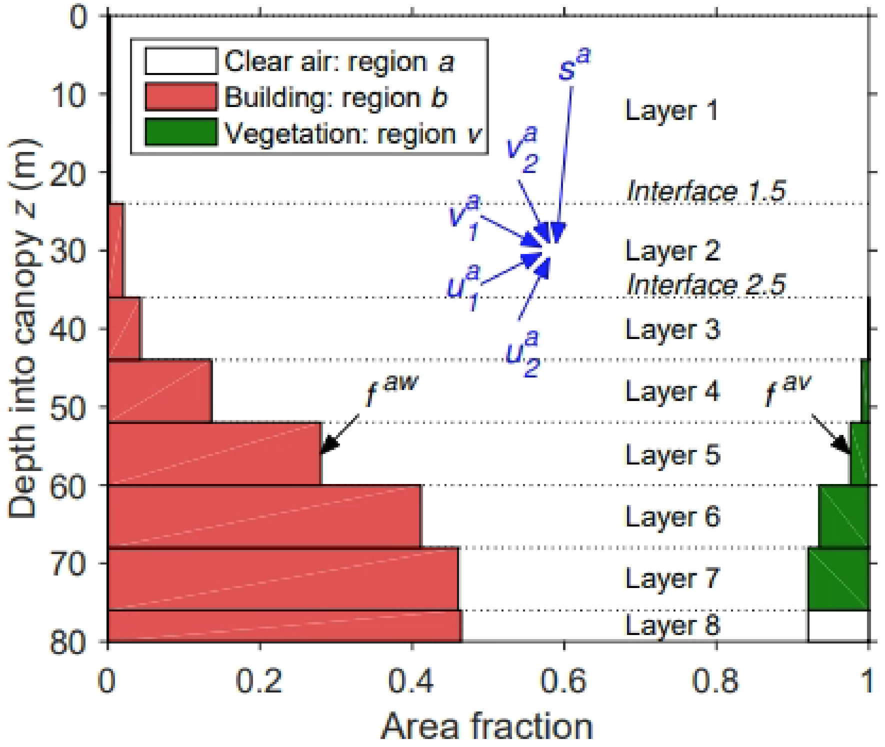
# Surface optics (currently outside ecRad)

- Surface scheme computes grid box mean skin temperature, longwave emissivity, shortwave direct and diffuse albedo in six spectral intervals.

- More sophisticated coupling between radiation and the surface is in preparation.
  - Hogan et al., (2018) describe a method for representing 3D- radiative interactions in forest canopies
  - Use SPARTACUS for 3D radiative transfer in urban areas (Hogan 2019)

*Russell Square, London*




*Hogan 2019*

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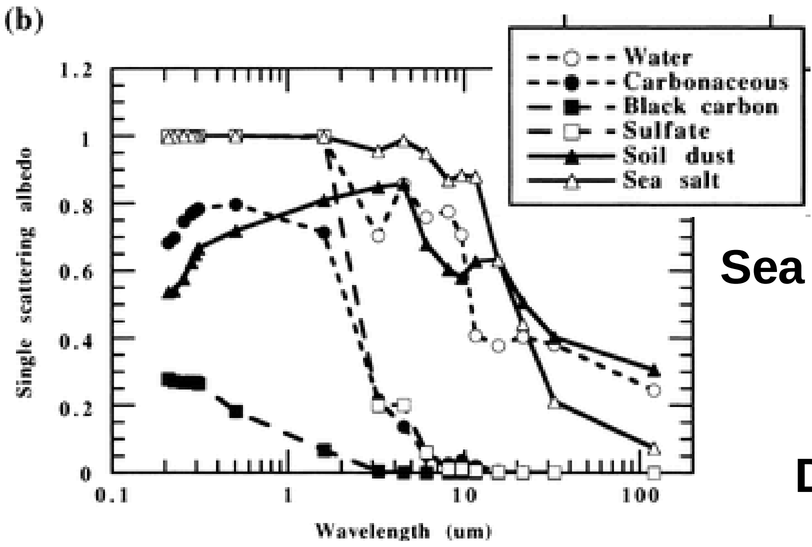
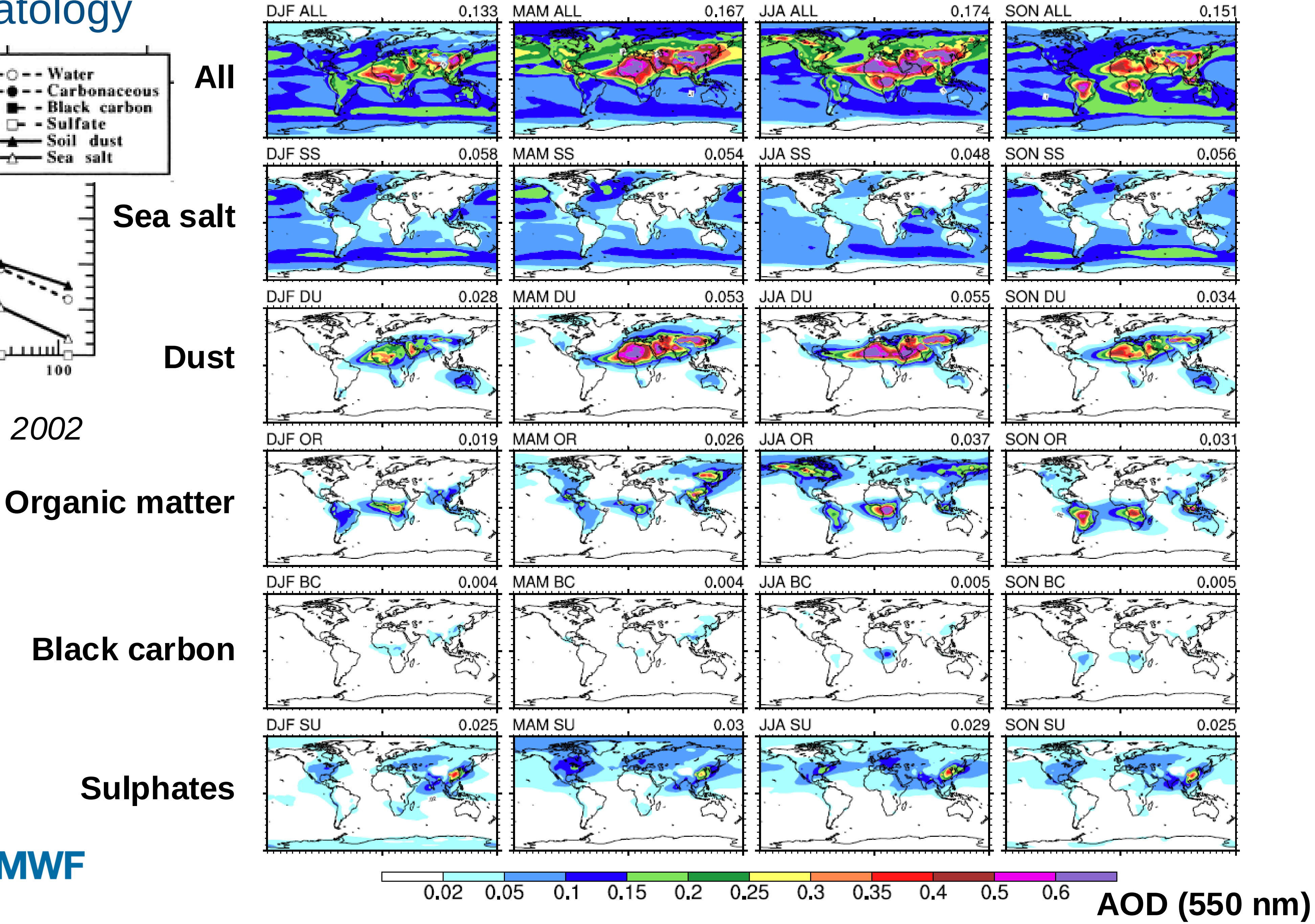
# Aerosols optics

- While aerosols play an important role in determining climate, their day to day variability is generally of secondary importance for medium-range weather forecasts.
- However, the mean radiative effect of aerosols is important to include as it can be significant, particularly for absorbing aerosols (see e.g., Benedetti and Vitart, 2018).
- Within IFS, CAMS monthly climatologies (now 3D in CY46R1) are used to account for direct effects.
- Day-to-day variability can be important in certain cases – my work.
- Indirect effects of aerosols are partially accounted for in cloud scheme (e.g., parameterizations of $N_d$ from wind speed or land/sea mask).

