Challenges for radiation in NWP models

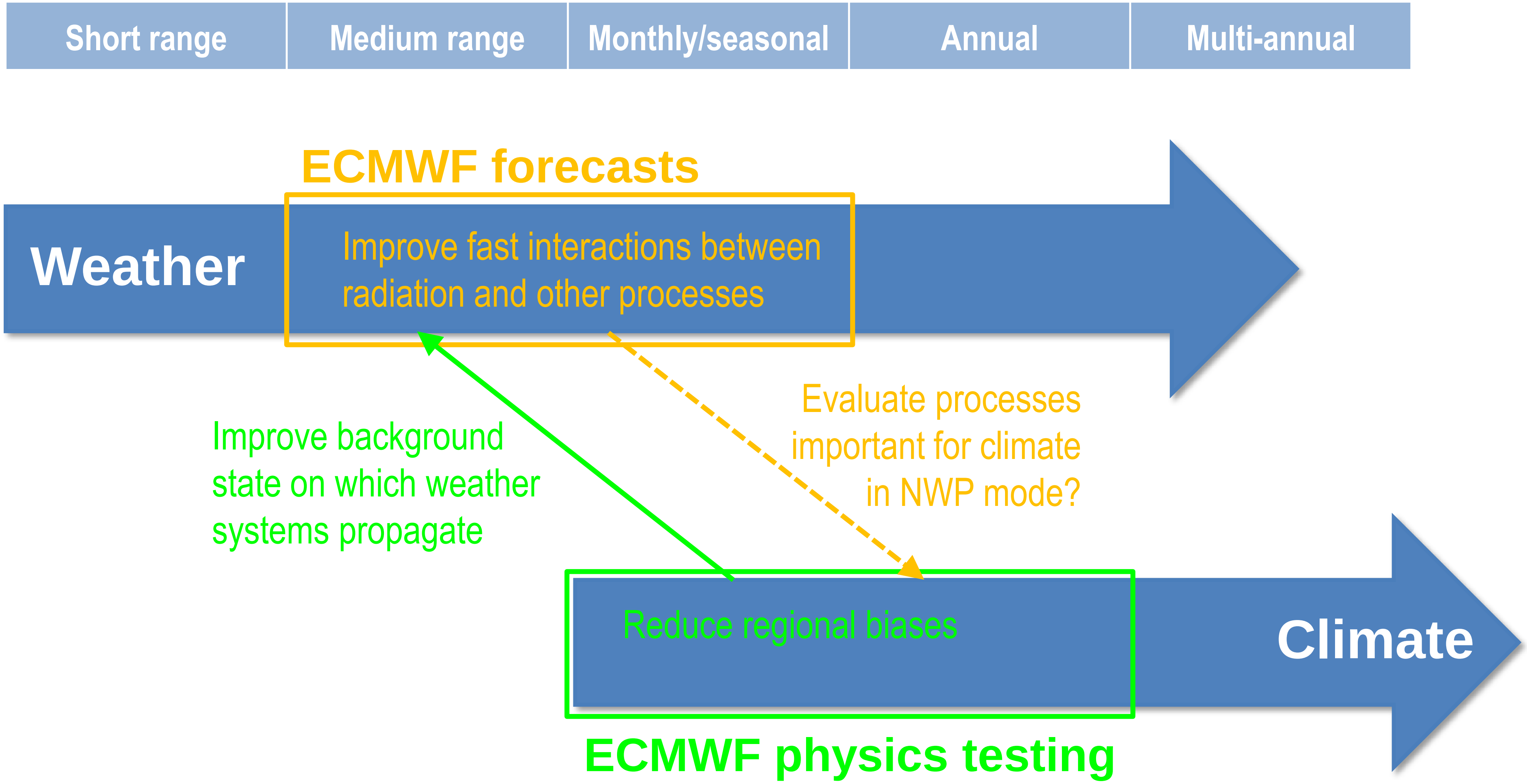
Robin Hogan, Alessio Bozzo, Mark Fielding, Howard Barker, Frederic Vitart, Sophia Schaefer, Inna Polichtchouk and many colleagues at ECMWF

r.j.hogan@ecmwf.int

ECMWF

Radiation and predictability

- Predictability of the first kind: *anomalies via initial conditions*
- Predictability of the second kind: *means via boundary conditions*



Challenges for radiation in NWP models

Solar spectrum

Non-LTE effects

Water vapour biases

Middle atmosphere

Ozone

Code optimization

GPUs

Efficiency

Spatial/temporal/spectral resolution

Clouds

Overlap

Sub-grid heterogeneity

3D effects

Particle size

Longwave scattering

Optical properties

Water vapour continuum

Clear-sky absorption

Aerosols

Sea emissivity

Snow albedo

Forests

Coastlines

Urban areas

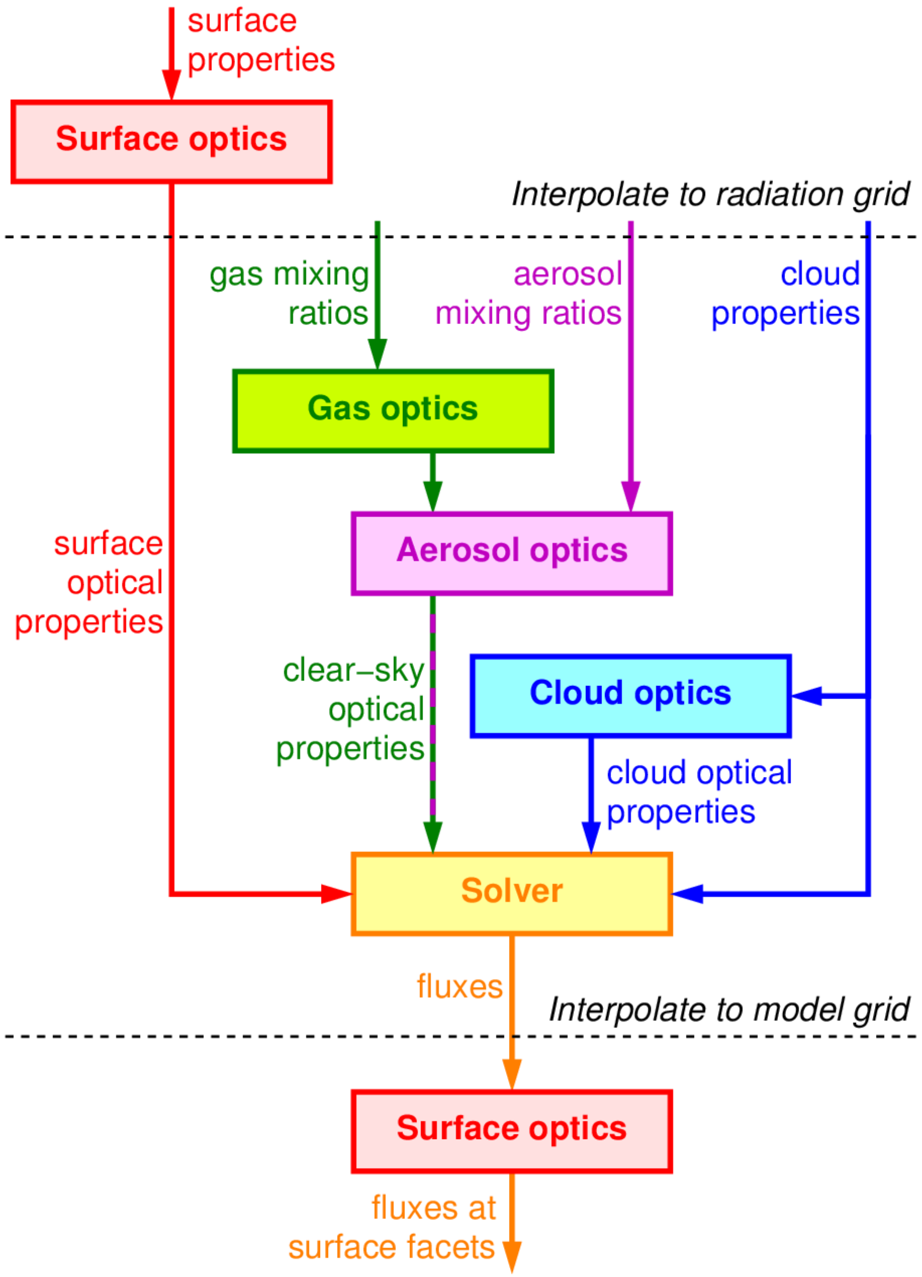
Surface

Orography

Land albedo datasets

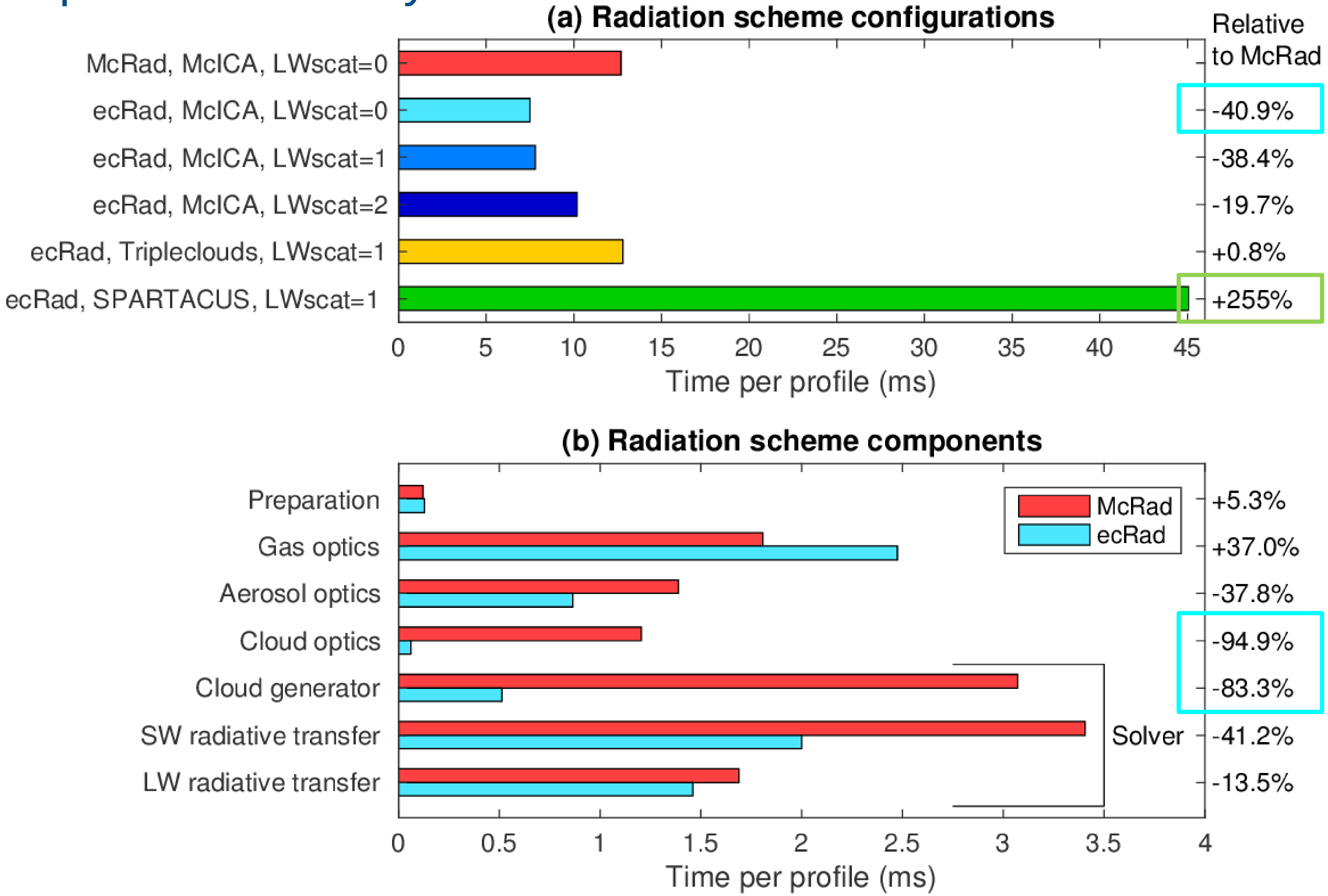
Modular radiation scheme for ECMWF: ecRad

