Radiation in Numerical Weather Prediction

Recent advances and future challenges

Robin Hogan and many colleagues at ECMWF

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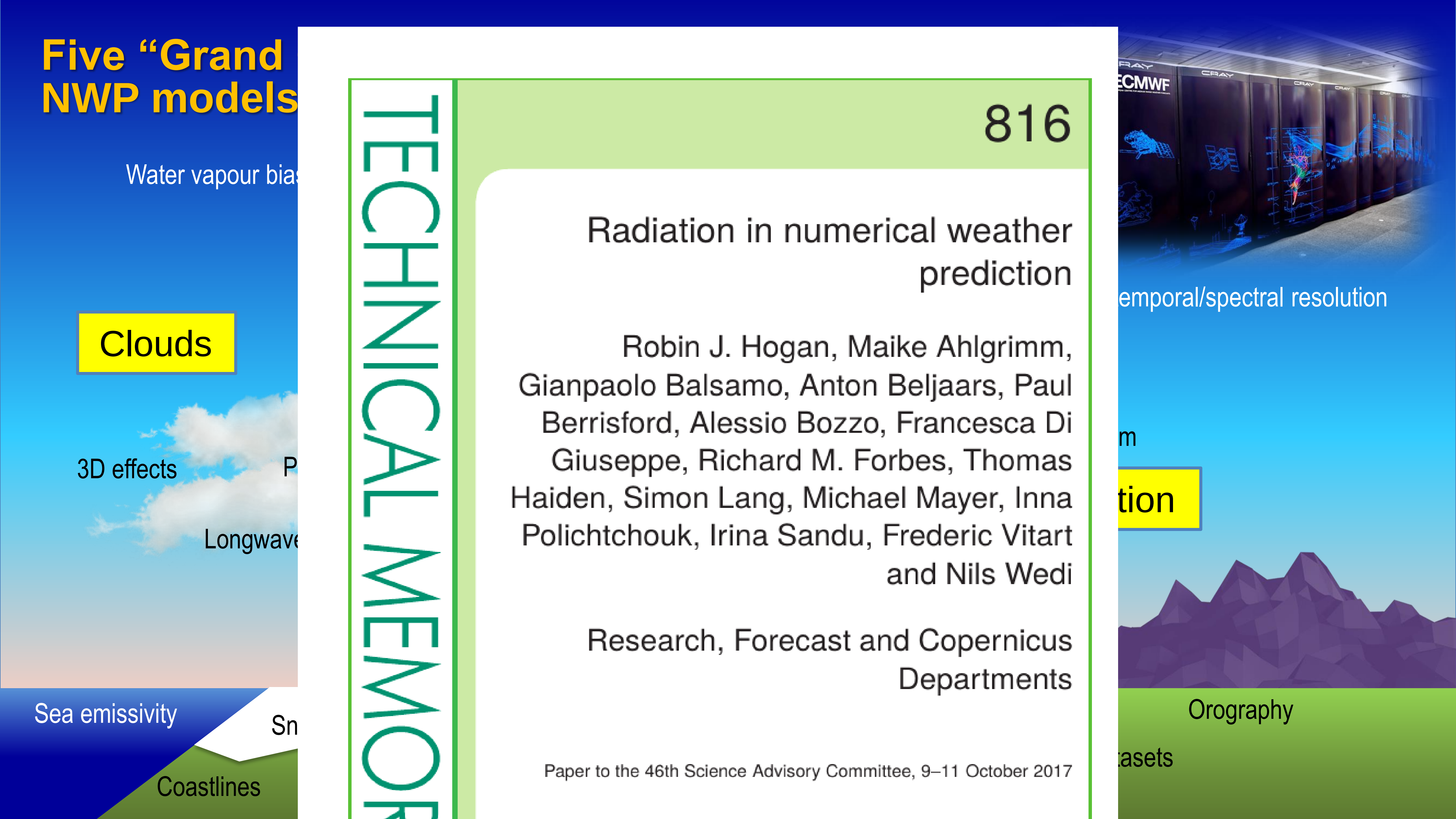
ECMWF



TECHNICAL MEMO

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Radiation in numerical weather prediction

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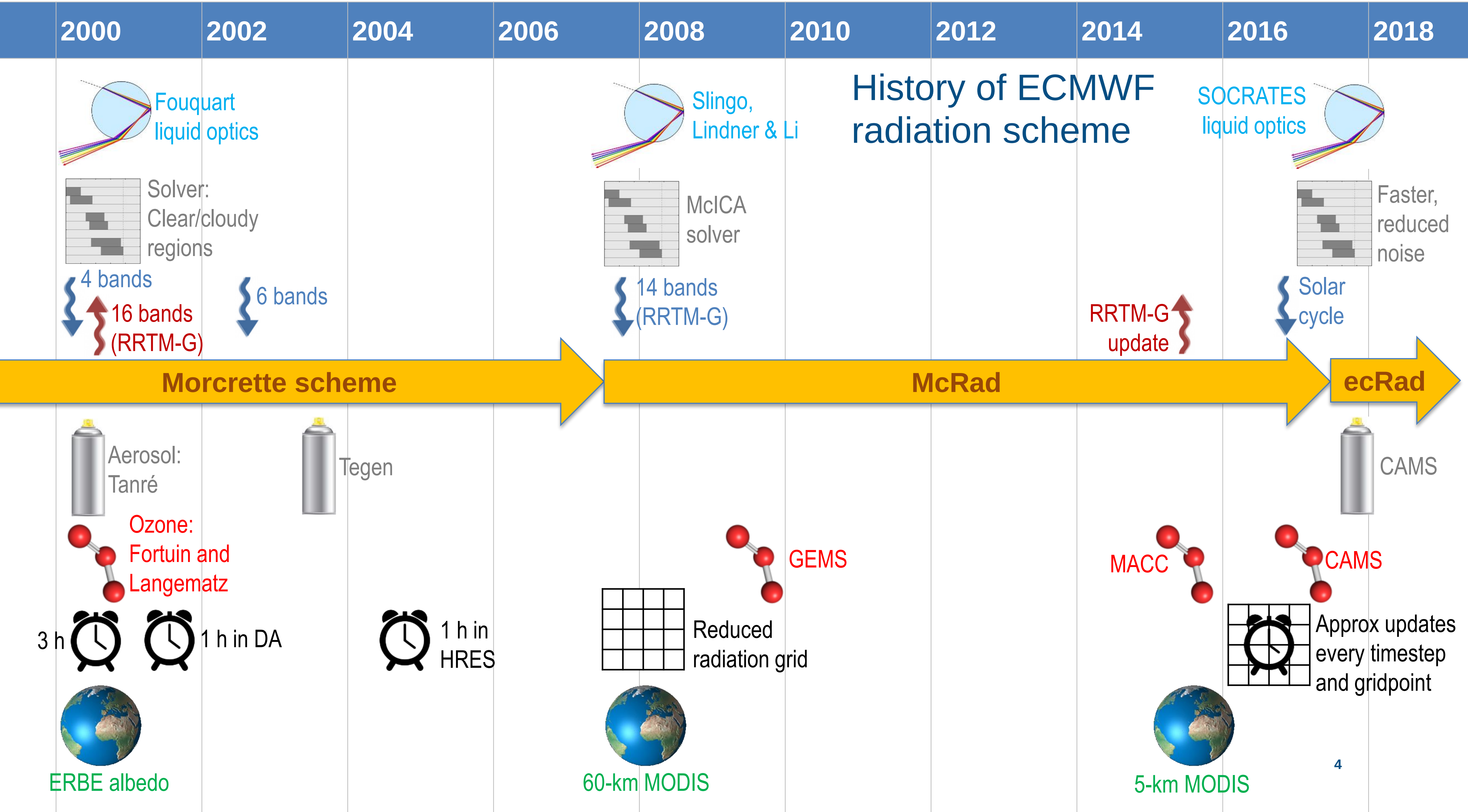
Research, Forecast and Copernicus Departments

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

Overview of talk

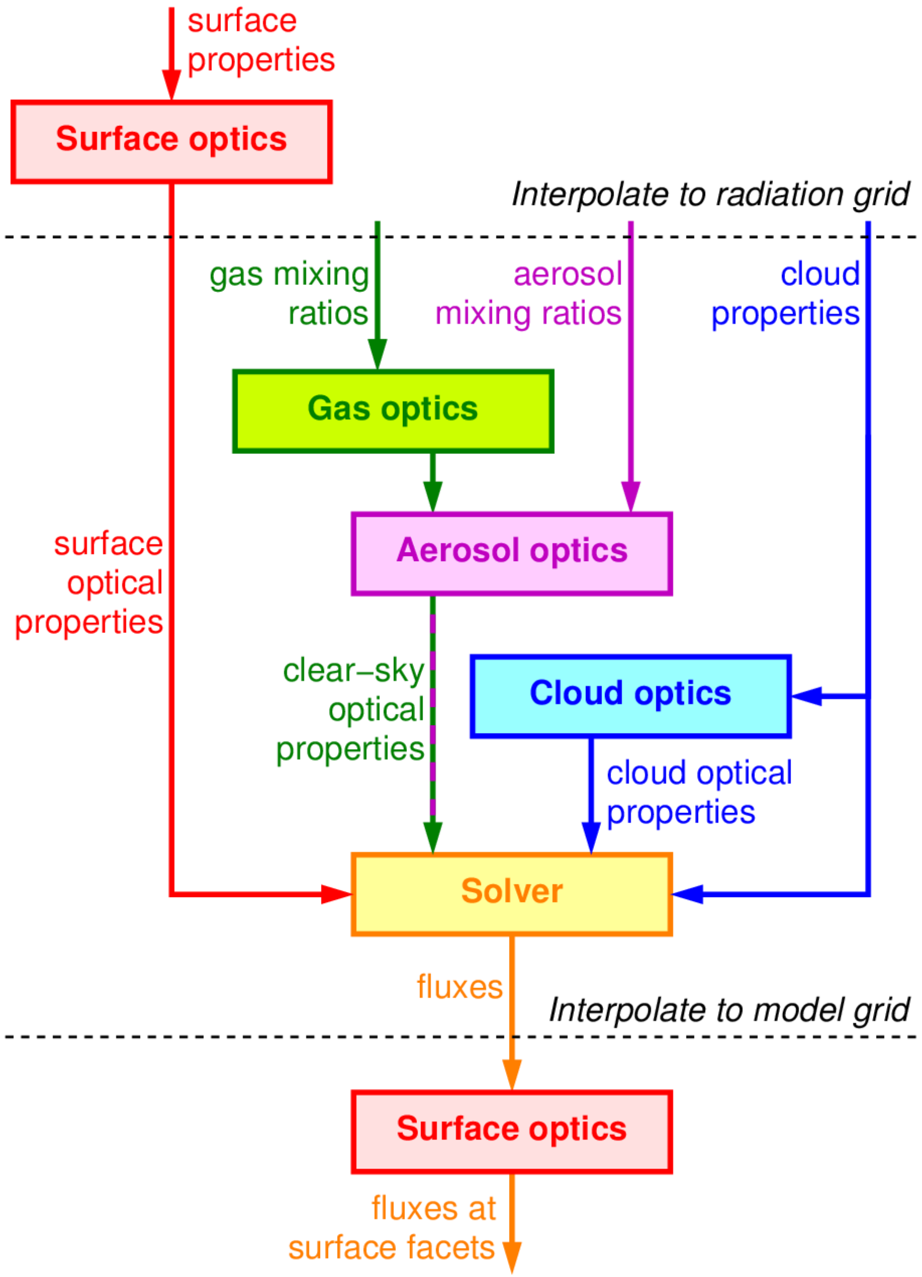
- Brief history of the ECMWF radiation scheme
- ecRad: a new radiation scheme
- Climate of the ECMWF Integrated Forecasting System (IFS)
- Five “Grand Challenges” for radiation in NWP
    1. Surface... *and a new way to treat 3D radiative effects*
    2. Clouds
    3. Clear-sky absorption
    4. Middle atmosphere
    5. Efficiency
- Outlook



2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
History of ECMWF radiation scheme
Fouquart liquid optics
Solver: Clear/cloudy regions
4 bands
16 bands (RRTM-G)
6 bands
Slingo, Lindner & Li
McICA solver
14 bands (RRTM-G)
RRTM-G update
SOCRATES liquid optics
Faster, reduced noise
Solar cycle
Morcrette scheme
McRad
ecRad
Aerosol: Tanré
Tegen
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
ERBE albedo
60-km MODIS
5-km MODIS

Modular design of ecRad

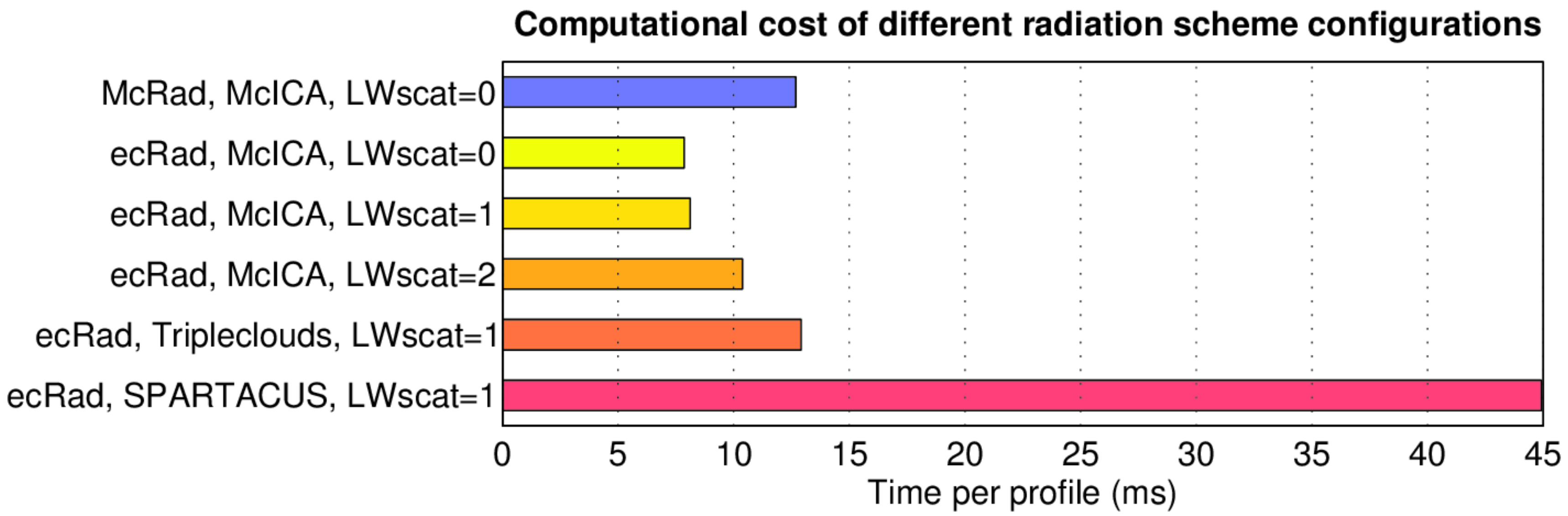
- Gas optics
  - RRTM-G (as before)
  - Plan to develop new scheme with far fewer spectral intervals
- Aerosol optics
  - Number of species set at run time and optical properties configured by NetCDF file
  - Supports Tegen and CAMS (prognostic & diagnostic)
- Cloud optics
  - Liquid clouds: more accurate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

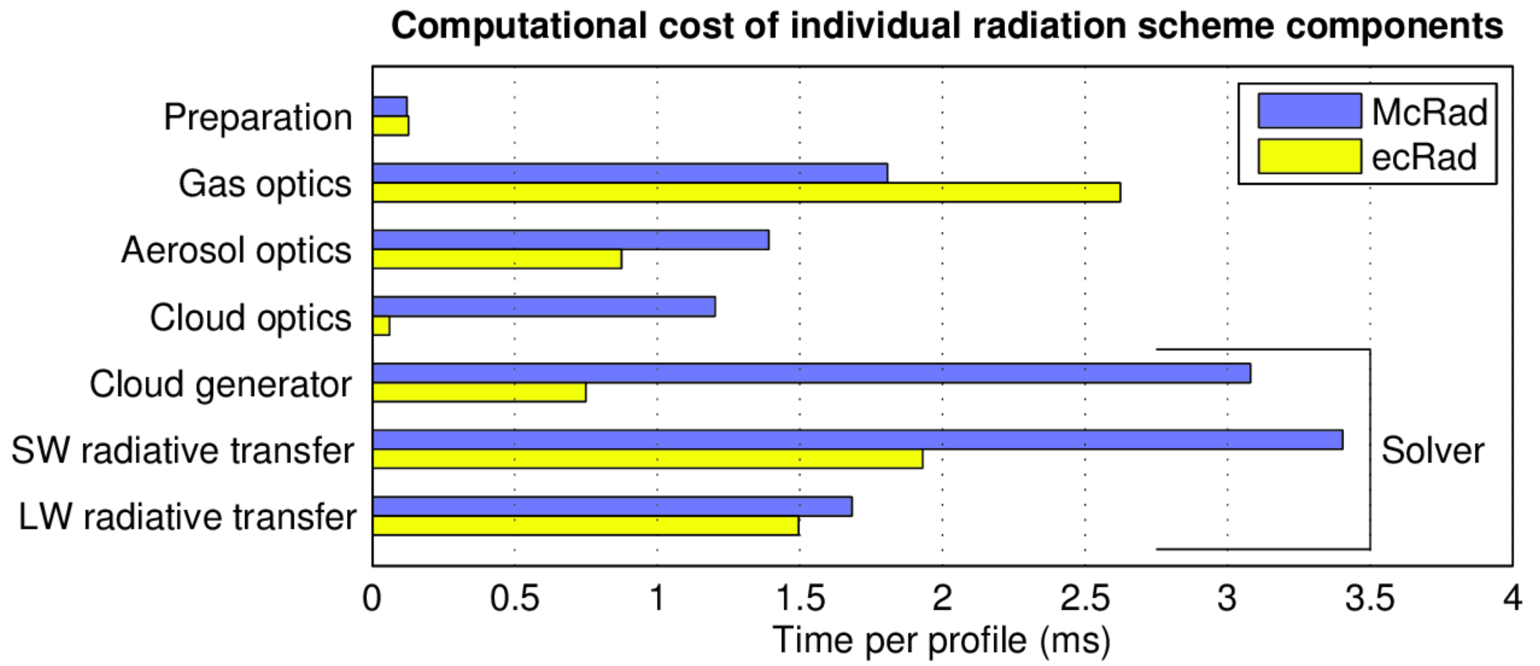


- Solver
  - McICA, Tripleclouds or SPARTACUS solvers
  - SPARTACUS makes the IFS the only global model that can do 3D radiative effects
  - Better solution to longwave equations improves tropopause & stratopause
  - Longwave scattering optional
  - Can configure cloud overlap, width and shape of PDF
- *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