# CAMS aerosol climatology




*Takemura et al., 2002*

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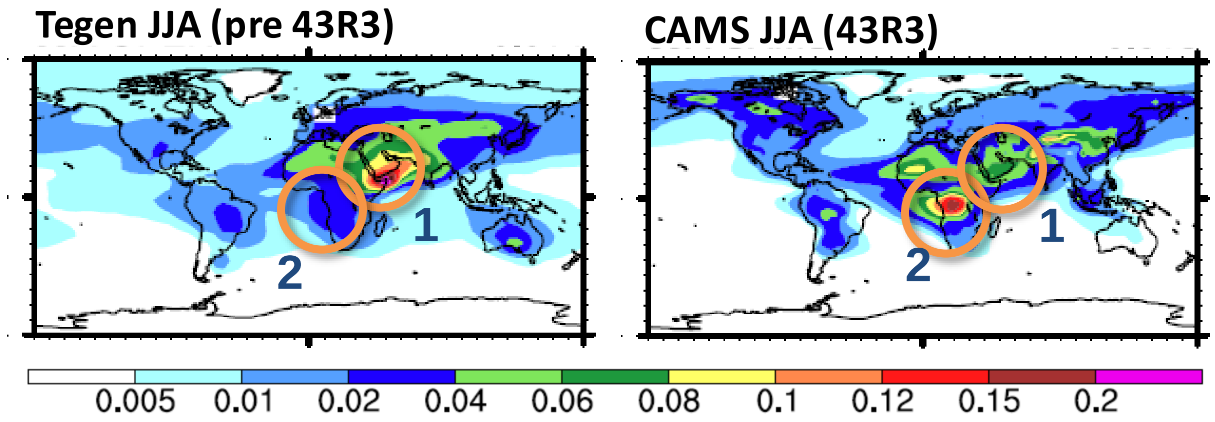
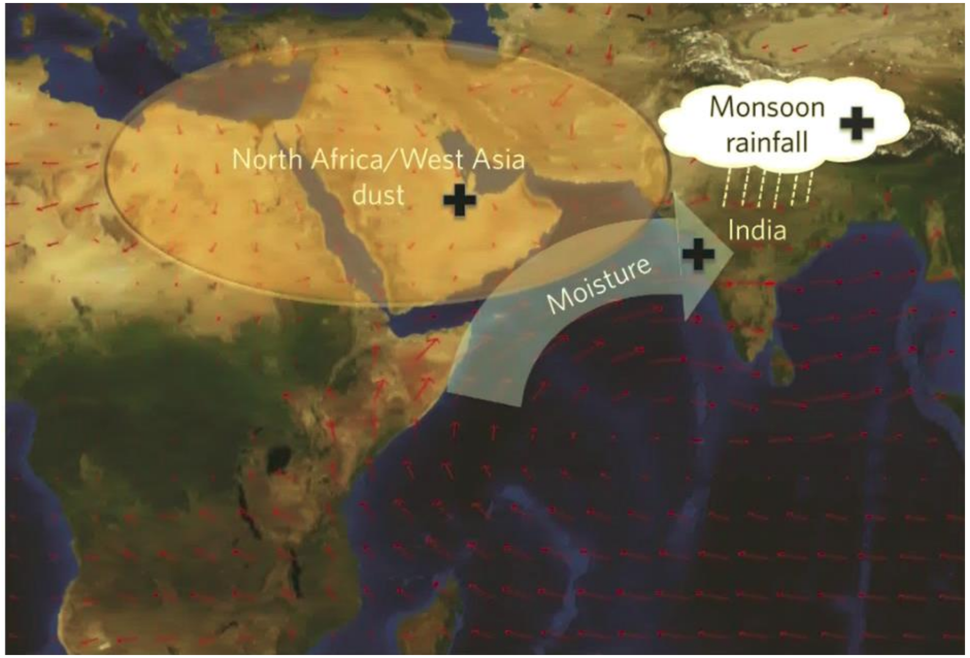
# Impact of updating aerosol climatology

- Atmospheric forcing depends on *absorption* optical depth:



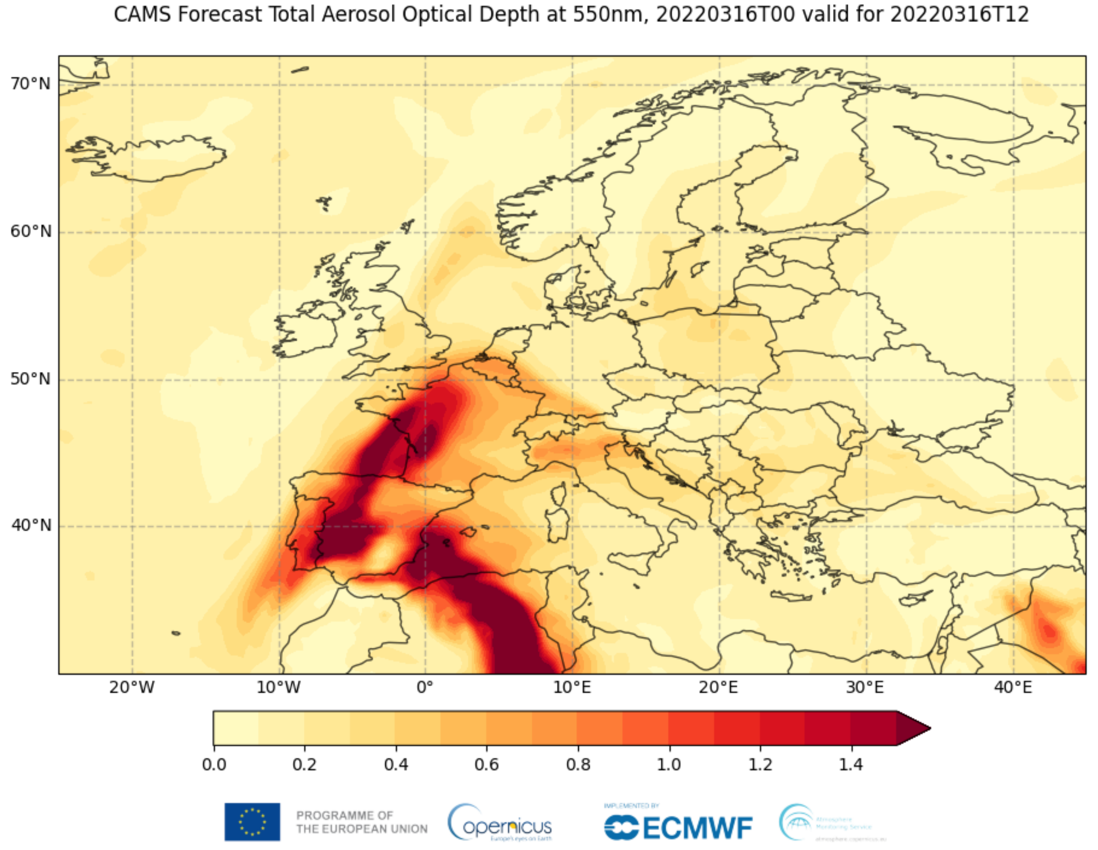




*Vinoj et al., 2014*

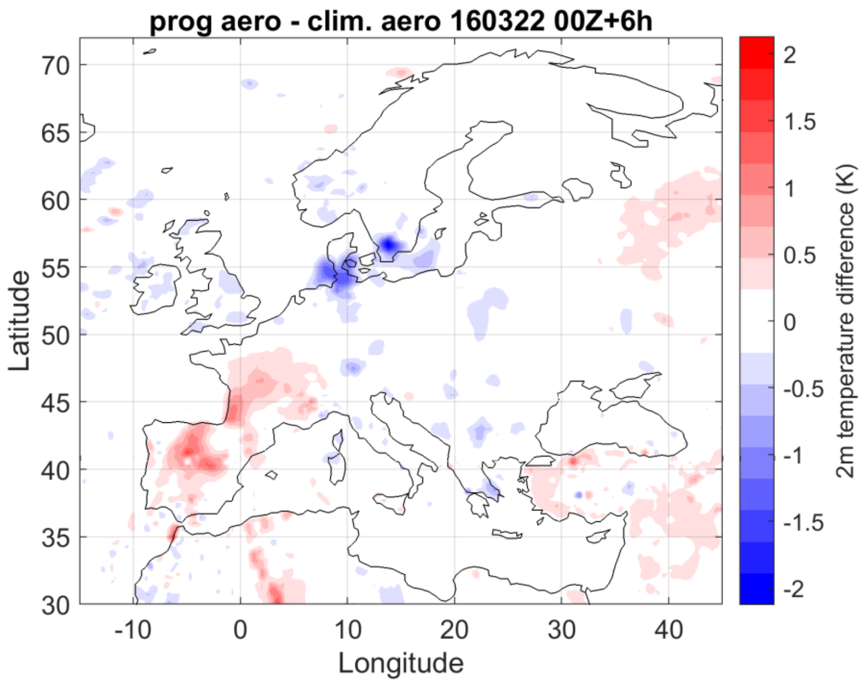
1. Decreased absorption over Arabia in new CAMS climatology weakens the overactive Indian Summer Monsoon, halving the overestimate in monsoon rainfall (Bozzo et al., 2017)
2. Increased absorption over Africa degraded 850-hPa temperature, traced to excessive biomass burning in CAMS.

# Impacts of dust outbreaks over Europe

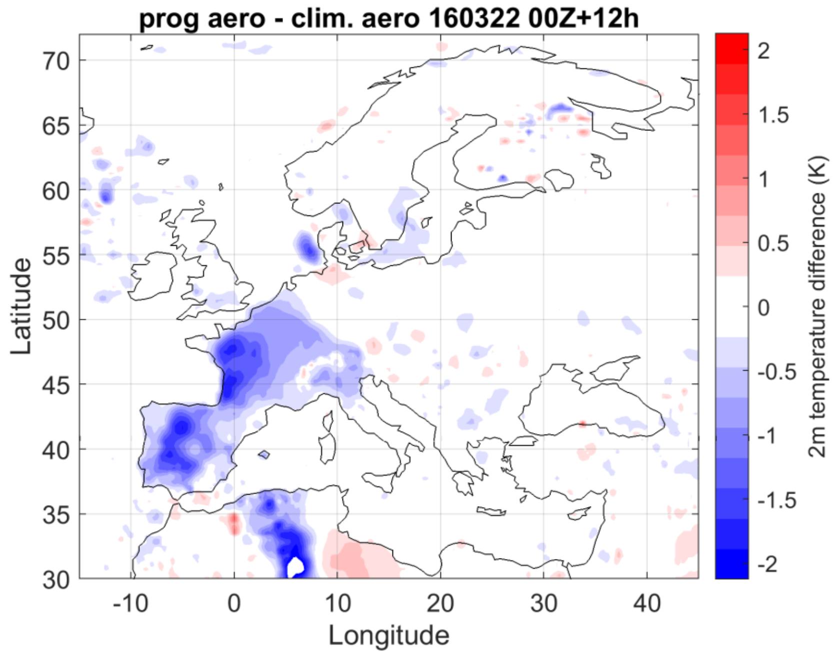
- Saharan dust outbreaks can cause large surface temperature errors in ECMWF operational forecast (Magnusson et al., 2021)
- CAMS forecasts using prognostic aerosol reduces errors




