The ECMWF radiation scheme

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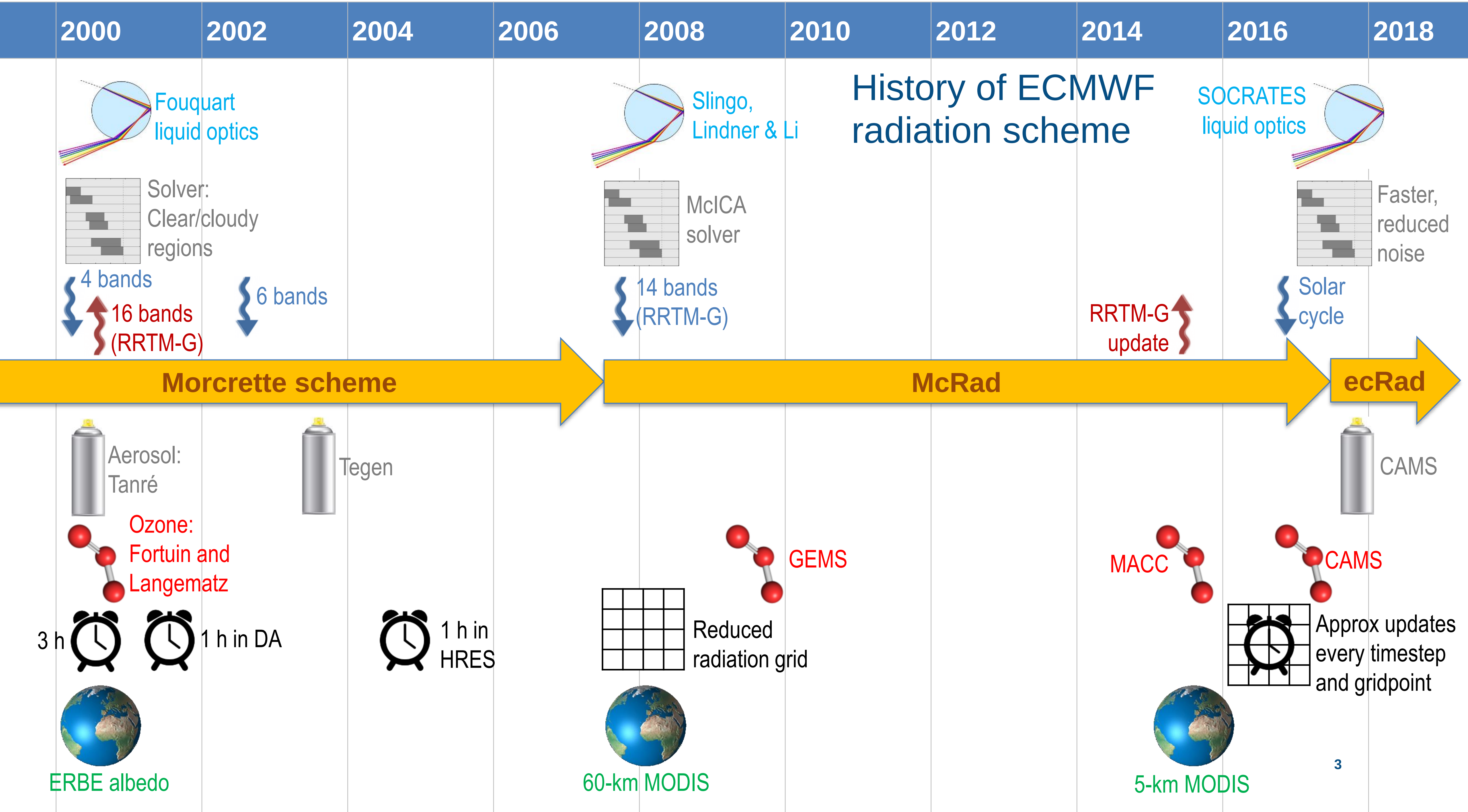
With contributions from Alessio Bozzo

Outline

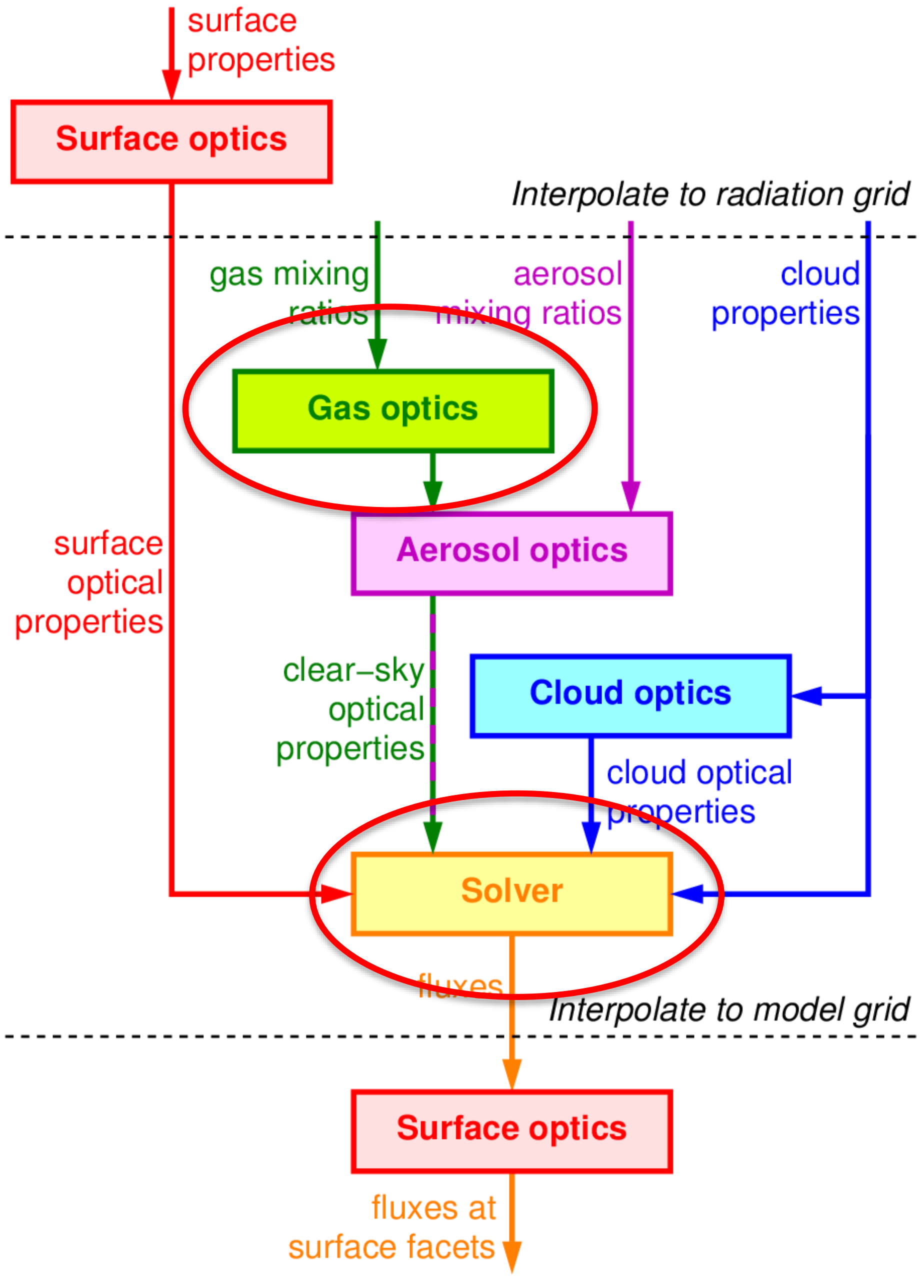
- History of the ECMWF radiation scheme
- Overview of the current scheme: ecRad
- Treatment of gases (Correlated-k) and clouds (McICA)
- Optimization considerations (spectral vs spatial vs temporal)
- Testing the radiative impact of changes to parameterizations
- Do aerosols matter for NWP?
- Remaining challenges

History of ECMWF radiation scheme



Modular design of ecRad

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



surface properties

Surface optics

Interpolate to radiation grid

gas mixing ratios

aerosol mixing ratios

cloud properties

Gas optics

surface optical properties

Aerosol optics

clear–sky optical properties

Cloud optics

cloud optical properties

Solver

fluxes

Interpolate to model grid

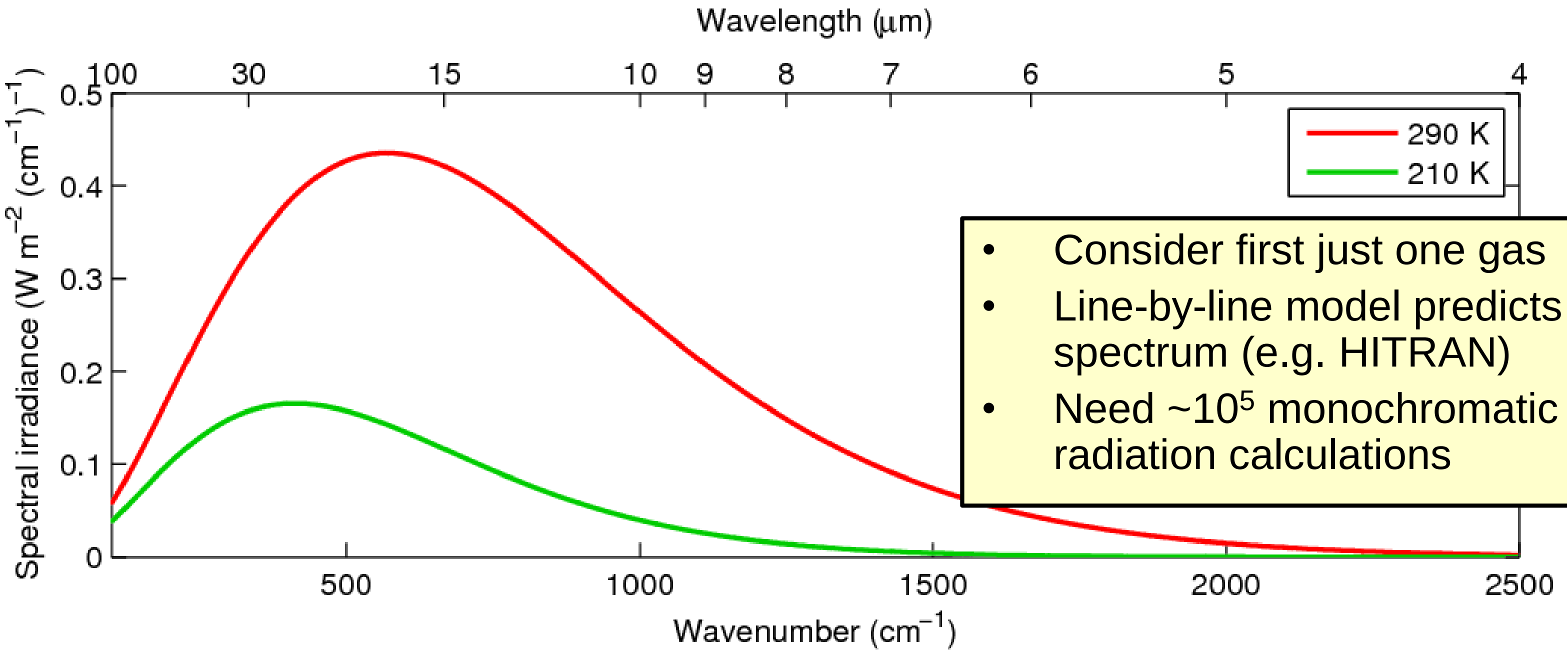
Surface optics

fluxes at surface facets

- 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

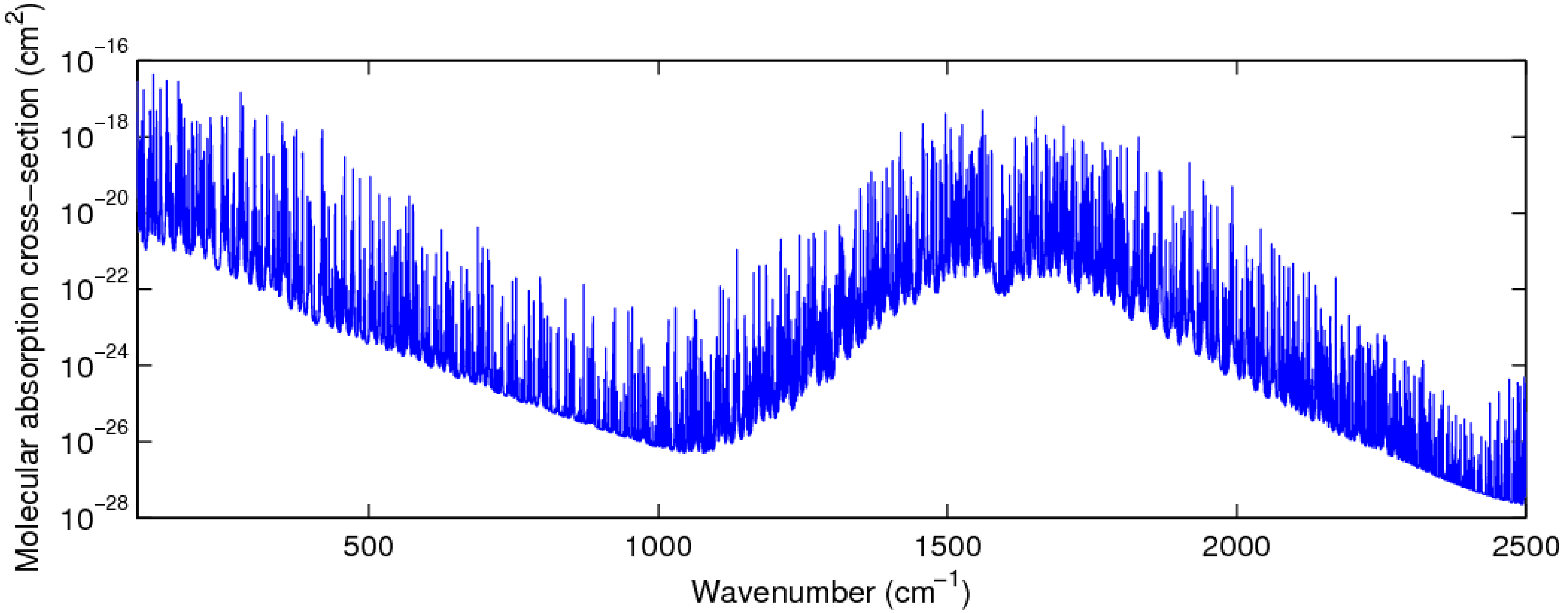
GAS OPTICS: How do we integrate across the spectrum?