Improved efficiency

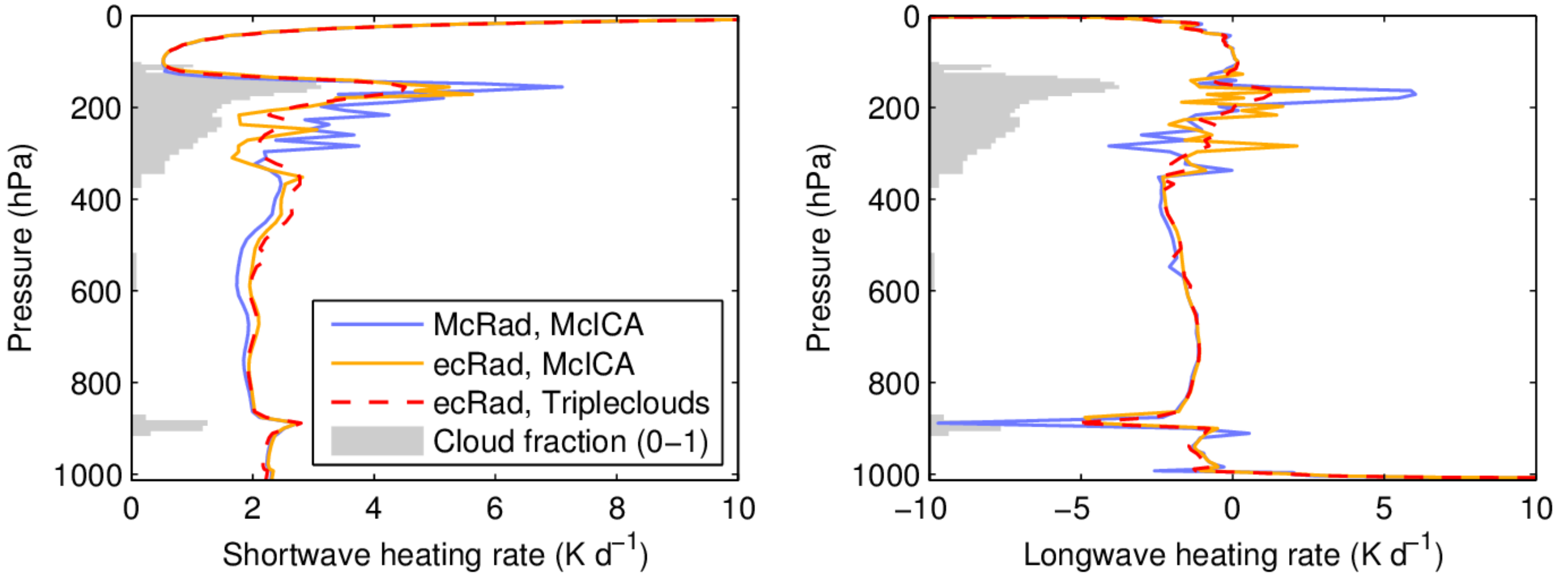
- 31-35% faster than McRad in same McICA configuration
- Much faster treatment of cloud optics and cloud generator
- Full longwave scattering (LWscat=2) is 32% slower than no longwave scattering (LWscat=0)
- But longwave scattering by clouds alone (LWscat=1) is only 3% slower



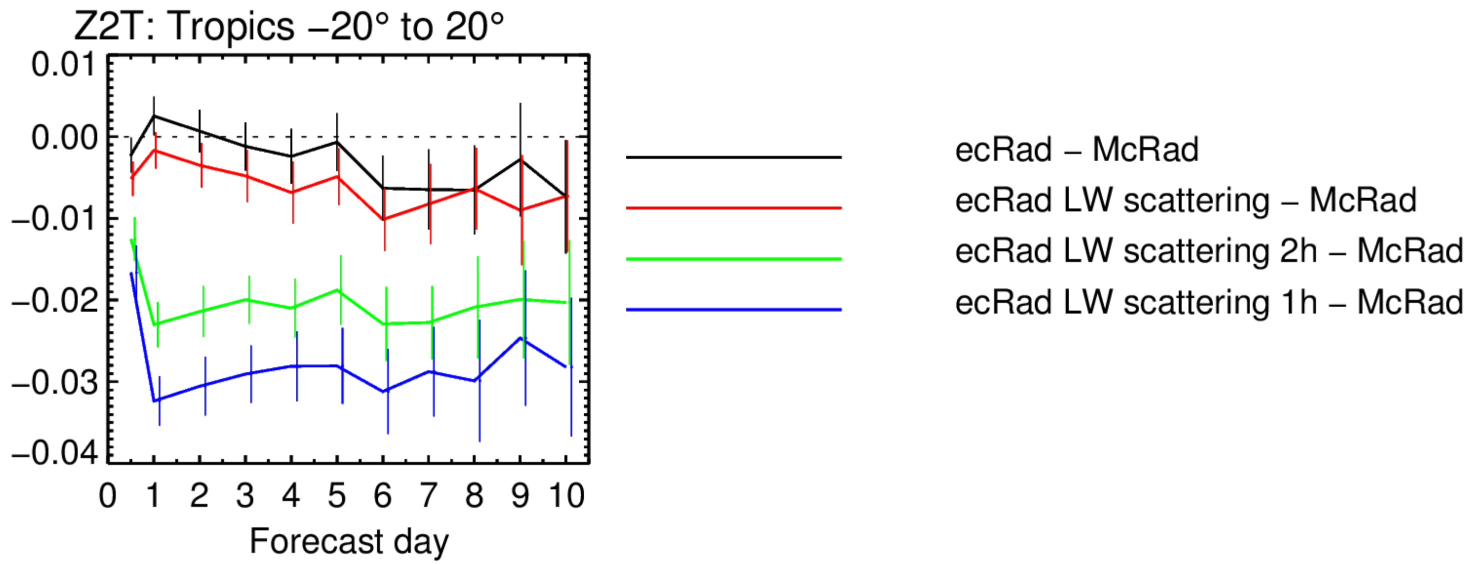


Improved accuracy

- As well as being much faster, reformulation of McICA scheme generates less stochastic noise



- RMS forecast error in 2-m temperature reduced by 0-0.5%
- Longwave scattering leads to additional 0.5-1% improvement
- Main gain from reinvesting time saving into calling radiation scheme every 2 or 1 h instead of every 3 h (2-3%)



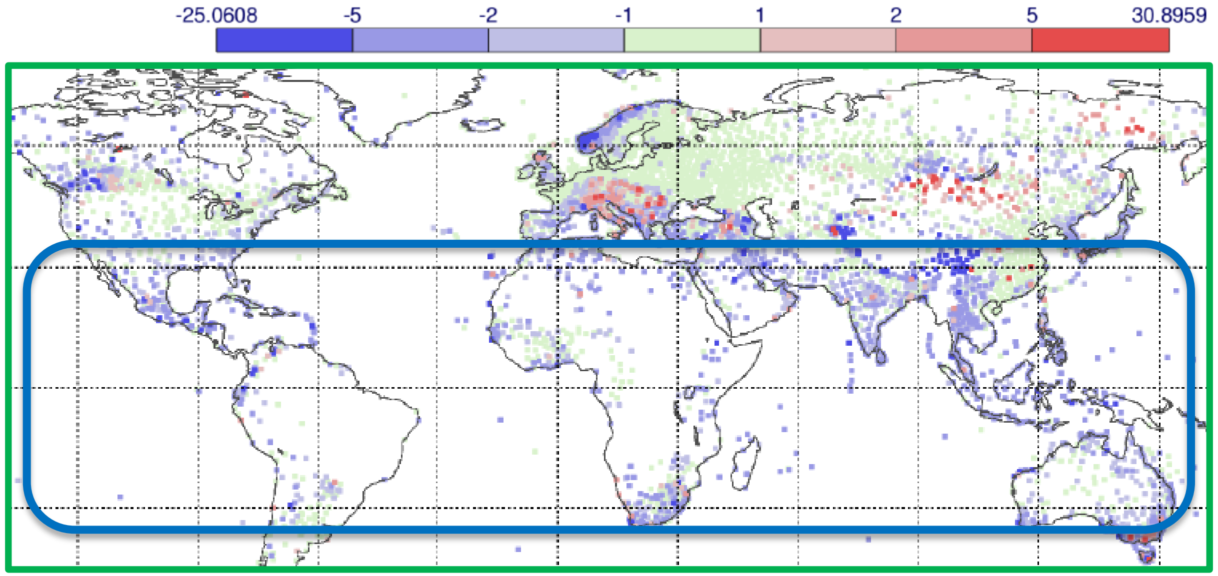
Evaluation of surface radiation budget against Wild et al. (2015) observations (W m^{-2})

	Global SW dn	Global LW dn	Global SW net	Global SW net	Land SW dn	Land LW dn	Land SW net	Land LW net
Observations	184.7	341.5	160.1	−56.7	184	306	136	−66
43 climate models	4 ± 5	−2 ± 4	5 ± 4	−2 ± 3	6 ± 10	−4 ± 7	5 ± 8	3 ± 6
ERA-Interim	3.7	−0.1	4.5	0.1	3.6	−2.0	4.1	−1.0
ERA5	3.5	−2.3	3.7	−1.2	5.3	−2.4	1.8	1.1
Uncoupled IFS climate 43R3	−0.2	−2.2	0.5	−0.3	−0.4	−0.2	−1.5	0.4
Coupled IFS climate 43R3	−0.4	−0.9	0.3	−0.3	0.4	0.7	−1.1	0.0

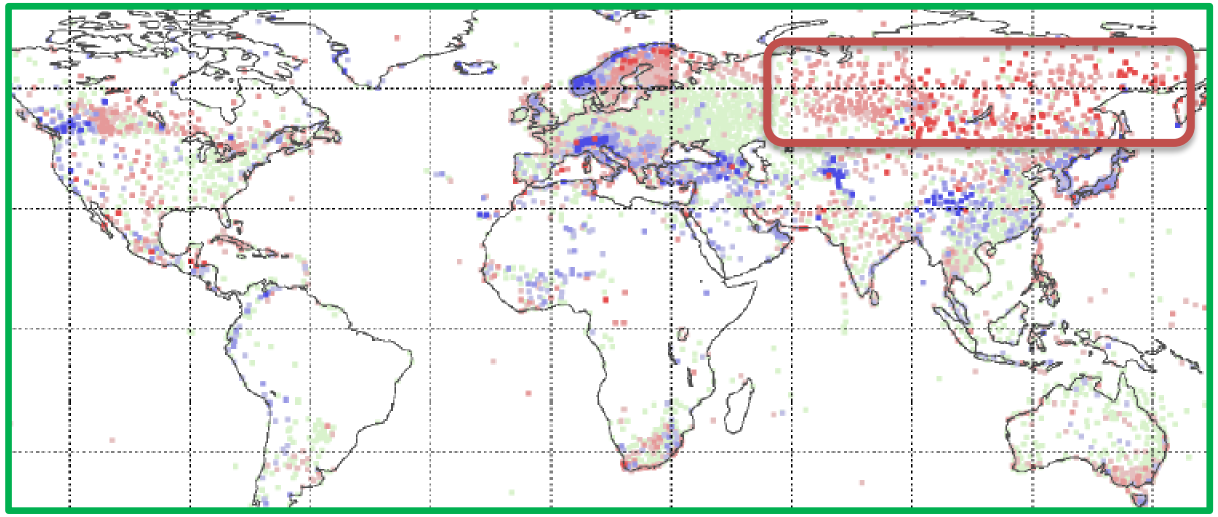
<2 ≥2 ≥4 W m^{-2}

Challenge 1: Surface

(a) Maximum temperature, NH winter



(b) Minimum temperature, NH winter

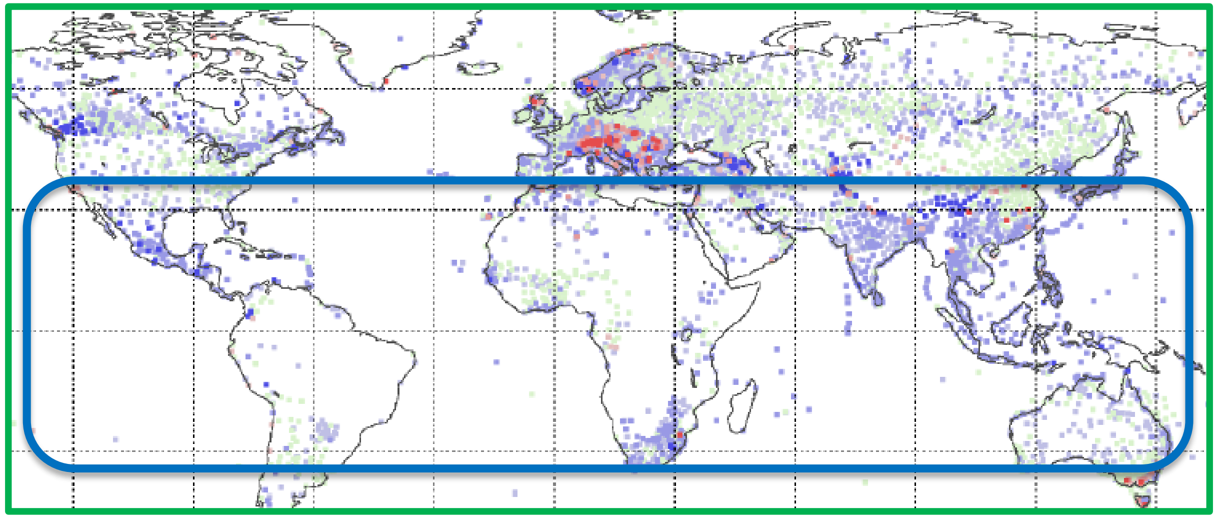


Tropics ~2 K too cold in the day

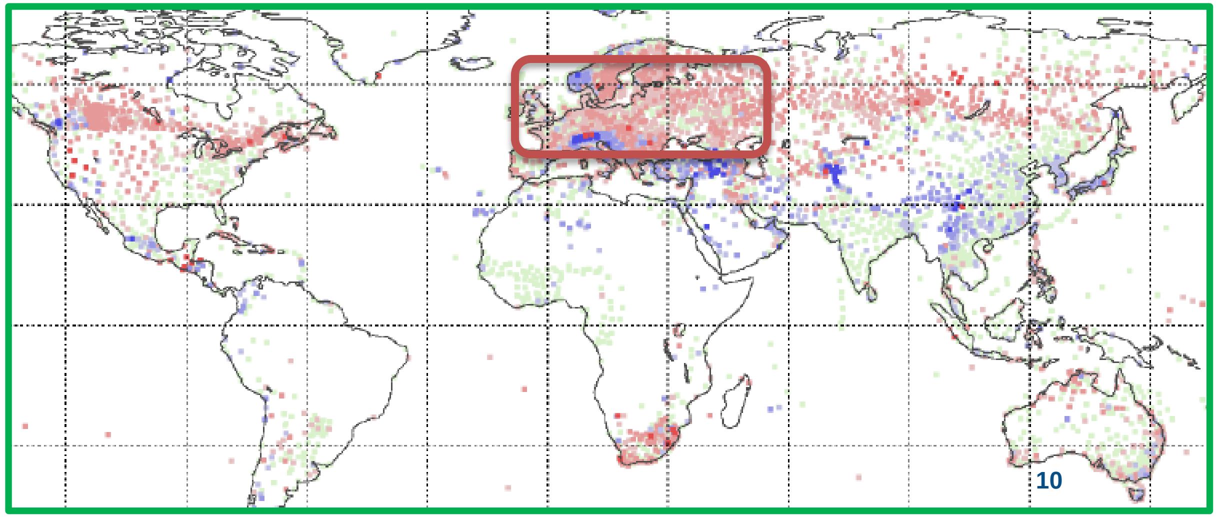
Europe ~0.5 K too cold, except summer T_{min} too warm

Boreal forests ~5 K too warm at night in winter

(c) Maximum temperature, NH summer

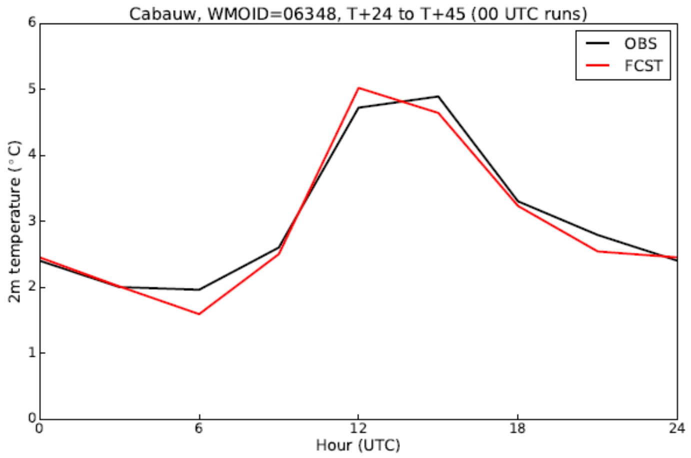


(d) Minimum temperature, NH summer

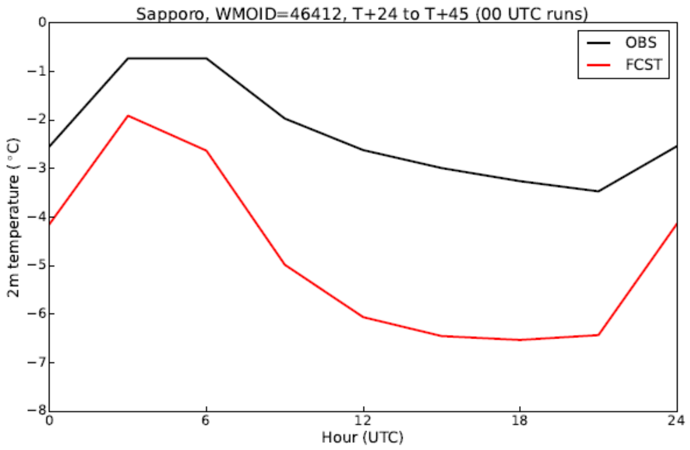


What is the cause of near-surface temperature errors at individual sites?