Warming effect during night




Cooling effect during day



# Cloud optics

- Converts model cloud liquid/ice water content to optical scattering properties via relatively simple parametrizations.
- Uncertainty in cloud microphysical/radiative properties provides one of the greatest sources of error in the radiative transfer for any given cloudy profile.
- Plans for more consistent definitions between physics schemes + DA…

Liquid water cloud optics:

- Slingo (1989) and Lindner and Li (2000)
- SOCRATES

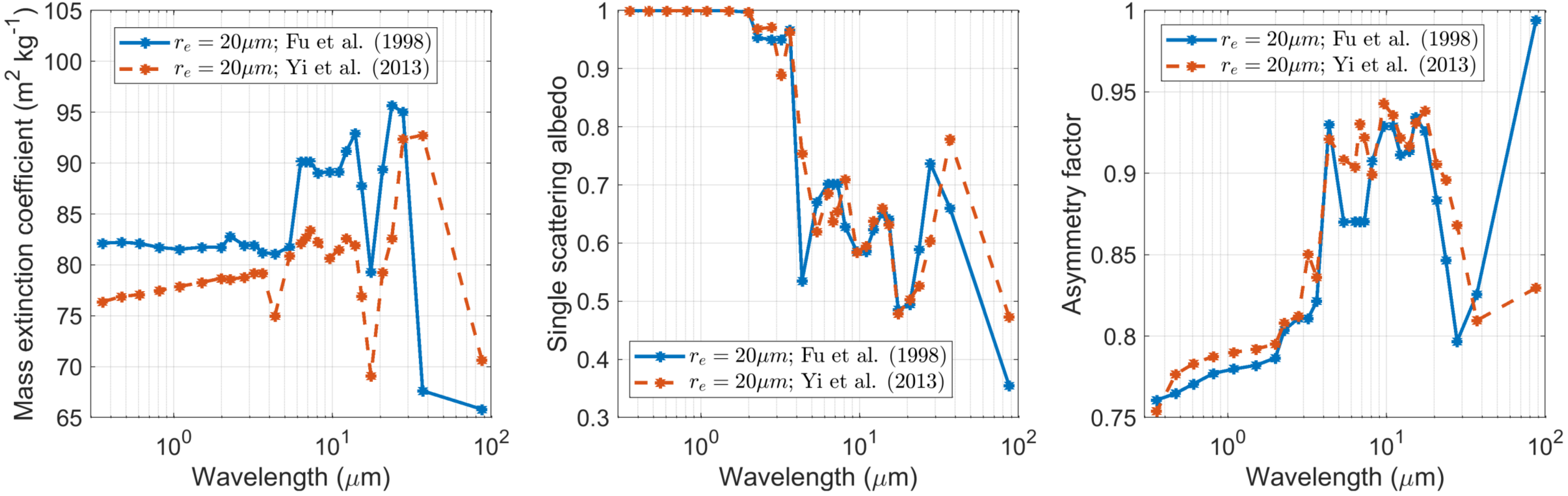
Ice cloud optics:

- Fu (1996) and Fu et al., (1998)
- Yi et al., (2013)
- Baran et al., (2014)

*Used operationally*

*All make assumptions on particle size distribution and particle habit(s)*

# Fu vs Yi ice scattering properties



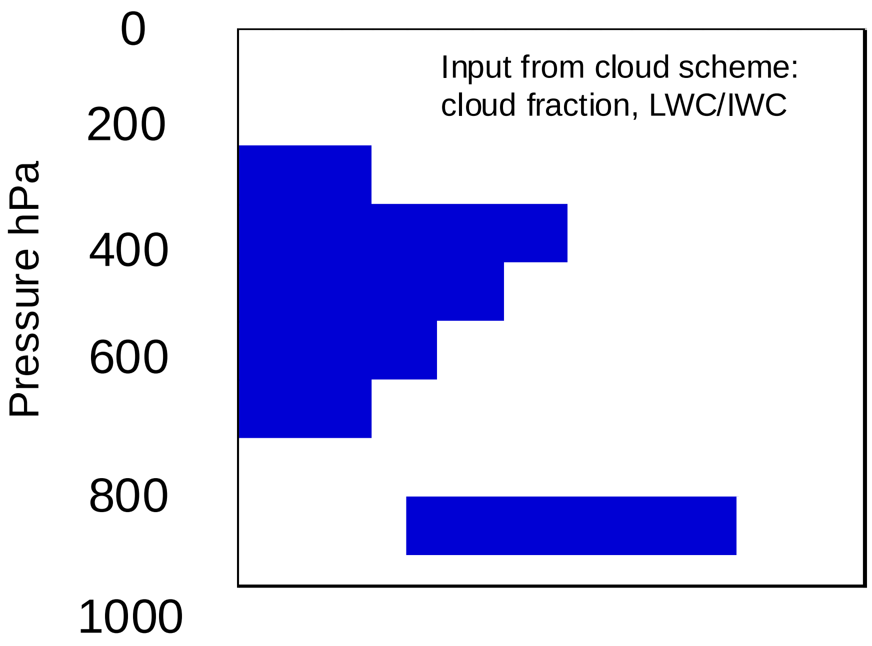
# Solver

- Combines clear-sky and cloudy optical properties according to the cloud fraction and assumptions on cloud inhomogeneity and overlap, and computes irradiance profiles.
- Four solvers are currently available in ecrad:
  - Homogeneous: Fast solver using binary cloud fraction
  - McICA: Monte Carlo Independent Column Approximation

    *Used operationally*
  - Tripleclouds: Deterministic handling of cloud overlap and cloud inhomogeneity
  - SPARTACUS: Tripleclouds + 3D effects

# Improving the representation of cloud radiative effects (1)

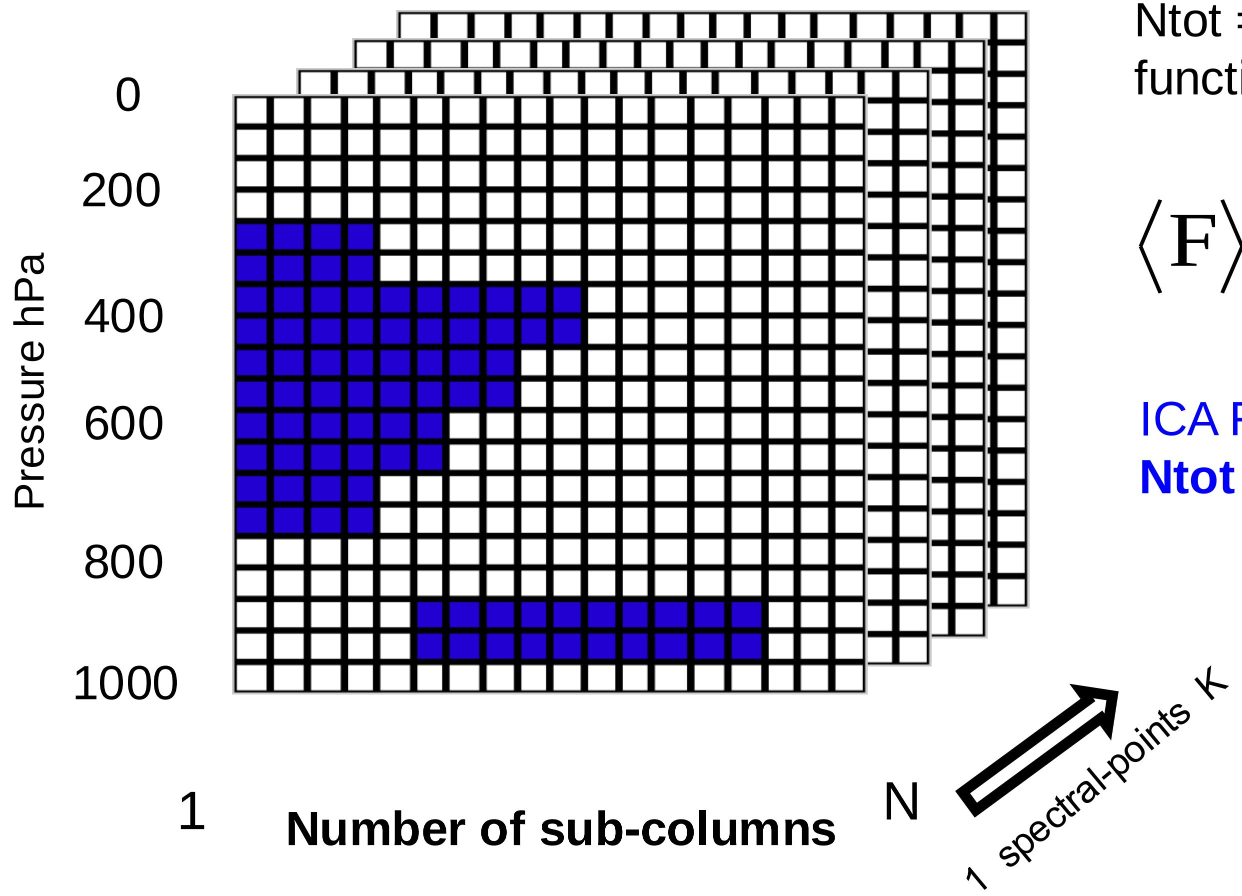
## most models until ~2000




Easy way to tackle the problem: compute the clear and cloud part of the grid box (according to cloud fraction and overlap at each level) and merge fluxes

# Improving cloud radiative effects (2)

## independent column approximation ICA (if we had infinite computing power)




K = number of spectral intervals (k-terms)