- 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



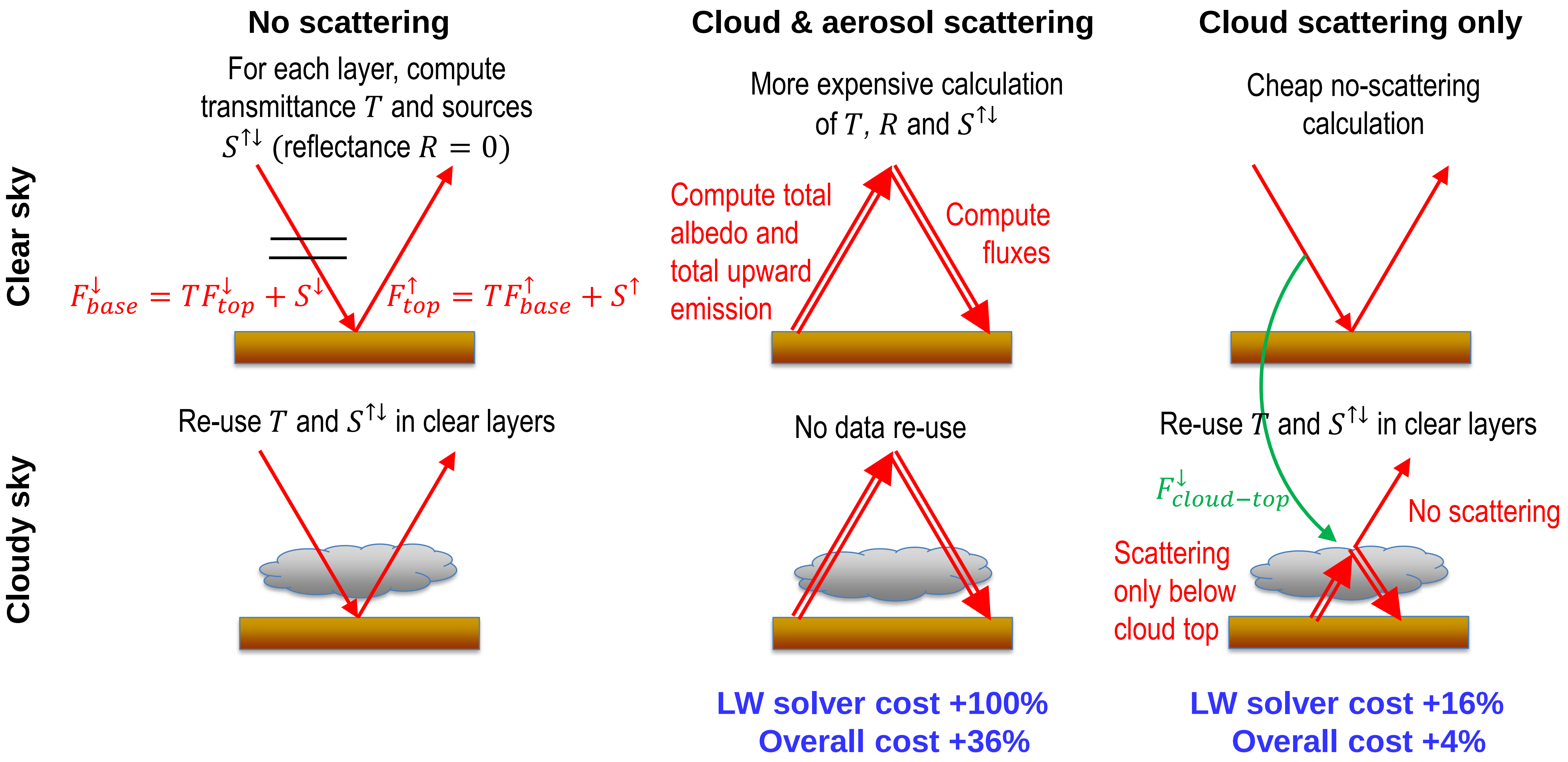
- Solver
  - McICA, Tripleclouds or SPARTACUS solvers
  - SPARTACUS makes the IFS the only global model that can do 3D radiative effects
  - Better solution to longwave equations improves tropopause & stratopause
  - Longwave scattering optional
  - Can configure cloud overlap, width and shape of PDF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

Improved efficiency



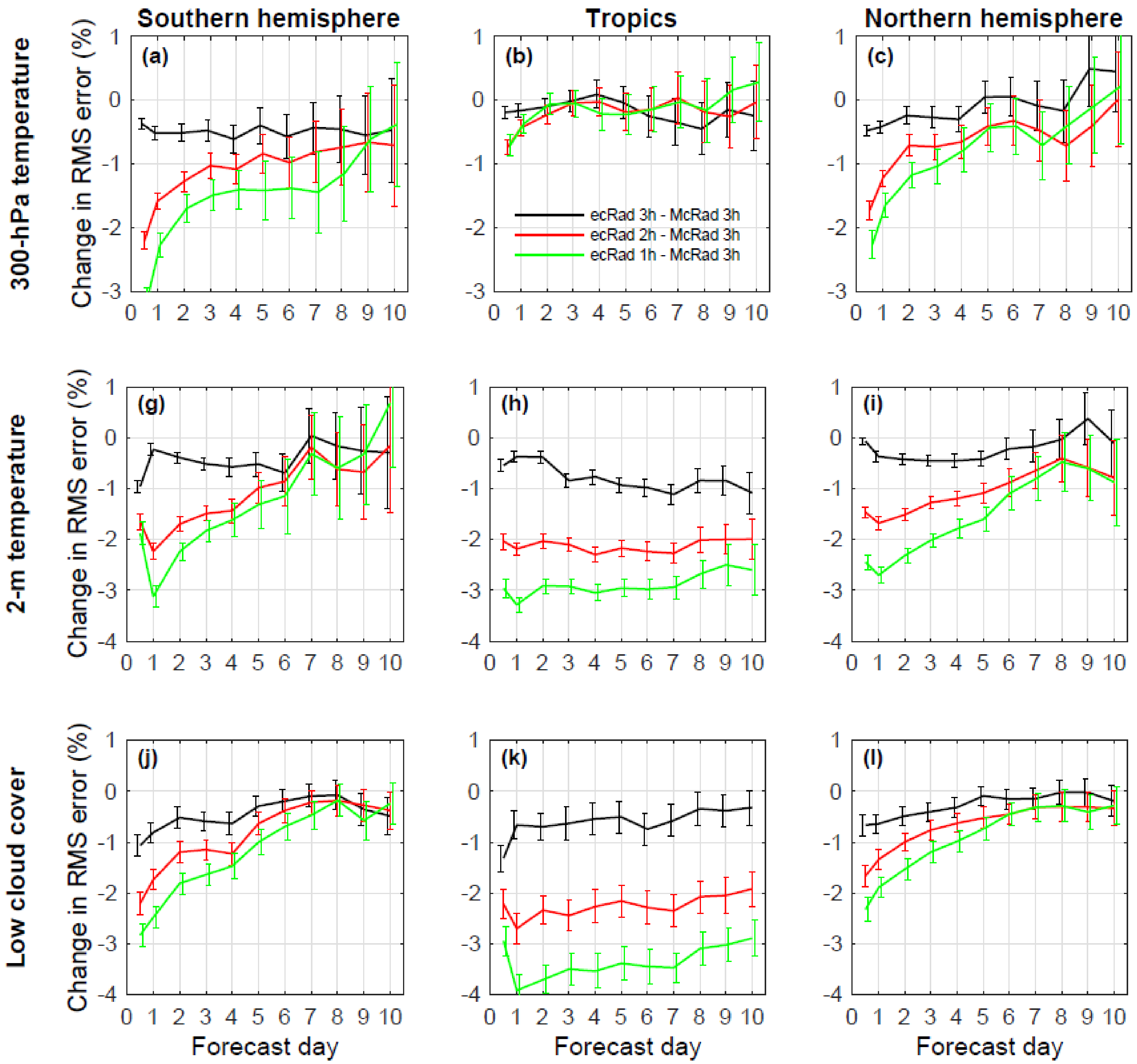
- Much faster than original scheme in operational configuration
- 3D radiation is more expensive, but feasible in research mode
- Cloud treatment is much faster

Fast longwave scattering for clouds but not aerosols



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 (possibly) reduced McICA noise
- 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 plans to use 1 h radiation from operational cycle 46R1
  - Temperature RMSE down by 3%



Hogan & Bozzo (submitted to JAMES)

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

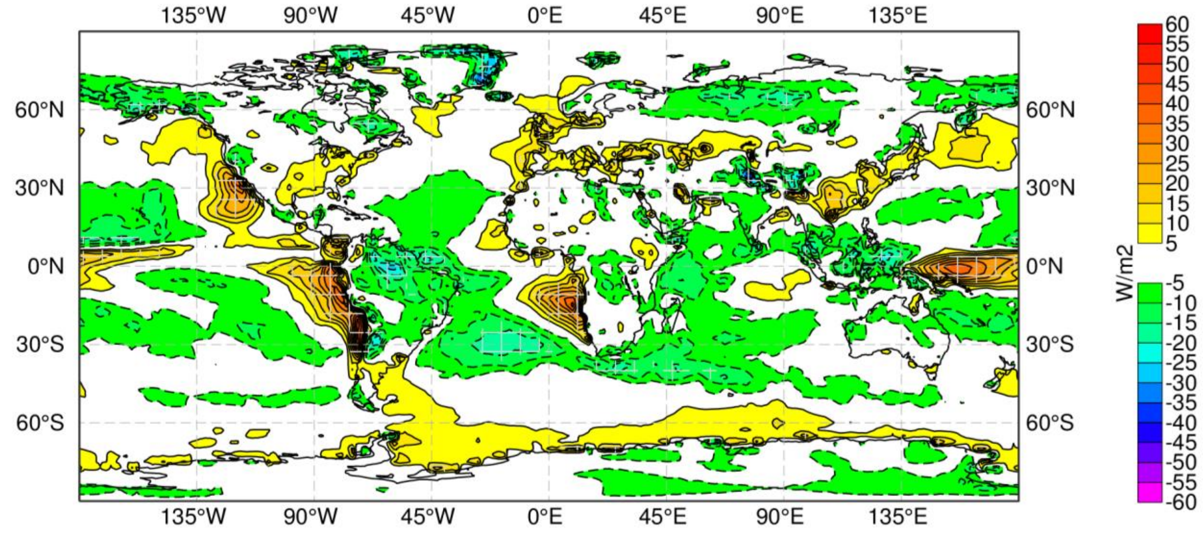
- ECMWF has lowest spatial resolution for radiation
  - Experiments show this barely degrades forecasts (unlike 3-h radiation timestep)
- Met Office NWP model uses 3.7 times fewer g-points than RRTM-G
- Full-spectrum correlated-k estimates of coarsest possible spectral resolution