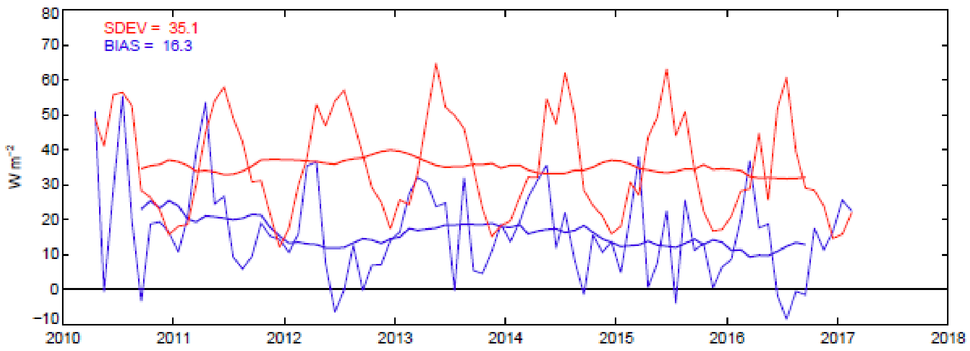
Cabauw December 2016 to February 2017



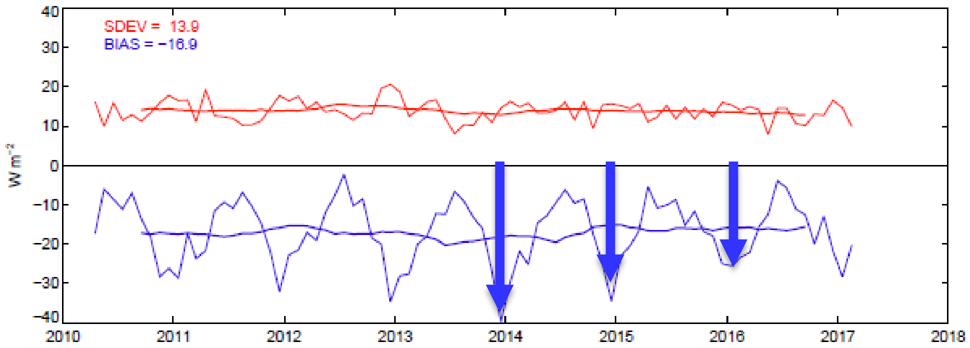
Sapporo December 2016 to February 2017



Sapporo shortwave



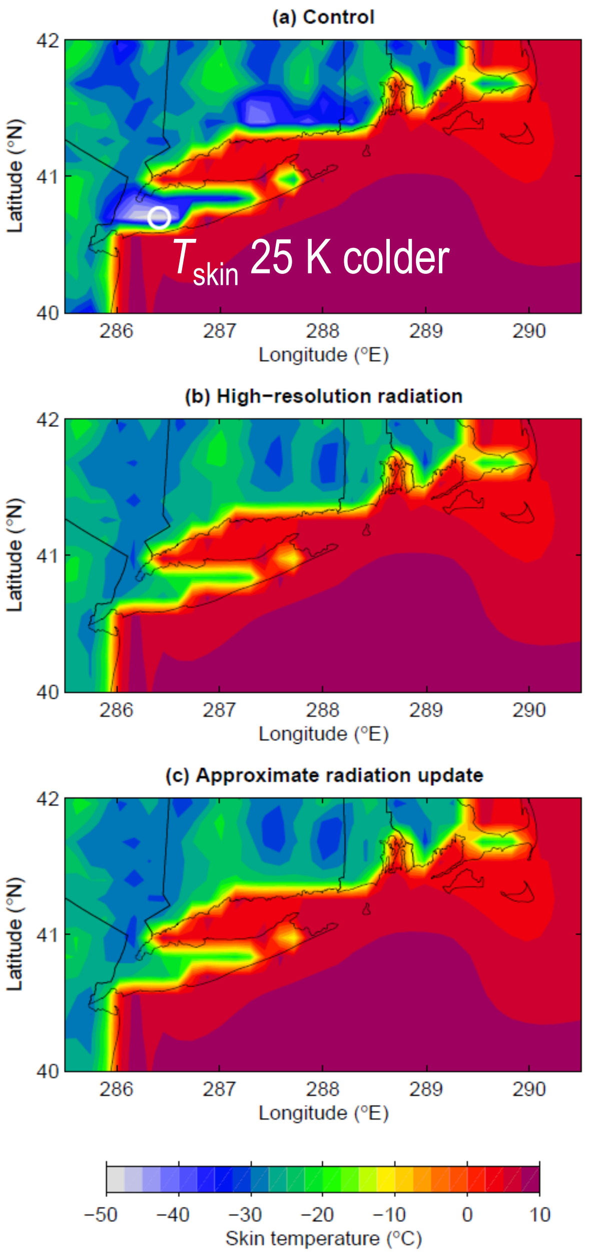
Sapporo longwave



- Some locations are much more difficult than others!
  - Sapporo is a large city, by the coast, surrounded by mountains, with large annual snowfall
- ECMWF has a new task force to unpick the causes of surface temperature errors (including BL, clouds, surface schemes)
- *But there are obvious areas where radiation needs to be improved, e.g. coastlines, forests and urban areas*

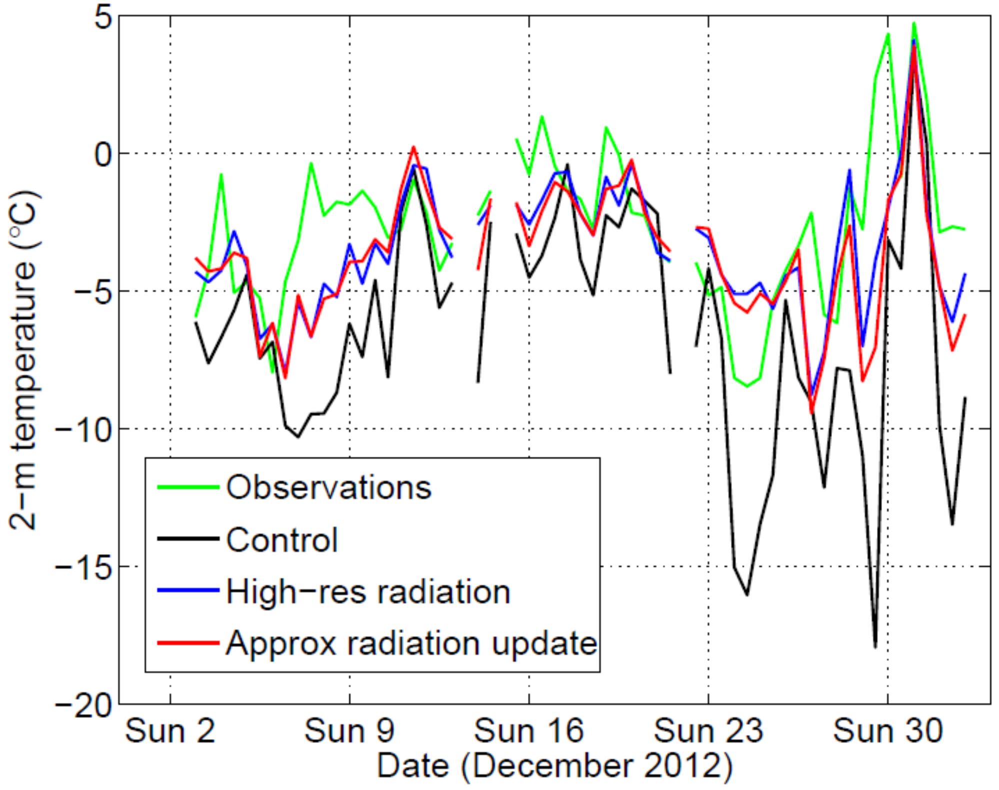
- Far too little downwelling LW: not enough cloud?
- Early evening error could also be signature of urban heat island (Oke 1982), not in model

Approximate radiation updates (operational from March 2016)



- Since McRad, coarser radiation grid (6-10 times fewer gridpoints) led to errors at coastlines: sea temperature and albedo used to compute net fluxes over adjacent land area
- Benchmark calculation is from running radiation every gridbox and timestep (radiation 24x more expensive)
- Now perform approximate updates of flux profile every model gridbox and timestep, using local skin temperature and surface albedo (radiation only 2% more expensive)

0700 Local Time, 4 Jan 2014

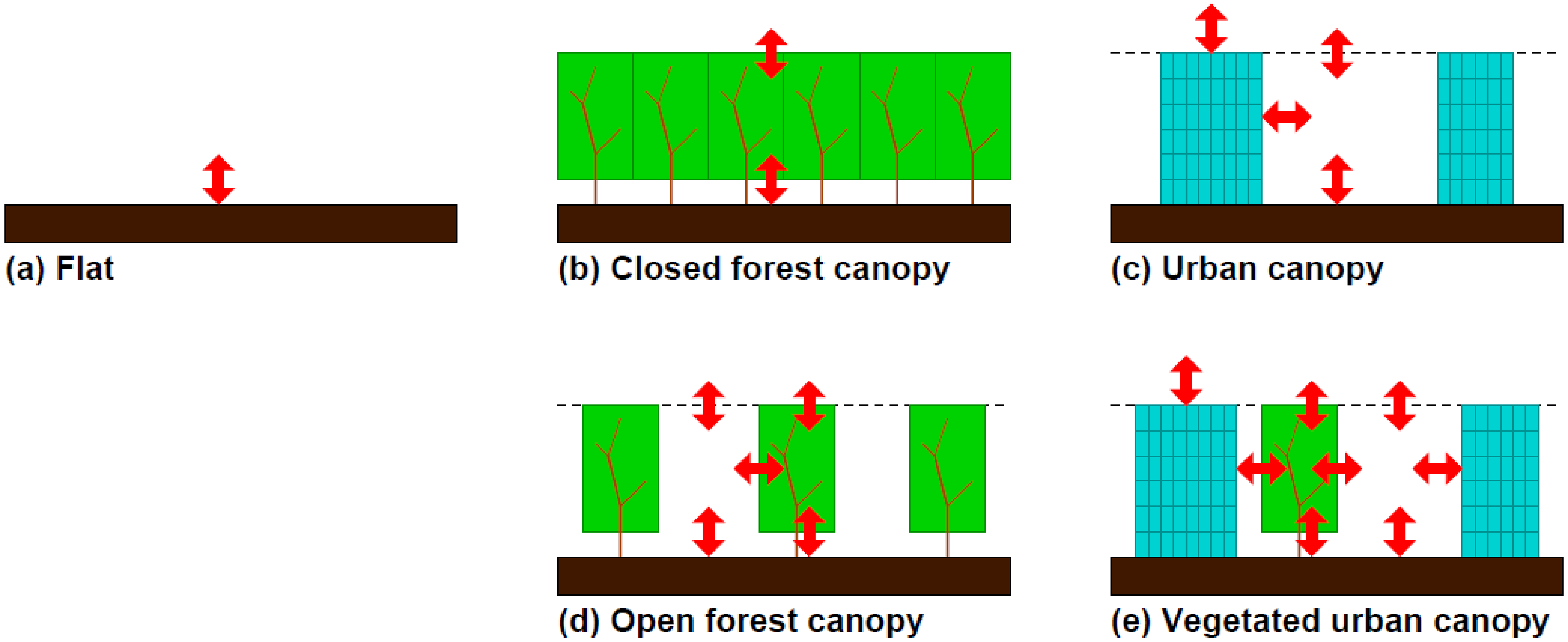


Approximate update scheme better matches observations (coastal point in northern Norway)

Hogan and Bozzo (JAMES 2015)

Towards a consistent treatment of complex surfaces

- Reflectance of vegetation over snow is very crudely modelled at ECMWF, leading to large temperature errors; absorbed sunlight by vegetation is used in dynamic vegetation models, transpiration rates in NWP and CO_2 emission in chemistry models
- Urban areas ignored completely (except for albedo), yet most users of ECMWF forecasts are in cities!
- *How can we represent complex 3D effects efficiently in radiation schemes? …SPARTACUS!*



Beer-Lambert law for direct flux, two-stream equations for diffuse flux

Original idea from Schuster (1905)

Extinction coefficient (gas, aerosol & cloud optical depth per metre)

Gradient of flux with height

Loss of flux by scattering or absorption

Gain in flux by scattering from other direction

Downwelling direct flux: $$-\frac{\partial s}{\partial z} = -\sigma / \mu_0$$

Upwelling diffuse flux: $$\frac{\partial u}{\partial z} = \sigma\left(-\gamma_1 u + \gamma_2 v + \gamma_3 s\right)$$

Downwelling diffuse flux: $$-\frac{\partial v}{\partial z} = \sigma\left(-\gamma_1 v + \gamma_2 u + \gamma_4 s\right)$$

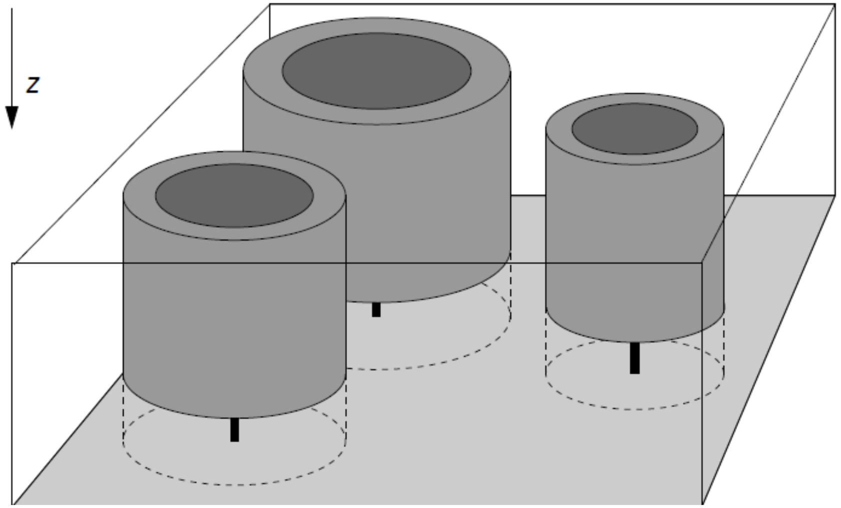
Gain from scattering of the direct solar beam

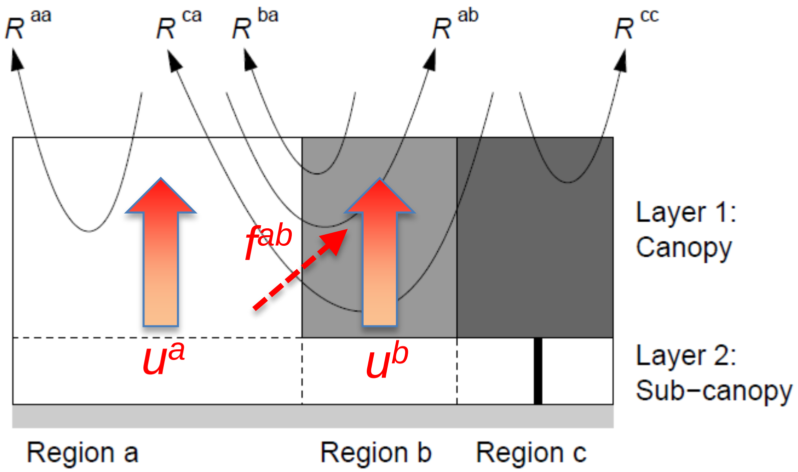
- Coefficients γ_1 to γ_4 are simple functions of single scattering albedo (scattering / scattering+absorption) and asymmetry factor (mean cosine of scattering angle)
- Analytic solution to system of 3 coupled ODEs by Meador & Weaver (1980)

The SPARTACUS method applied to forests

SPARTACUS = Speedy Algorithm for Radiative Transfer through Cloud Sides (Hogan et al. 2016)

- Idea: apply the two-stream equations in each of three regions *a–c*
- New terms represent horizontal exchange of radiation between regions: if trees are randomly distributed then they are a function only of *effective tree diameter*





Define each flux component as a vector:

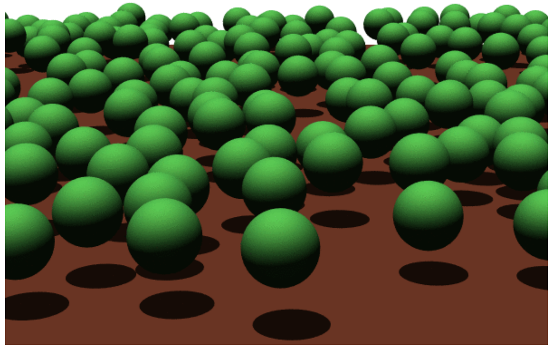
$$\mathbf{u} = \begin{pmatrix} u^a \\ u^b \\ \vdots \end{pmatrix}$$

- Solve system of nine ODEs in terms of a *matrix exponential*

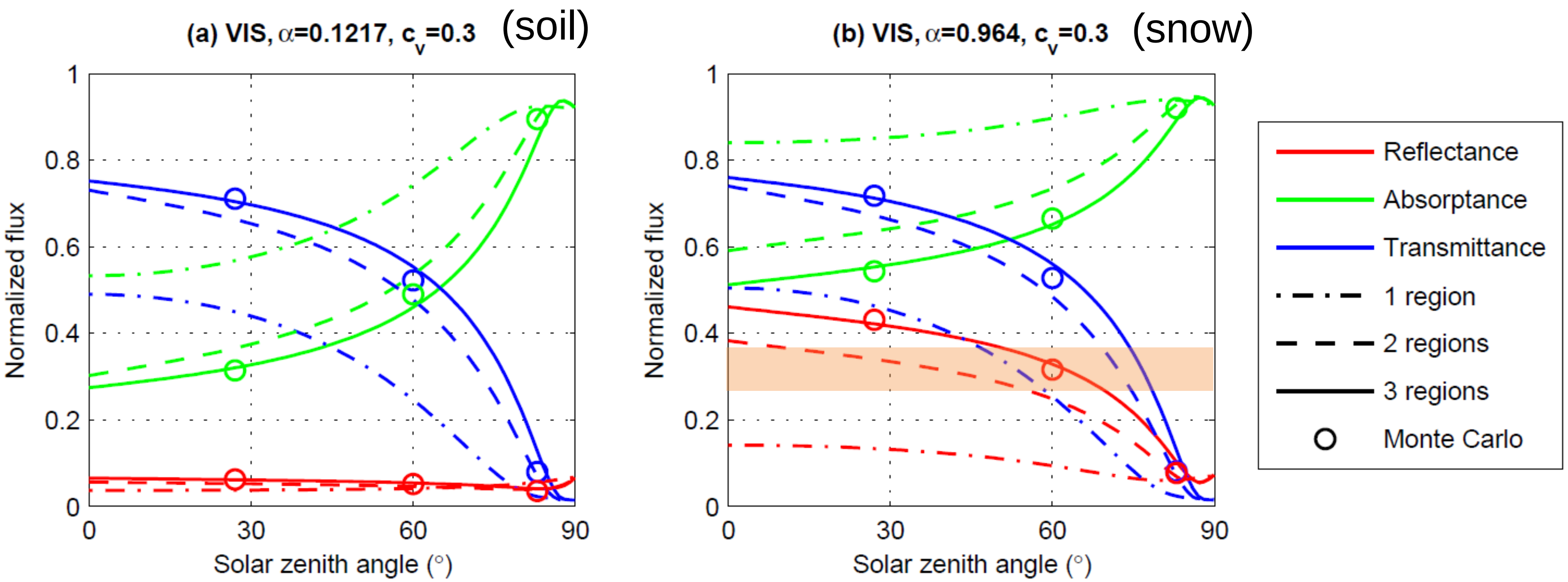
$$\frac{d}{dz}\begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix} = \Gamma \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix} \longrightarrow \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=z_1} = \exp(\Gamma z_1) \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=0}$$