<F> average flux in the grid box
N = number of independent sub-columns
Ntot = total number of transmission function computations

$$\langle \mathrm{F} \rangle = \frac{1}{N} \sum_{n=1}^{N} F_n$$

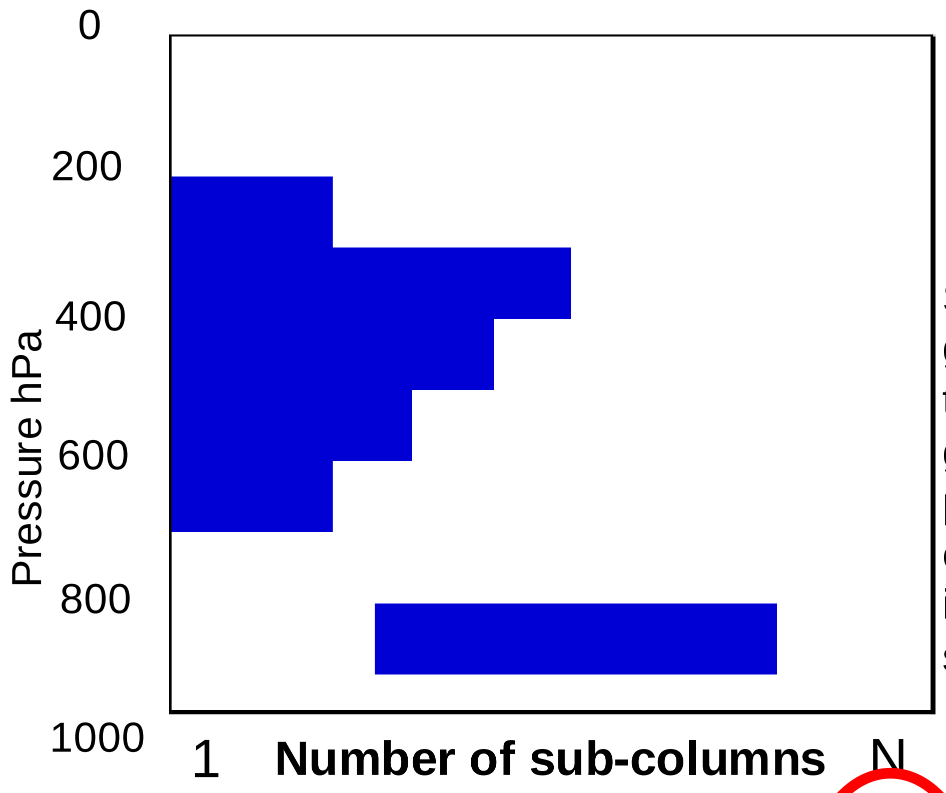
ICA RT scheme:
**Ntot = N * K ~ O(10^3)**

# Improving cloud radiative effects (3)

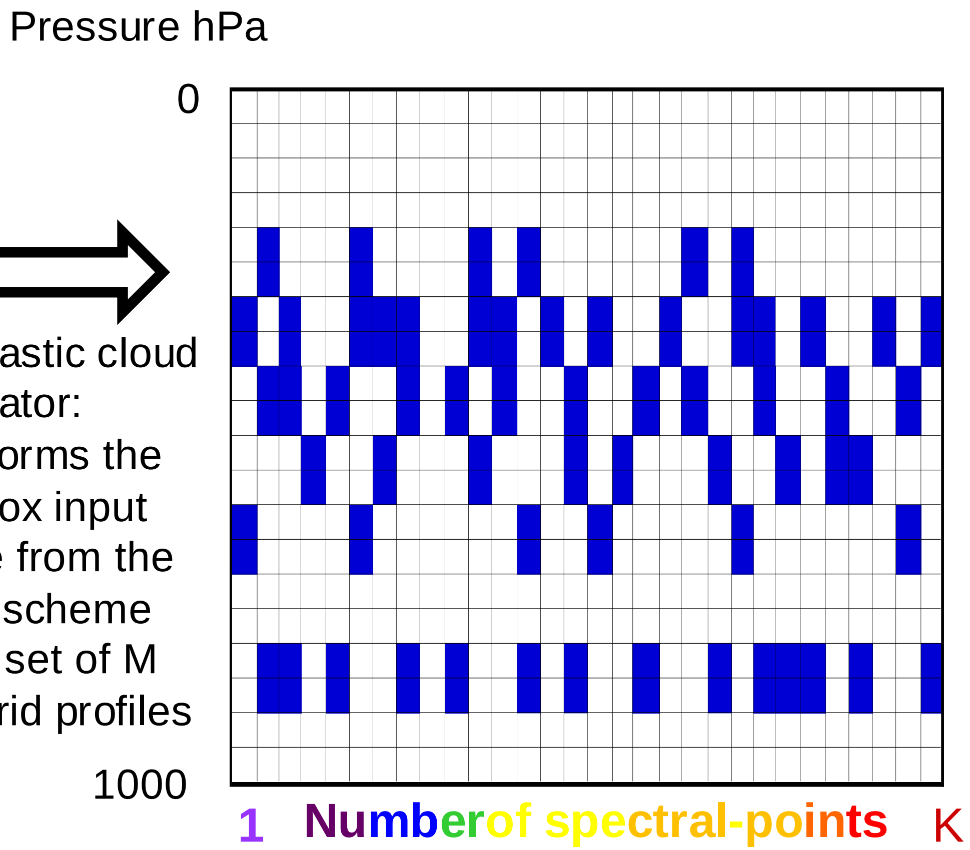
## Monte Carlo Independent Column Approximation McICA

Barker et al. (2003), Pincus et al. (2003)

Cloud generator: Raisanen et al. (2004)




Stochastic cloud generator: transforms the grid-box input profile from the cloud scheme into a set of M sub-grid profiles




McICA: approximates $$< F >= \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} c_k F_{n,k}$$ into $$< F > \sim \sum_{k=1}^{K} c_k F_{n_k,k}$$

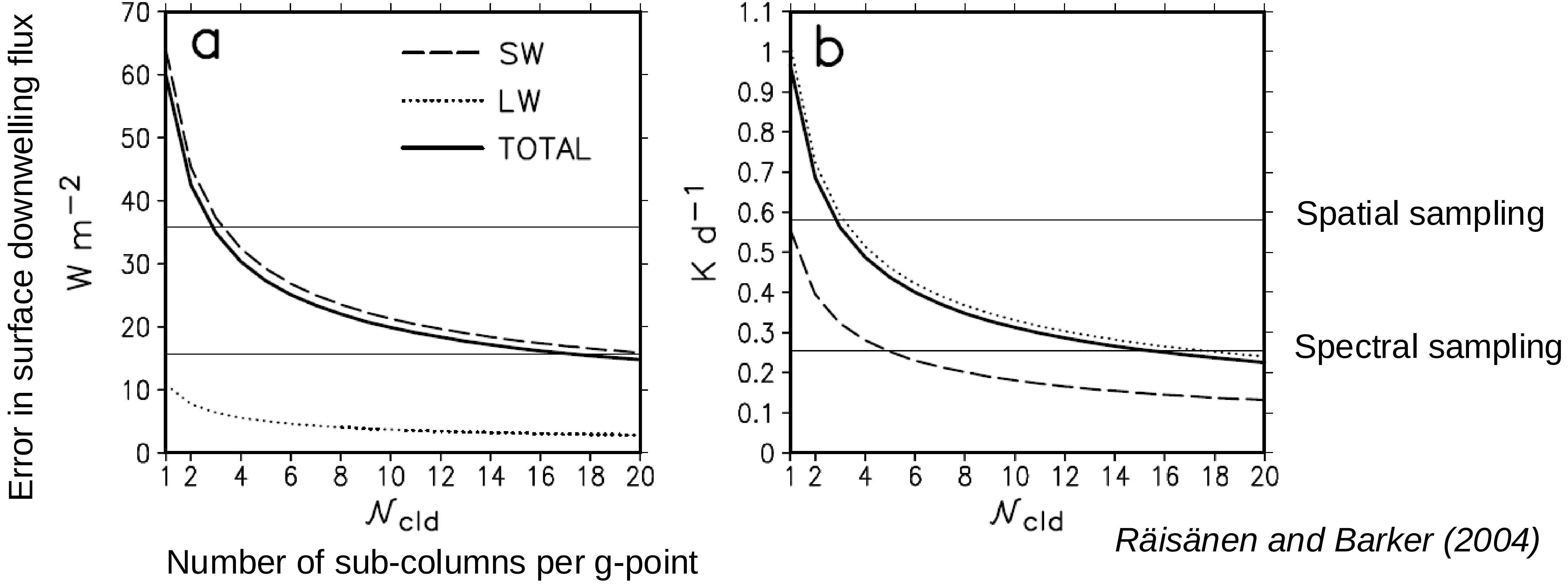
randomly assigning a different cloud profile for each spectral-point from the distribution of M profiles created by a cloud generator

# Advantages of McICA

- Approximates a full ‘ICA’ calculation in an intuitive way
- Each sub-column is fast to compute: cloud fraction is either 1 or 0
- Easy to implement different overlap schemes or subgrid-cloud inhomogeneity scheme
- Can choose balance between computational cost and noise by using more sub-columns per k-term.

# Disadvantages of McICA

- McICA is inherently noisy, particularly for LW heating rates




*Räisänen and Barker (2004)*

- Non-differentiable.