IFS model climate: ***the good***…

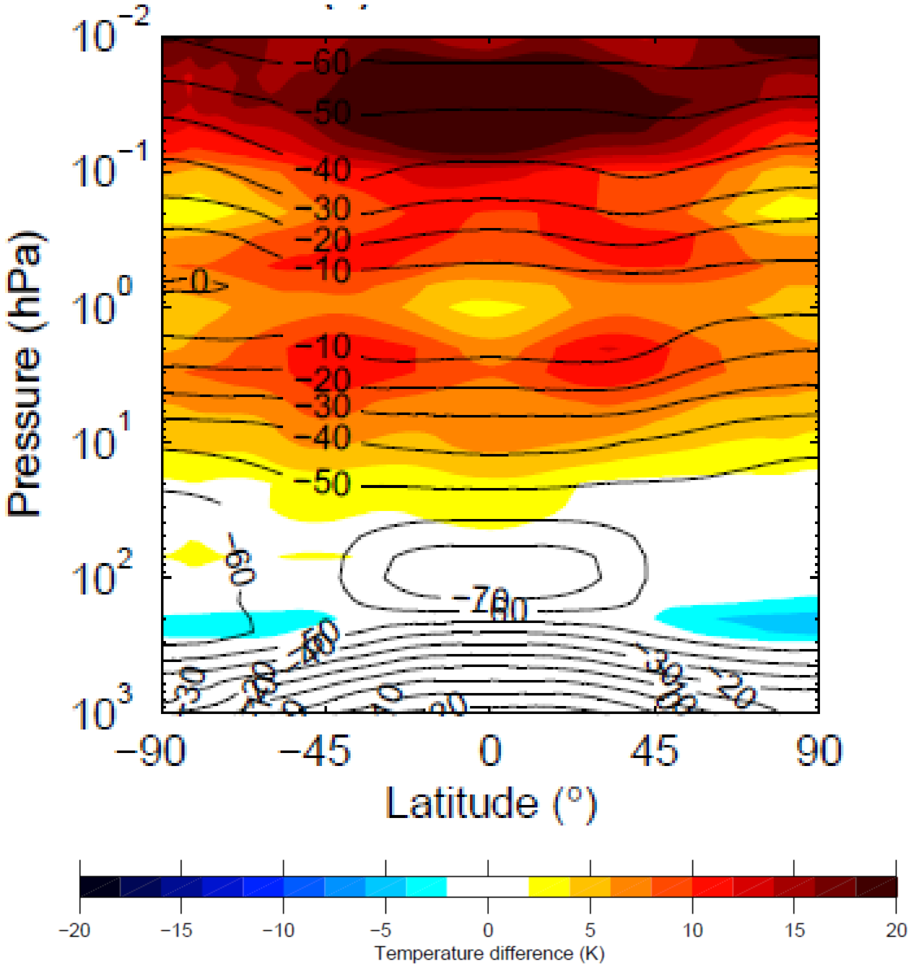
<2 ≥2 ≥4 W m^{-2}

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
ERA-Interim	**3.7**	**−0.1**	**3.6**	**−2.0**
Coupled IFS climate	**−0.4**	**−0.9**	**0.4**	**0.7**

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

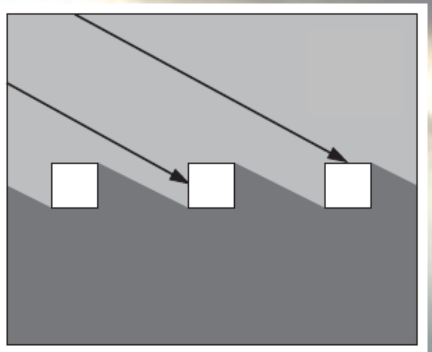


*…**and the ugly** (middle-atmosphere temperature bias)*

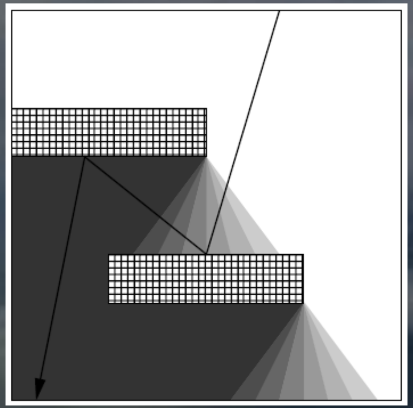


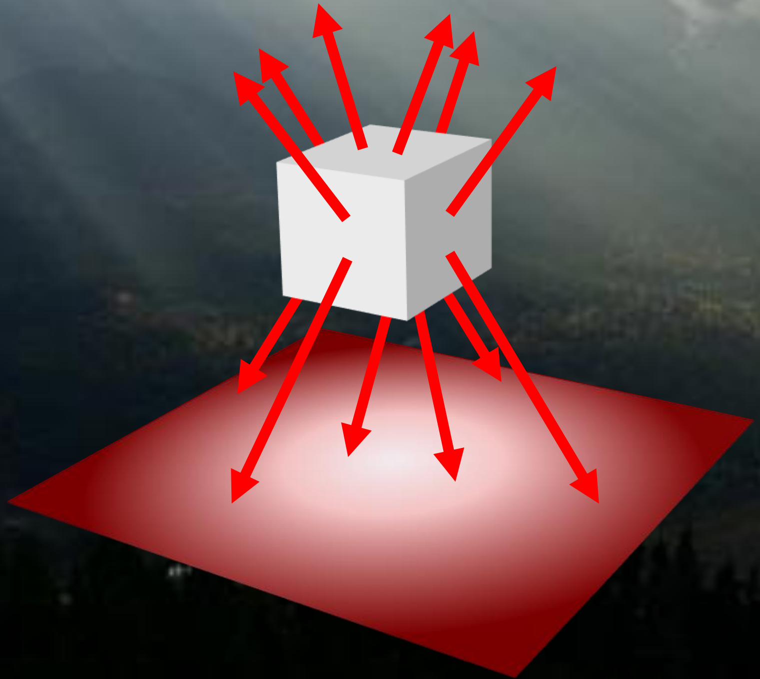
Errors due to neglecting 3D effects

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



- **Shortwave entrapment**
  - 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

Evaluation of "SPARTACUS" solver for representing 3D radiative effects

- "Speedy Algorithm for Radiative Transfer through Cloud Sides": solve two-stream equations for (a) clear and (b,c) cloudy regions but add terms for lateral exchange
- For direct beam (considering two regions):

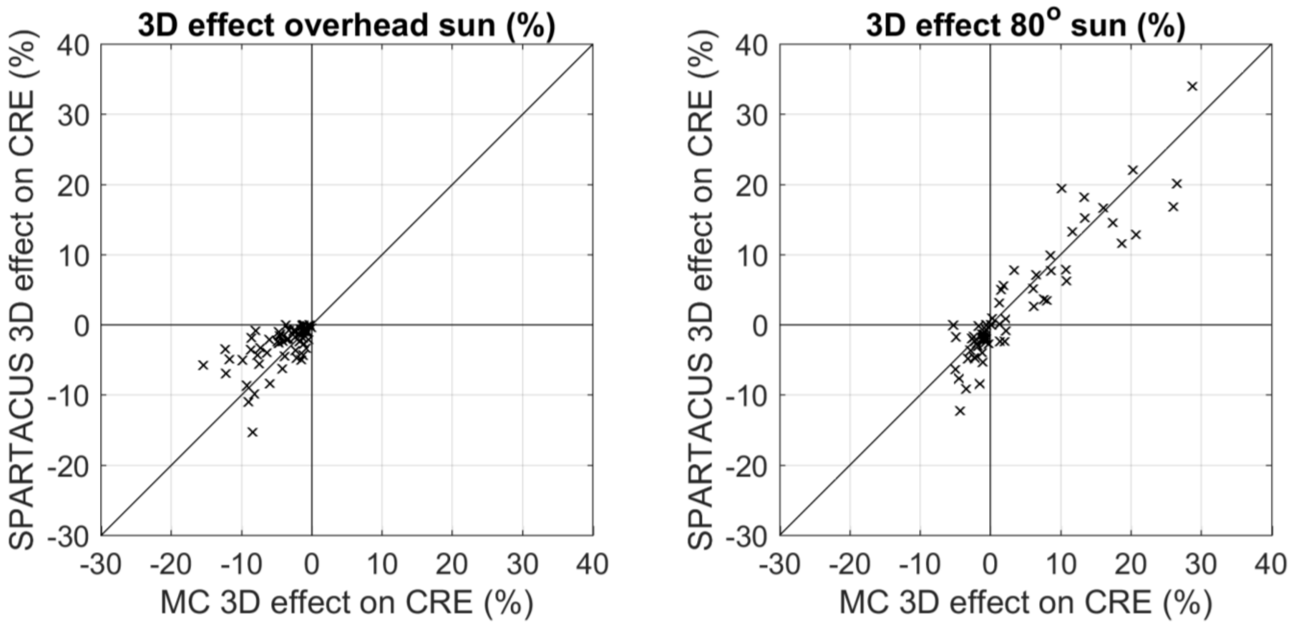
$$\frac{dF^a}{d\delta'} = -\frac{\delta^a}{\mu_0}F^a - f_{\text{dir}}^{ab}F^a + f_{\text{dir}}^{ba}F^b$$

$$\frac{dF^b}{d\delta'} = -\frac{\delta^b}{\mu_0}F^b - f_{\text{dir}}^{ba}F^b + f_{\text{dir}}^{ab}F^a$$

- Geometric terms f^{ab} depend on a parameterization of "cloud scale"

Hogan et al. (2016)

- Tested offline against Monte Carlo calculations for 59 varied scenes from Canadian and Met Office models at ~200 m resolution

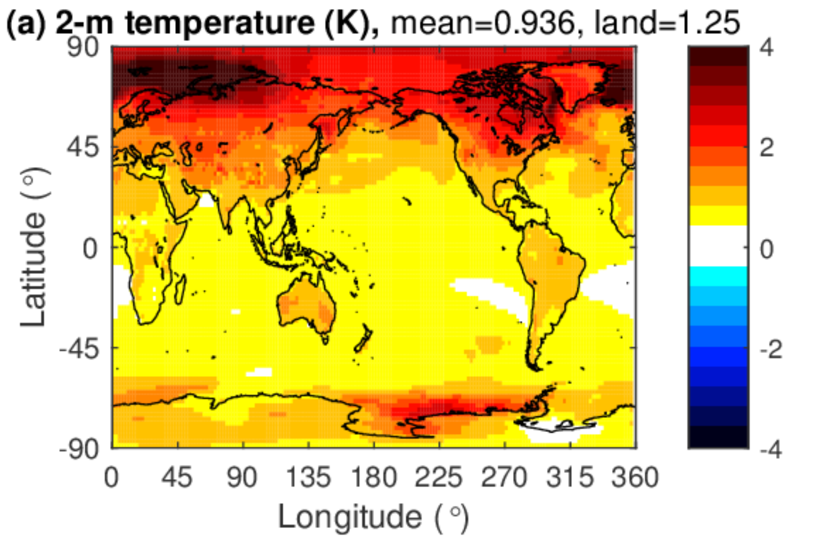


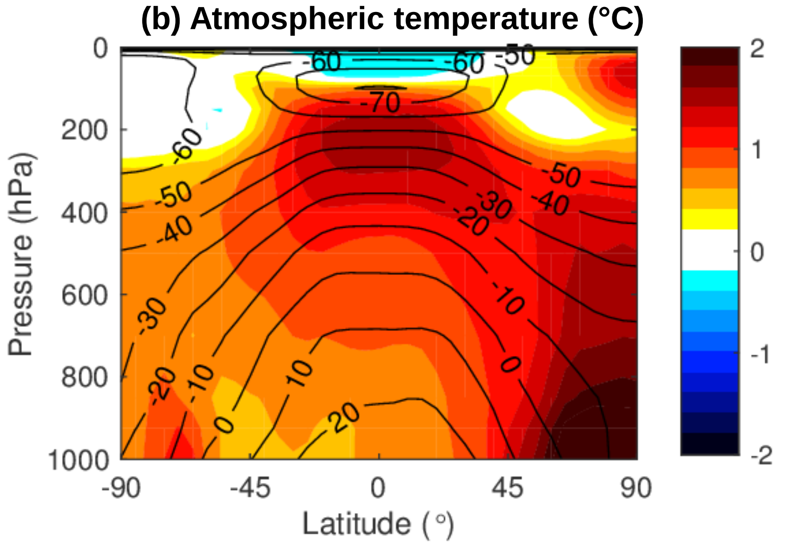
Entrapment dominates **Side illumination dominates**