Evaluation against Monte Carlo calculations

Reflectance of forests over snow in current IFS (Dutra et al. 2010)



RAMI4PILPS "Open Forest Canopy" scenario



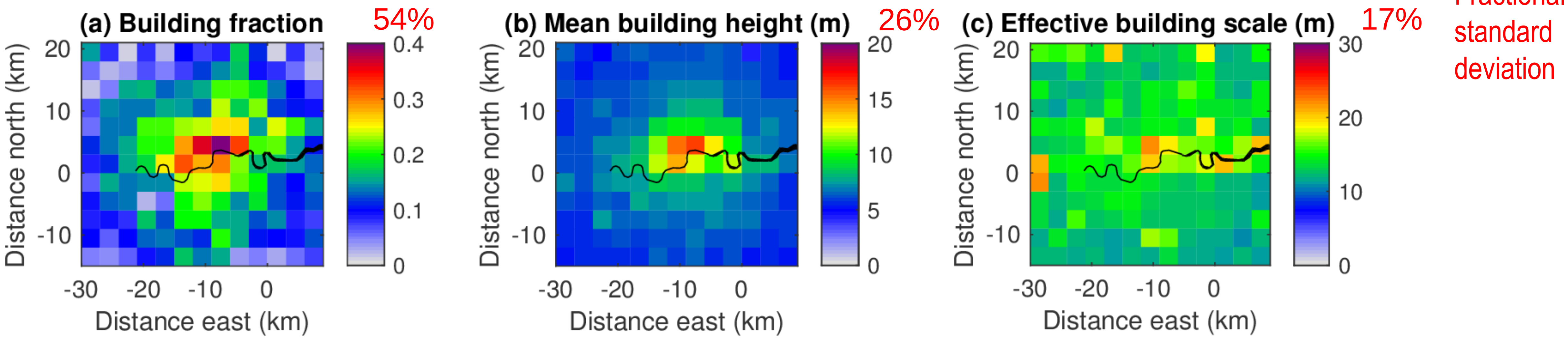
- 1-region: homogenize forest horizontally, Sellers (1985) e.g. JULES model
  - Significantly less reflective; photosynthesis rate too high
- 2-region SPARTACUS: homogenize trees
  - Passable approximation, especially when leaf-area index poorly known
- 3-region SPARTACUS: horizontal structure of trees represented
  - Excellent fit to Monte Carlo calculations

Hogan et al. (GMD 2018)

ECMWF

Preliminary application of SPARTACUS to urban areas

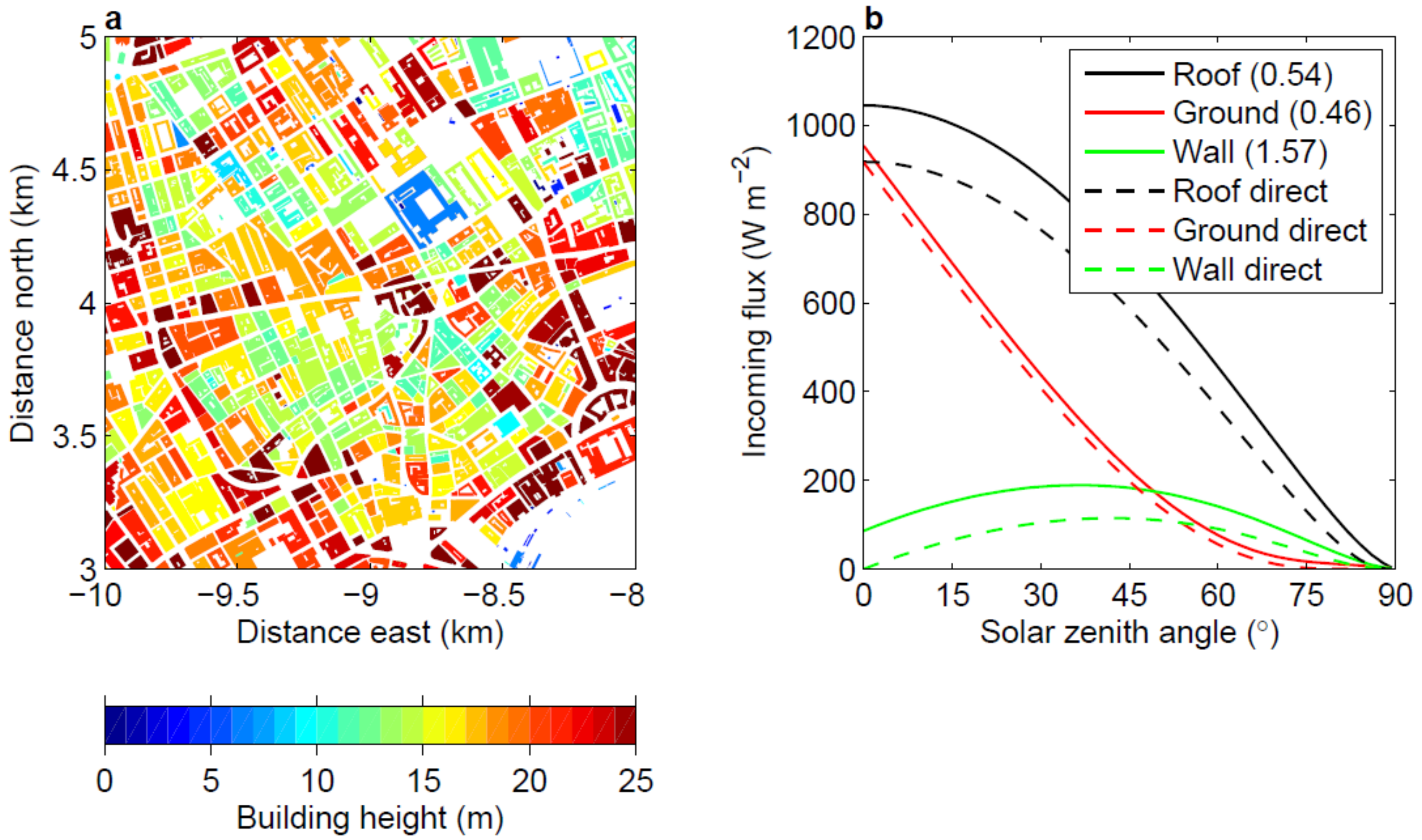
- Currently urban areas are forests or cropland in the ECMWF model!
- Development of an “urban tile” in progress, including turbulent and radiative exchanges between facets
- To apply SPARTACUS to cities, only three geometric variables are required:



- Analysis of building geometry: “effective building scale” is amazingly constant for London: 13.7±2.3 m
  - Effective building scale *S*: size of a cube in an equivalent idealized city composed of randomly positioned cubes with the same building perimeter *P* and coverage *A* as the actual city: $S = 4A(1-A)/P$

ECMWF

Example *broadband* calculation for central London



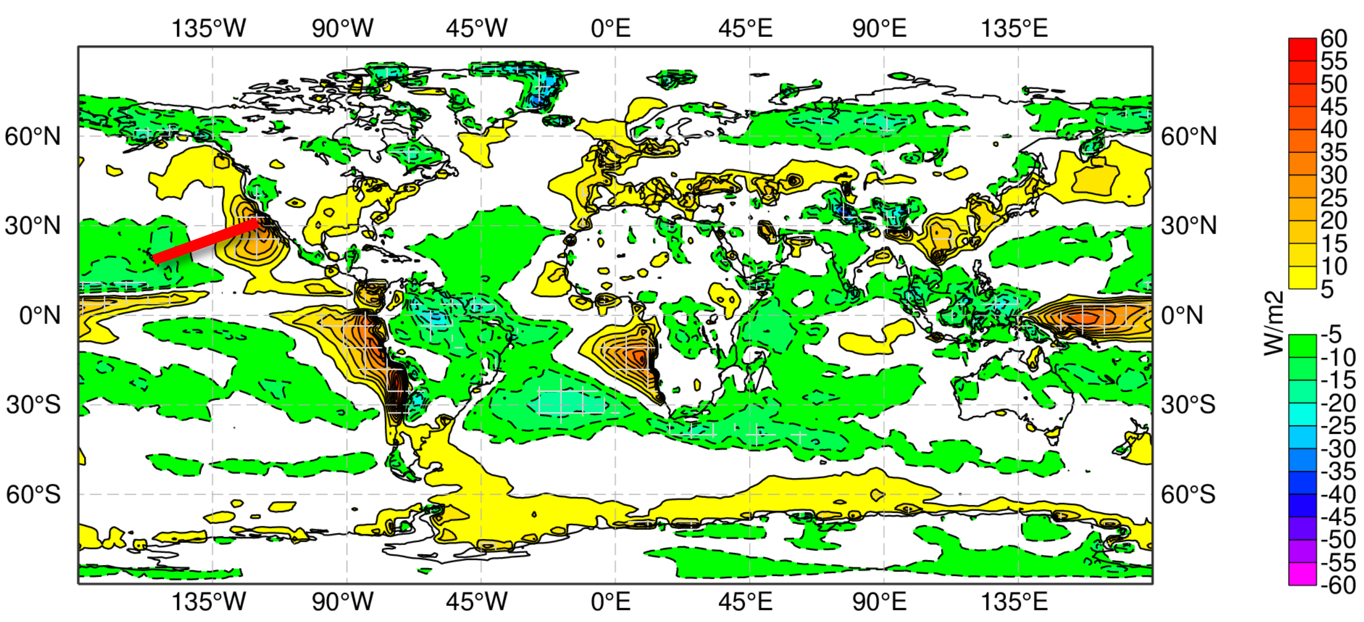
- Next step: evaluation!

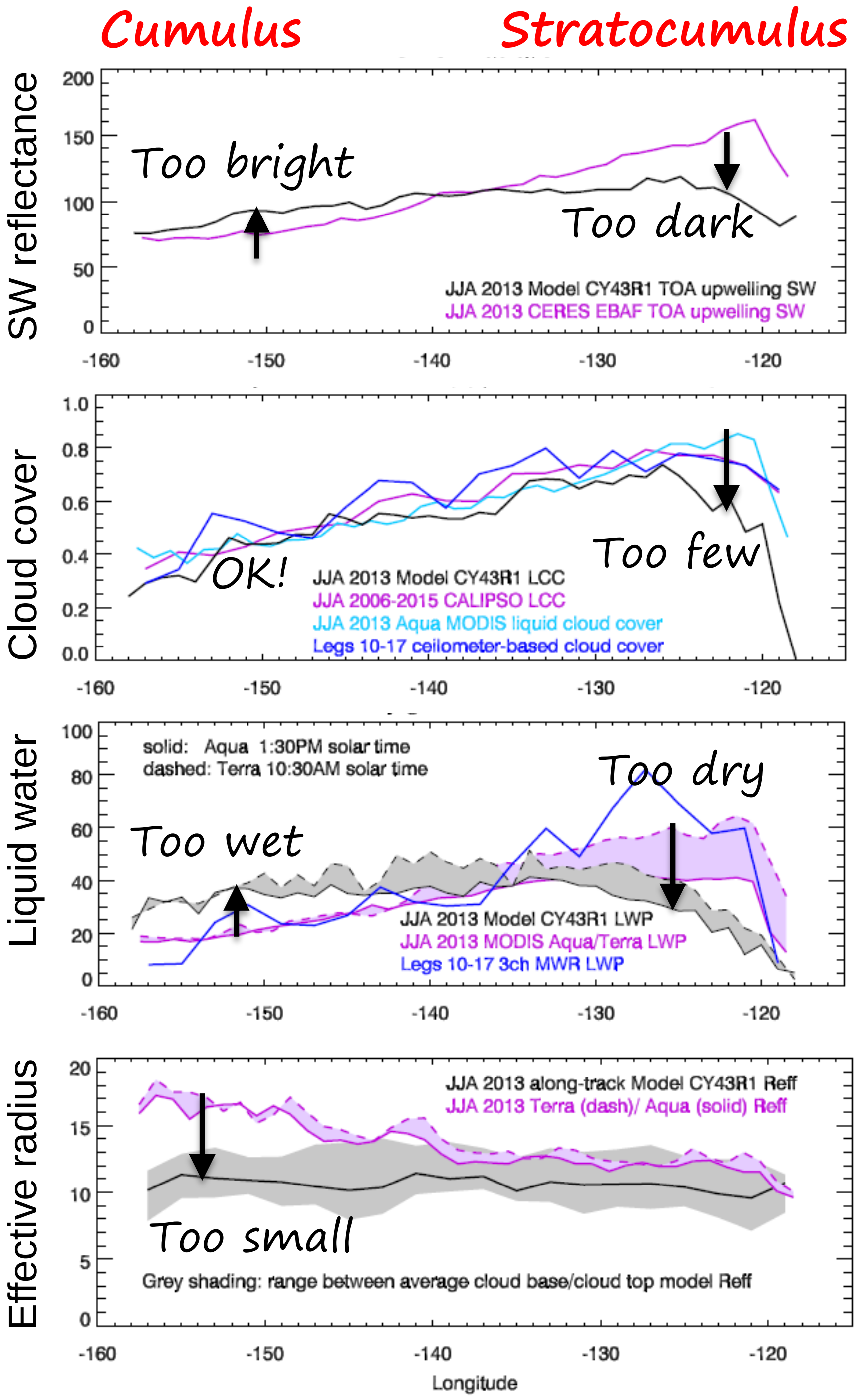
Challenge 2: Clouds

ECMWF

What is cause of errors in SW cloud radiative effect?

MAGIC ship track

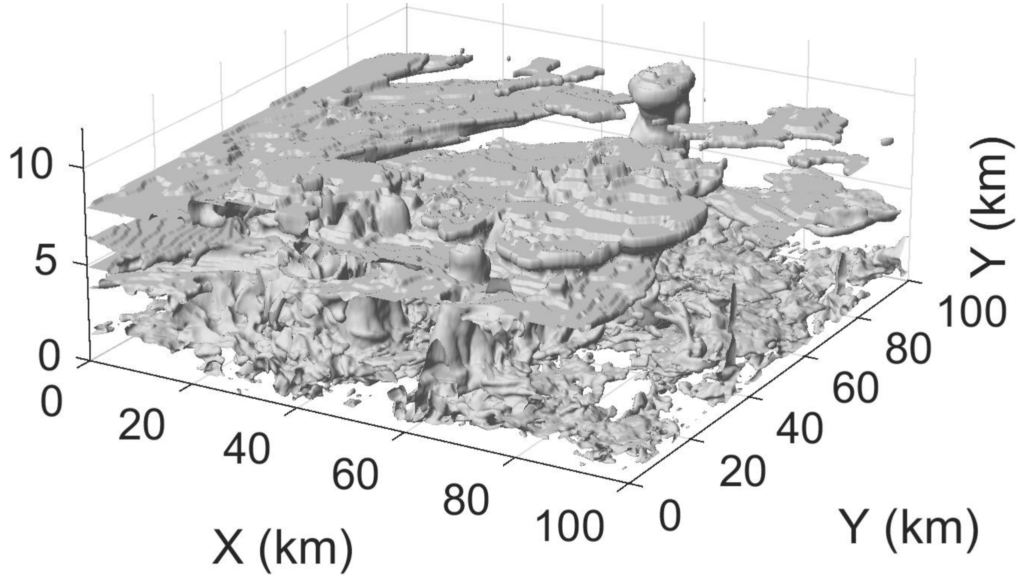


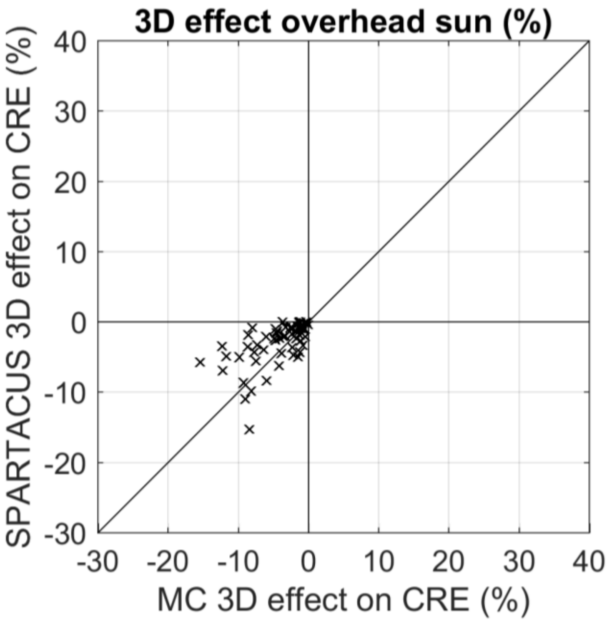


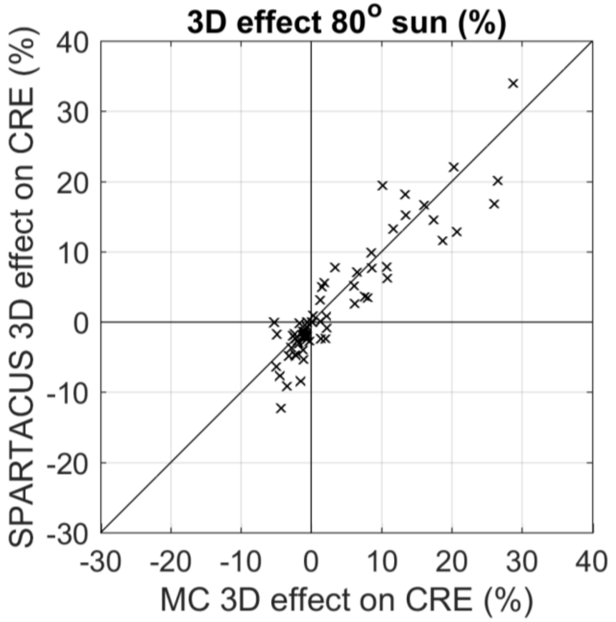
- Cumulus in many models are "*too bright, too few*"
- Cumulus in IFS are *too bright, too wet*, with droplets *too small*
- *Treatment of cloud sub-grid structure in radiation also significantly affects cloud radiative effect*