Planck function

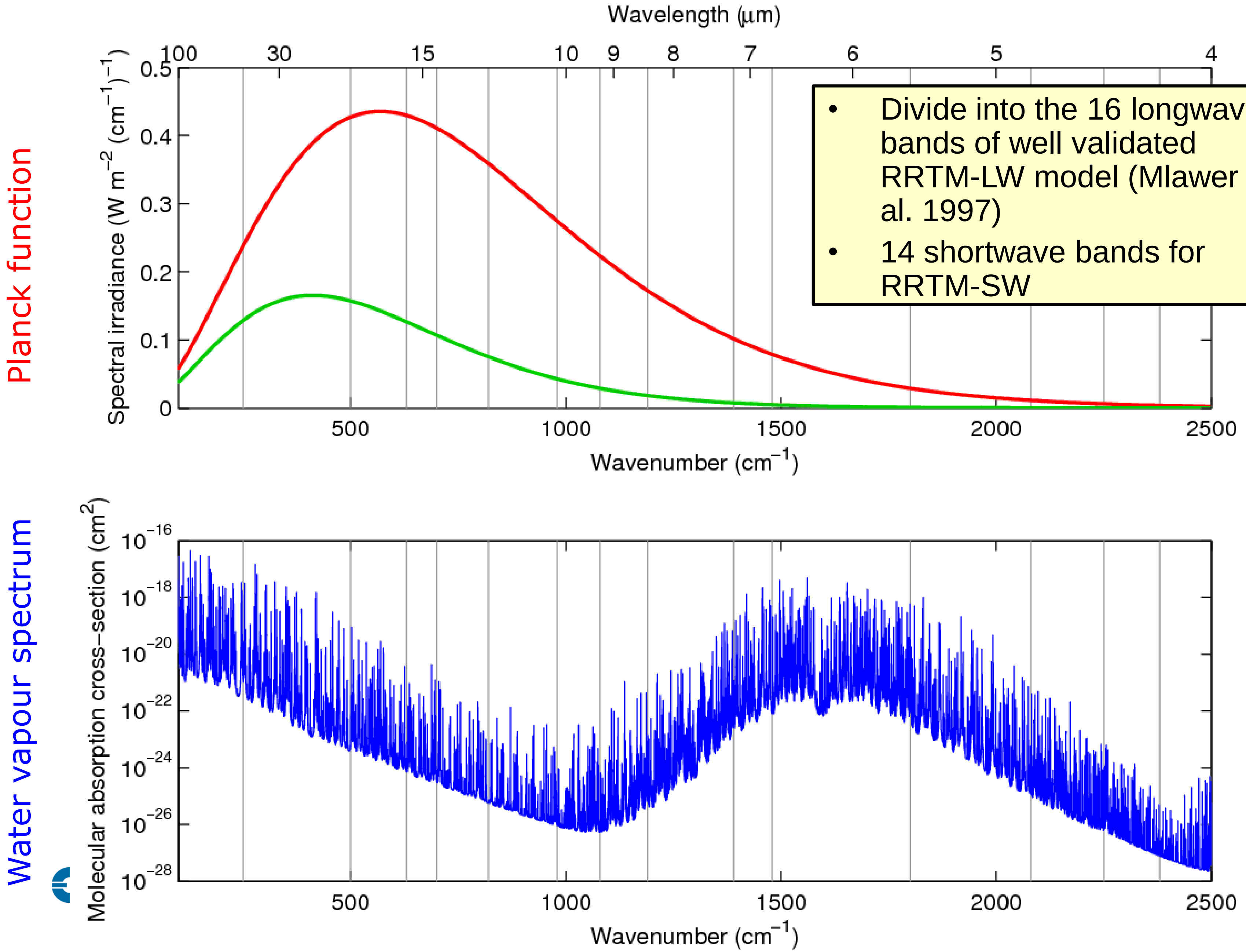


- Consider first just one gas
- Line-by-line model predicts spectrum (e.g. HITRAN)
- Need ~10^5 monochromatic radiation calculations

Water vapour spectrum



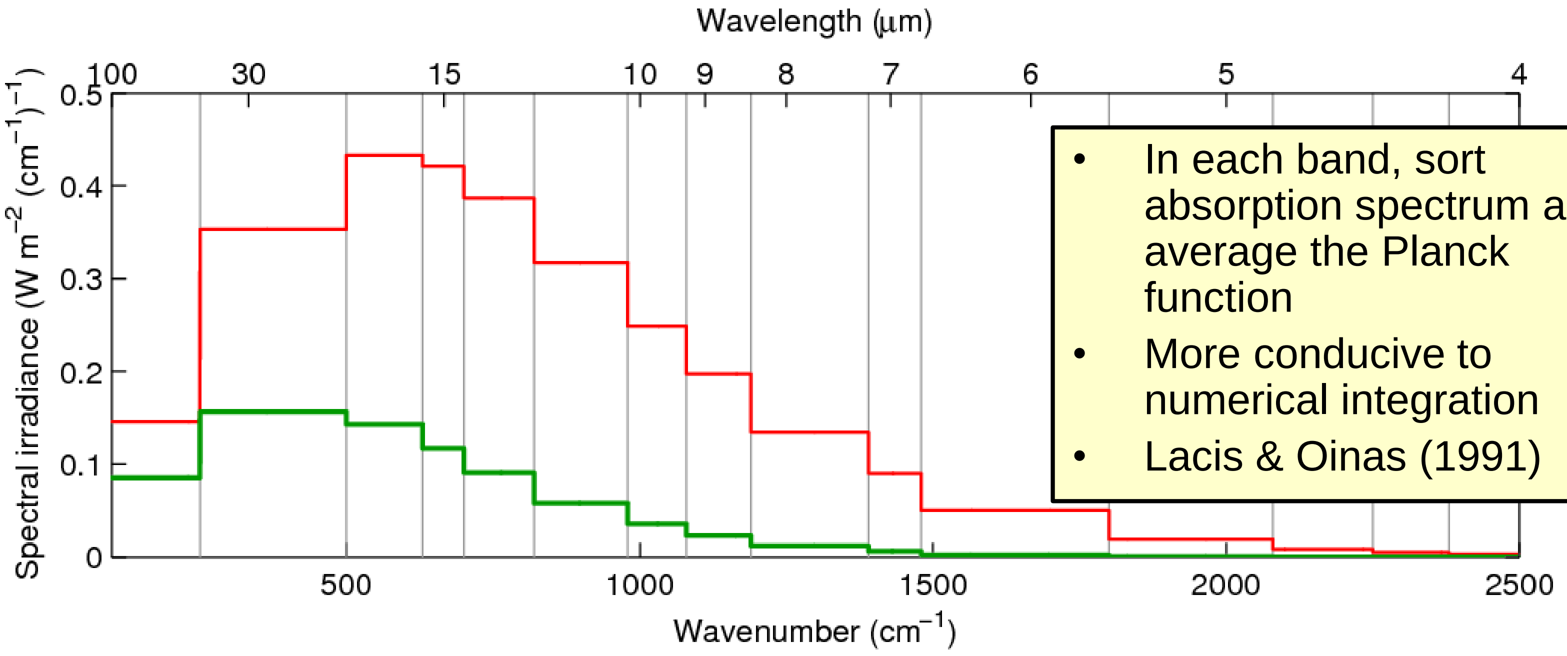
Divide into bands



- Divide into the 16 longwave bands of well validated RRTM-LW model (Mlawer et al. 1997)
- 14 shortwave bands for RRTM-SW

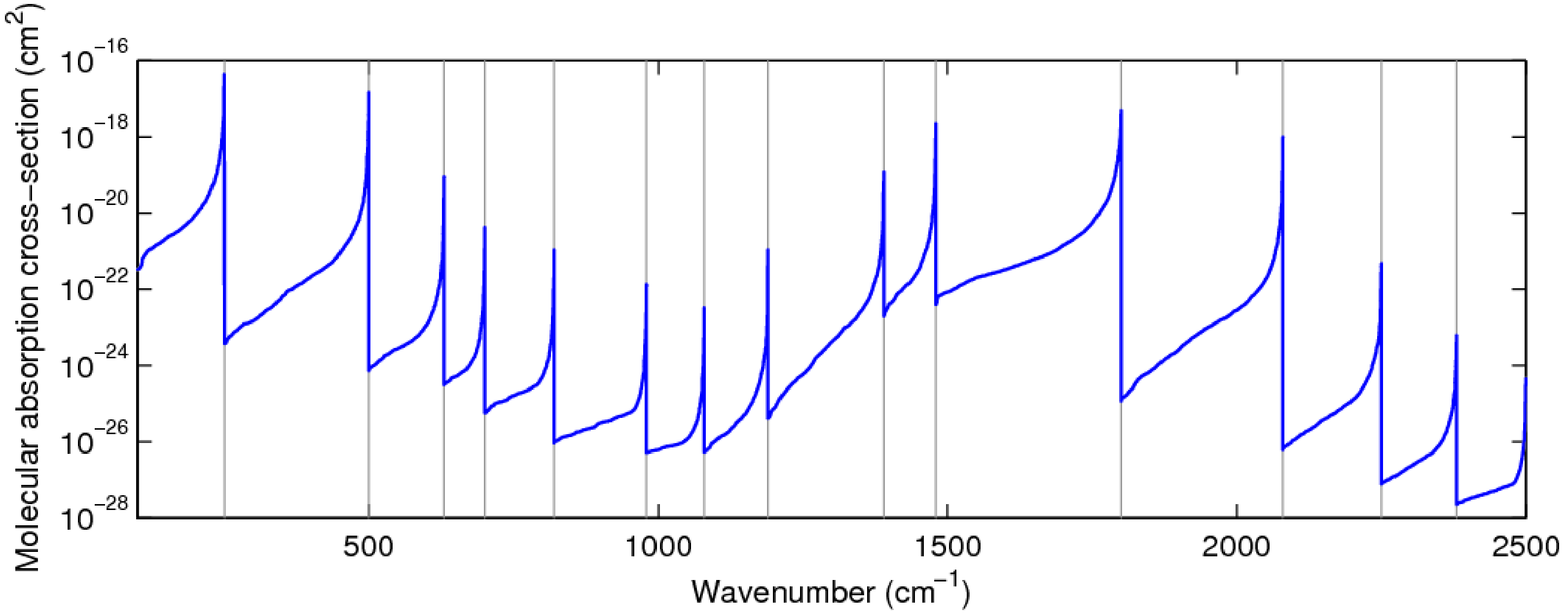
The k-distribution method

Planck function

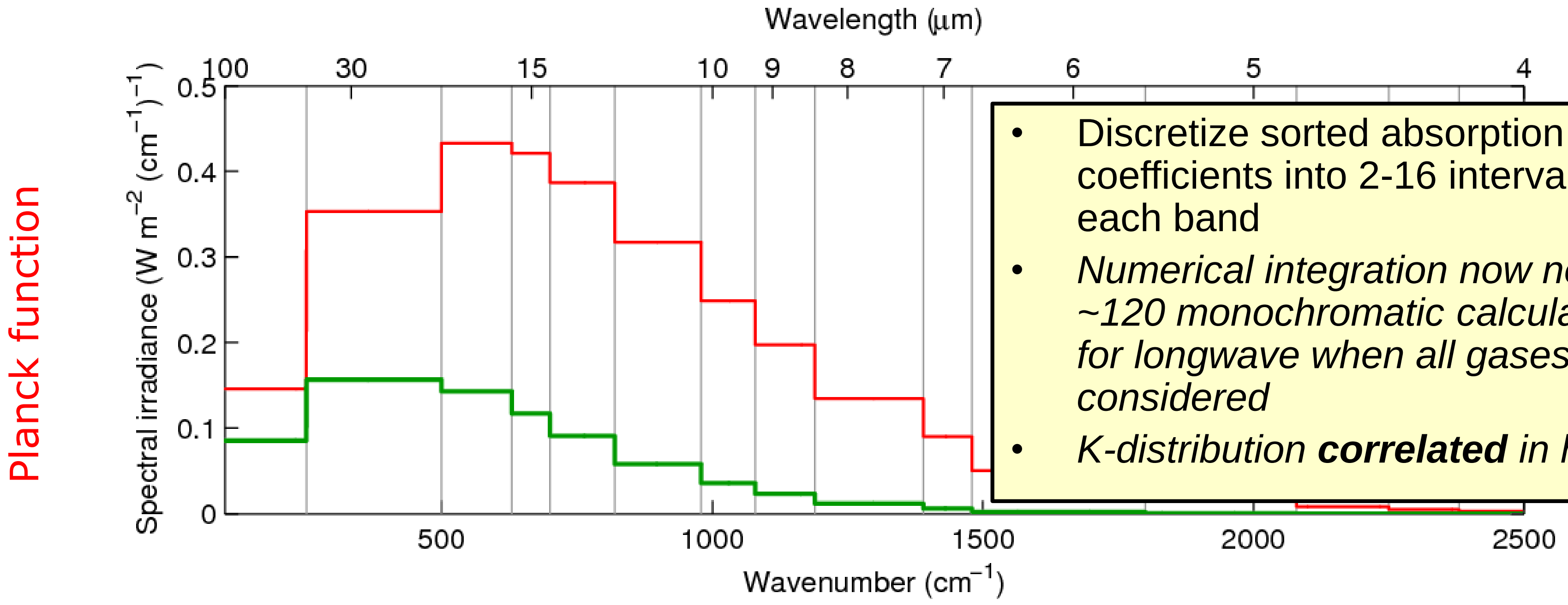


- In each band, sort absorption spectrum and average the Planck function
- More conducive to numerical integration
- Lacis & Oinas (1991)