Global impact of the specification of cloud structure and 3D effects

- Shonk and Hogan (2010) estimated the instantaneous change to cloud radiative effect of sub-grid cloud structure and overlap (W m^{-2})
- Best estimate from SPARTACUS suggests *3D effects have similar net impact to overlap decorrelation, but opposite sign*
- Impact of turning on 3D effects in a free-running coupled simulation of the ECMWF model (5 member 20 years, average final 5 years): *warm the surface by around 1 K, improve Arctic sea-ice bias*

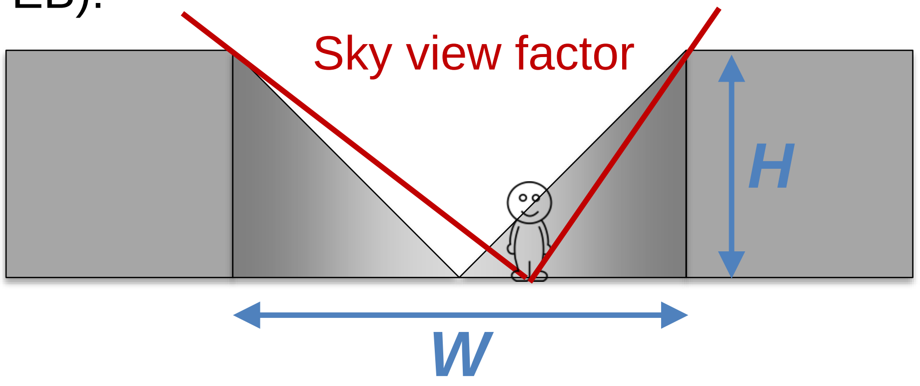
Mechanism	Shortwave surface	Longwave surface	Net surface
Add horizontal structure	+6.7	-2.9	+3.8 (±2)
Add overlap decorrelation (EXP-RAN minus MAX-RAN)	-4.1	+2.2	-1.9 (±0.2)
Add 3D effects	+0.9	+1.2	+2.1



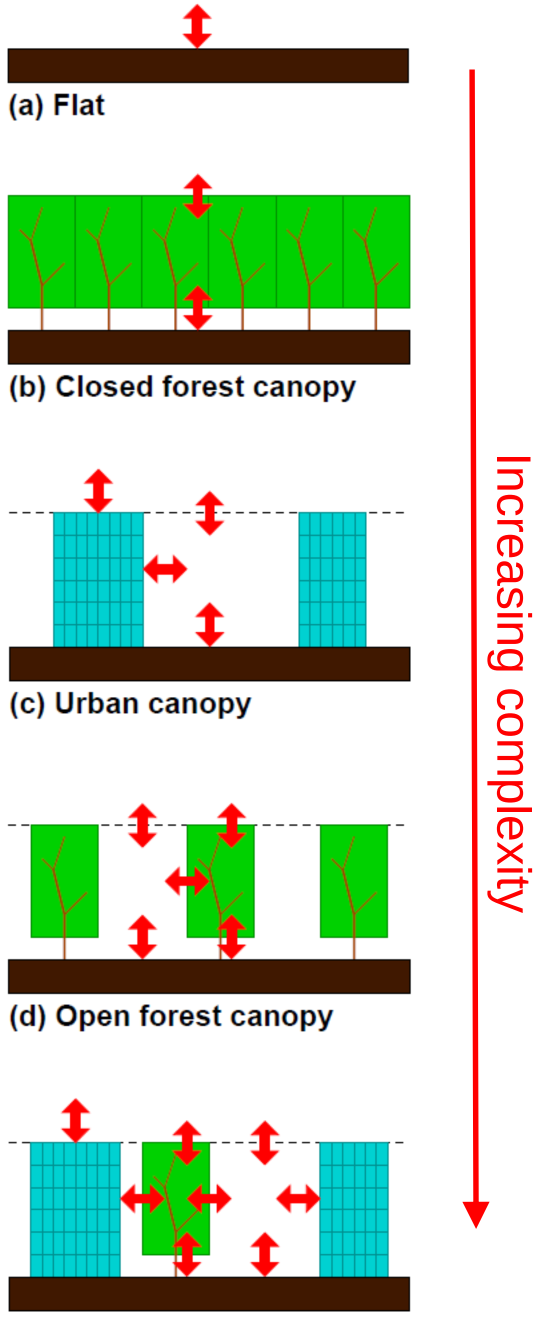


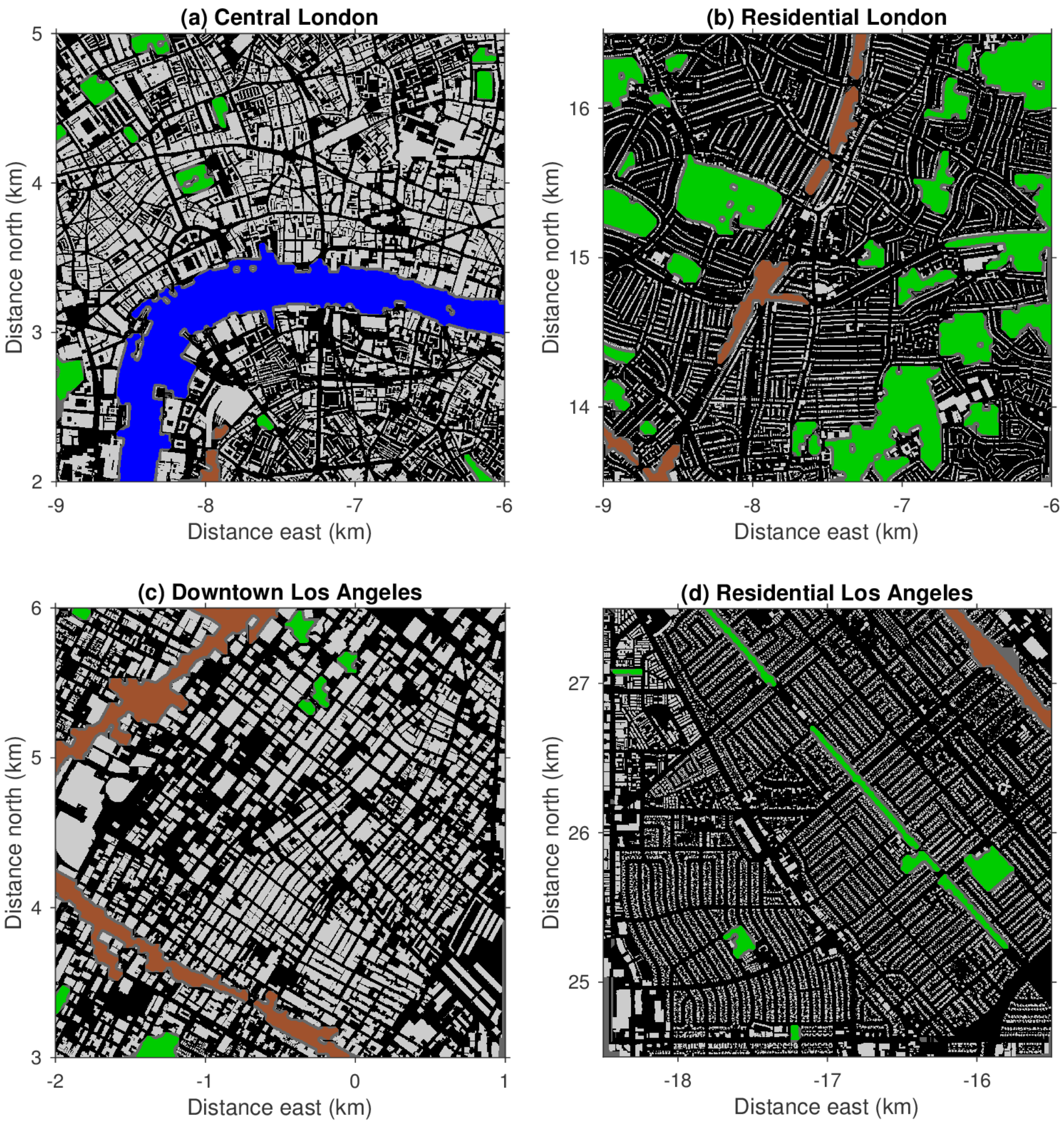
Towards a consistent radiative treatment of complex surfaces

- The IFS currently treats urban areas as crops, grassland or forest ☹
- The *infinite street canyon in vacuum* is ubiquitous in urban models (e.g. MORUSES, TEB):



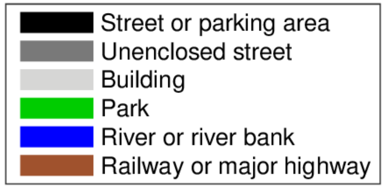
- Can we instead use a more realistic *two-stream treatment*?
  - Scattering/absorption by walls treated by SPARTACUS-like exchange terms
  - Add gas/aerosol in the canopy *coupled spectrally* to the atmosphere above
  - Use a building-separation distribution fitted to observations
  - Possibly add street trees by solving two-stream equations in clear/vegetated regions with coupling terms (SPARTACUS-Vegetation: Hogan et al. 2018)