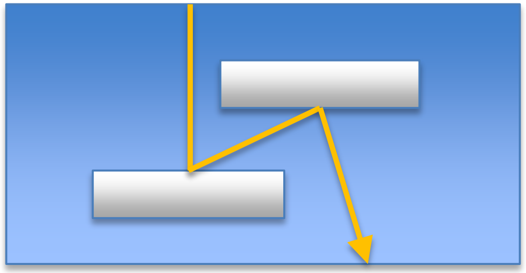
Evaluation of “SPARTACUS” solver for representing 3D radiative effects

- ecRad is the only GCM radiation scheme with option to represent 3D effects rigorously in shortwave and longwave (4.5x more expensive)
- Tested offline against Monte Carlo calculations for 59 varied scenes from Canadian and Met Office models at ~200 m resolution

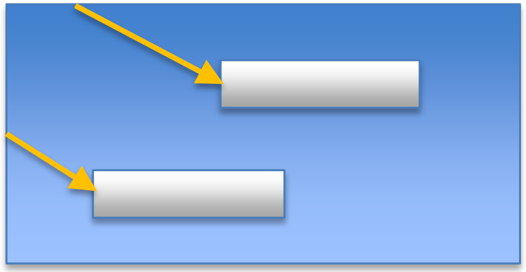








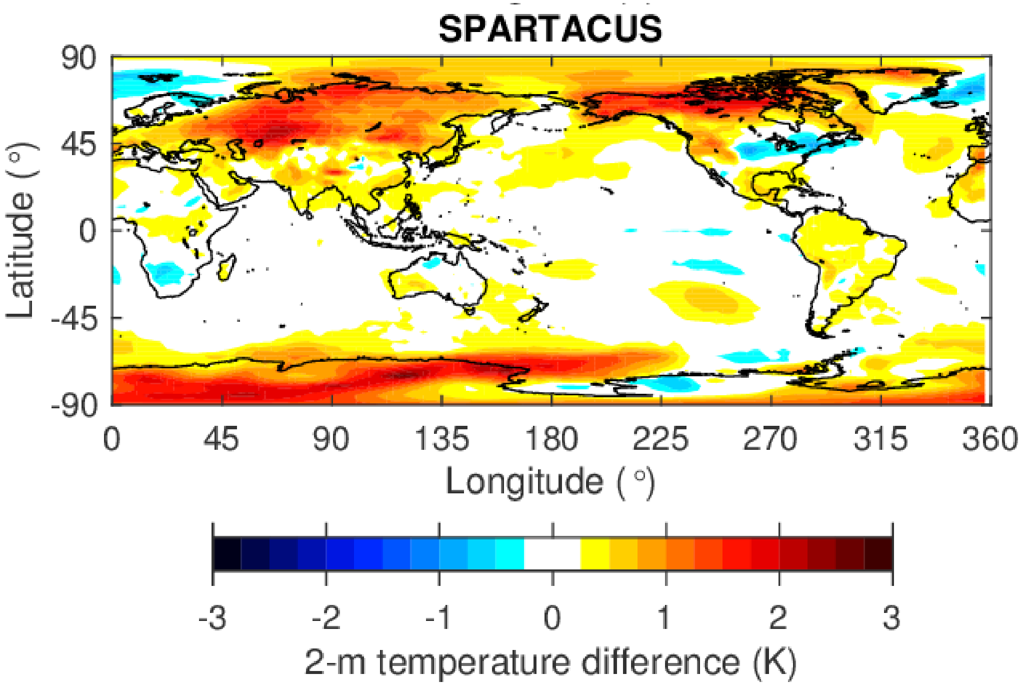
Encroachment under clouds *reduces* cloud radiative effect

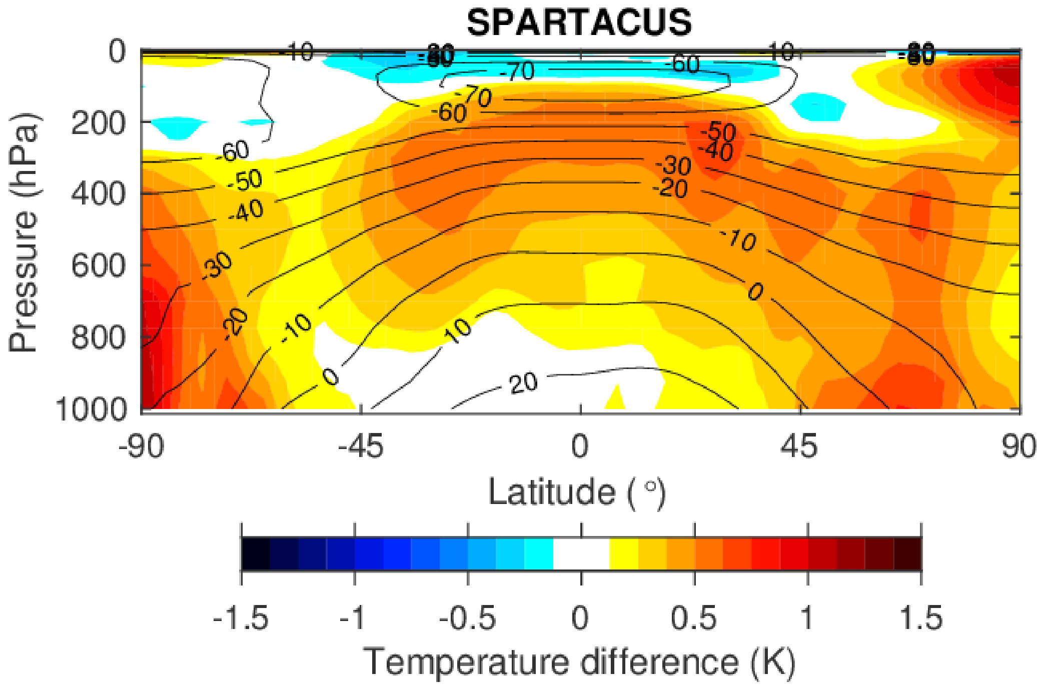


Interception by cloud sides *increases* cloud radiative effect

Impact in 4x 1-year coupled simulations

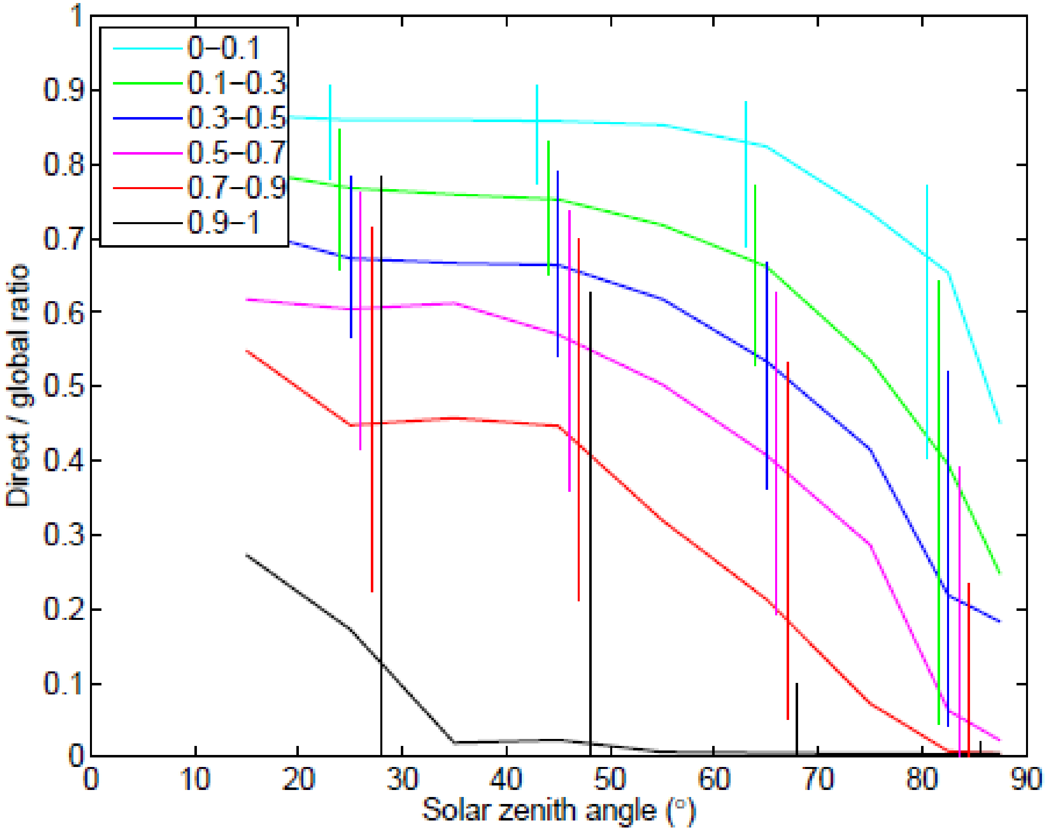
- Global-mean surface downwelling longwave and shortwave both increased by around 1 W m^{-2}
- Similar magnitude to effect of uncertainties in cloud structure, overlap and particle size
- Land surface warms by 0.5 degrees



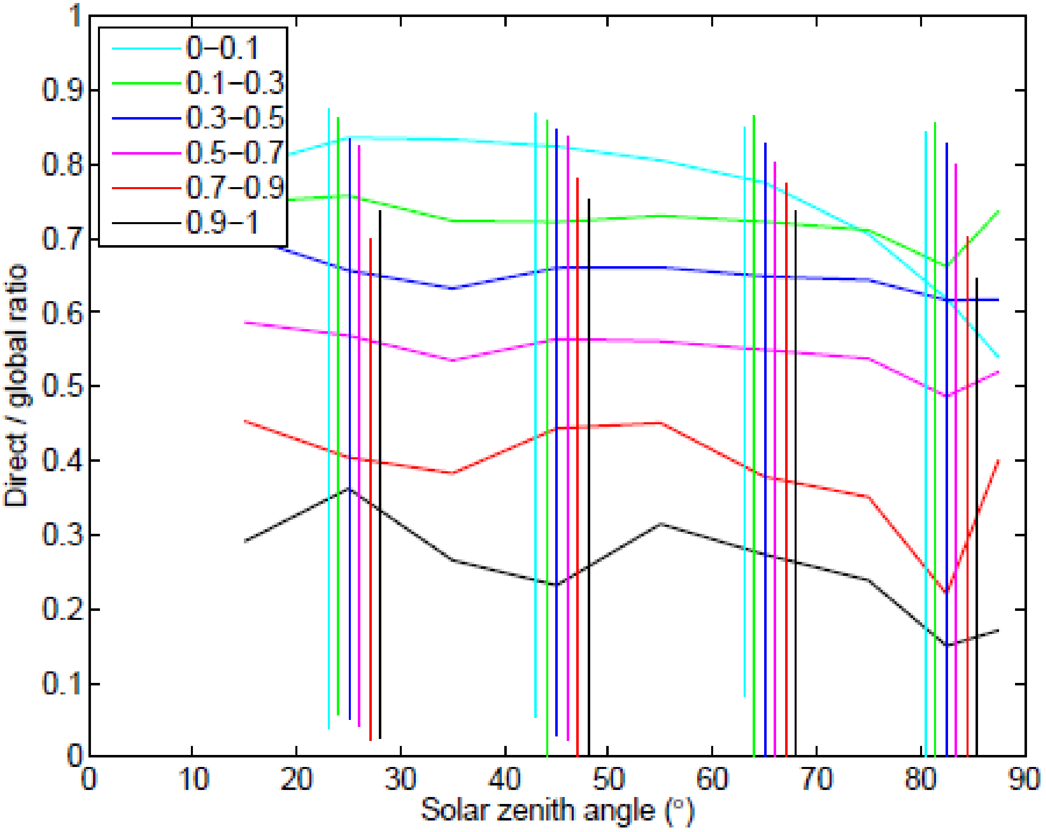


- Need longer climate simulations to see effect with the full ocean response

3D effects could significantly improve forecasts for solar power



- Observed direct-beam fraction for different low-cloud covers



- IFS forecast without 3D effects

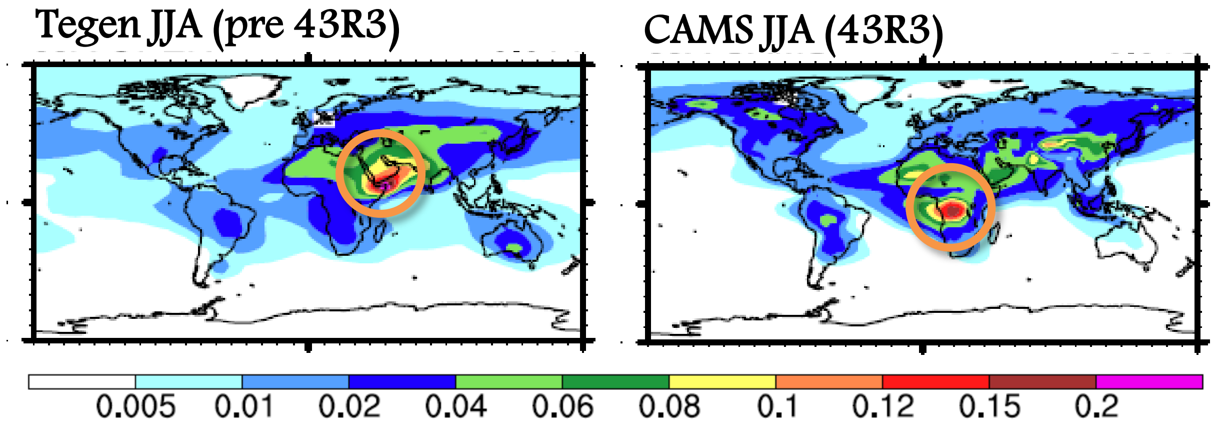
Challenge 3: Clear-sky shortwave absorption

ECMWF

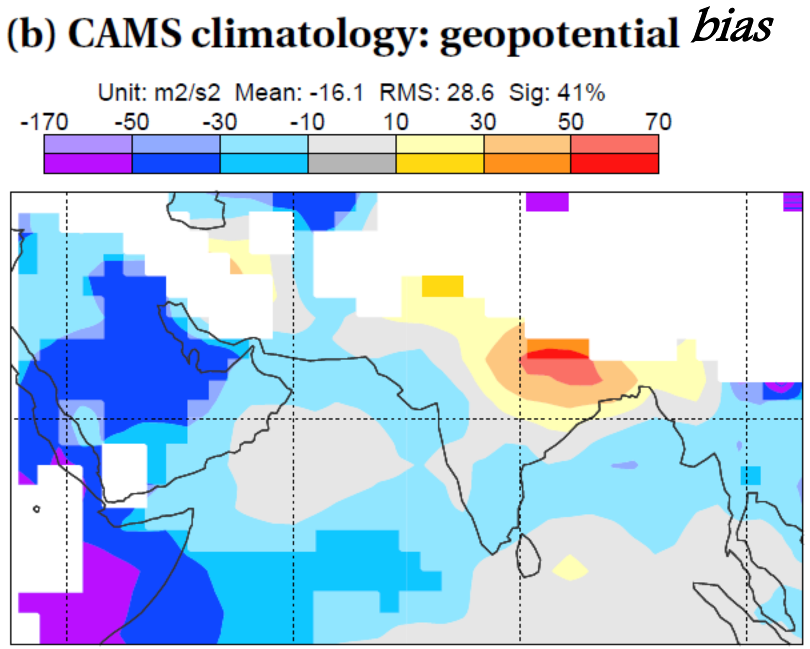
Aerosols

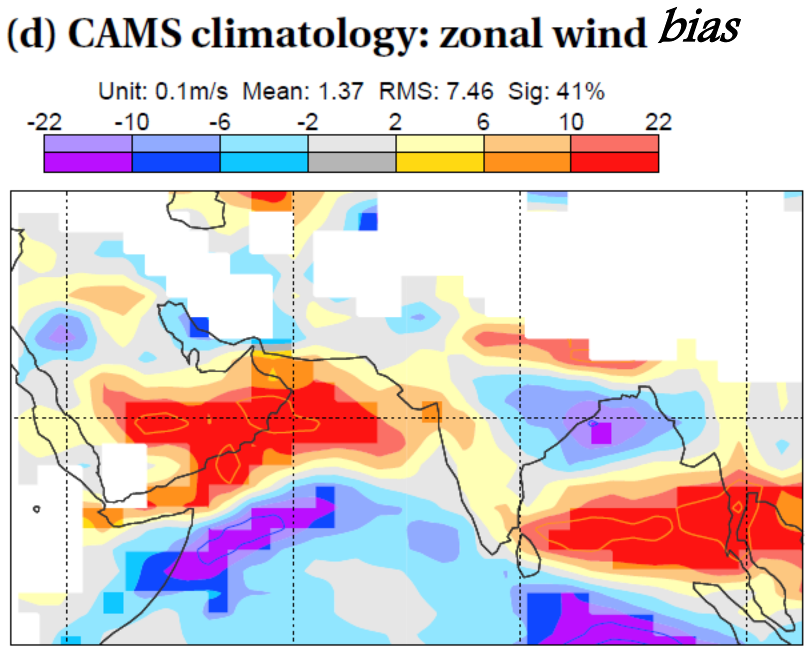
Bozzo et al. (2017)