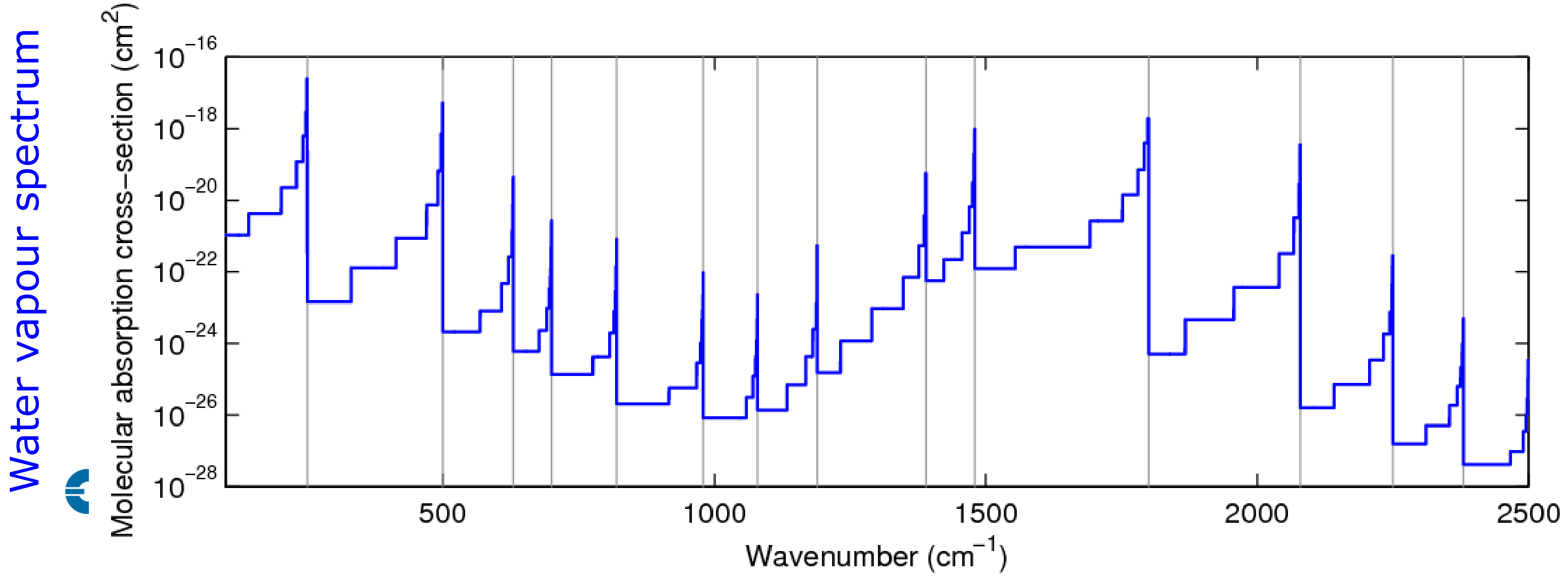
Water vapour spectrum



The correlated k-distribution (CKD) method



- Discretize sorted absorption coefficients into 2-16 intervals in each band
- *Numerical integration now needs ~120 monochromatic calculations for longwave when all gases considered*
- *K-distribution **correlated** in height*



RRTMG-LW configuration

16 BANDS

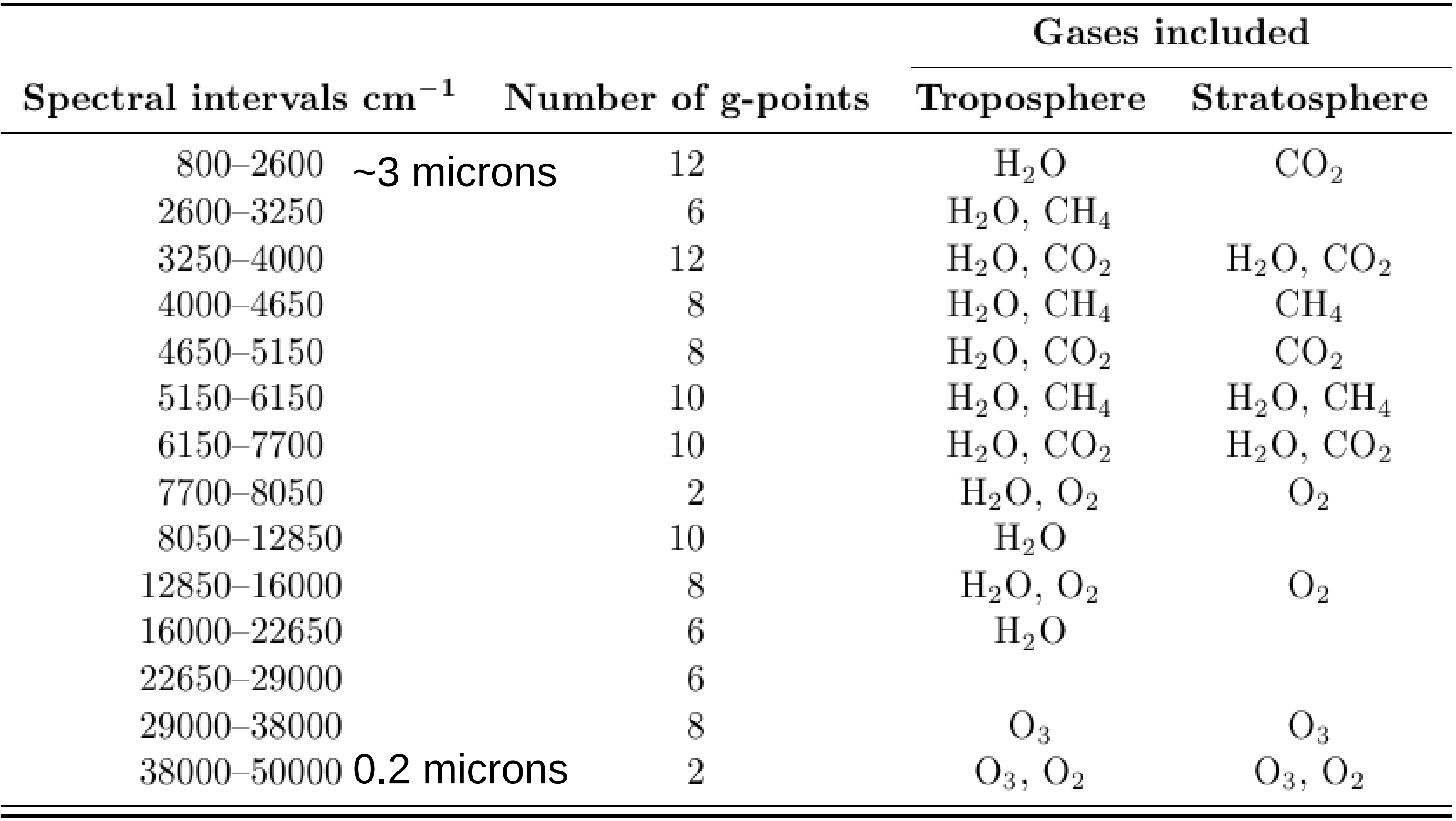
~100 hPa

		Gases included	
Spectral intervals cm^{-1}	Number of g-points	Troposphere	Stratosphere
10–250 ~100 microns	8	H_2O	H_2O
250–500	14	H_2O	H_2O
500–630	16	H_2O, CO_2	H_2O, CO_2
630–700	14	H_2O, CO_2	O_3, CO_2
700–820	16	H_2O, CO_2, CCl_4	O_3, CO_2, CCl_4
820–980	8	H_2O, CFC11, CFC12	CFC11, CFC12
980–1080	12	H_2O, O_3	O_3
1080–1180	8	H_2O, CFC12, CFC22	O_3, CFC12, CFC22
1180–1390	12	H_2O, CH_4	CH_4
1390–1480	6	H_2O	H_2O
1480–1800	8	H_2O	H_2O
1800–2080	8	H_2O	
2080–2250	4	H_2O, N_2O	
2250–2380	2	CO_2	CO_2
2380–2600	2	N_2O, CO_2	
2600–3000 ~3 microns	2	H_2O, CH_4	

140 spectral points (too many? Perhaps…)

RRTMG-SW configuration

14 BANDS

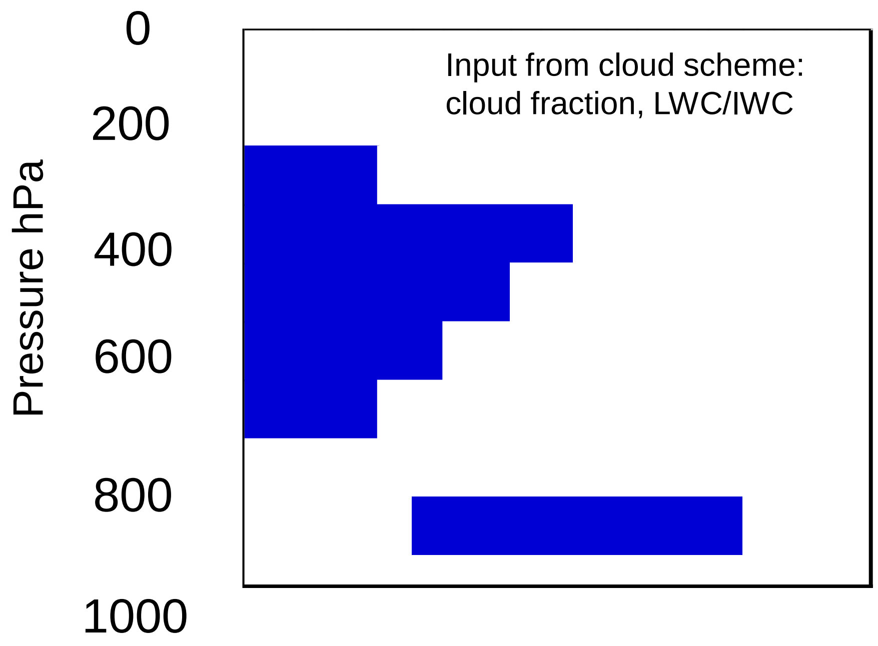


		Gases included	
Spectral intervals cm^{-1}	Number of g-points	Troposphere	Stratosphere
800–2600 ~3 microns	12	H_2O	CO_2
2600–3250	6	H_2O, CH_4	
3250–4000	12	H_2O, CO_2	H_2O, CO_2
4000–4650	8	H_2O, CH_4	CH_4
4650–5150	8	H_2O, CO_2	CO_2
5150–6150	10	H_2O, CH_4	H_2O, CH_4
6150–7700	10	H_2O, CO_2	H_2O, CO_2
7700–8050	2	H_2O, O_2	O_2
8050–12850	10	H_2O	
12850–16000	8	H_2O, O_2	O_2
16000–22650	6	H_2O	
22650–29000	6		
29000–38000	8	O_3	O_3
38000–50000 0.2 microns	2	O_3, O_2	O_3, O_2

112 spectral points (too many? Perhaps….)

Improving the representation of cloud radiative effects (1)

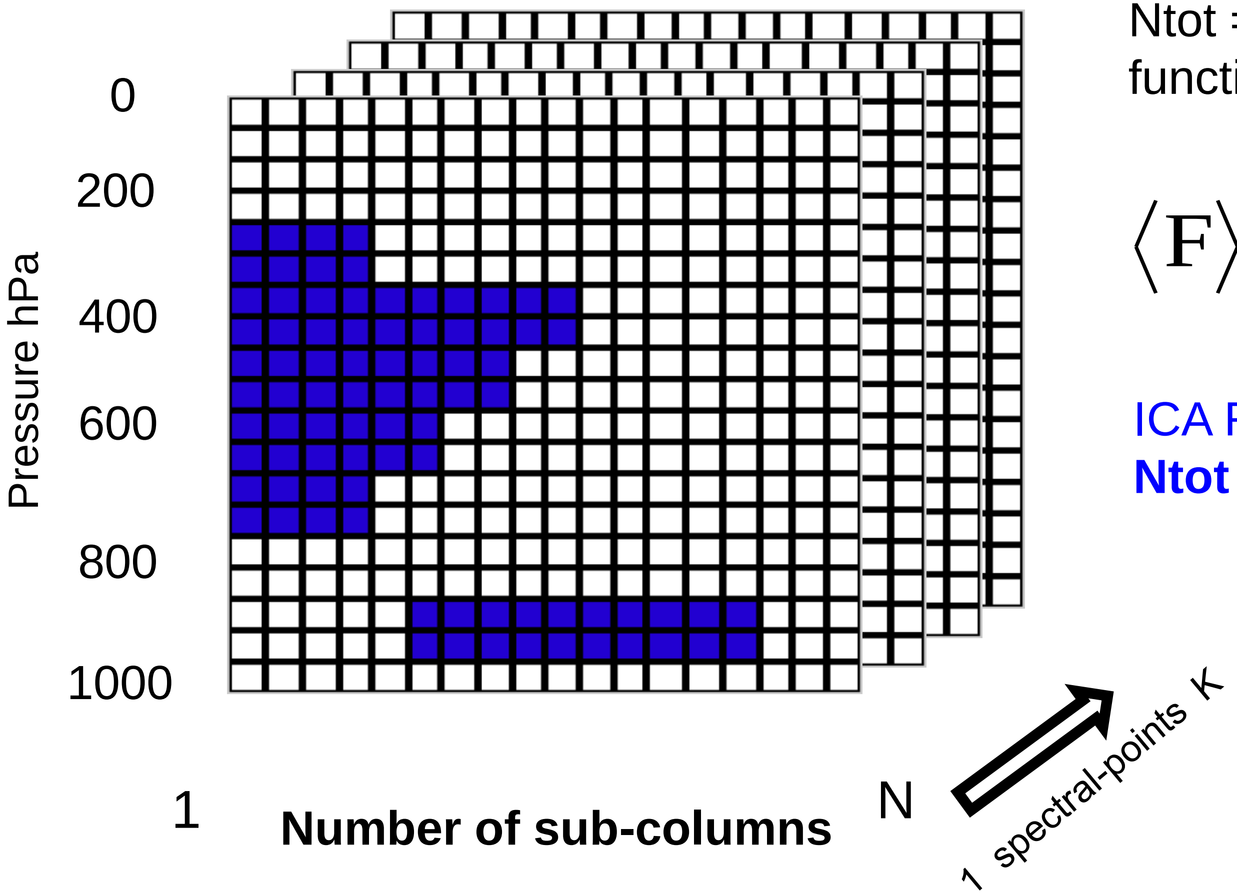
most models until ~2000



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 (g-points)