# Optimising ecRad – spectral vs spatial vs temporal considerations

# ECMWF calls radiation scheme relatively infrequently

- Temporal, spatial and spectral resolution in various global NWP models:

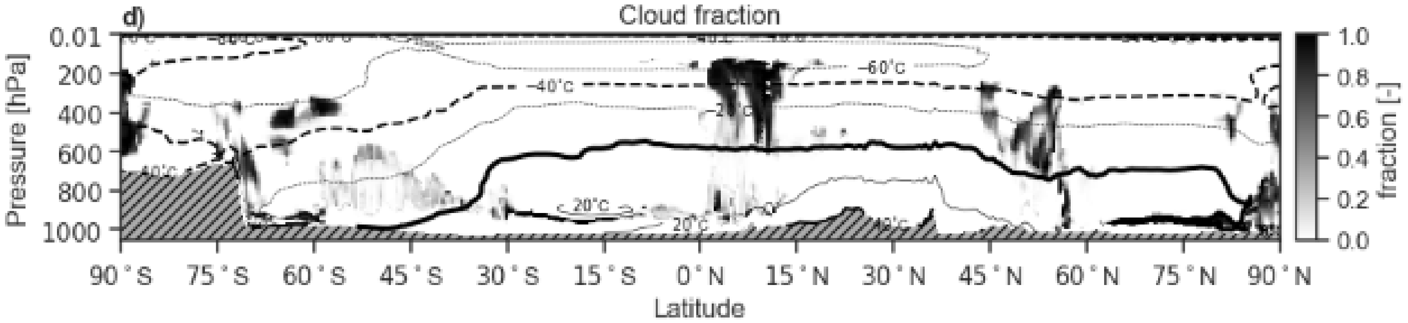
| Centre | Radiation timestep (h) | | Horiz. coarsening | | Bands | | Spectral intervals | |
|---|---|---|---|---|---|---|---|---|
| | HRES | ENS | HRES | ENS | SW | LW | SW | LW |
| ECMWF | 1 | ~~3~~ 1 | 10.24 | 6.25 | 14 | 16 | 112 | 140 |
| NCEP | 1 | 1 | 1 | 1 | 14 | 16 | 112 | 140 |
| DWD | 0.4 | 0.6 | 4 | 4 | 14 | 16 | 112 | 140 |
| Météo France | 1 | 1 | 1 | 1 | 6 | 16 | – | 140 |
| Met Office | 1 | 1 | 1 | 1 | 6 | 9 | 21 | 47 |
| CMC | 1 | 1 | 1 | 1 | 4 | 9 | 40 | 57 |
| JMA | 1 | 1 (SW), 3 (LW) | 4 | 4 | 16 | 11 | 22 | 156 |
| FSCK | – | – | – | – | 2 | 1 | ~ 15 | ~ 32 |

- ECMWF has lowest spatial resolution for radiation
  - Experiments show this barely degrades forecasts (unlike 3-h radiation timestep)
- Met Office NWP model uses 3.7 times fewer g-points than RRTM-G
- Full-spectrum correlated-k estimates of coarsest possible spectral resolution

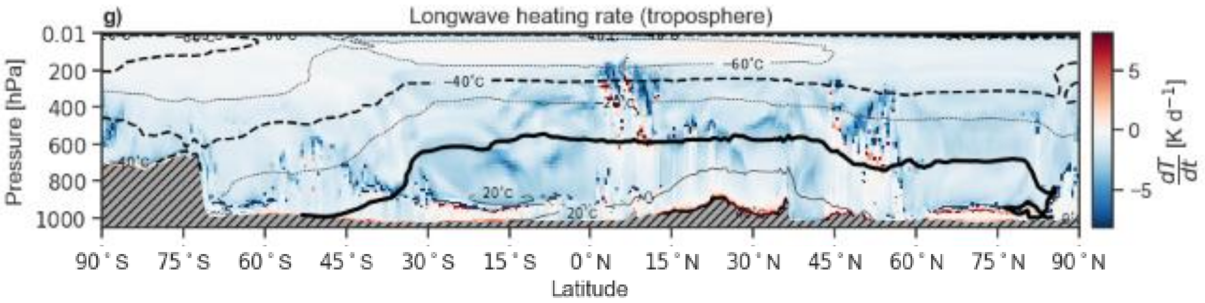
# Using ecCKD gas optics could increase efficiency and accuracy greatly

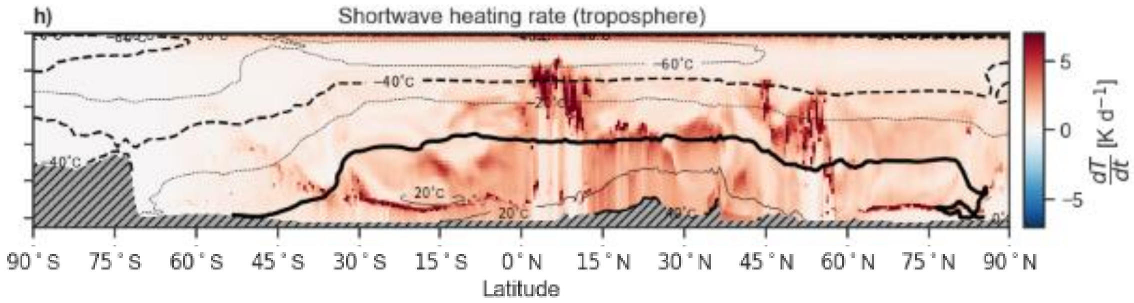
- ecRad tutorial dataset: ERA5 pole-to-pole slice from 11 July 2019:

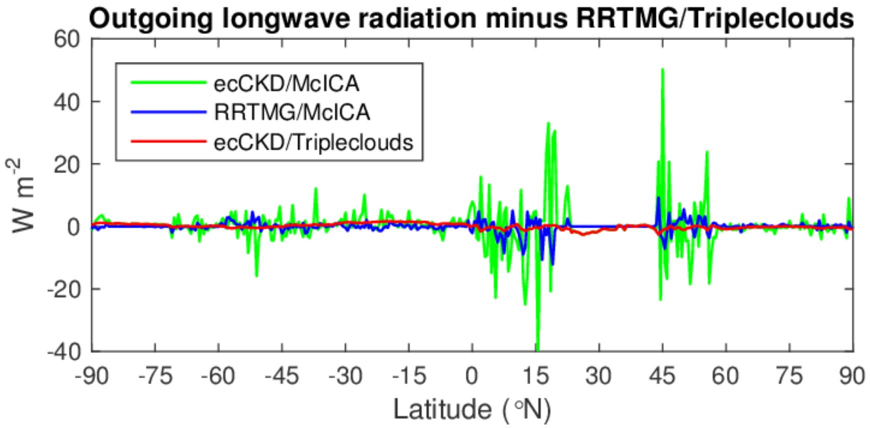
*Thanks to Shannon Mason*

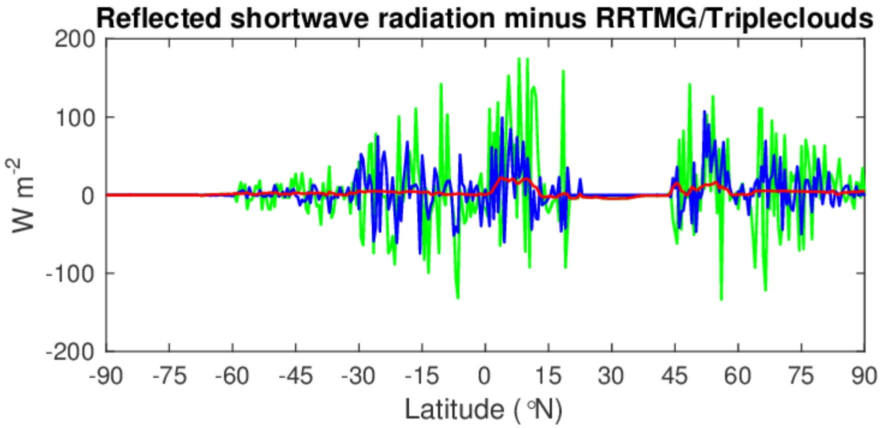



We want to use noise-free Tripleclouds solver but is it too expensive?



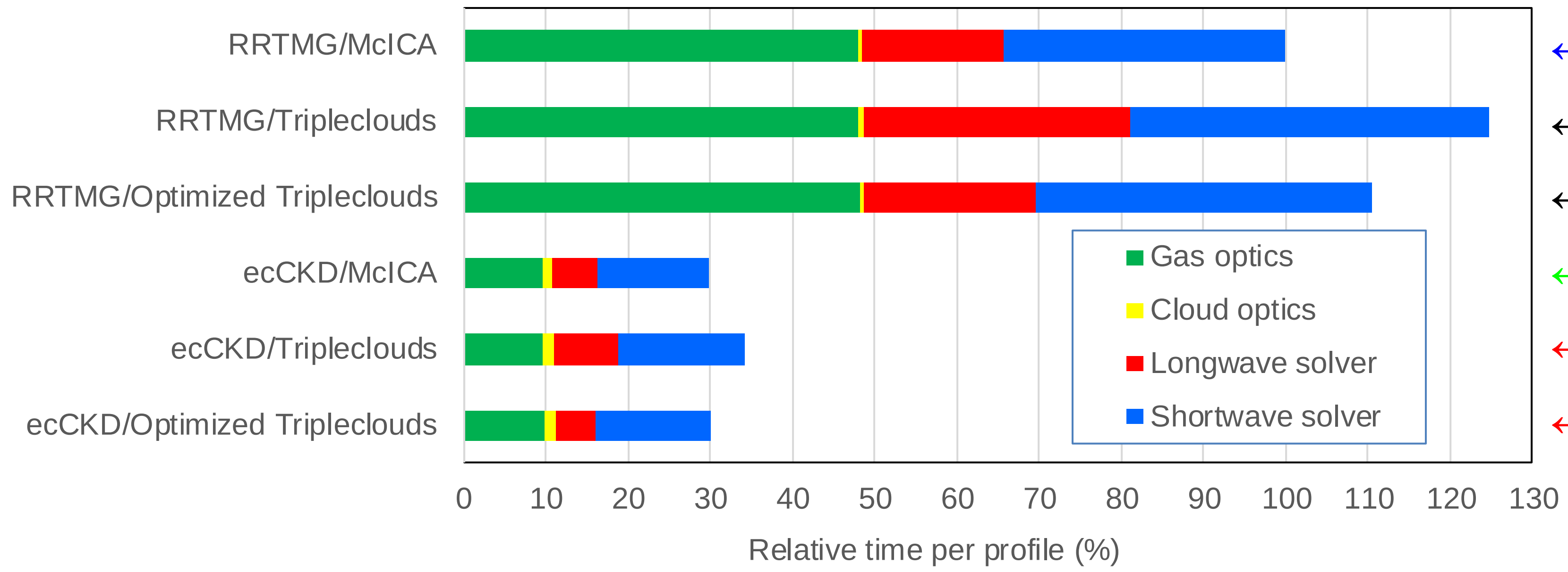




- RRTMG, Tripleclouds solver
- ecCKD, Tripleclouds solver
- RRTMG, McICA solver
  - Currently operational
- ecCKD, McICA solver