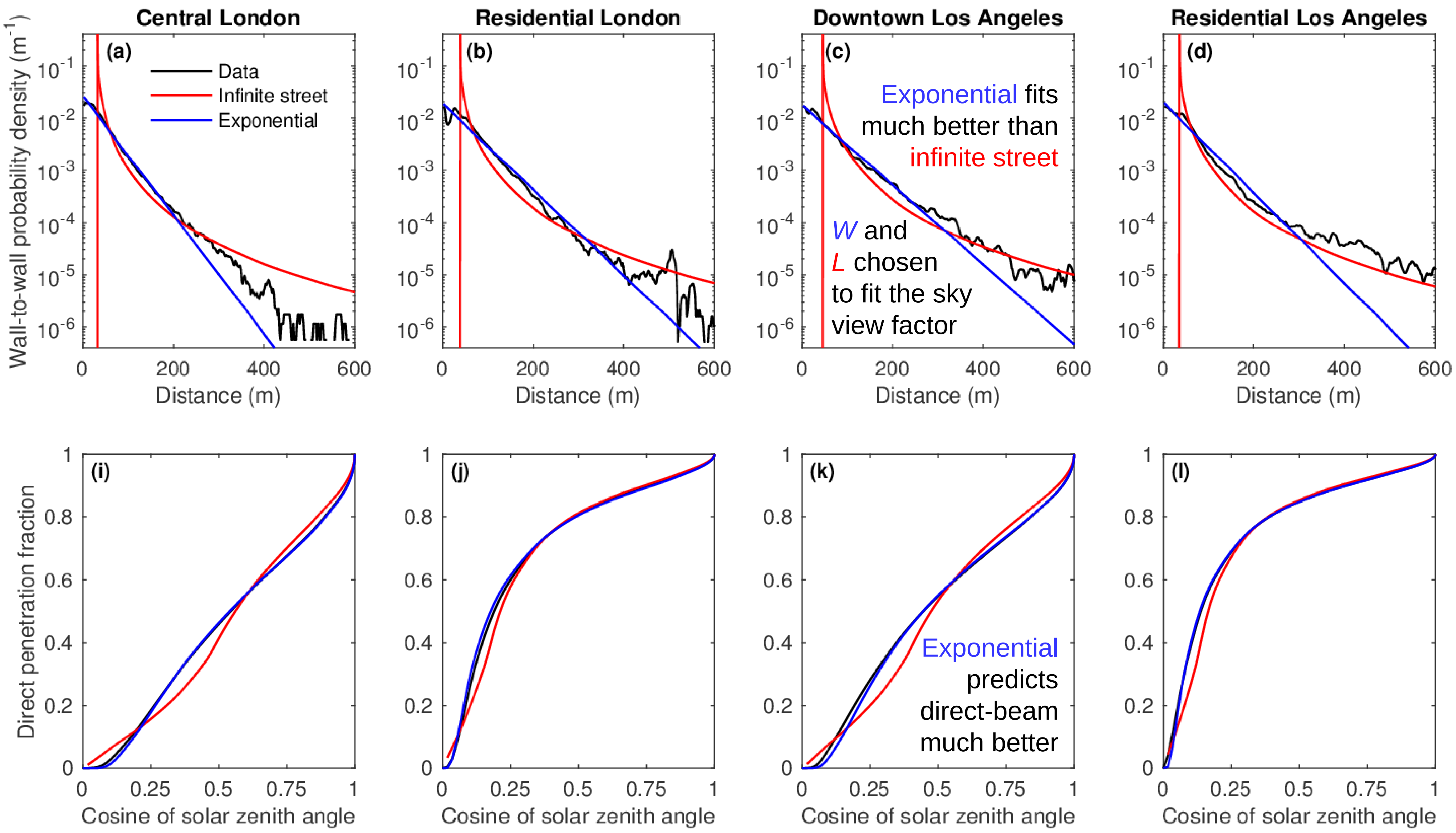




Geometry of real cities

- Geometry aspects of radiative transfer determined entirely by
  - Building height *H* (assumed constant)
  - The probability distribution of wall-to-wall distances $p_{ww}(x)$
- If probability distribution is exponential:
  - $p_{ww}(x) = \exp\left(-\frac{x}{L}\right)/L$
- …then the propagation of direct solar radiation through the urban canopy follows Beers law, and is easy to incorporate into a two-stream scheme:
  - $F_{dir,street} = F_{dir,top}\exp\left(-\frac{H}{L}\tan\theta_0\right)$

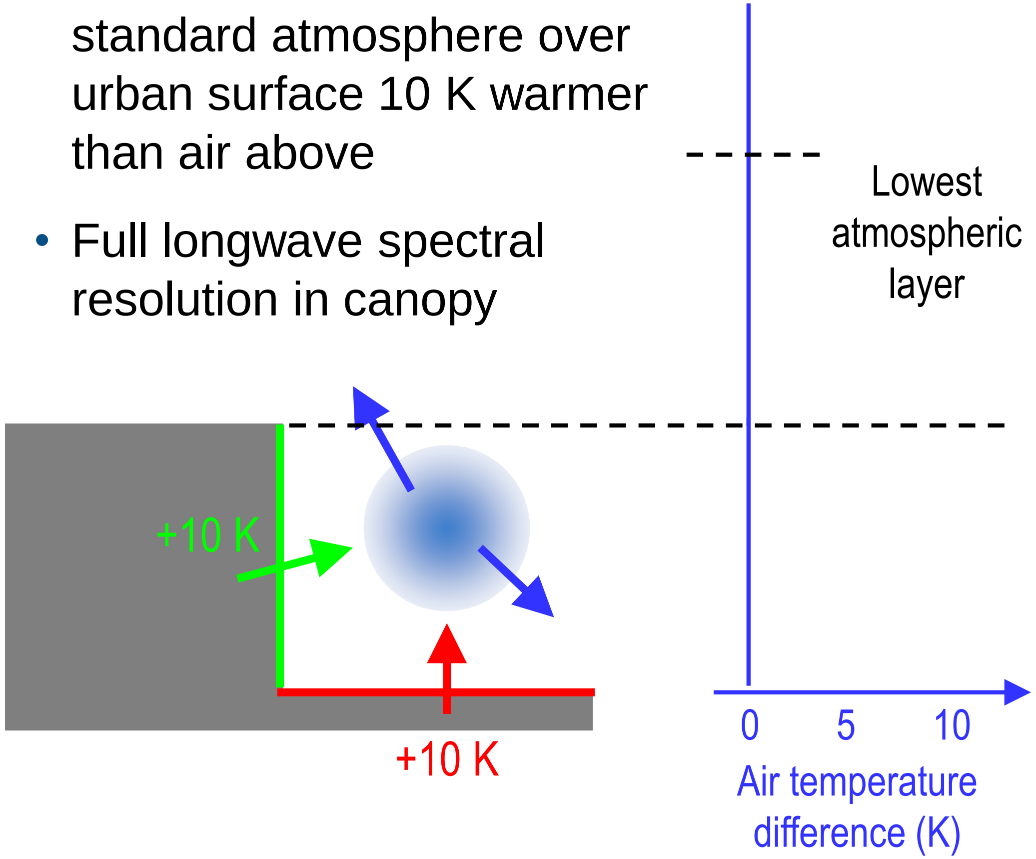


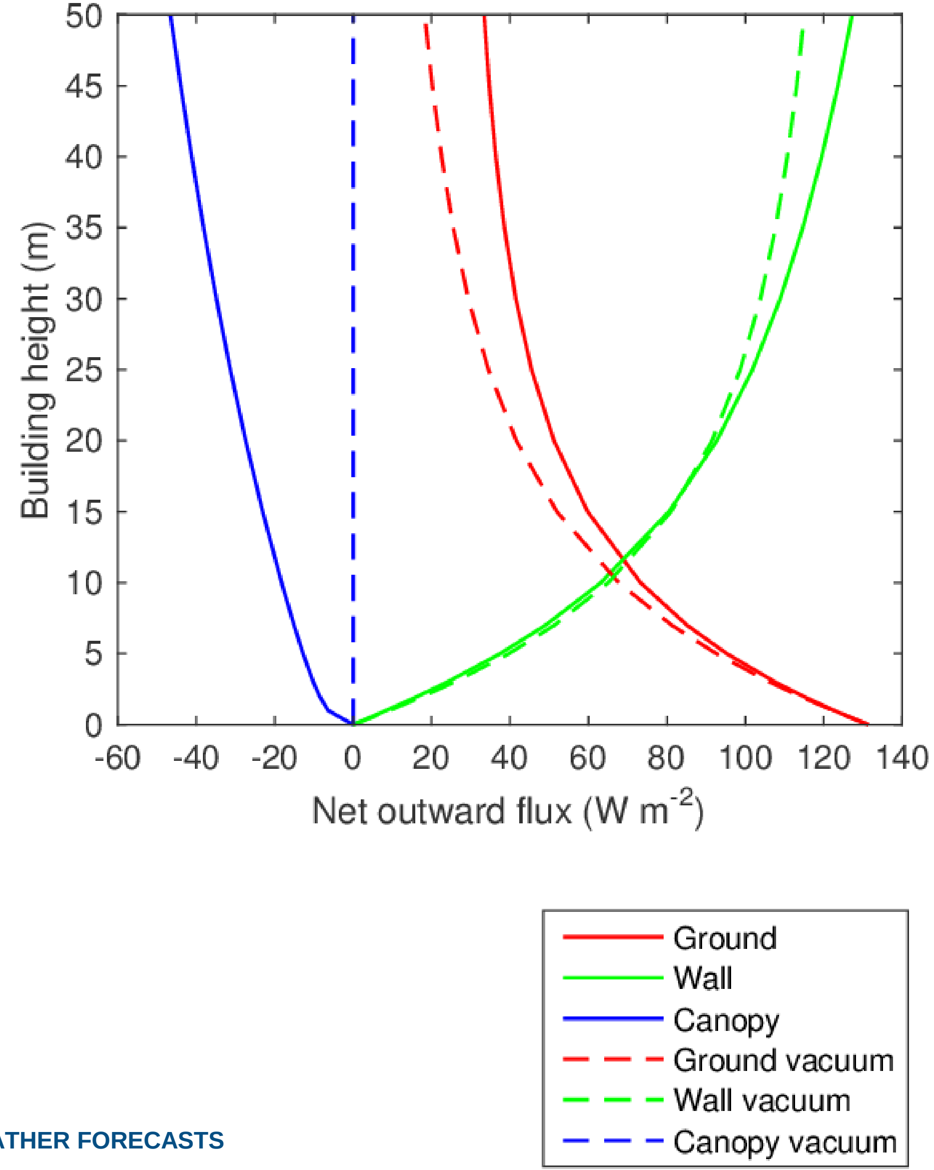


Central London
Residential London
Downtown Los Angeles
Residential Los Angeles
(a)
(b)
(c)
(d)
Data
Infinite street
Exponential
Exponential fits much better than infinite street
W and L chosen to fit the sky view factor
Wall-to-wall probability density (m^-1)
Distance (m)
(i)
(j)
(k)
(l)
Exponential predicts direct-beam much better
Direct penetration fraction
Cosine of solar zenith angle

How important is air in the canopy for LW radiative transfer?