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

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

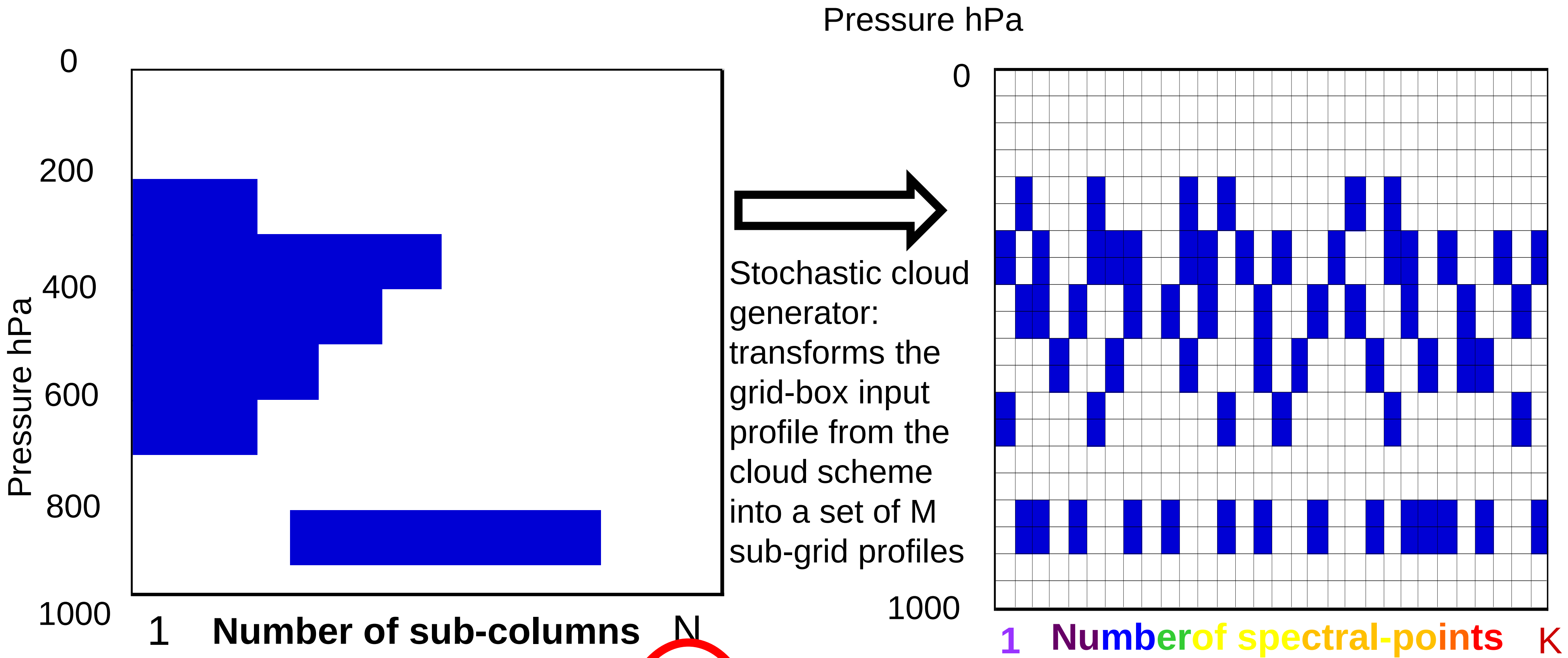
ICA RT scheme:
Ntot = N * K ~ O(10^3)

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

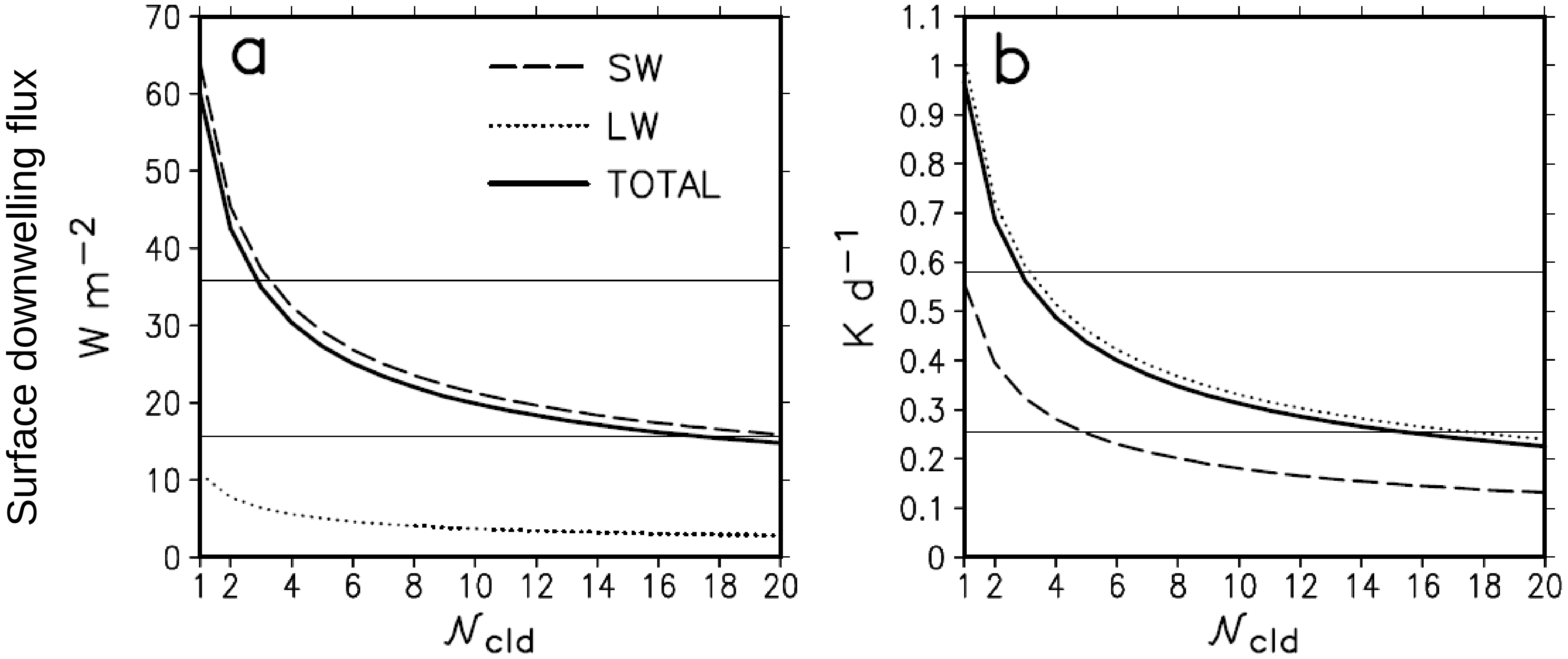
randomly assigning a different cloud profile for each spectral-point from the distribution of M profiles created by a cloud generator

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
- Easy to implement subgrid-cloud inhomogeneity scheme
- Efficient when optimized

Disadvantages of McICA (1)

- McICA is inherently noisy, particularly for LW heating rates



Number of sub-columns per g-point

Räisänen and Barker (2004)

Disadvantages of McICA (2)

- Two optimisations have been suggested:

<u>Spatial sampling:</u>

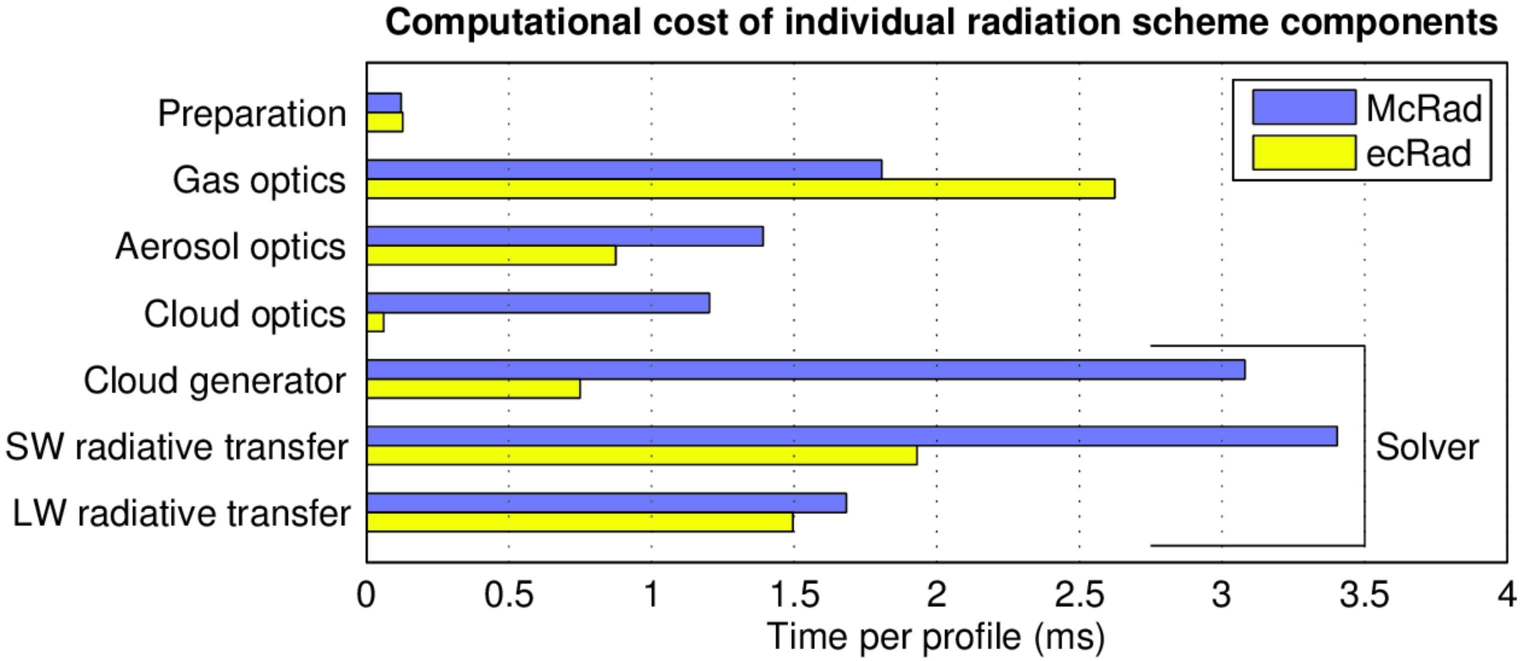
- ➢ Given that clear-sky fluxes are computed at every g-point for diagnostic purposes, only need to sample cloudy profiles
- ➢ Compute the all-sky fluxes according to the diagnosed total integrated cloud fraction

<u>Spectral sampling:</u>

- ➢ Some g-points have a greater contribution to cloud radiative effect than others
- ➢ Use additional sub-columns for g-points that contribute the most
- ➢ Requires prior knowledge of which g-points are most senstitive. Could be different depending on situation and what metric you want to minimize (e.g., surface or TOA?)