# Computational cost of various configurations of ecRad (offline)




← Current operational configuration

← Original Tripleclouds is 25% slower

← *After optimizing*

← ecCKD is fast but McICA too noisy

← Original Tripleclouds is 15% slower

← *Optimized Tripleclouds around the same cost as McICA!*

- **An accurate gas optics model with a noise-free solver can be implemented with only 30% the cost of RRTMG**
- Clouds implemented generically: easy to add rain, snow, graupel etc with different optical properties
- Potential to make TL/AD consistent: use cheap ecCKD gas optics model with differentiable Tripleclouds solver

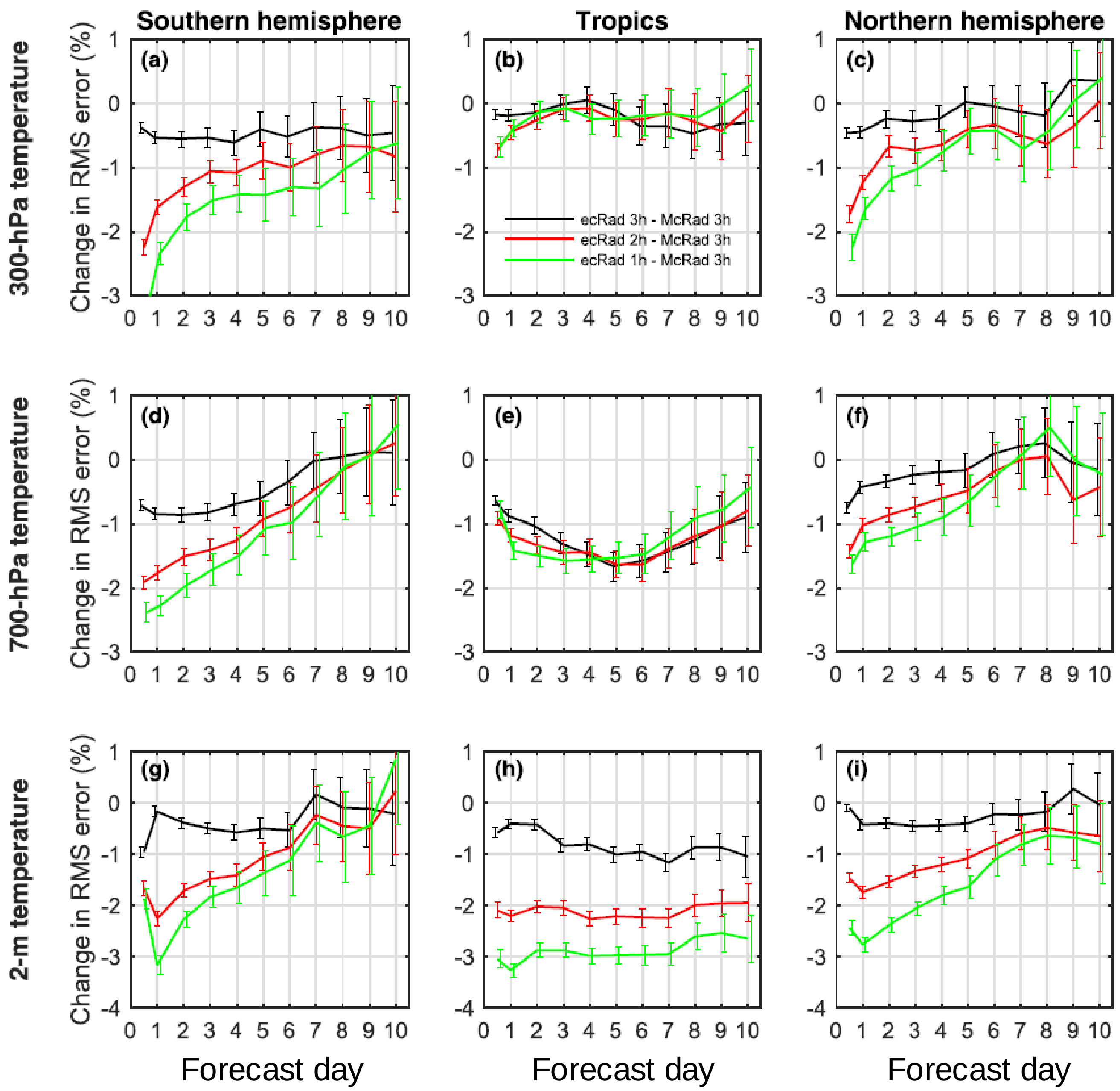
# Evaluating the impact of radiation scheme changes on forecast skill

# Impact of radiation timestep on forecast skill scores

300 hPa temperature

700 hPa temperature

2-m temperature




3h

2h

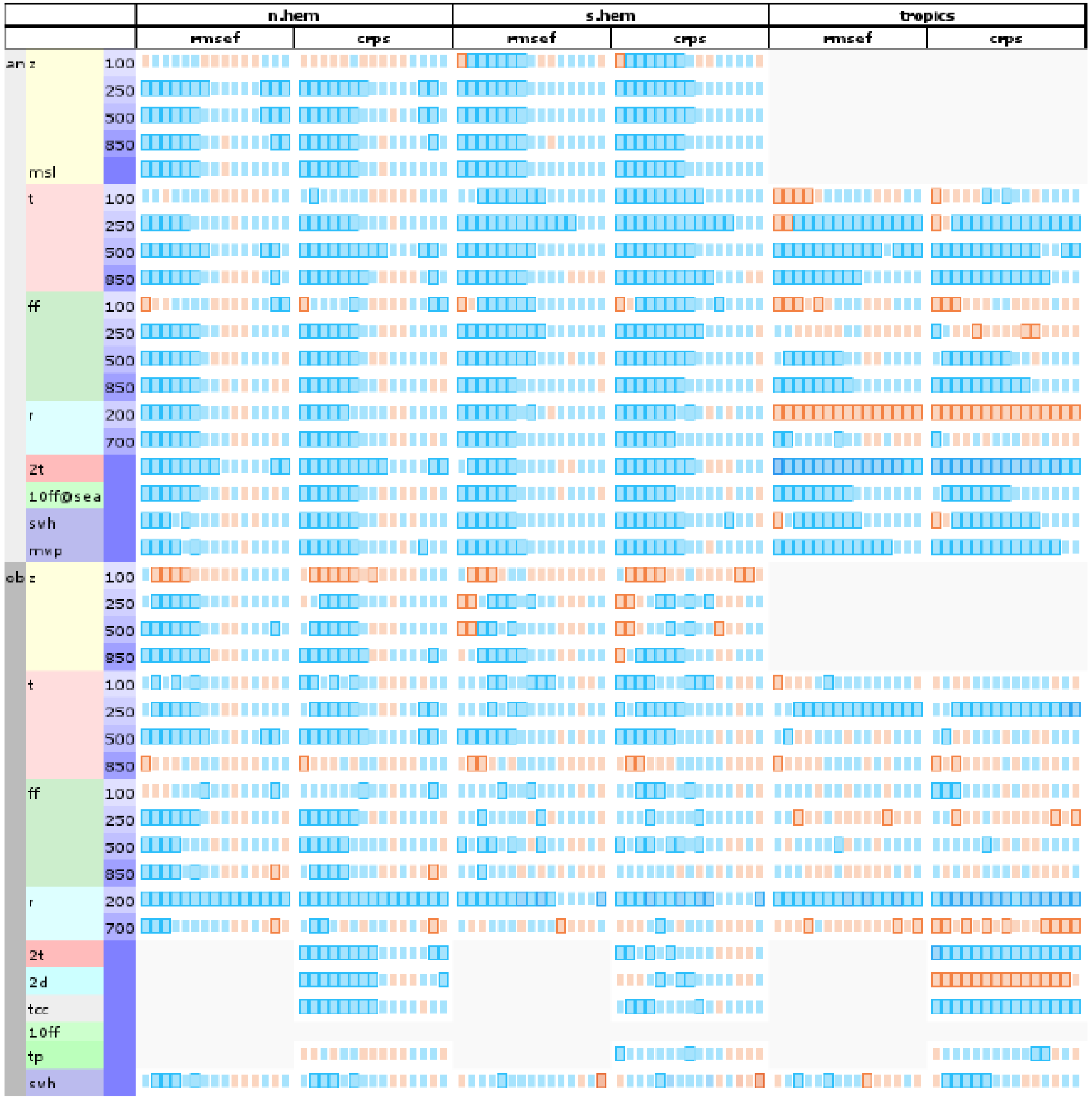
1h

Normalised change in RMSE using ecRad with respect to the old McRad scheme
Values <0 mean that the IFS performs better using ecRad