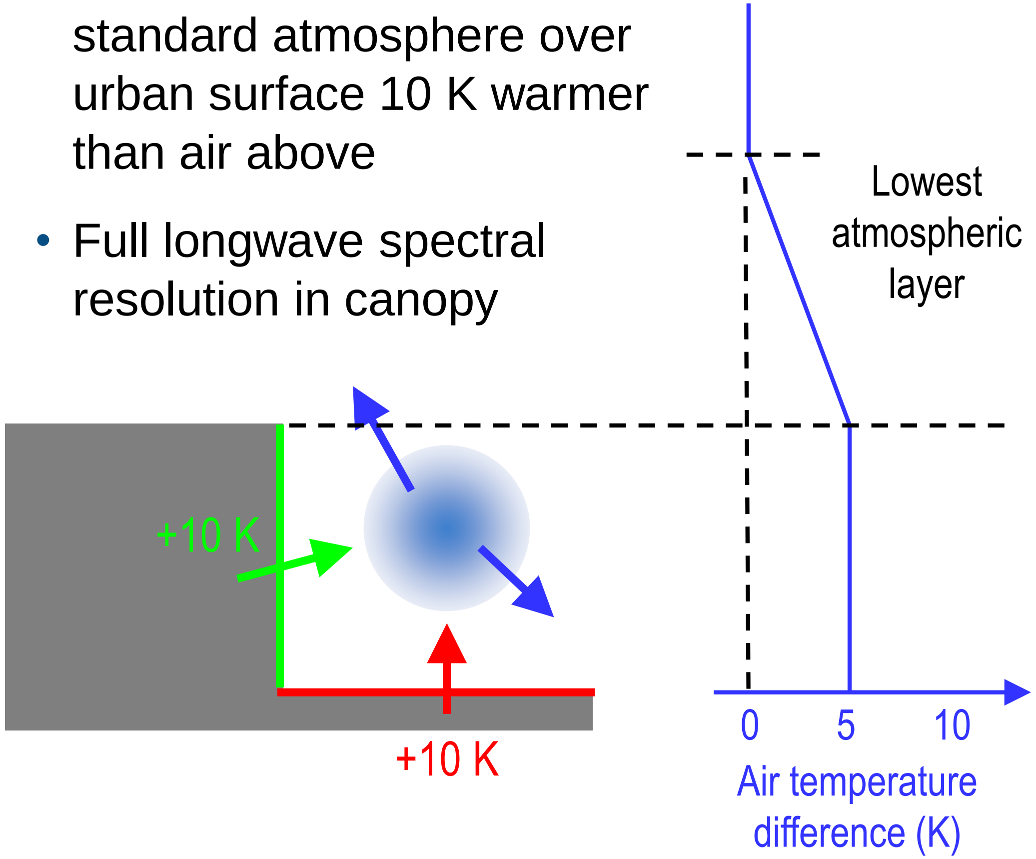
- Offline ecRad with MLS standard atmosphere over urban surface 10 K warmer than air above
- Full longwave spectral resolution in canopy

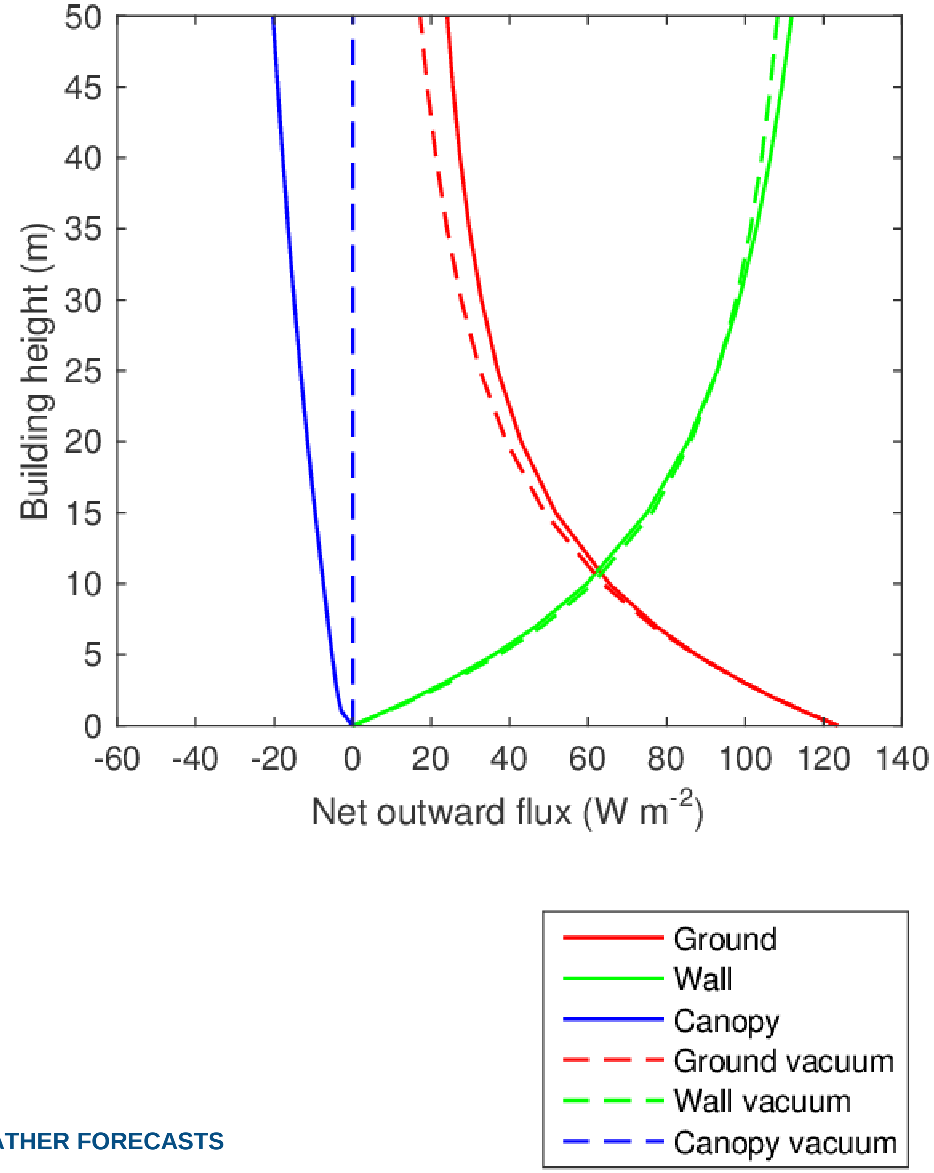




How important is air in the canopy for LW radiative transfer?

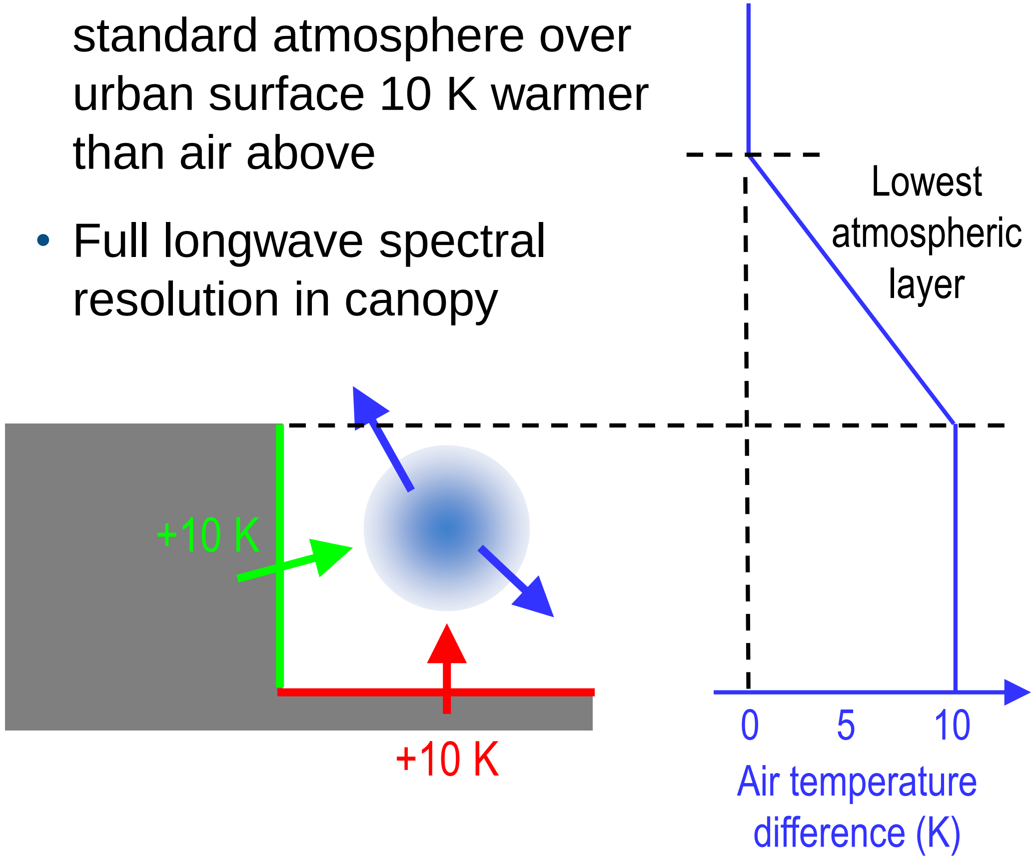
- Offline ecRad with MLS standard atmosphere over urban surface 10 K warmer than air above
- Full longwave spectral resolution in canopy

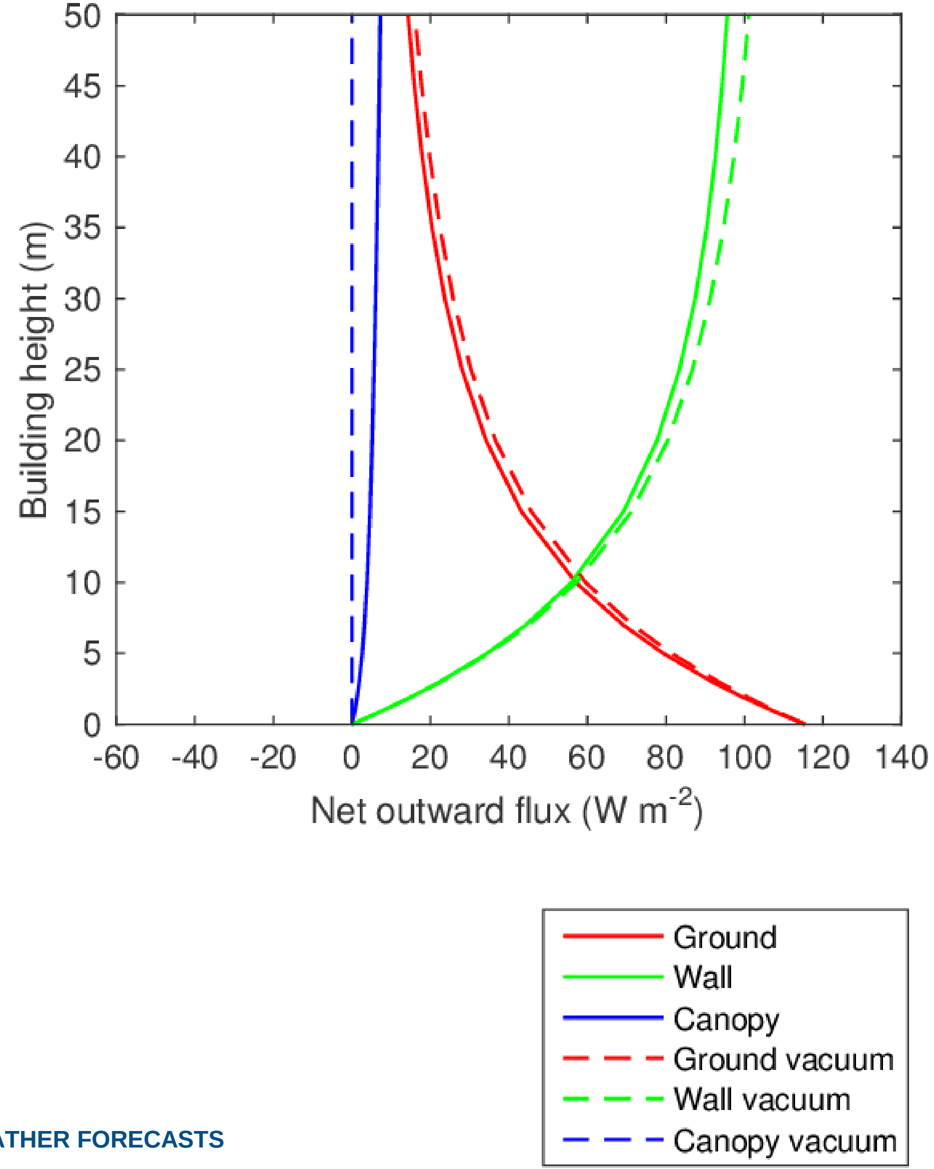




How important is air in the canopy for LW radiative transfer?