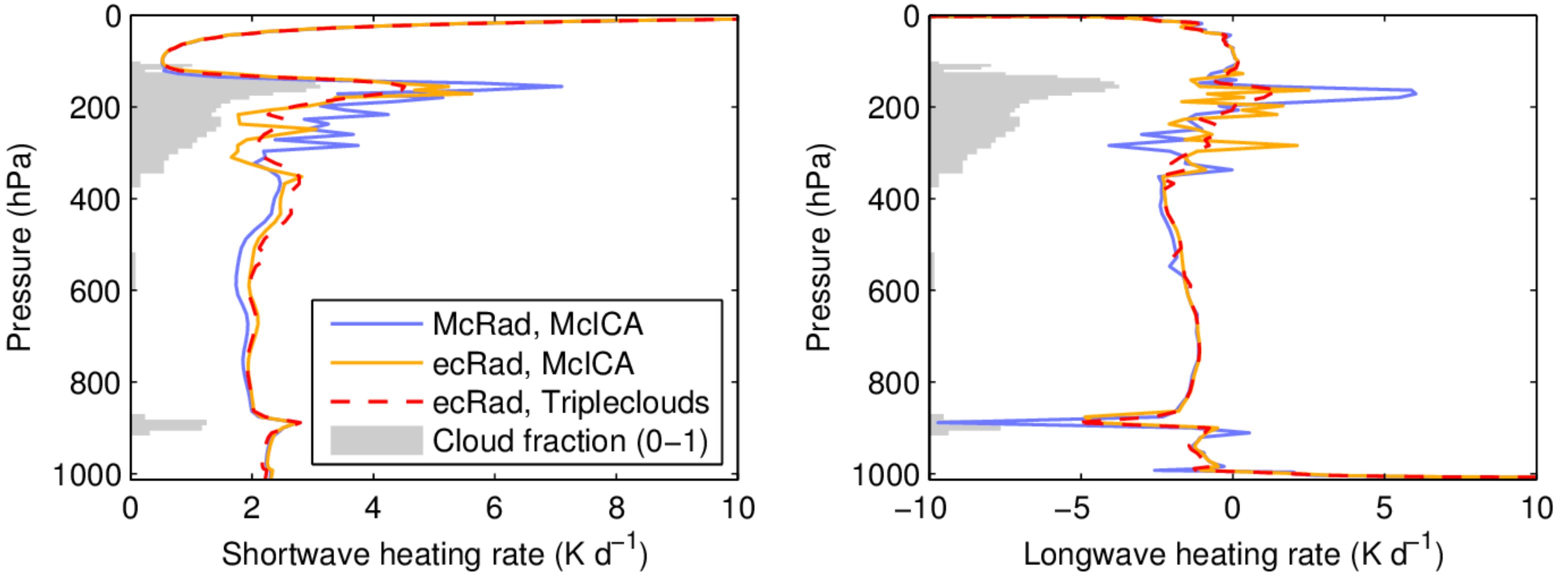
ecRad: Improved efficiency

- 31-35% faster than McRad
- Much faster treatment of cloud optics and cloud generator
- with longwave scattering by clouds alone (LWscat=1) is only 3% slower



ecRad: Improved accuracy

- As well as being much faster, reformulation of McICA scheme generates less stochastic noise
- Better LW fluxes in the stratosphere

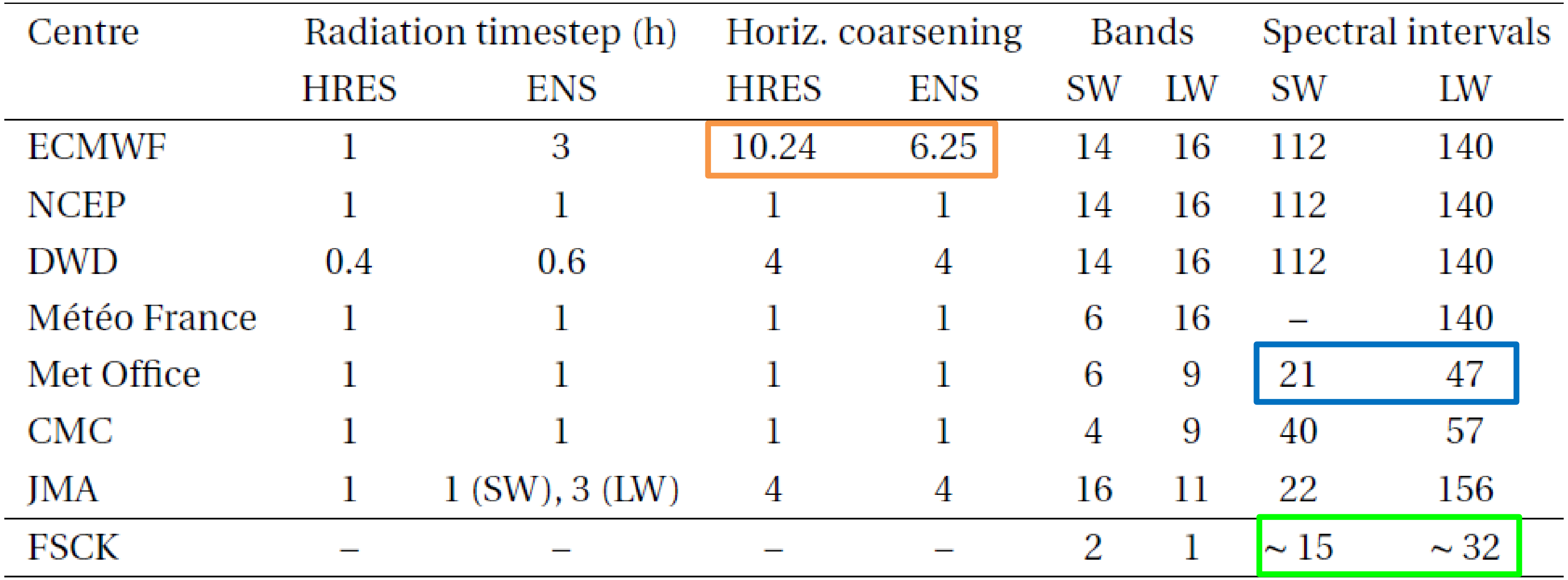


Radiation in ECMWF: temporal and spatial resolution

- Even if optimised and much faster than before ecRad is computationally expensive
- Operationally, the RT code runs on a spatial grid coarser (6-10 times fewer gridpoints) than the rest of the physics and with a longer time step
  - HiRes 10 day forecasts: model Tco1279 (~9 km at the equator) ecRad Tco511 (~20 km). Model time step 10 min, ecRad 1h
  - Ensemble forecasts: model Tco639 (~16 km), ecRad Tco255 (~30 km). Model time step 20min, ecRad 3h
- LW flux constant between radiation calls, SW flux adjusted for correct solar zenith angle and path length. Minor impact on diurnal cycle, larger for the 3h time step

Are we using our computer time wisely?

- 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	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

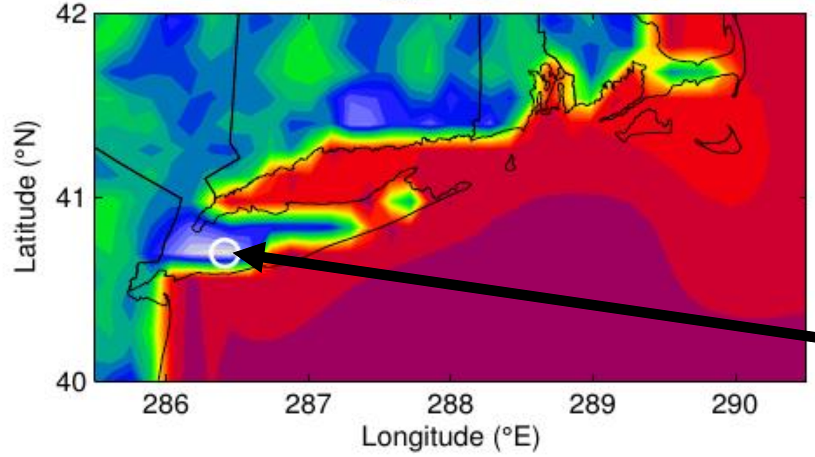
- ECMWF has lowest spatial resolution for radiation
  - Experiments show this barely degrades forecasts (unlike 3-h radiation timestep)
- Met Office NWP model uses 3.7 times fewer g-points than RRTM-G
- Full-spectrum correlated-k estimates of coarsest possible spectral resolution

Mitigating extreme temperature errors at coastlines

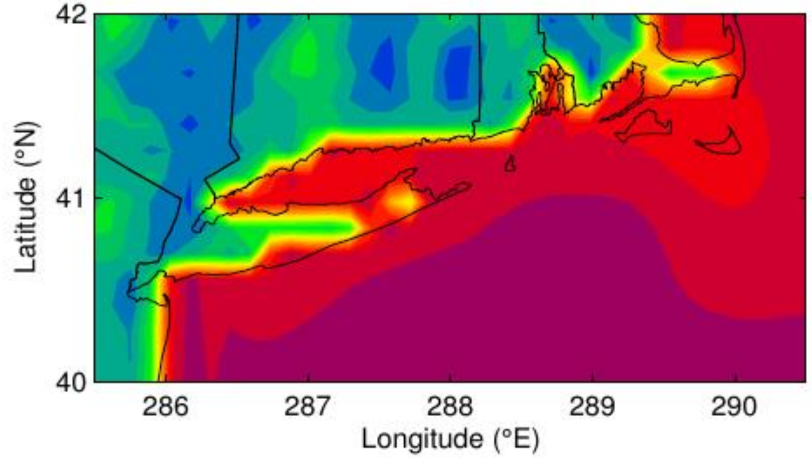
a cold case

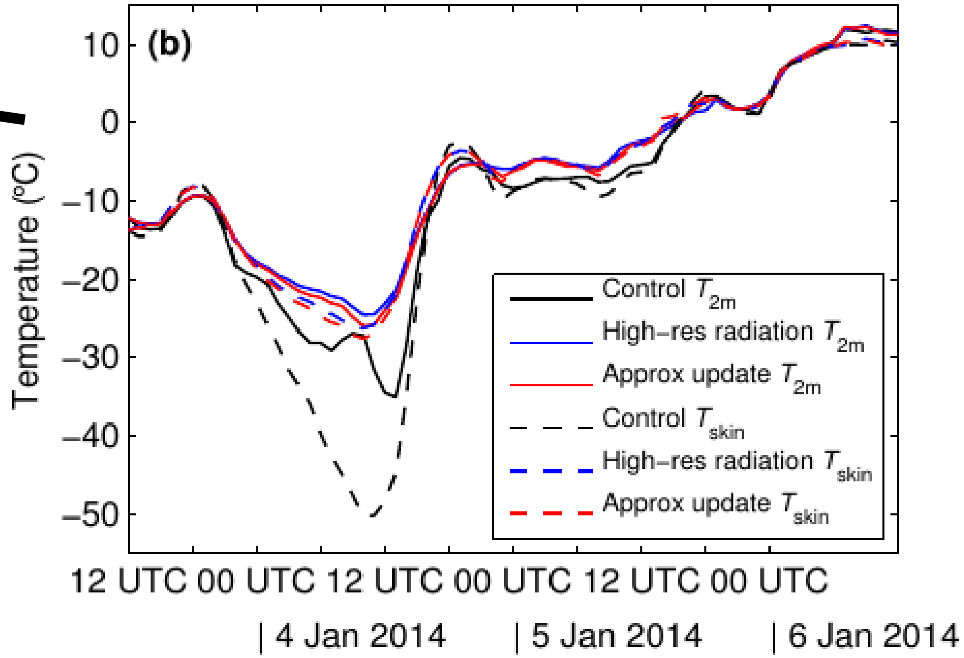
Approximate solution of the surface energy balance taking into account local albedo and changes in the skin temperature reduces the impact of the coarse radiation grid and time step