- 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?*

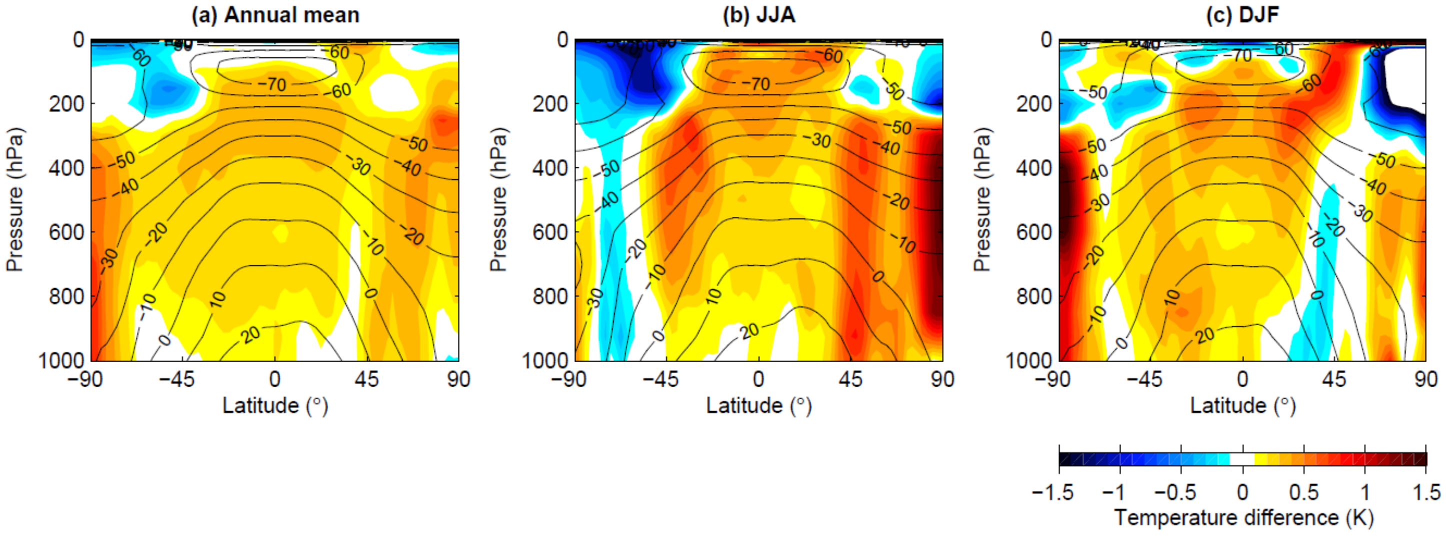




Revised water vapour continuum in near infrared

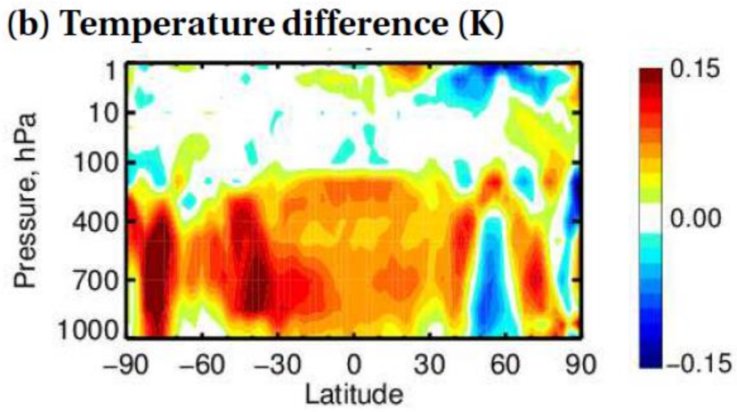
- Measurements from “CAVIAR” project (Shine et al. 2016) suggest water vapour continuum in near-IR could be up to a factor of 10 too small in RRTM-G
- Tested CAVIAR continuum in IFS
- In coupled climate runs, troposphere warms by ~0.5 K; 1 K over summer pole
- In uncoupled forecasts, marginal improvement in skill in tropical temperature and mid-latitude winds
- Need to reassess with *coupled* forecasts

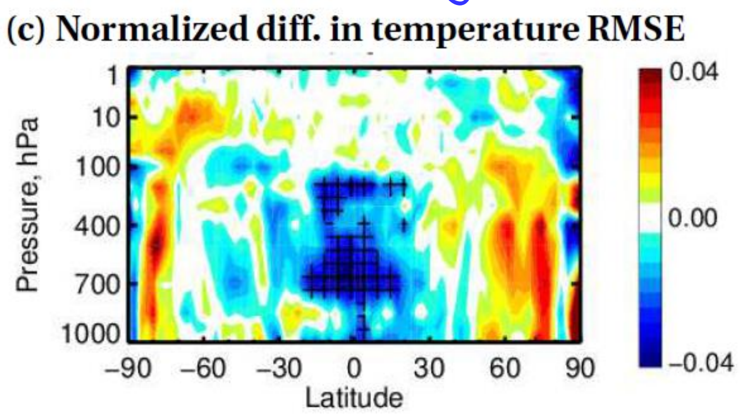
Impact on climate of coupled model

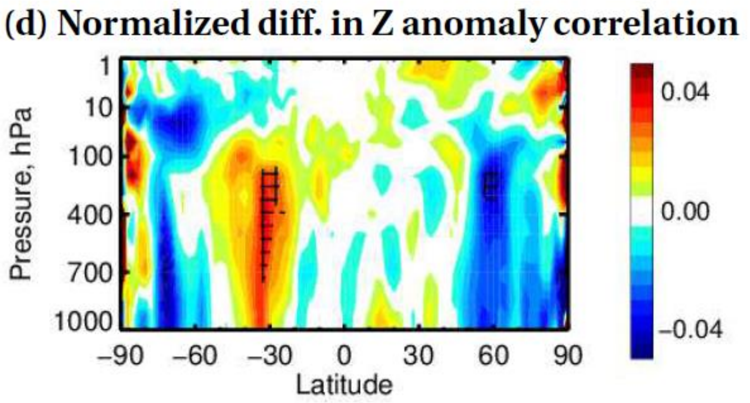


Blue is good

Red is good





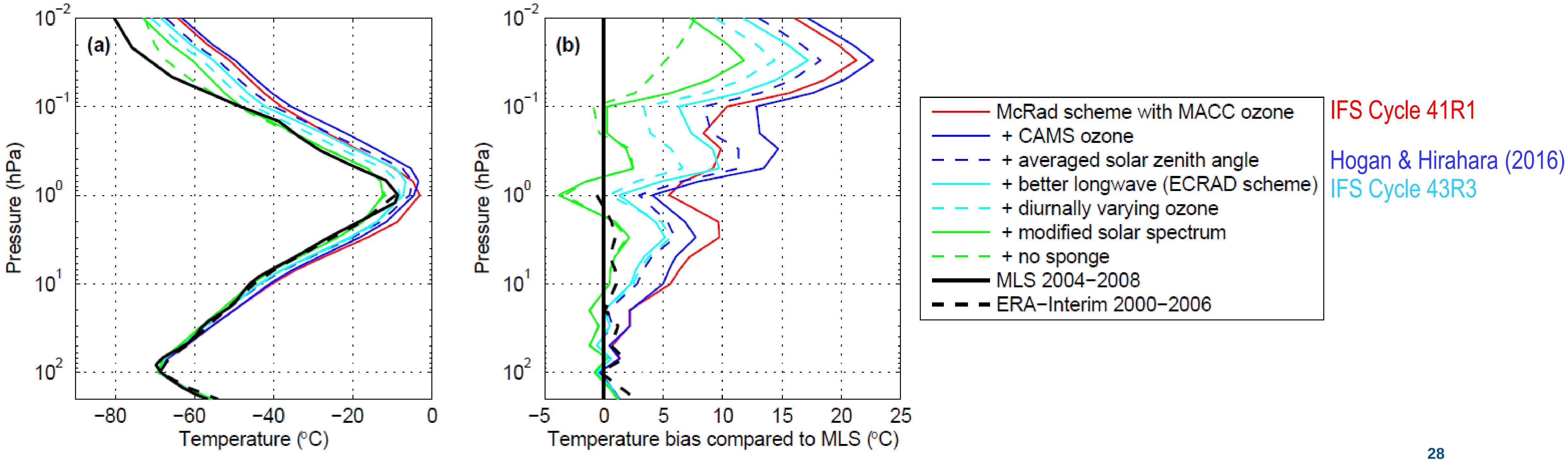


Challenge 4: Middle atmosphere

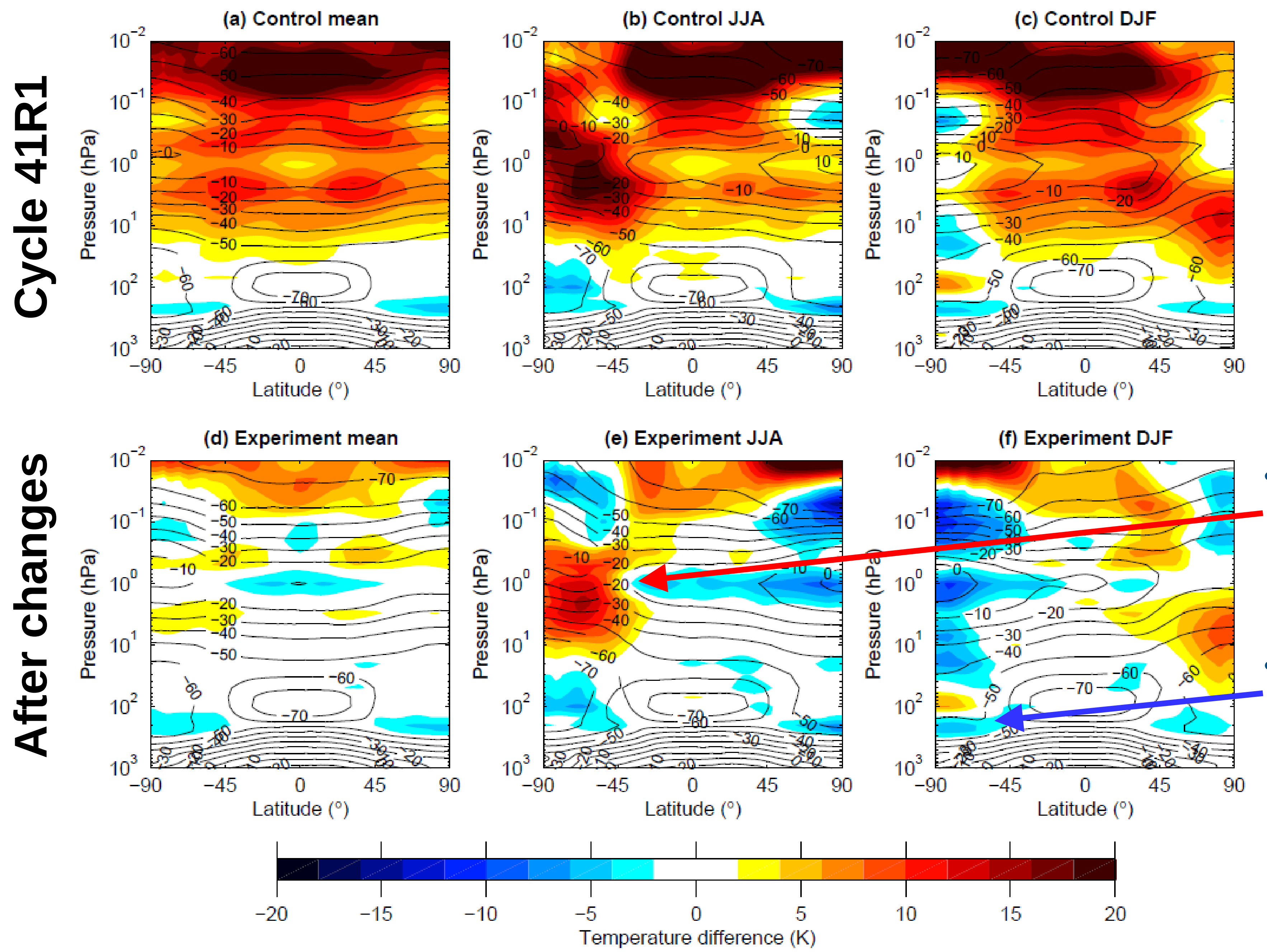
ECMWF

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*

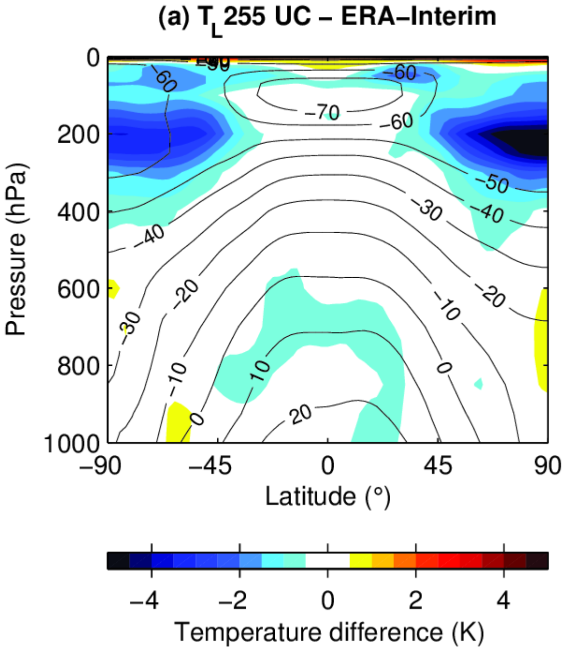


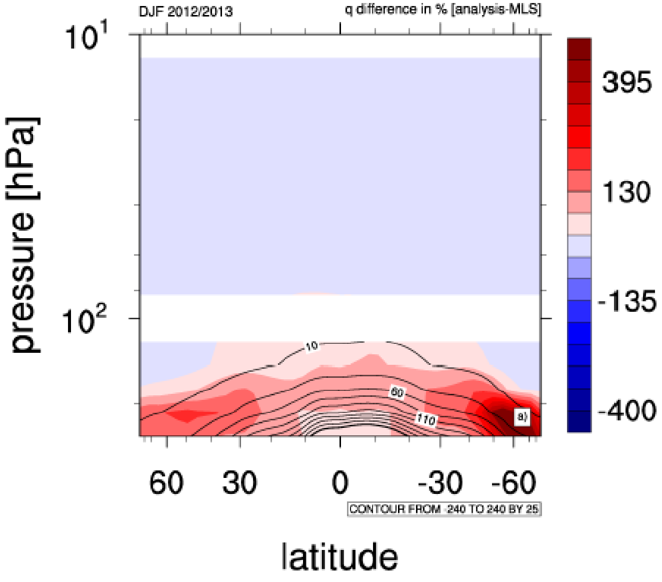
Seasonal biases

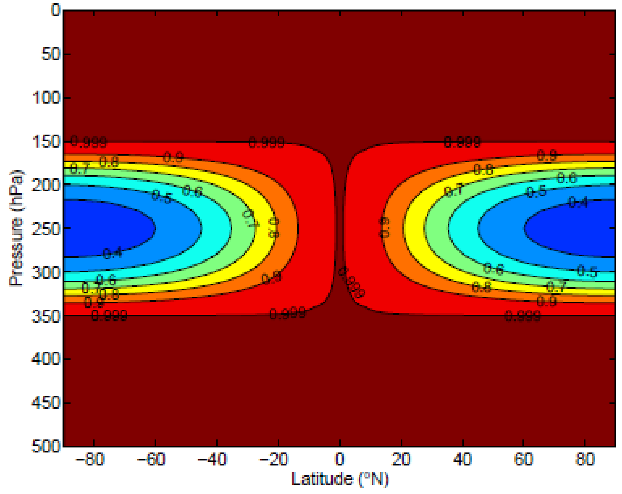


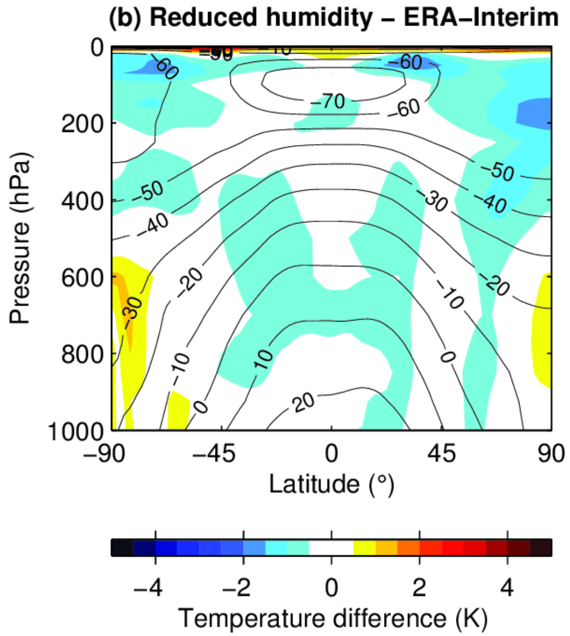
- Even after improving the annual/global mean, large warm biases remain at stratopause in winter polar
- More important for troposphere forecasting is persistent cold bias at lower stratosphere

Exploring the cause of the polar lower stratosphere cold bias









- Up to 5 K too cold
- Problem in IFS for at least 25 years
- Common to most/all global models

- Water vapour bias compared to MLS (%)
- Erroneous transport of water vapour from troposphere, emits too strongly in longwave

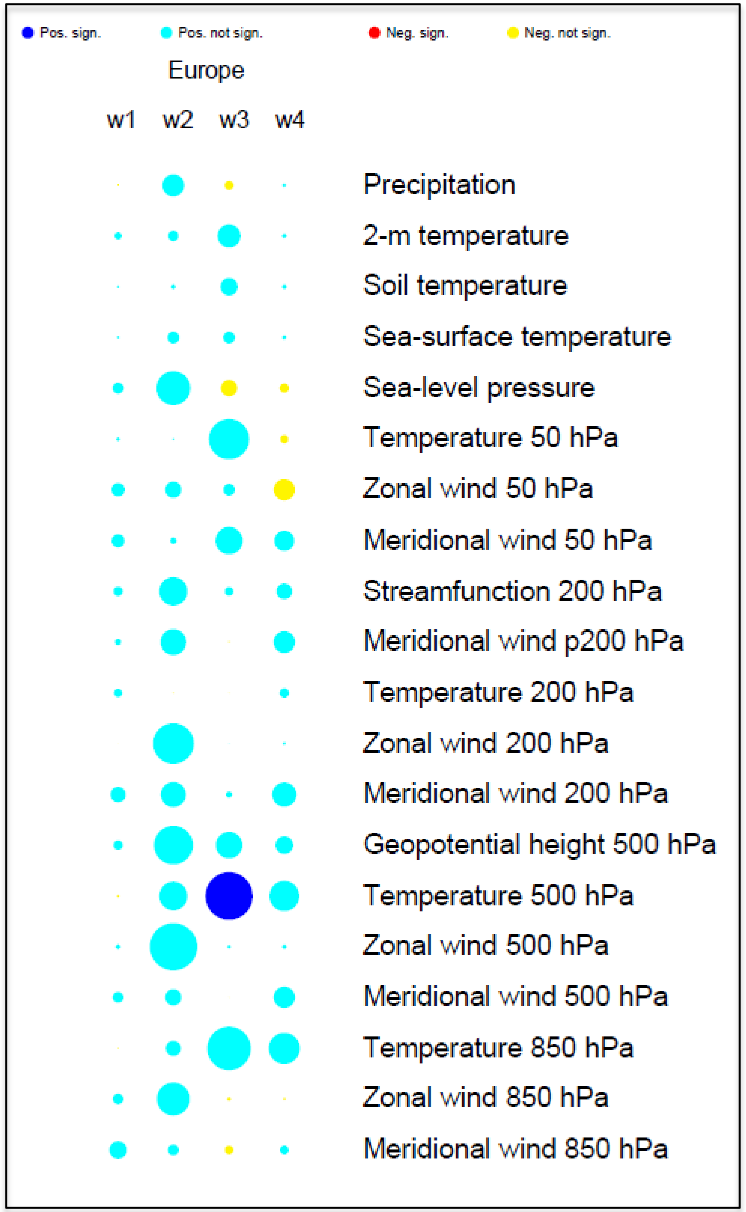
- What if we artificially reduce humidity seen by radiation?
- *Just for experimental purposes, not operations!*

- Cold bias removed!