- Offline ecRad with MLS standard atmosphere over urban surface 10 K warmer than air above
- Full longwave spectral resolution in canopy



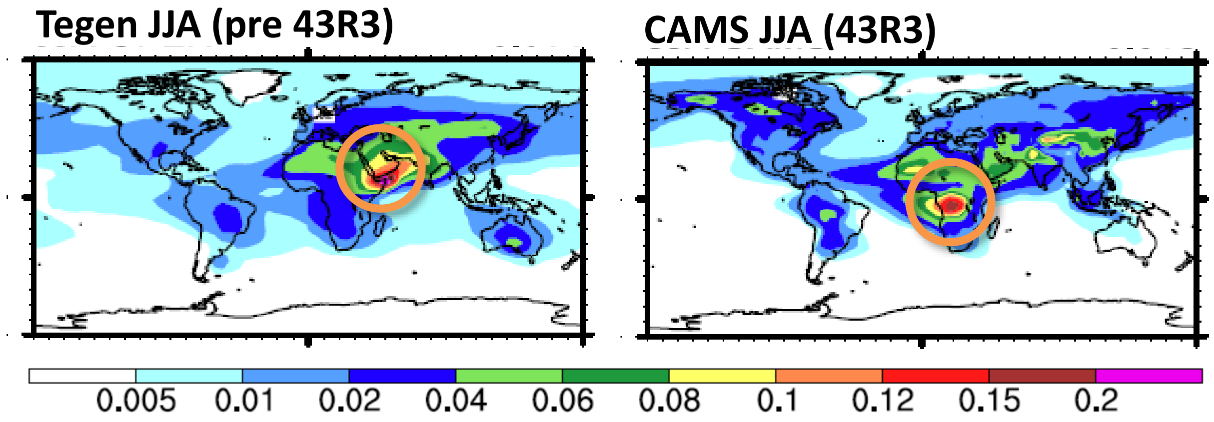


- *Validation needed!*

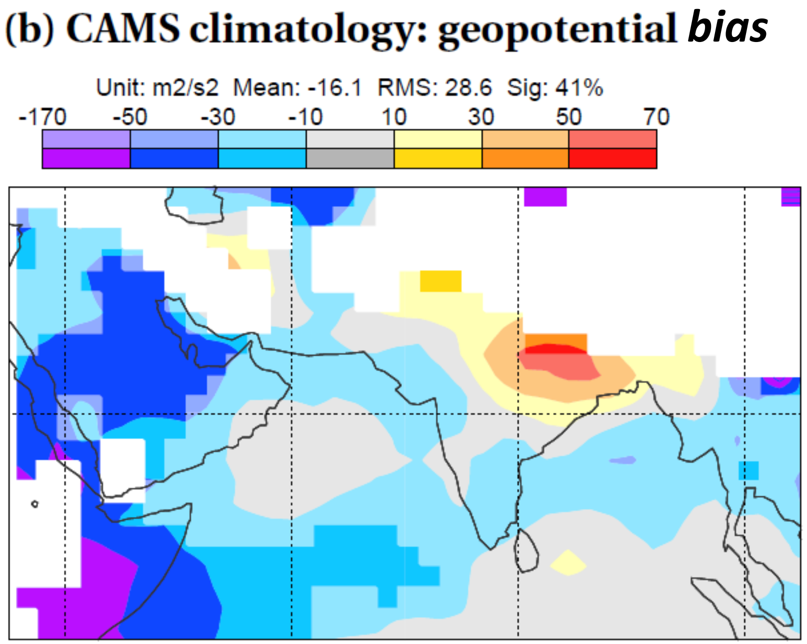
Aerosols

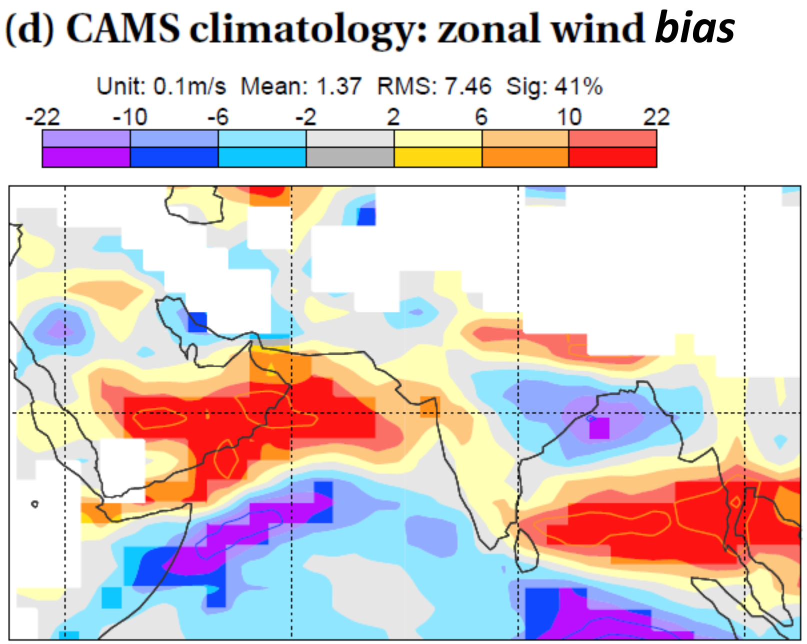
Bozzo et al. (2017)

- Atmospheric forcing depends on *absorption* optical depth:



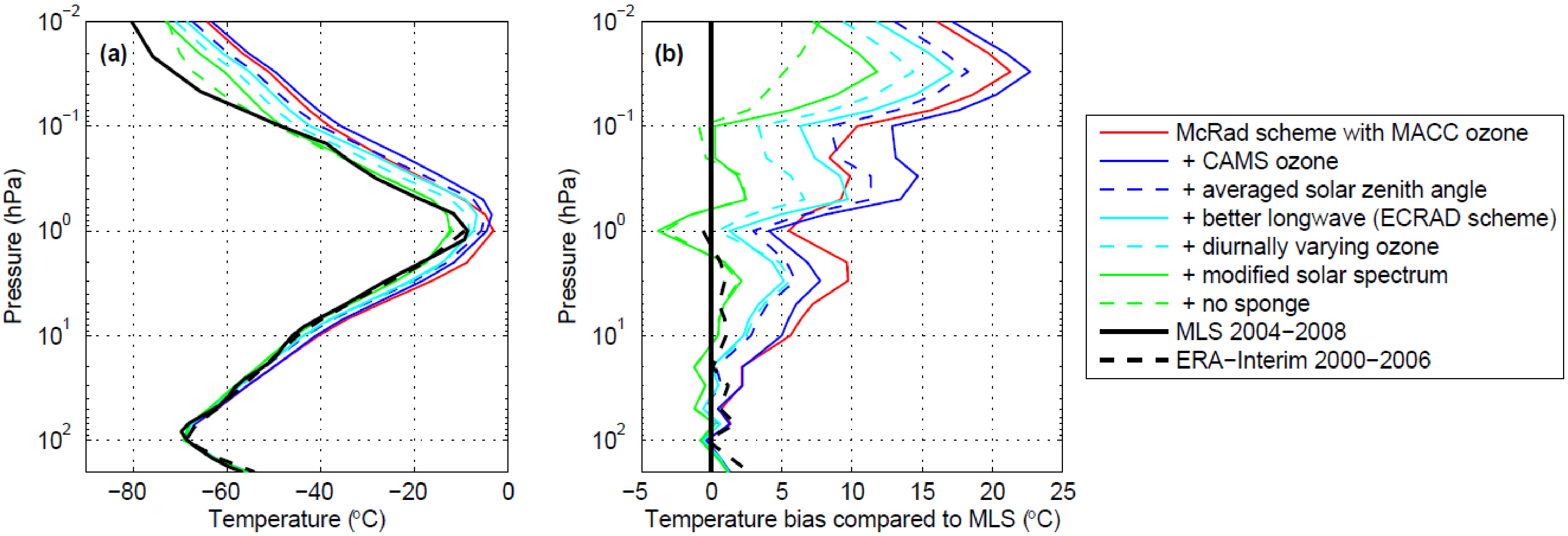
- Reduced absorption over Arabia in new CAMS climatology weakens the overactive Indian Summer Monsoon, halving the overestimate in monsoon rainfall
- Increased absorption over Africa degraded 850-hPa temperature, traced to excessive biomass burning in CAMS
- *We can measure the impact of aerosols on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





Middle atmosphere 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*

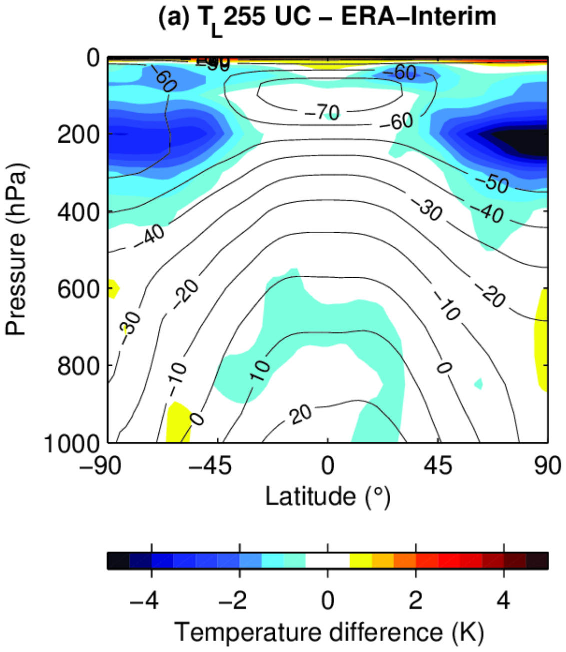


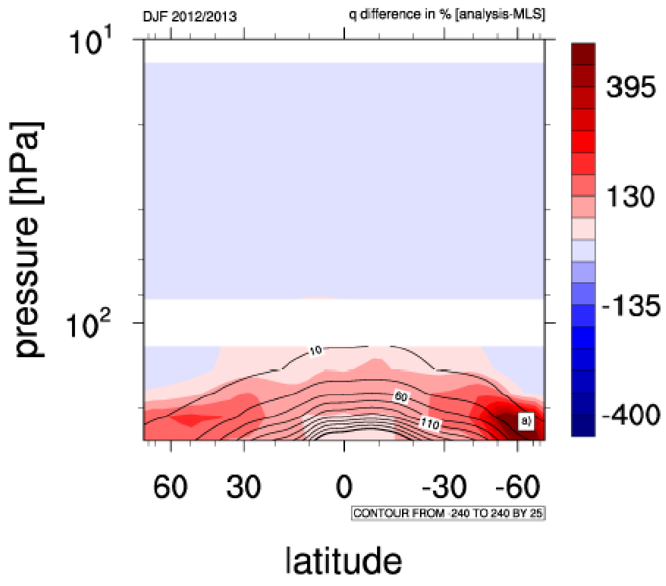
IFS Cycle 41R1

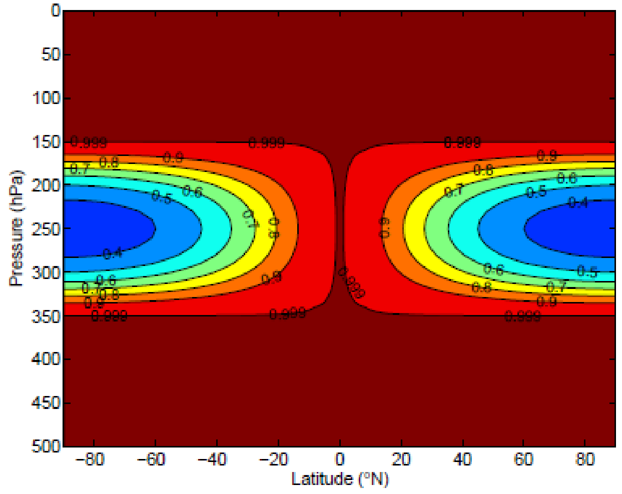
Hogan & Hirahara (2016)