(a) Control



(b) High−resolution radiation



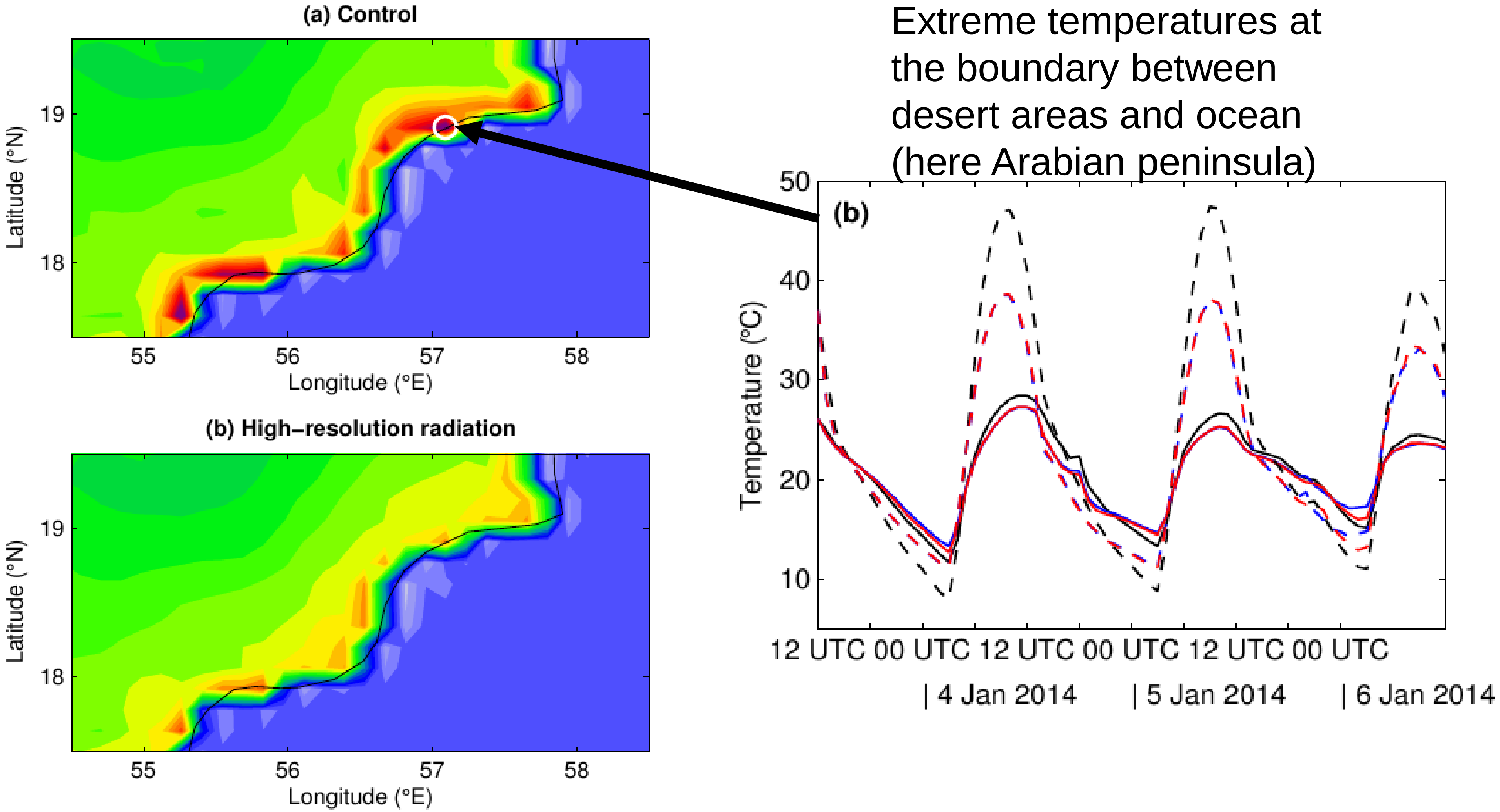


Hogan&Bozzo 2015

Mitigating extreme temperature errors at coastlines

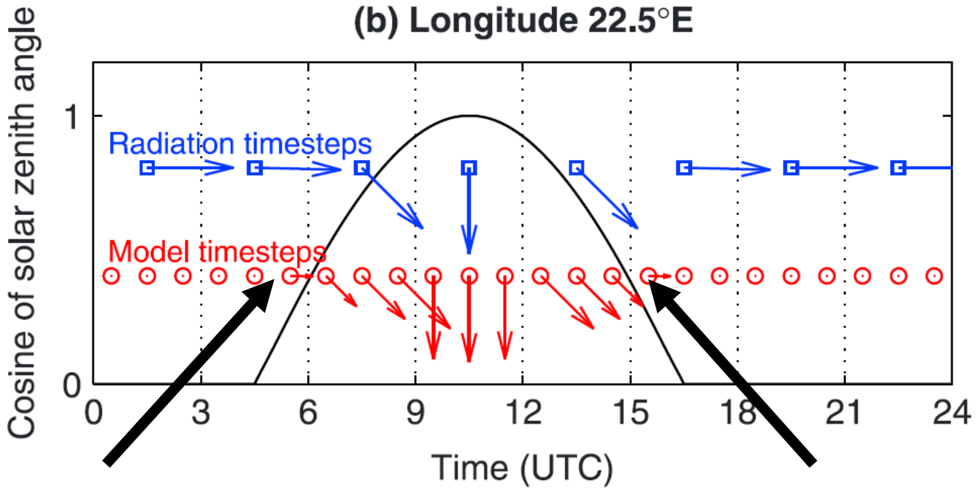
a warm case

Extreme temperatures at the boundary between desert areas and ocean (here Arabian peninsula)



Hogan&Bozzo 2015

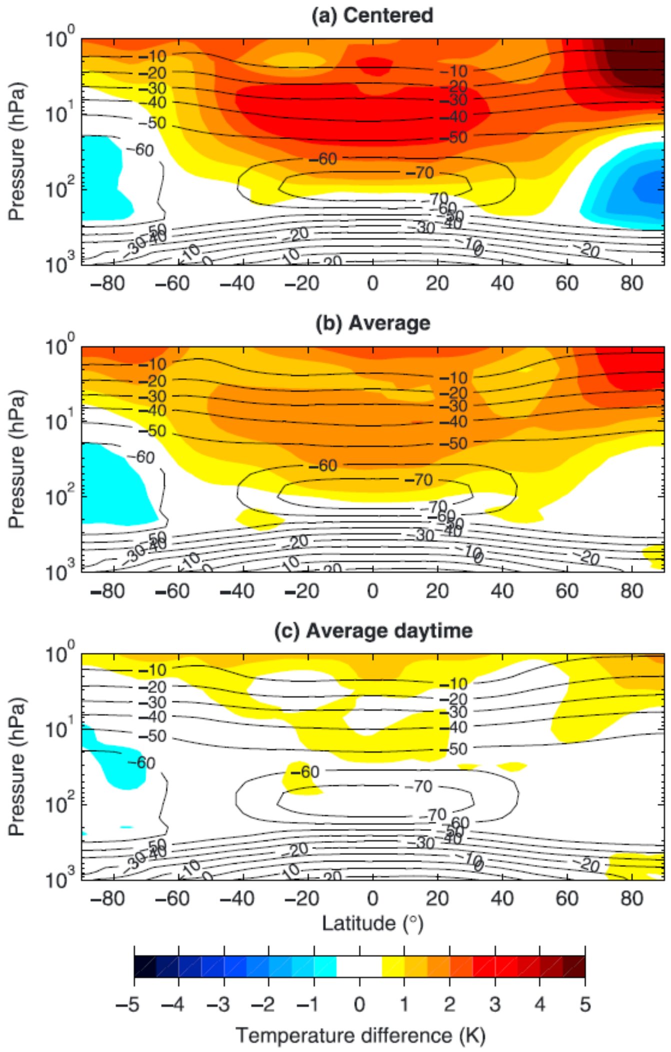
Accounting for solar zenith angle between time steps



SZA averaged between time steps: too shallow Sun's elevation at dusk and dawn -> too large path length -> too large O3 absorption in the stratosphere.

Fix: computing the averaged SZA between time steps but only for the sun lit portion

Larger errors for radiation time step>=3h



Hogan and Hirahara, 2015

ECMWF

Impacts of changing a radiation scheme

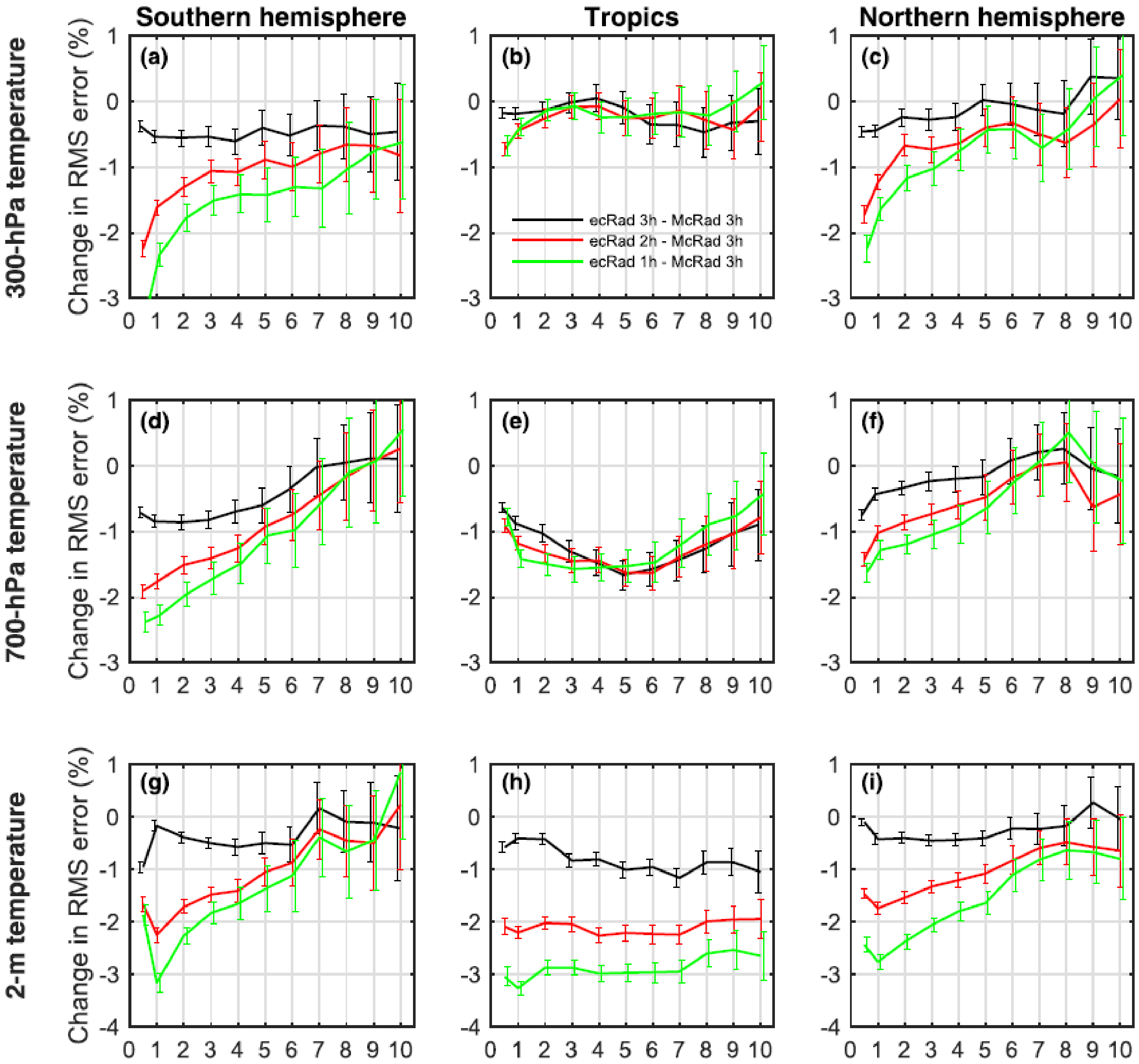
- Forecast skill
  - Set of 10-days forecasts generally over summer and winter seasons
  - Evaluation against analysis and observations
  - Impact on forecast skill scores at different lead times
- Mean model climate
  - Set of small ensembles of 1-year long forecast
  - Good to evaluate mean model biases
  - Coupled and un-coupled experiments

Impact of radiation timestep on forecast skill scores

300 hPa temperature

700 hPa temperature

2-m temperature



3h

2h

1h

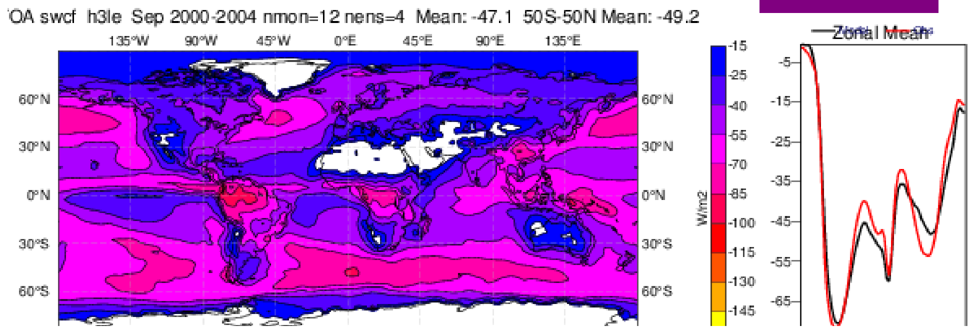
Normalised change in RMSE using ecRad with respect to the old McRad scheme

Values <0 mean that the IFS performs better using ecRad

Current radiation biases in ECMWF model (46r1) "climate" runs

TOA SWCF Radiation

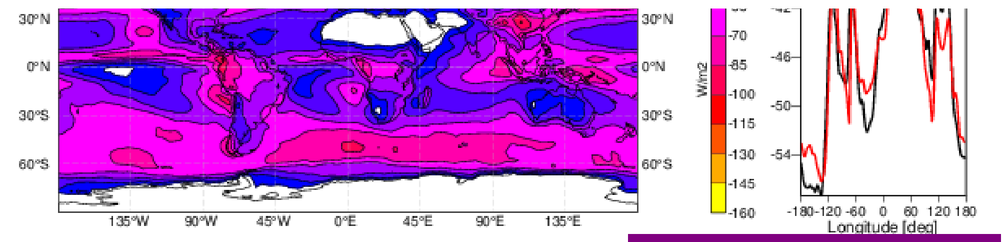
Model



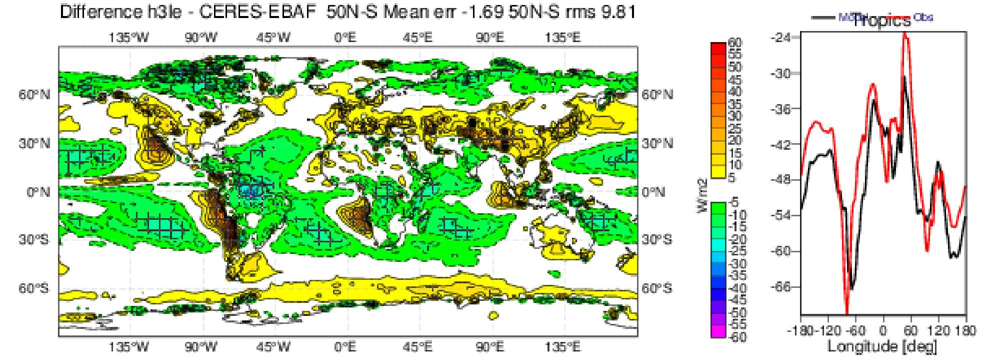
Too much cloudiness over tropical oceans

Too much reflection at TOA, too little downward SW radiation at the ocean surface. Not enough reflection in stratocumulus regions and close to Antarctica