Impact of removing polar cold bias

- Monthly forecast experiment artificially reducing humidity seen by radiation leads to improvement in troposphere monthly forecast skill
- *Renewed impetus to solve problem properly: is it due to numerical diffusion of water vapour, overshooting convection or too little ice sedimentation in upper stratospheric clouds?*

Thanks to Frederic Vitart
(blue is good!)

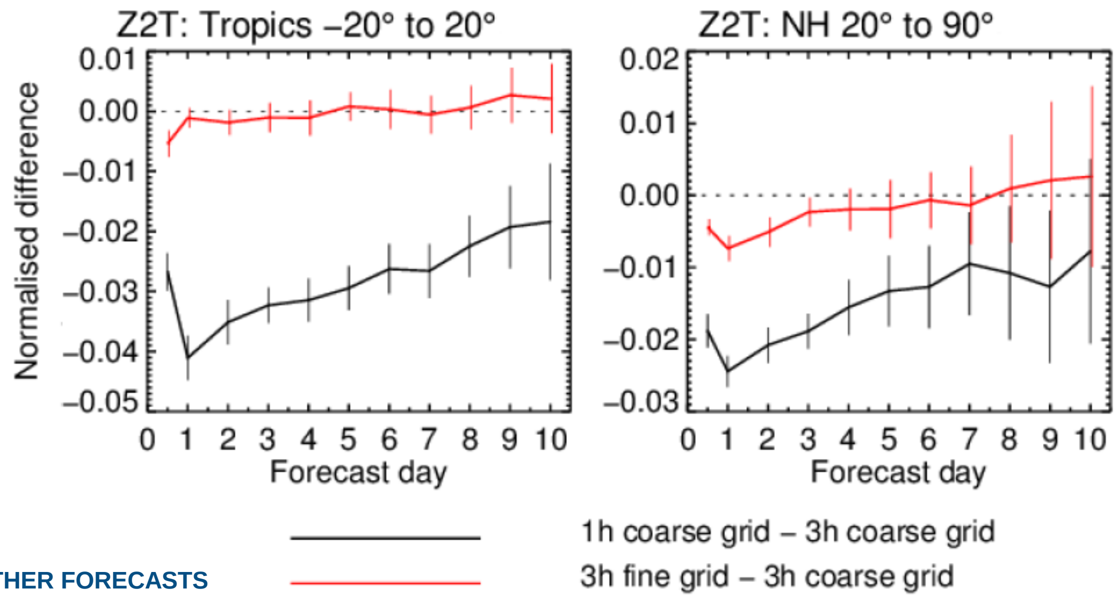


Challenge 5: Efficiency

Efficiency: temporal versus spatial resolution

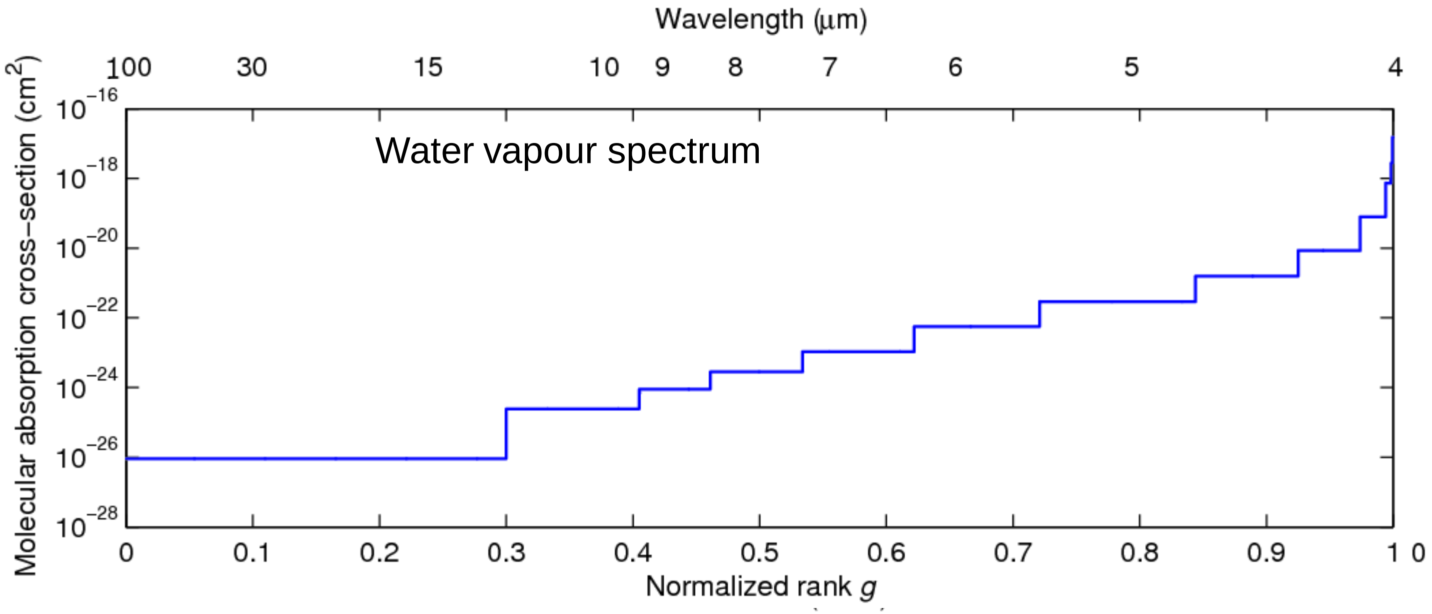
- Radiation is now 5% of high-resolution (HRES) model time, compared to 19% a decade ago
- Cost of radiation is a trade-off between temporal/spatial/spectral resolution and physical sophistication, and compared to other global NWP centres, ECMWF *has lowest temporal/spatial resolution* and *highest spectral 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 1 h radiation in ENS and more physical sophistication (longwave scattering, 3D effects)?*

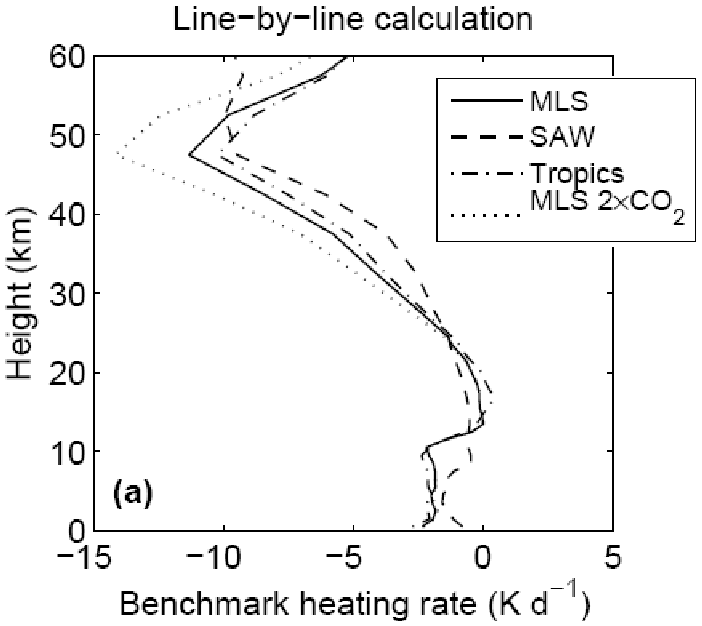
Centre	Radiation timestep (h)		Horiz. coarsening		Spectral intervals	
	HRES	ENS	HRES	ENS	SW	LW
ECMWF	1	3	10.24	6.25	112	140
NCEP	1	1	1	1	112	140
DWD	0.4	0.6	4	4	112	140
Météo France	1	1	1	1	–	140
Met Office	1	1	1	1	21	47
CMC	1	1	1	1	40	57
JMA	1	1 (SW), 3 (LW)	4	4	22	156
FSCK	–	–	–	–	~ 15	~ 32

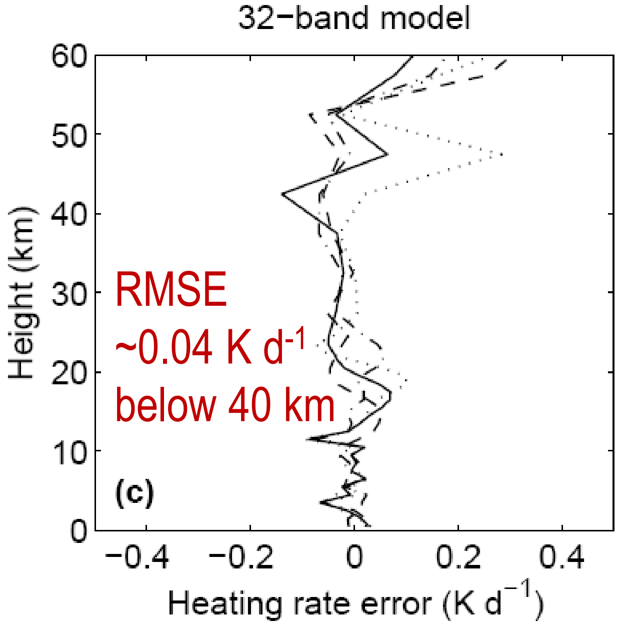


How can we optimize the spectral integration?

- 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)

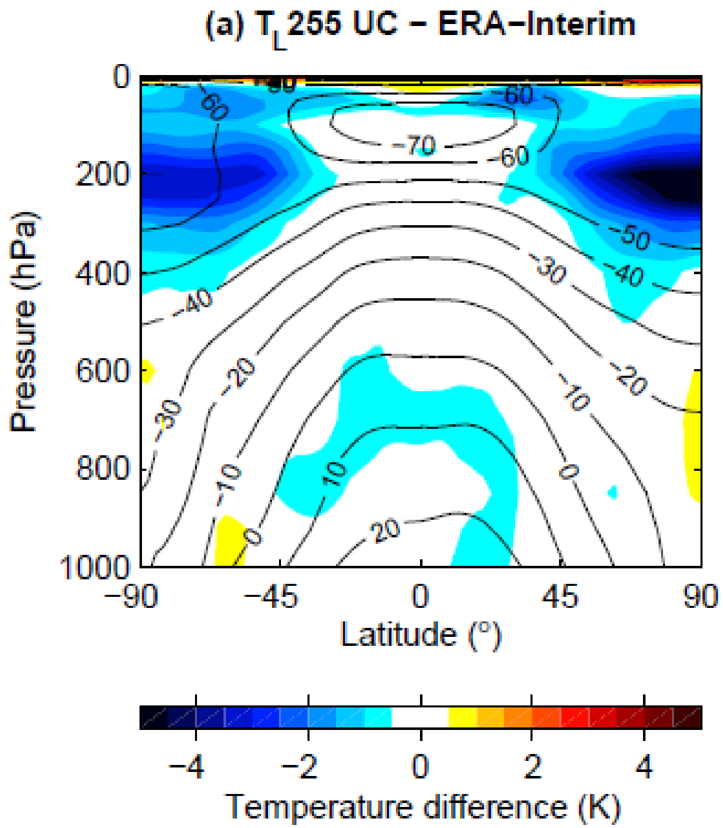
Summary and outlook

- 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
- Outlook for the “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, we need 1-h radiation timestep in all model configurations

Why do we need a good radiation scheme in NWP models?

- Radiation provides the energy that drives the global circulation, and hence determines the model climate
  - The tropospheric climate of the IFS is in many ways excellent
- A good climate model is not enough, we want to push the boundaries of predictive skill:
  - Shorter range 2-m temperature forecasts, where surface treatment is important
  - Extended/seasonal timescales, where biases in *regional* and *stratospheric* climate become important, as well as the interaction of radiation with weather systems and weather regimes
- To make progress we have to get a lot of things right…

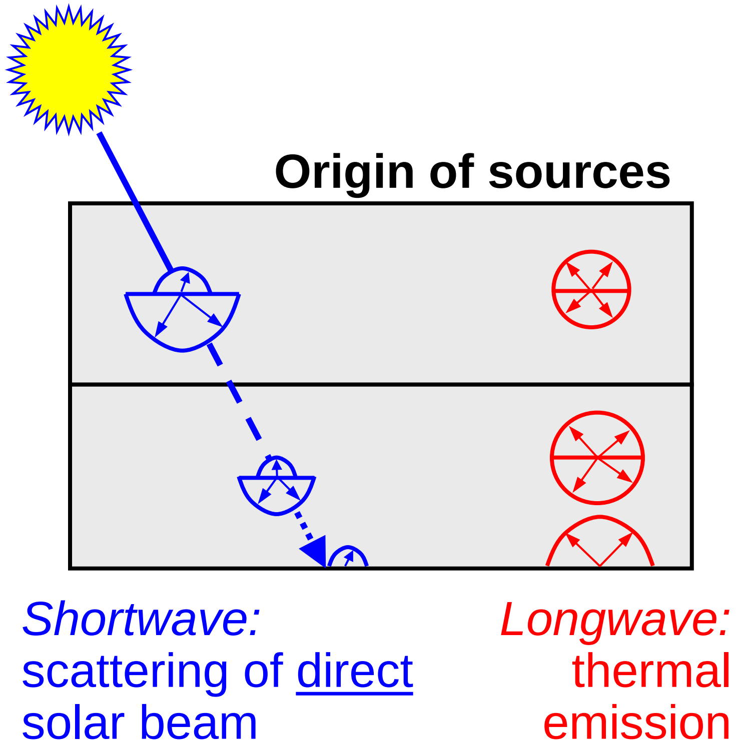
Model climate continued: annual-mean temperature

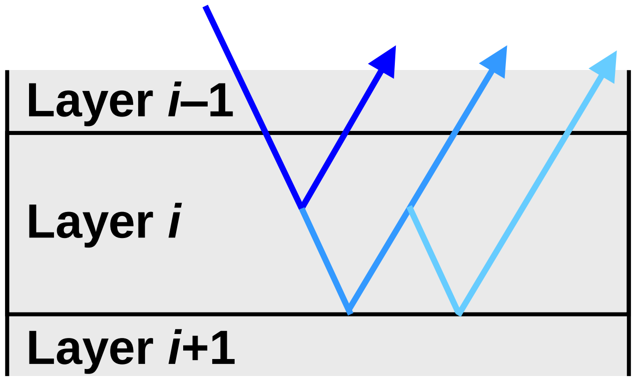


- Troposphere climate of uncoupled model is excellent
- Large longstanding cold bias in polar lower stratosphere

Exact solution

1. Meador & Weaver (1980) provide analytic solutions to 2-stream equations per layer in terms of:
   - Diffuse reflectance & transmittance R_i, T_i
   - "Sources" emerging from top and bottom of layer S_i^+, S_i^-
2. Adding Method (Lacis & Hansen 1974):
   - Sweep up: Compute albedos at half-levels
   - Sweep down: Compute fluxes at half-levels





$$A_{i-1/2} = R_i + T_i A_{i+1/2} T_i + T_i A_{i+1/2} R_i A_{i+1/2} T_i + \dots$$
$$= R_i + T_i (1 - A_{i+1/2} R_i)^{-1} A_{i+1/2} T_i$$

Diffuse albedo $A_{i+1/2}$

ECMWF

How do we relate exchange matrix to vegetation properties?