# Impact of radiation timestep on forecast skill scores

Vs Analysis

Vs Observations




1 hourly radiation is better

1 hourly radiation is worse

# Using radiation observations for forecast verification

# CERES evaluation of free running IFS (4x 1-year, cycle 47r1 coupled to ocean)

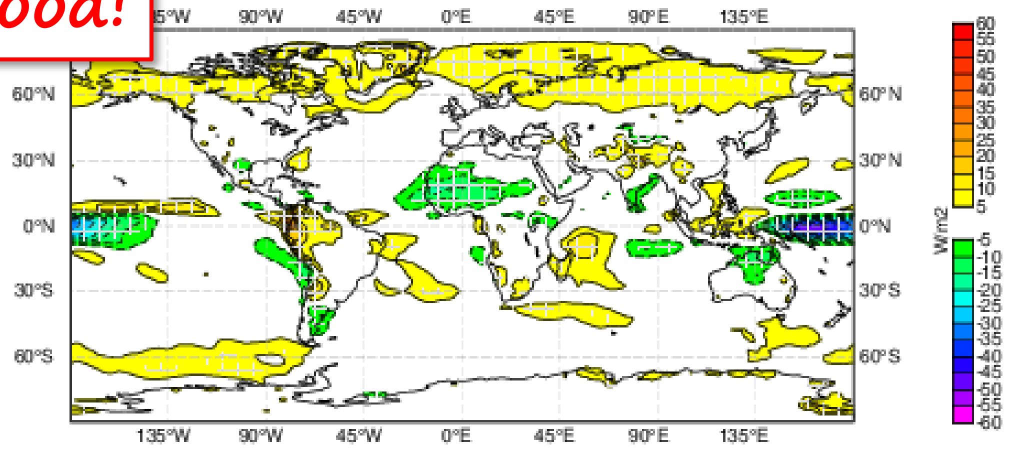
- Evaluation of each model cycle: [https://www.ecmwf.int/en/forecasts/charts/physics/physics_clim2000](https://www.ecmwf.int/en/forecasts/charts/physics/physics_clim2000)

| | Longwave bias | Shortwave bias |
|---|---|---|

**Net flux**

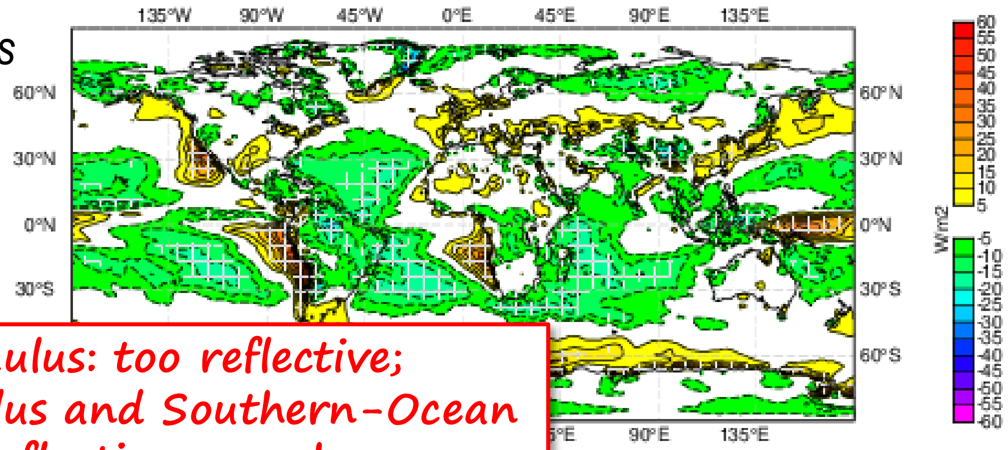
Good!

ence hcde - CERES-EBAF 90S-90N Mean err 1.15 rms 5.98



Net = down minus up, so a positive bias means too little upwelling

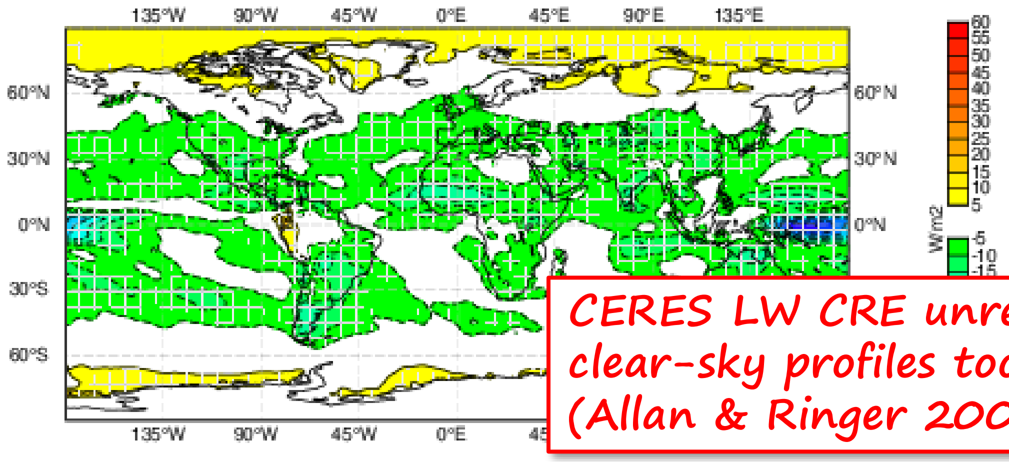
Difference hcde - CERES-EBAF 90S-90N Mean err -2.13 rms 9.4



Marine cumulus: too reflective; stratocumulus and Southern-Ocean cloud: not reflective enough

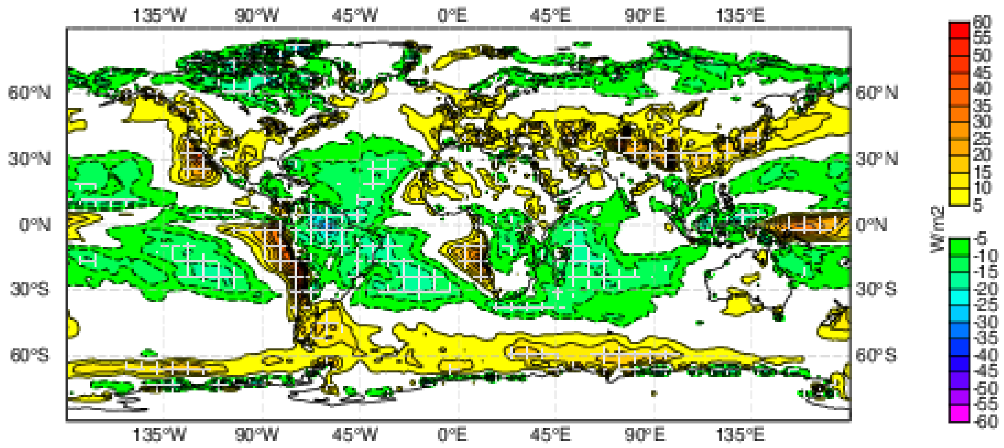
**Cloud Rad. Effect**

Difference hcde - CERES-EBAF 90S-90N Mean err -4.99 rms 7.6



CERES LW CRE unreliable: clear-sky profiles too dry (Allan & Ringer 2003)

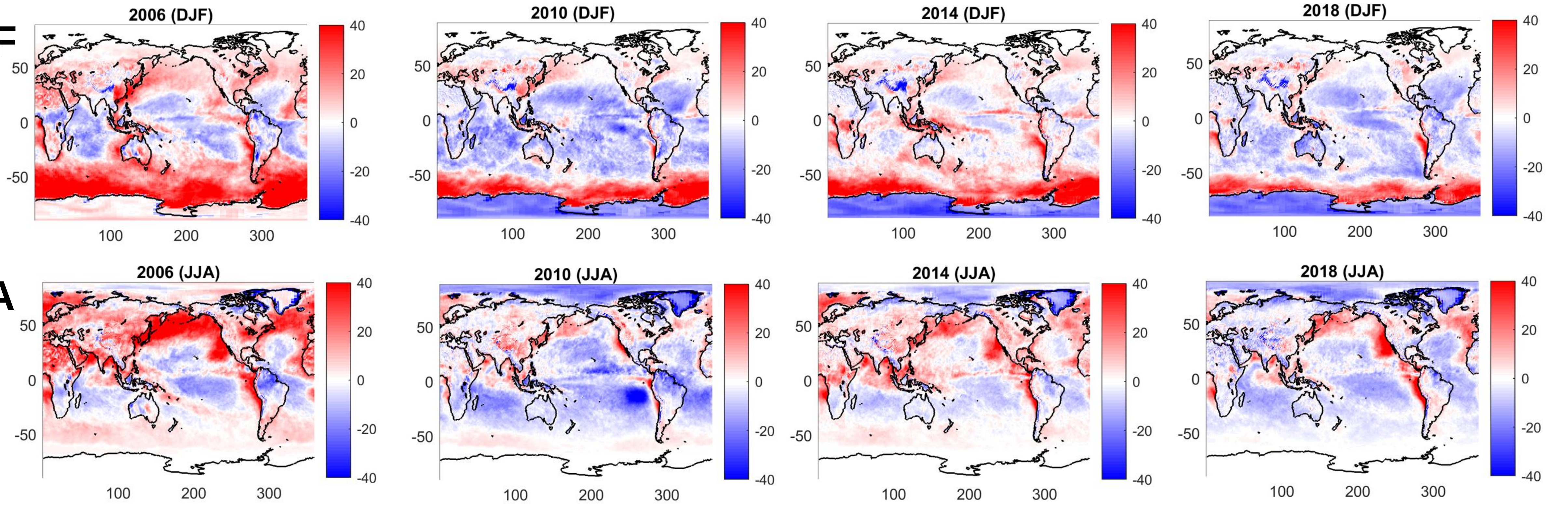
Difference hcde - CERES-EBAF 90S-90N Mean err -1.12 rms 9.69