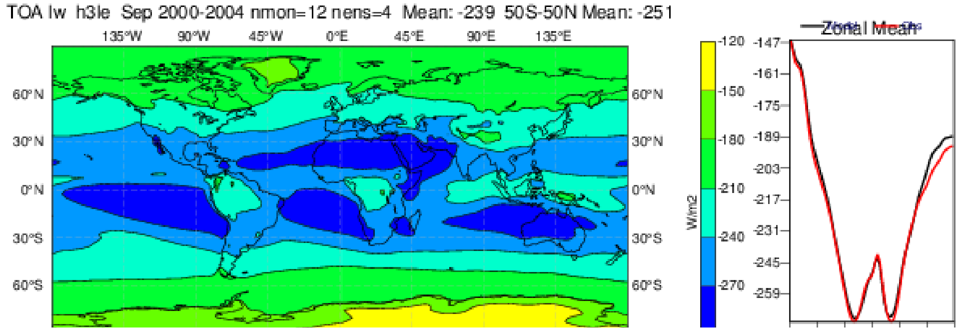
CERES



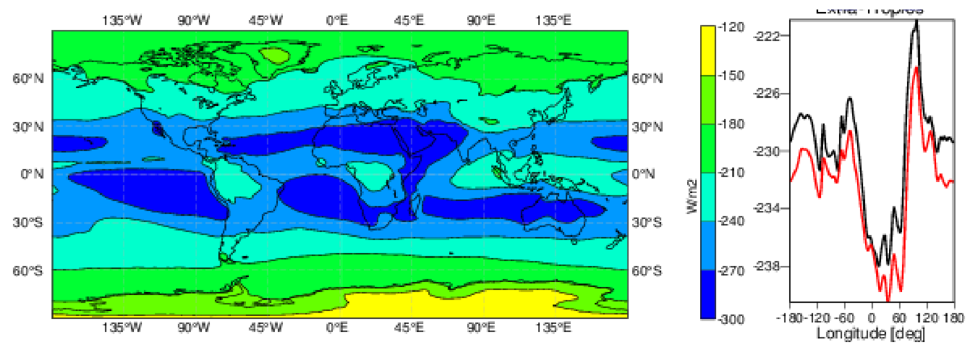
Model-CERES

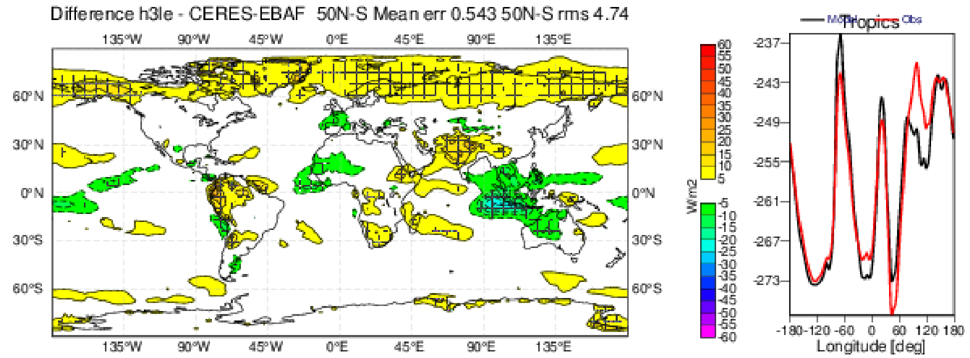


Outgoing LW Radiation



Cold bias in Artic, corrected previous errors over continents (too much OLR)





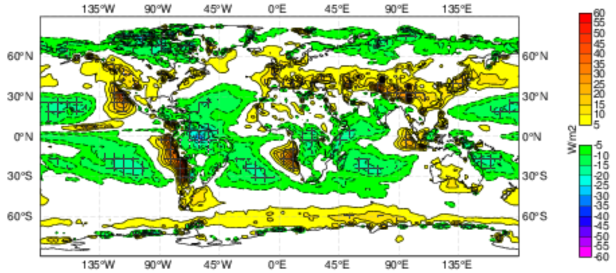
Higher or lower? Impacts of cloud radiative property changes

TOA net SW Radiation (down)

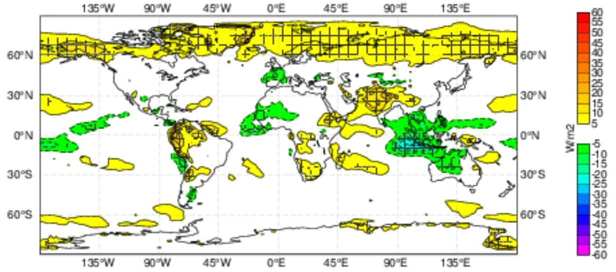
Outgoing LW Radiation

Control: CY46r1

Difference h3le - CERES-EBAF 50N-S Mean err -1.69 50N-S rms 9.81

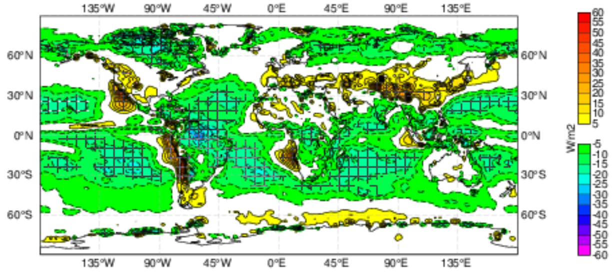


Difference h3le - CERES-EBAF 50N-S Mean err 0.543 50N-S rms 4.74

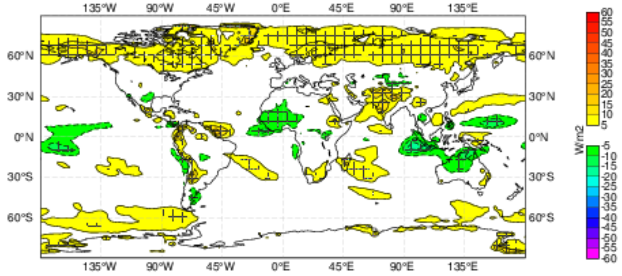


Liquid cloud effective radius x 0.8

Difference h4on - CERES-EBAF 50N-S Mean err -5.76 50N-S rms 11.4

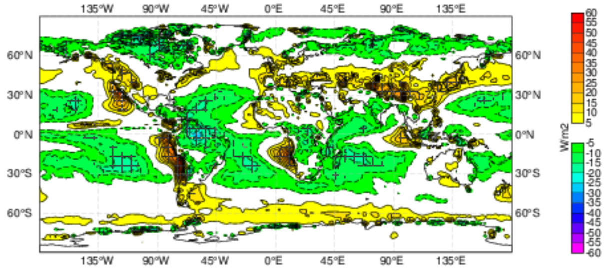


Difference h4on - CERES-EBAF 50N-S Mean err 0.856 50N-S rms 4.28

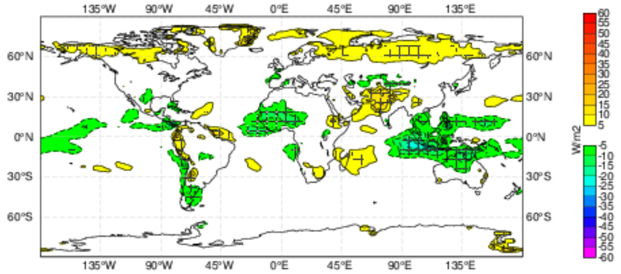


LW scattering OFF

Difference h4ms - CERES-EBAF 50N-S Mean err -1.86 50N-S rms 9.71

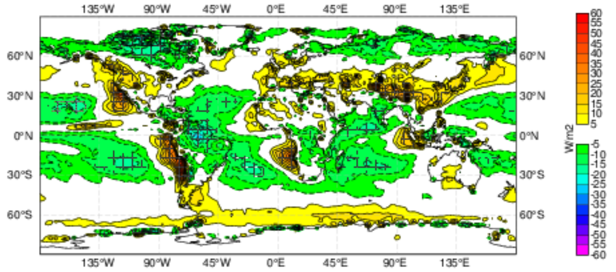


Difference h4ms - CERES-EBAF 50N-S Mean err -0.987 50N-S rms 4.54

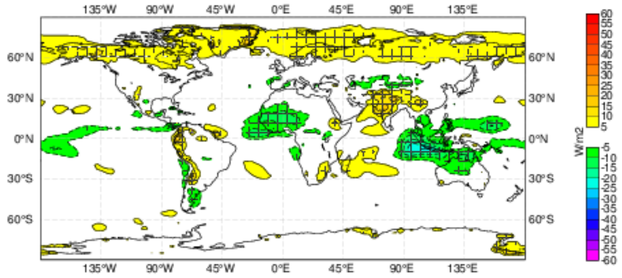


Yi scattering

Difference h4vx - CERES-EBAF 50N-S Mean err -1.75 50N-S rms 9.62



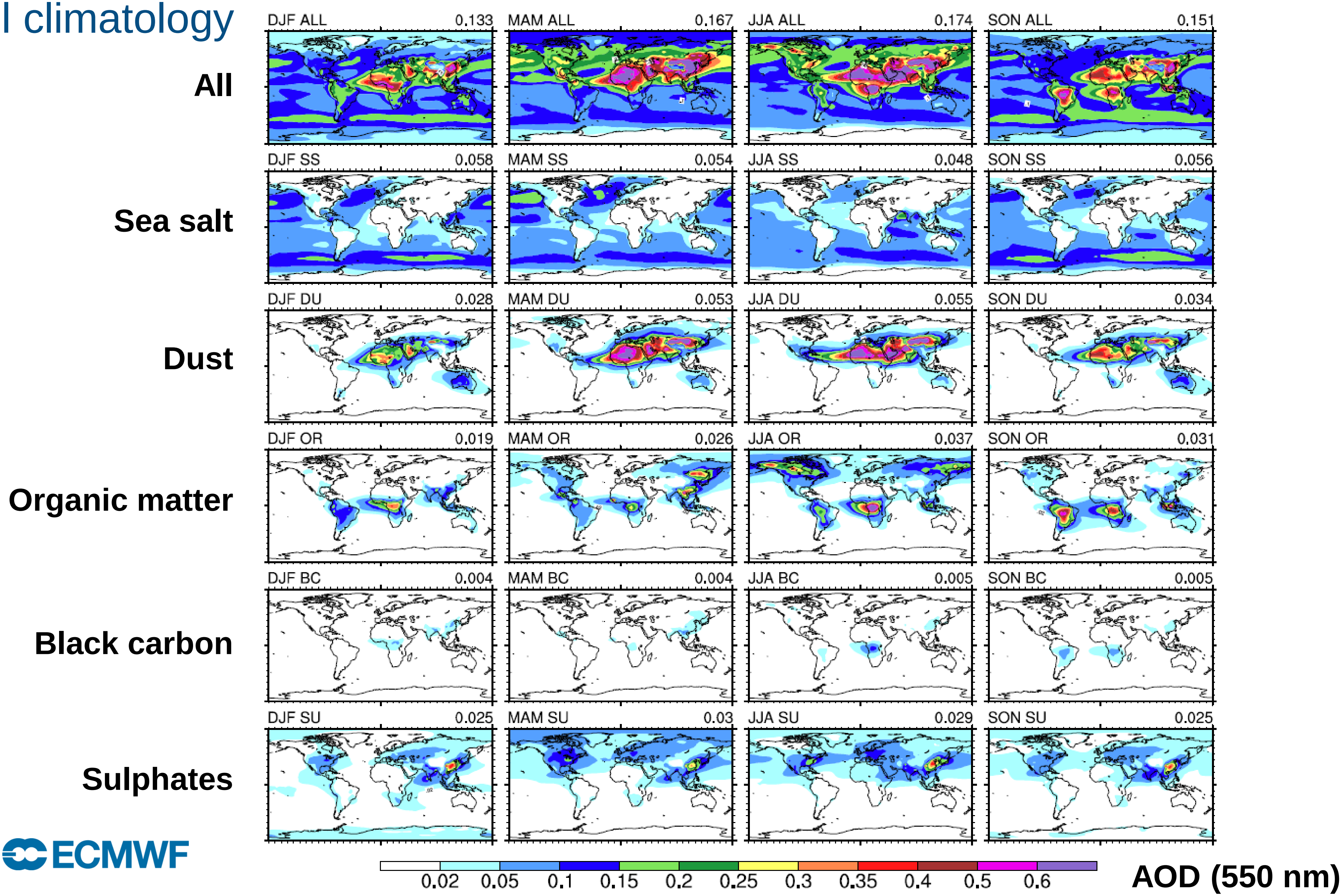
Difference h4vx - CERES-EBAF 50N-S Mean err -0.265 50N-S rms 4.63



Aerosols in NWP

- While aerosols play an important role in determining climate, their day to day variability is probably of secondary importance for NWP (e.g., prediction of temperature, winds).
- However, the radiative effect of aerosols is important to include as it can be significant, particularly for absorbing aerosols.
- Within IFS, CAMS monthly climatologies are used to account for direct effects.
- 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

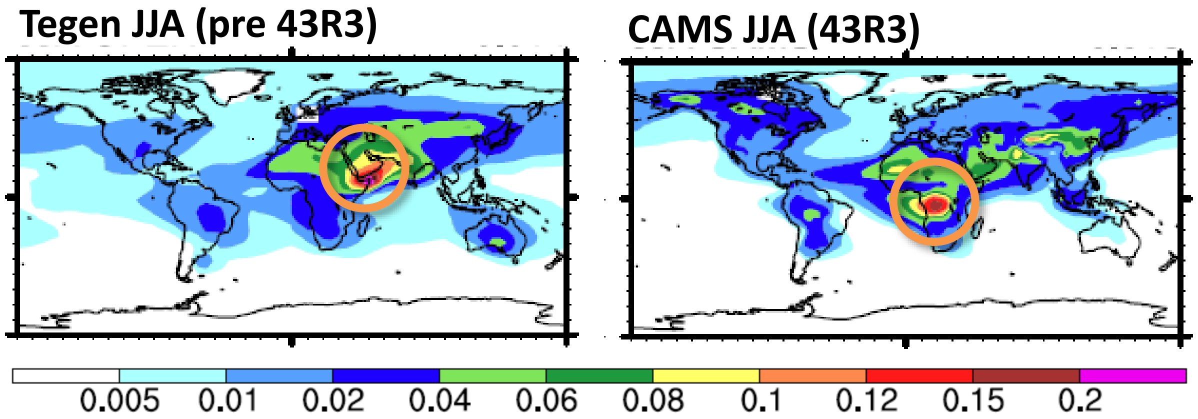


ECMWF

Aerosols

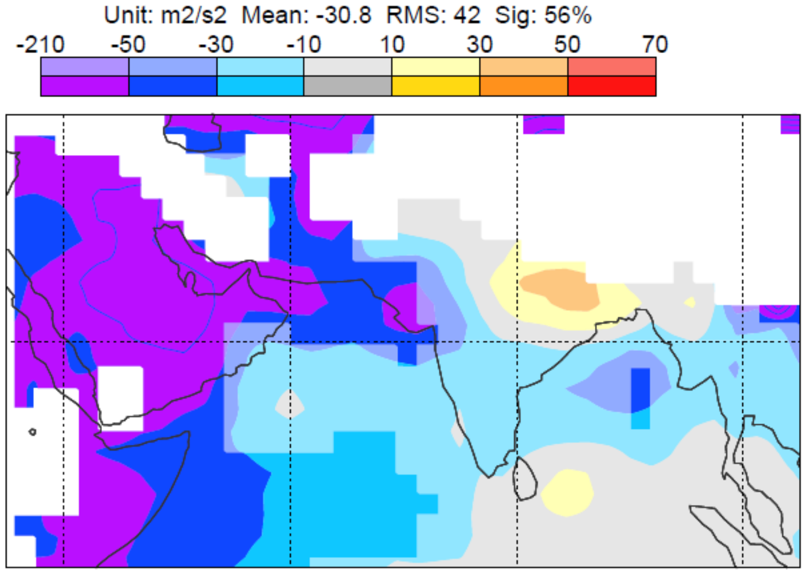
Bozzo et al. (2017)