- Write as:

$$\mathbf{\Gamma} = \begin{pmatrix} -\mathbf{\Gamma}_1 & -\mathbf{\Gamma}_2 & -\mathbf{\Gamma}_3 \\ \mathbf{\Gamma}_2 & \mathbf{\Gamma}_1 & \mathbf{\Gamma}_4 \\ & & \mathbf{\Gamma}_0 \end{pmatrix}$$

- Rate of change of diffuse radiation along its path is sum of old and new terms:

$$\mathbf{\Gamma}_1 = \begin{pmatrix} -\sigma^a \gamma_1^a & & \\ & -\sigma^b \gamma_1^b & \\ & & -\sigma^c \gamma_1^c \end{pmatrix} + \begin{pmatrix} -f_{\mathrm{diff}}^{ab} & +f_{\mathrm{diff}}^{ba} & \\ +f_{\mathrm{diff}}^{ab} & -f_{\mathrm{diff}}^{ba} - f_{\mathrm{diff}}^{bc} & +f_{\mathrm{diff}}^{cb} \\ & +f_{\mathrm{diff}}^{bc} & -f_{\mathrm{diff}}^{cb} \end{pmatrix}$$

- From geometry arguments, rate of exchange between regions *a* and *b* is:

$$f_{\mathrm{diff}}^{ab} = \frac{2c_v}{Dc_a}$$

c_v: Tree fractional cover

D: Tree crown diameter

Assumptions:

- Rate of exchange proportional to length of interface between regions
- Trees are randomly separated

Hogan, Quaife and Braghiere (GMD 2018)

Exact solution

- Solution to coupled ODEs in a single layer:

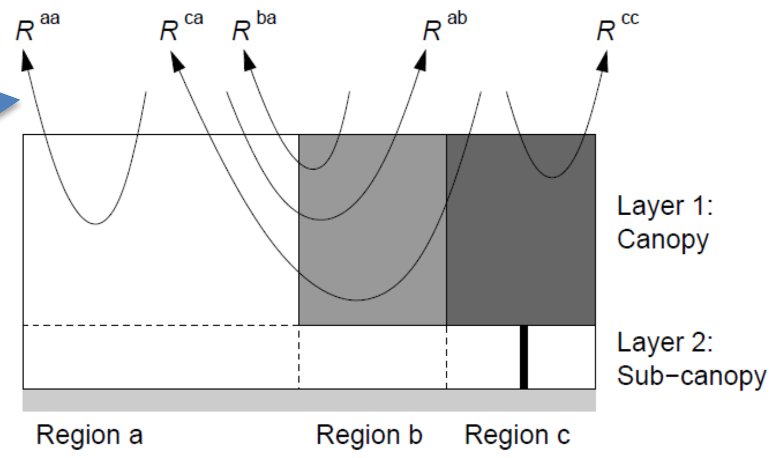
$$\begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=z_1} = \exp(\Gamma z_1) \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=0}$$

Matrix exponential

- Waterman (1981), Flatau & Stephens (1998)
- Can compute using Padé approximant plus scaling & squaring method (Higham 2005)

- Manipulate matrix exponential to get reflectance and transmission *matrices*:

$$\mathbf{R} = \begin{pmatrix} R^{aa} & R^{ba} & R^{ca} \\ R^{ab} & R^{bb} & R^{cb} \\ R^{ac} & R^{bc} & R^{cc} \end{pmatrix}$$

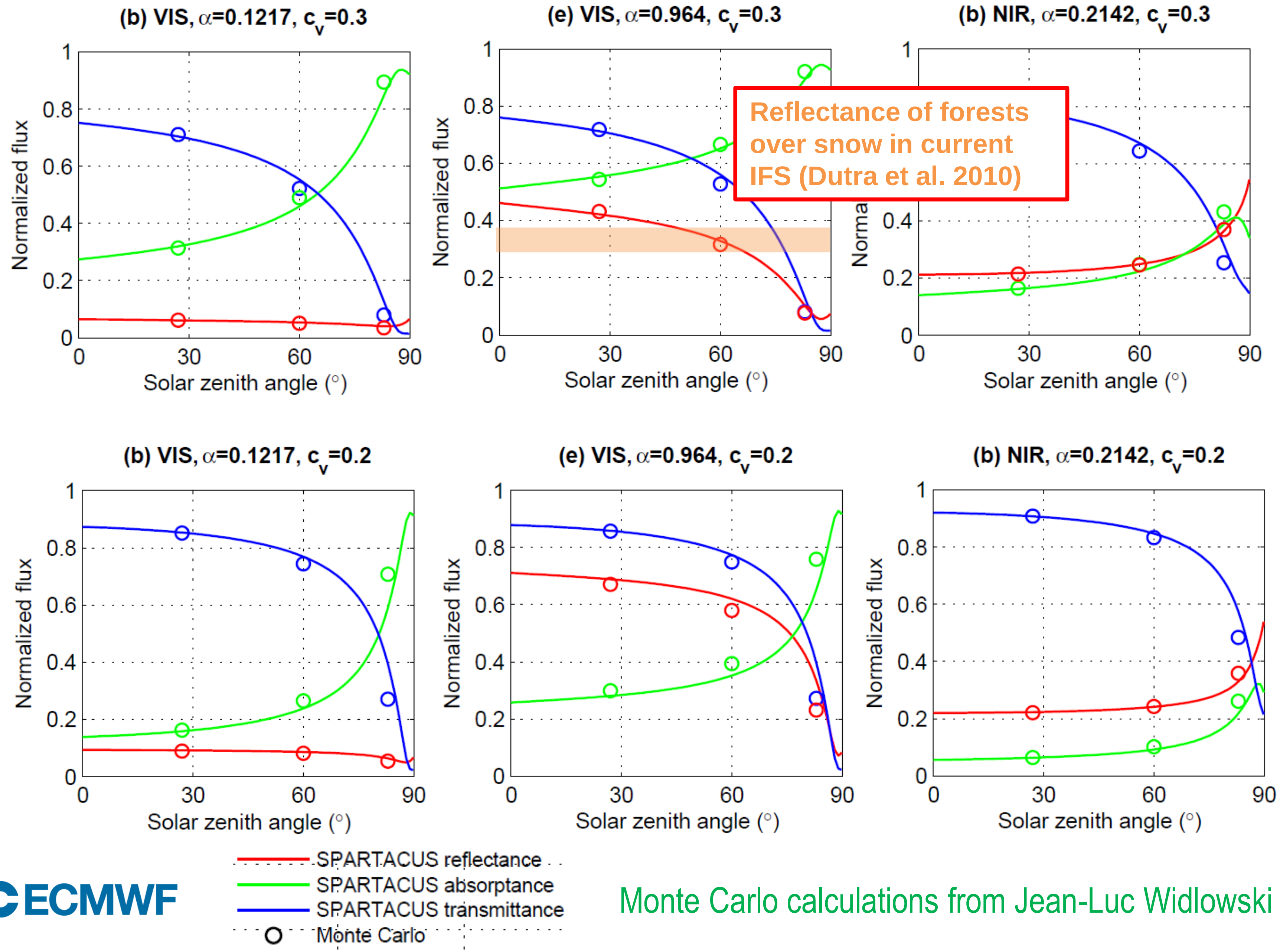


- Use matrix version of Adding Method to obtain flux profile

Visible, bare soil | Visible, snow | Near-infrared, bare soil

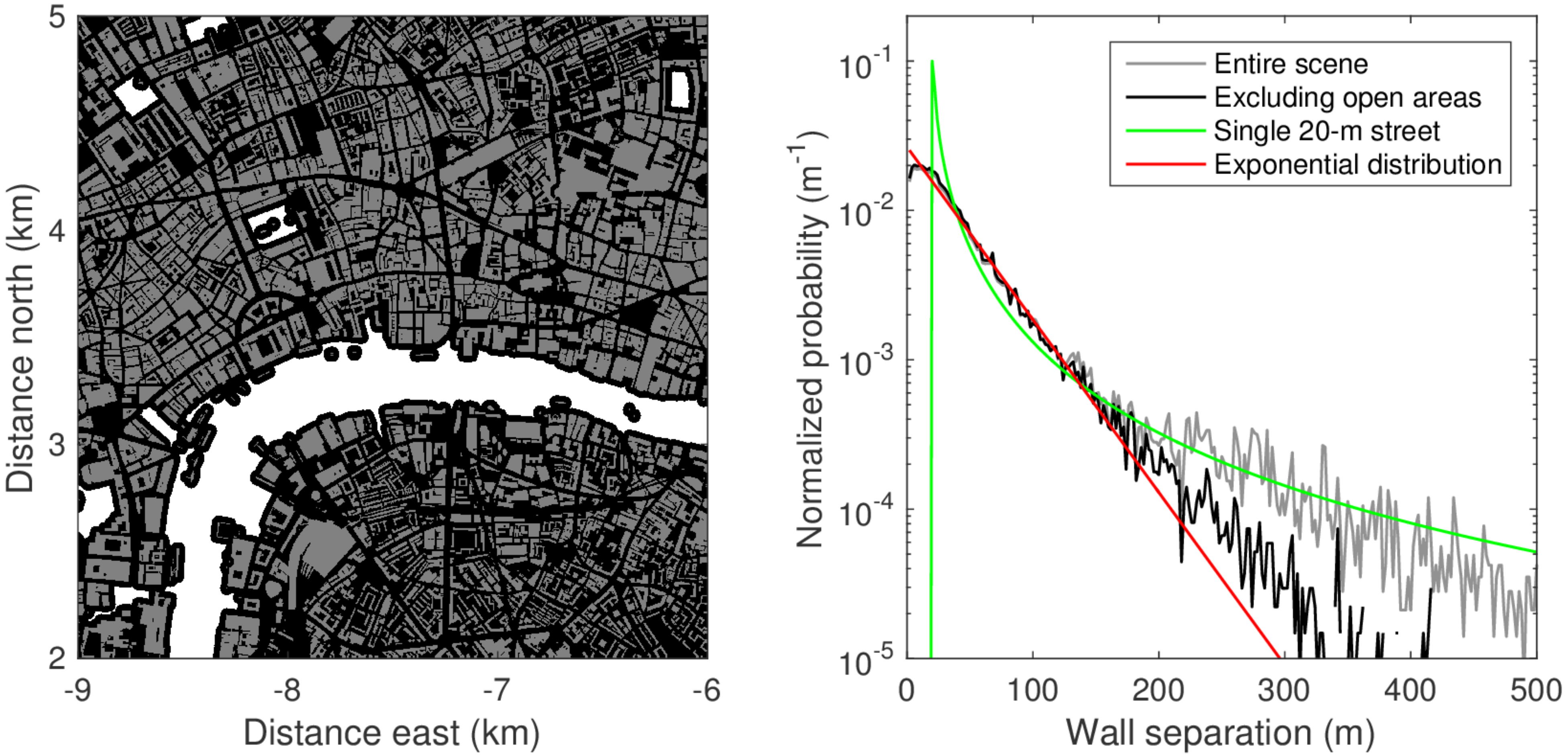
Open forest canopy

Shrubland

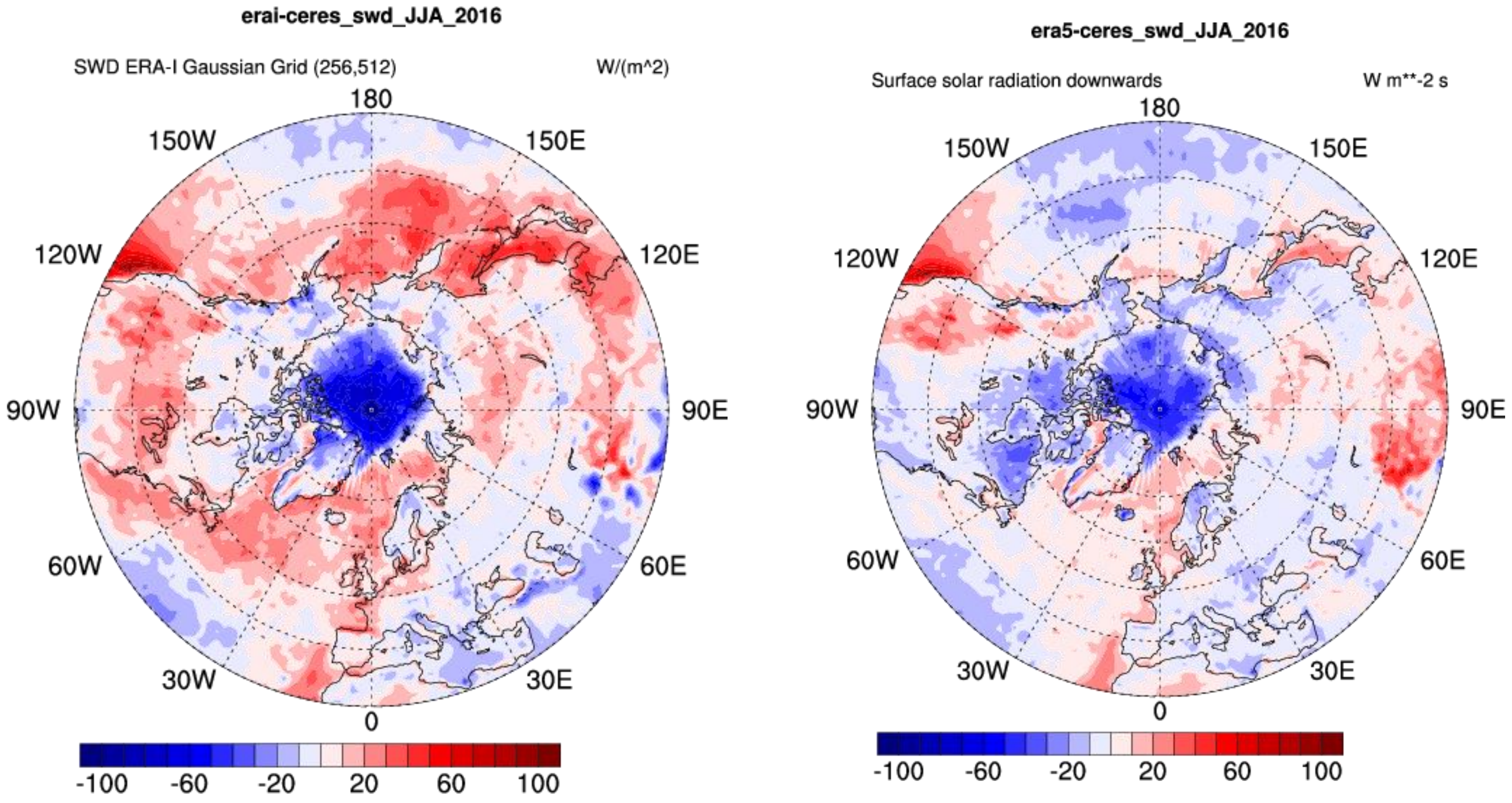


ECMWF

Monte Carlo calculations from Jean-Luc Widlowski

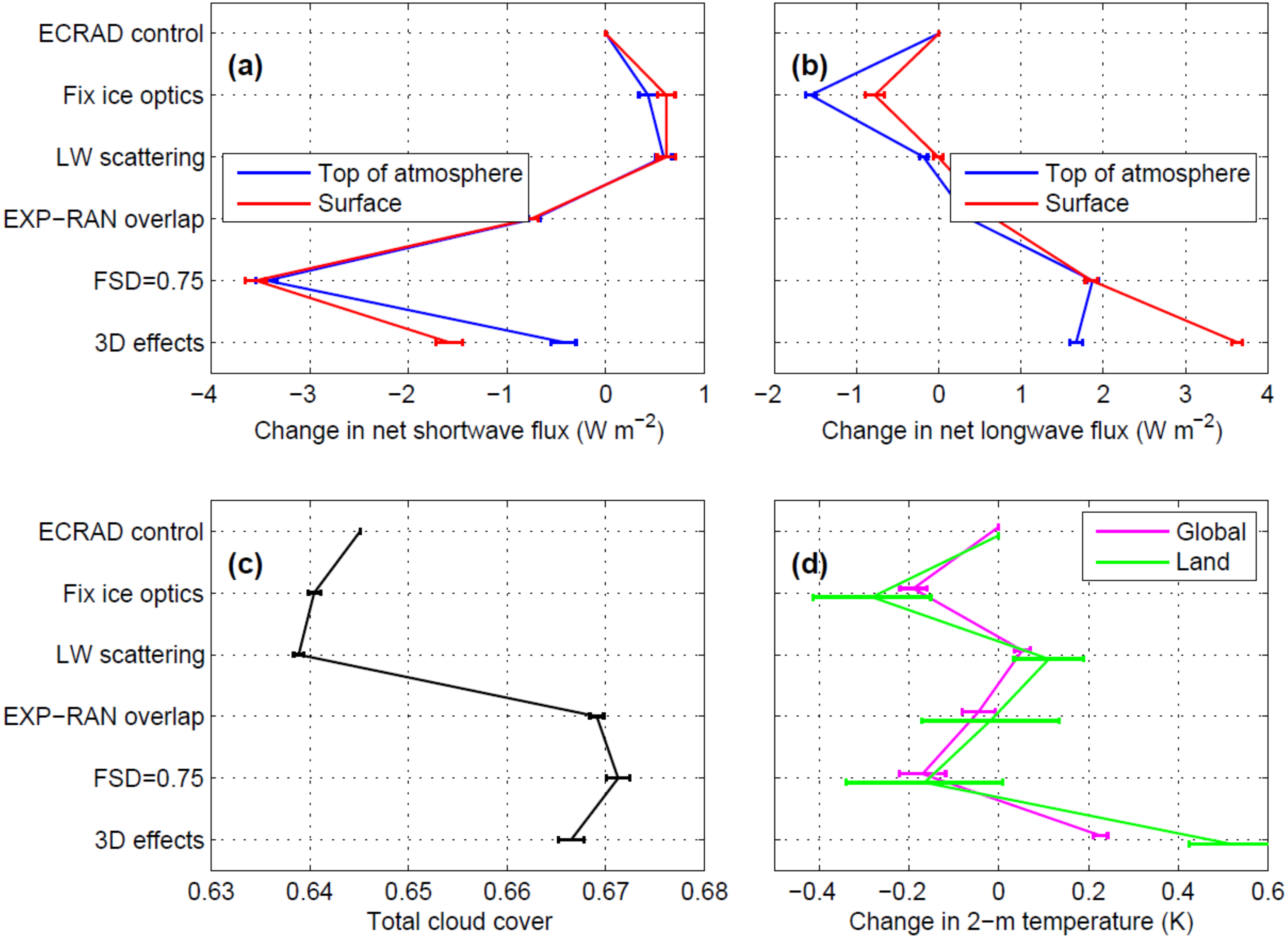

5
4
3
2
-9
-8
-7
-6
Distance north (km)
Distance east (km)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
100
200
300
400
500
Normalized probability (m^{-1})
Wall separation (m)
Entire scene
Excluding open areas
Single 20-m street
Exponential distribution

Arctic surface radiation errors in reanalysis estimated from CERES



Cumulative impact of improvements to clouds in radiation scheme

- Fix longstanding bug in LW ice optics: cools surface
- Countered by adding LW scattering (cost 10%)
- Replace EXP-EXP overlap with observationally based EXP-RAN overlap: cools
- Reduce sub-grid heterogeneity to more closely match observations: further cooling
- Introduce 3D effects (factor of 4.5 more expensive): significant warming
- *Further work required*



Test of revised water vapour continuum in near infrared

Impact on climate of coupled model

- Measurements from “CAVIAR” project (Shine et al. 2016) suggest water vapour continuum in near-IR could be up to a factor of 10 too small in RRTM-G
- In coupled climate runs, troposphere warms by ~0.5 K; 1 K over summer pole
- In uncoupled forecasts, marginal improvement in skill in tropical temperature and mid-latitude winds