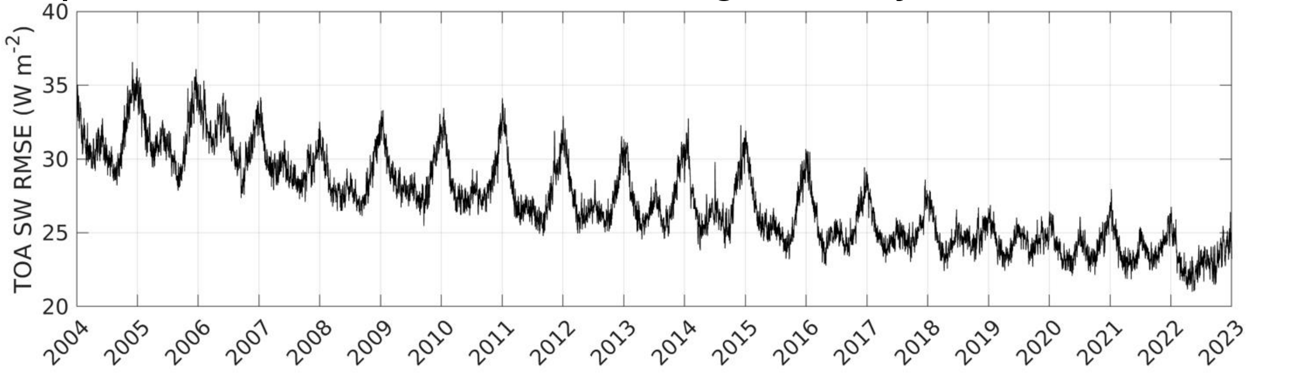
# Evaluation of net shortwave radiation in *operational* 24-h forecasts, 2003-present

**DJF**

**JJA**



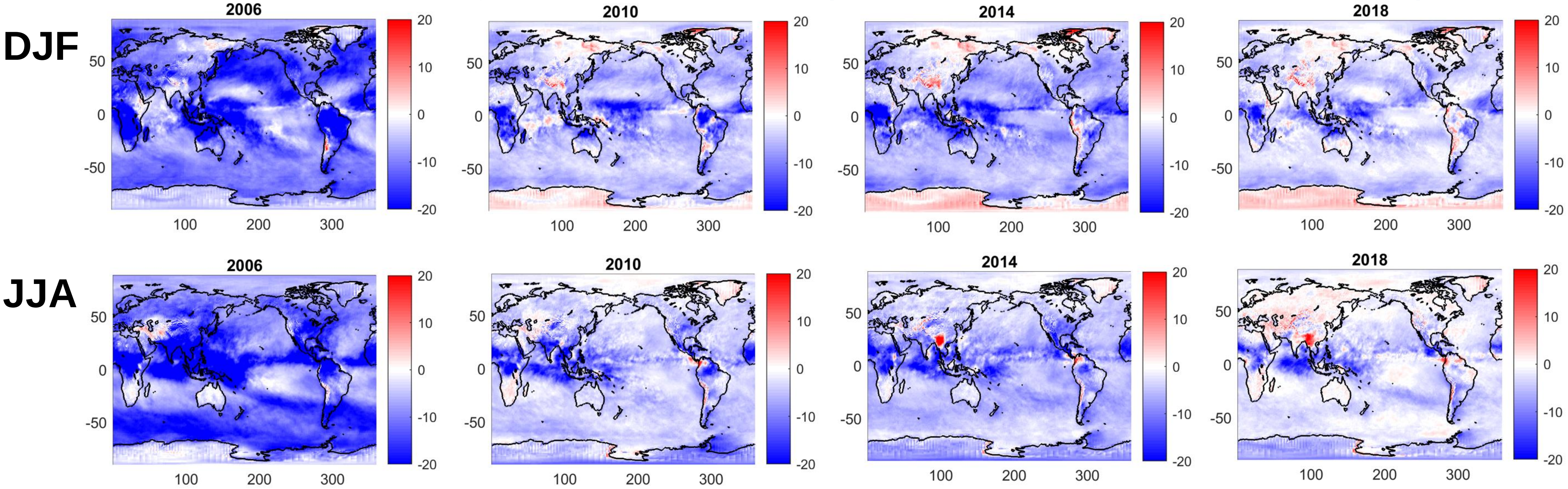

Comparison with CERES SYN 1 degree daily mean TOA fluxes




- Improvement in Southern-Ocean dark bias in DJF
- Antarctica too reflective
- Steady reduction in RMS error since 2003

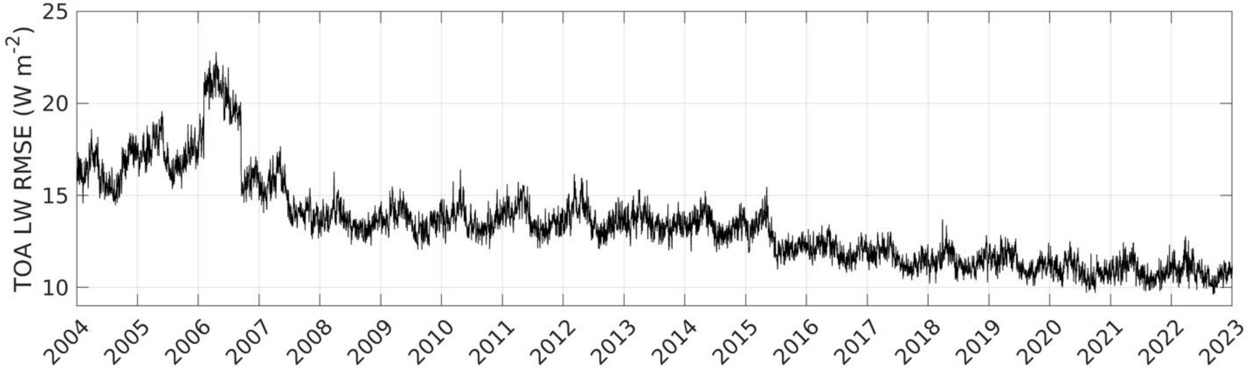
ECMWF

# Evaluation of net longwave radiation in *operational* 24-h forecasts , 2003-present

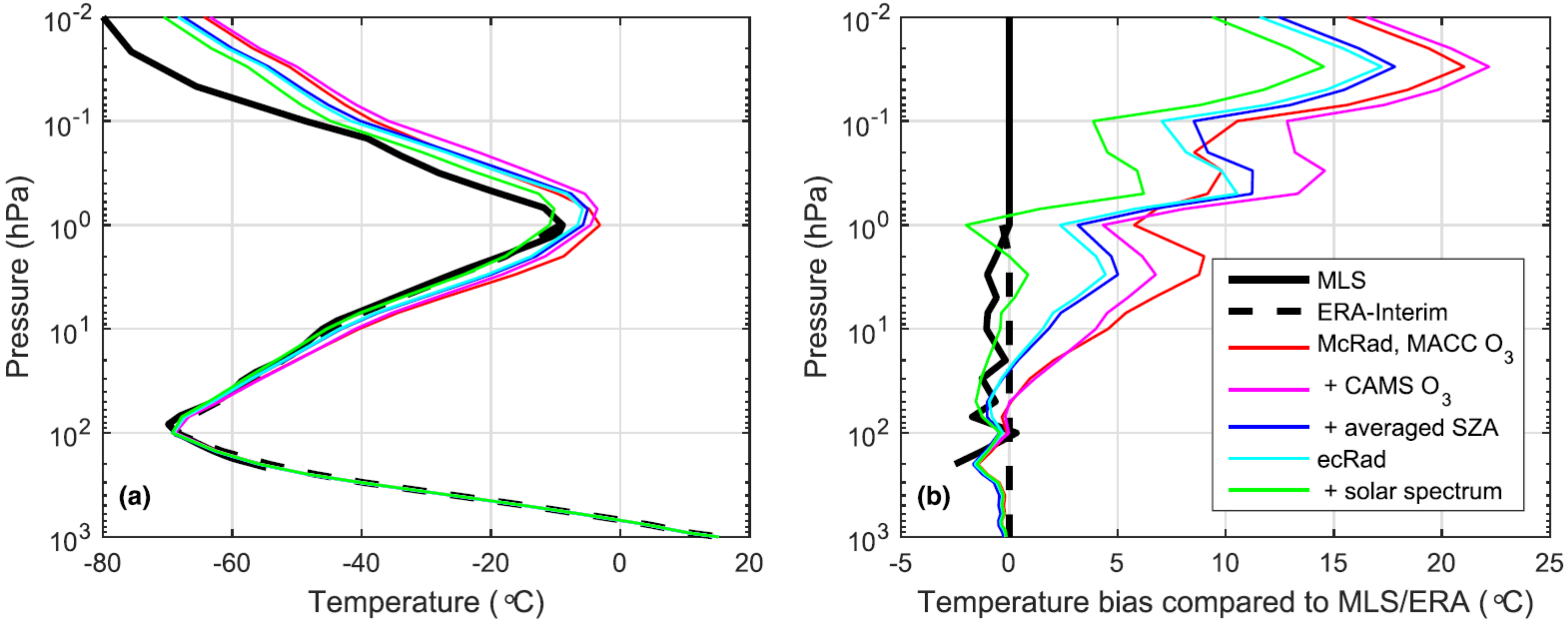



- Outgoing Longwave Radiation (OLR) bias reduced from +12 W $m^{-2}$ in 2006 to +2 W $m^{-2}$ in 2018
- OLR still too high over Indian Ocean: convective clouds not extensive or deep enough?

Comparison with CERES SYN 1 degree daily mean TOA fluxes



# Improving the middle atmosphere in the IFS




*Hogan and Bozzo (2018)*

# Five "Grand Challenges" for radiation in NWP models

Non-LTE effects

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

Coastlines

Urban areas

**Surface**

Orography

Land albedo datasets

# Summary and outlook

- ecRad scheme is good platform for future developments, but interaction and consistency between schemes is also very important
- Global tropospheric climate of the IFS is excellent, but need concerted effort on many fronts to tackle much larger regional and stratospheric biases
- Five Grand Challenges for the coming years:
  1. Overhaul surface treatment, including 3D interactions with cities and forests
  2. Package of physically-based improvements to clouds
  3. Role of aerosols in predictability; upgrade water vapour continuum
  4. Middle-atmosphere temperature bias reduced via new UV solar spectrum, but large biases persist.
  5. More efficient gas optics and spectral integration

# Further reading


TECHNICAL MEMORANDUM

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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

This paper has not been published and should be regarded as an Internal Report from ECMWF.
Permission to quote from it should be obtained from the ECMWF.

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme


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ECRAD: A new radiation scheme for the IFS

Robin J. Hogan and Alessio Bozzo

Research Department

November 2016

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