- Atmospheric forcing depends on *absorption* optical depth:

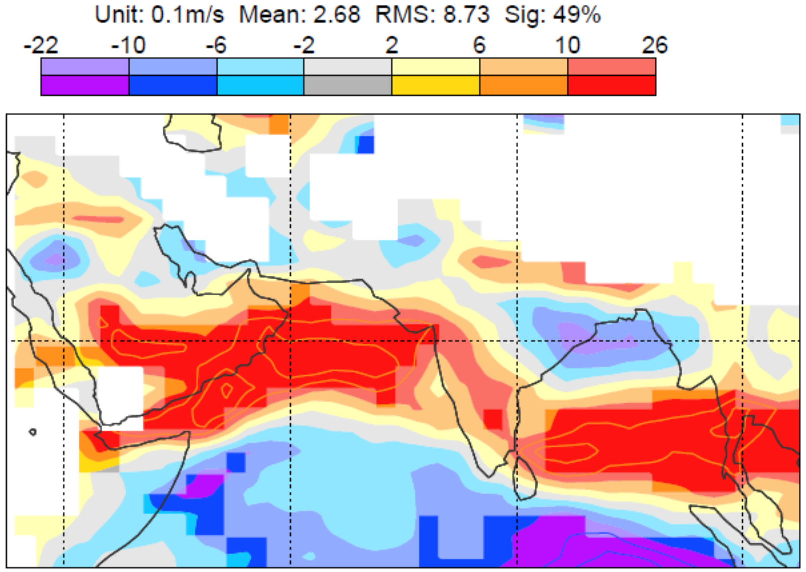


- Reduced absorption over Arabia in new CAMS climatology weakens the overactive Indian Summer Monsoon, halving the overestimate in monsoon rainfall
- Increased absorption over Africa degraded 850-hPa temperature, traced to excessive biomass burning in CAMS
- *We can measure the impact of aerosols on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

(a) Tegen climatology: geopotential ***bias***



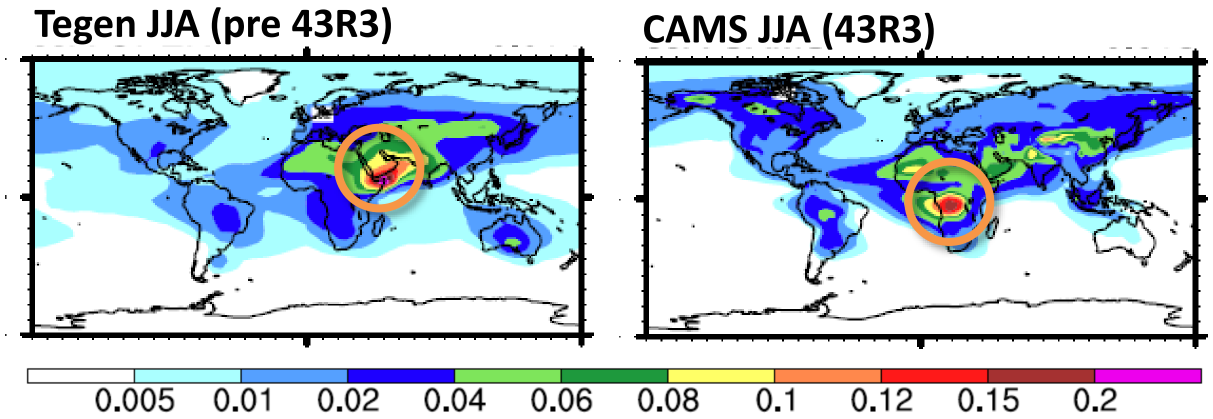
(c) Tegen climatology: zonal wind ***bias***



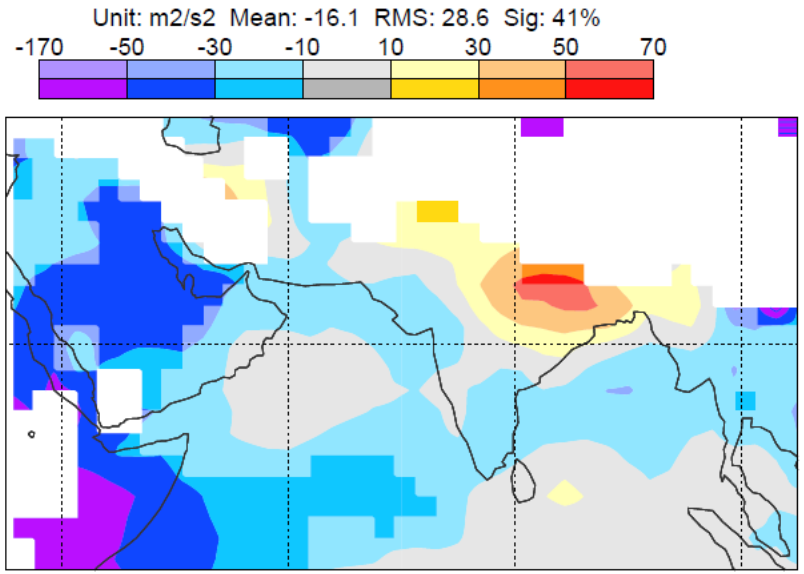
Aerosols

Bozzo et al. (2017)

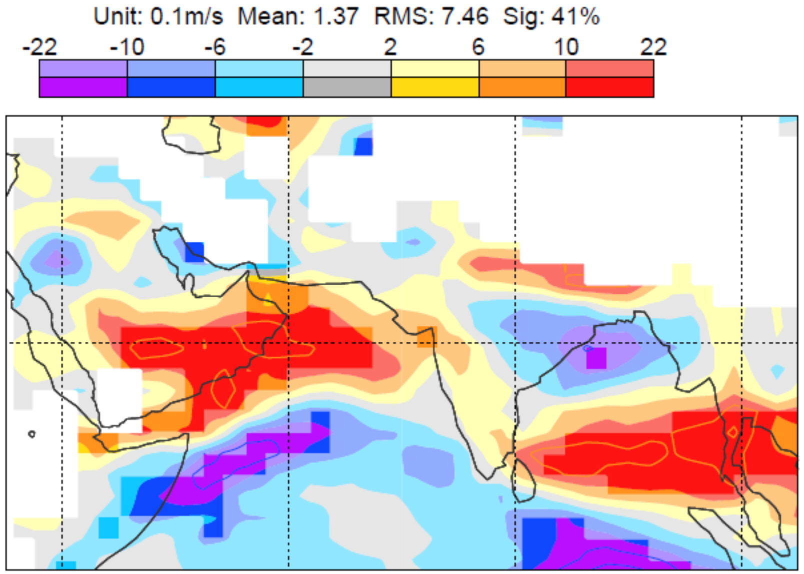
- Atmospheric forcing depends on *absorption* optical depth:



- 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?*



(b) CAMS climatology: geopotential *bias*



(d) CAMS climatology: zonal wind *bias*

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

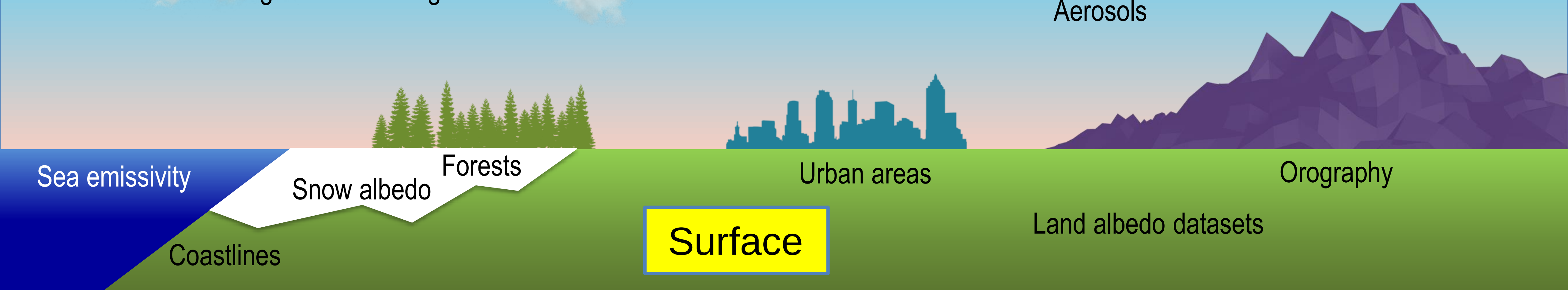
Optical properties

Longwave scattering

Water vapour continuum

Clear-sky absorption

Aerosols



Sea emissivity

Snow albedo

Forests

Coastlines

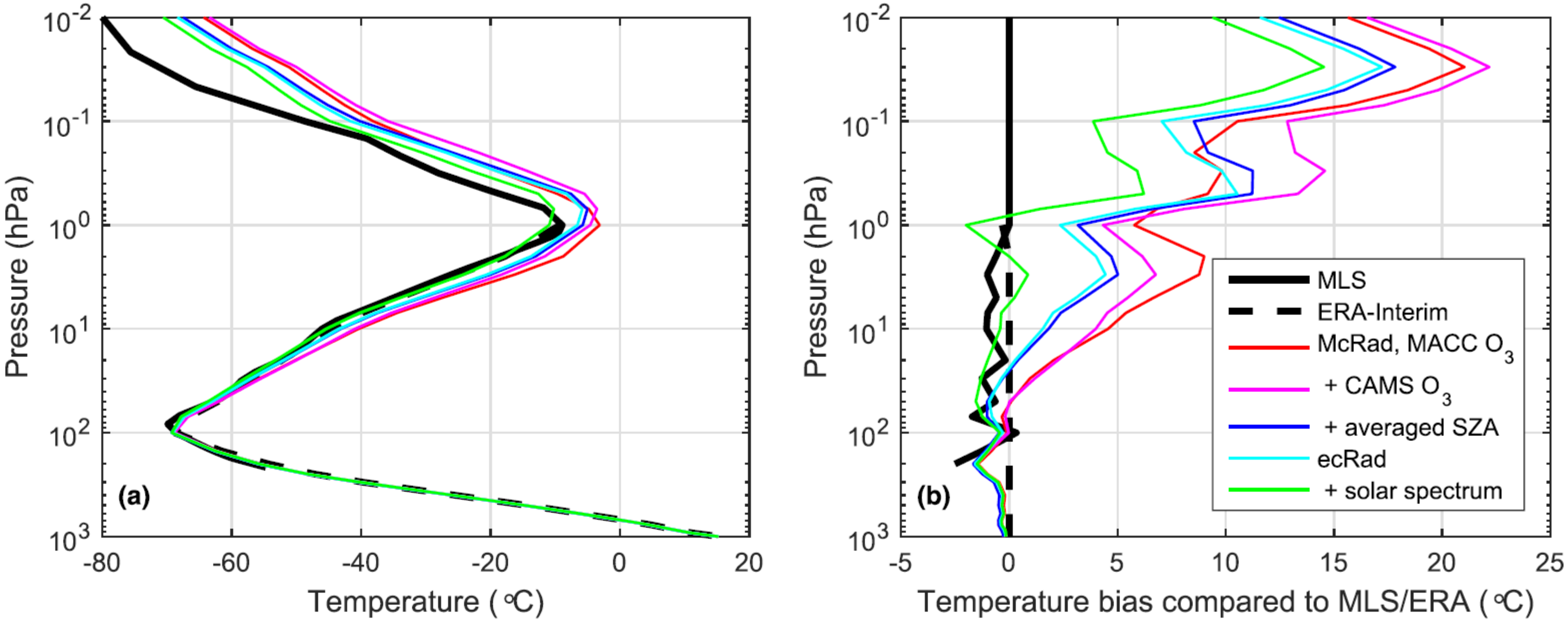
Urban areas

Orography

Land albedo datasets

Surface

Improving the middle atmosphere in the IFS



Hogan and Bozzo (2018)

Summary and outlook

- Global tropospheric climate of the IFS is excellent, but need concerted effort on many fronts to tackle much larger regional and stratospheric biases
- New ecRad scheme is good platform for future developments, but interaction and consistency between schemes is also very important
- Intriguing impacts of radiative heating on predictive skill: water vapour and stratosphere-troposphere coupling, and aerosols and monsoon systems
- Five main Grand Challenges in 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. Remove middle-atmosphere temperature bias via new UV solar spectrum
    5. Much more efficient gas optics and spectral integration

Further reading

TECHNICAL MEMORANDUM

816

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

TECHNICAL MEMORANDUM

787

ECRAD: A new radiation scheme for the IFS

Robin J. Hogan and Alessio Bozzo

Research Department

November 2016

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