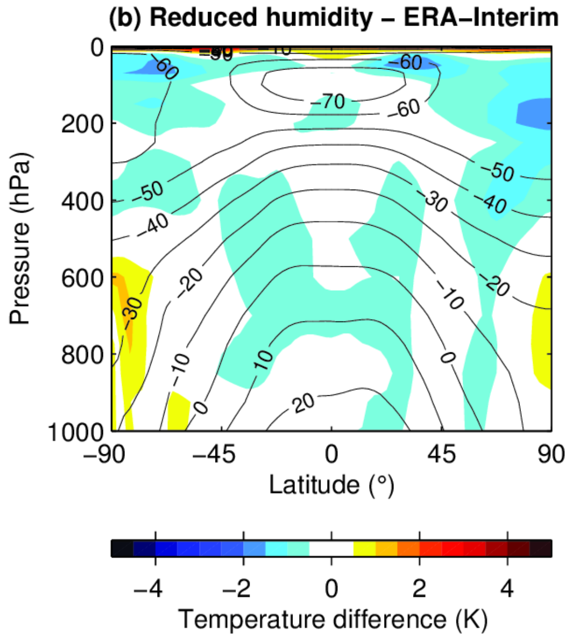
IFS Cycle 43R3

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

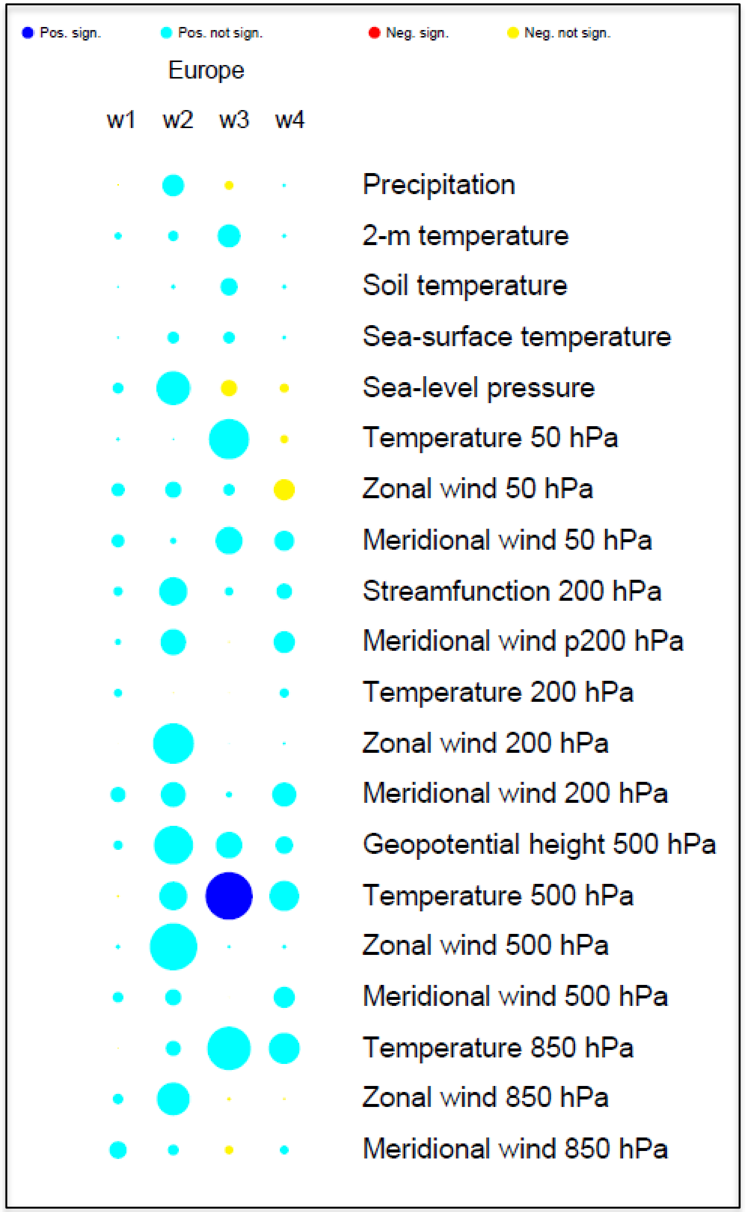
- What if we artificially reduce humidity seen by radiation?
- *Just for experimental purposes, not operations!*

- 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* (good example of radiation interacting with other processes)
- What's the dynamical mechanism? Is it related to polar vortex variability or QBO teleconnections?

- *In the last 2 months, Filip Vana has developed a better Semi-Lagrangian advection scheme for the IFS that largely cures the excessive humidity transport – next step is to verify that it also improves monthly predictive skill!*



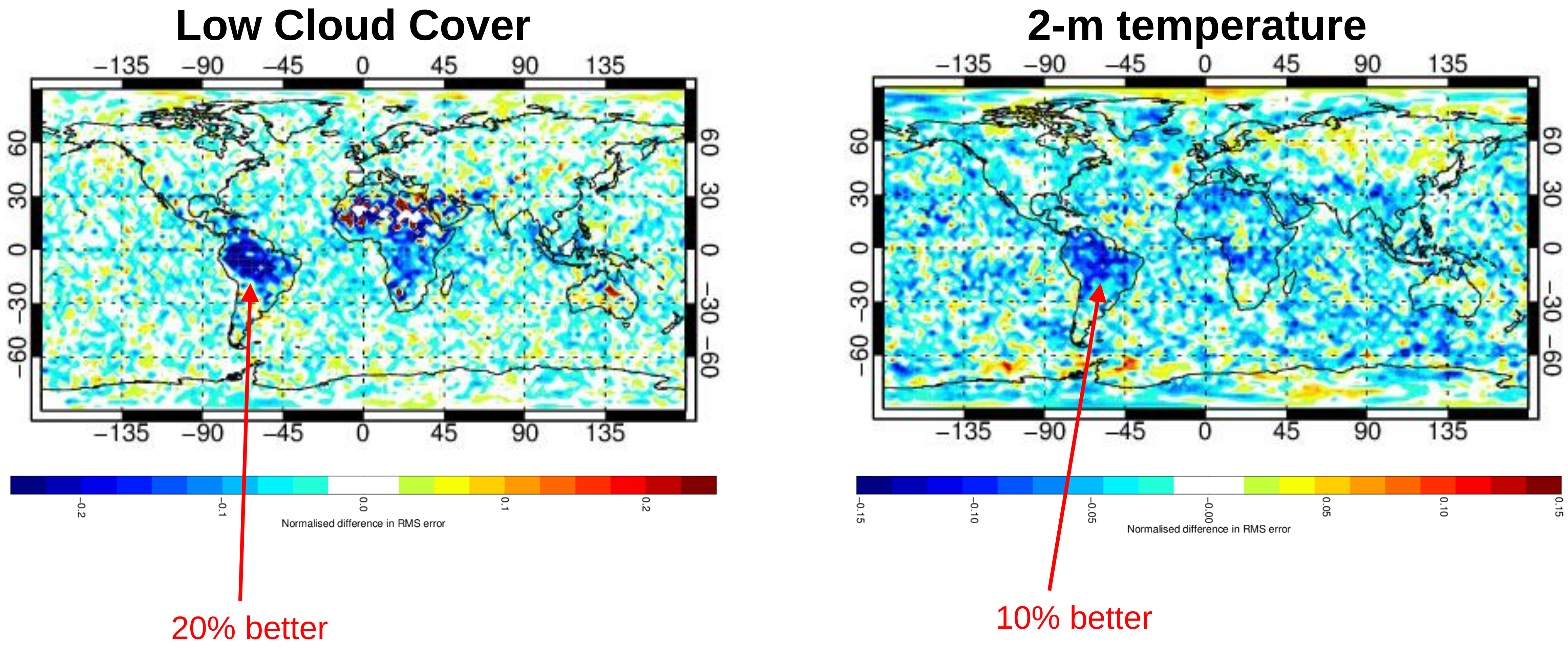
Thanks to Frederic Vitart
(blue is good!)

Summary and outlook

- Need to make progress on many fronts to improve radiative transfer in NWP models
- Traditional approach is to reduce biases in the *model climate,* for example:
  - Aerosol changes can improve tropical biases in monsoons
  - 3D radiation is an option in the ecRad radiation scheme, and can possibly improve polar biases
  - Fixing lower stratosphere temperature bias improves monthly forecast skill
- It is possible, but more tricky, to improve forecasts via other means
  - Understanding the interaction between radiation and other processes is crucial
  - Faster radiation schemes can be called more frequently leading to better cloud-radiation interactions
  - Better interaction with complex surfaces should improve local forecasts, especially in urban areas
- What are the opportunities from better collaboration between those working on radiation in weather and climate, and from the land surface up to the mesosphere (and other planets)?
- *I wish you all a stimulating and enjoyable workshop!*

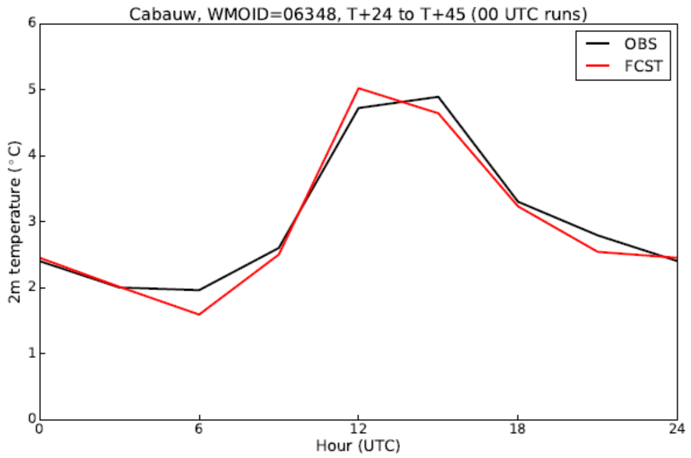
Why does more frequent radiation improve tropical forecasts?

- Fractional change to 5-day forecast RMSE… but what is the mechanism for improvement over rainforests?

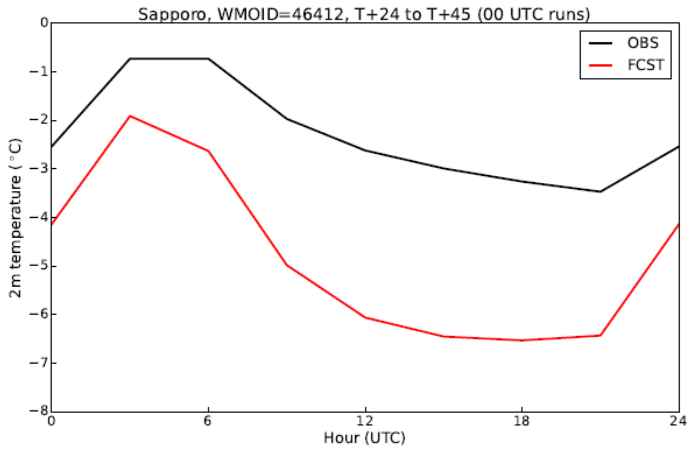


What is the cause of near-surface temperature errors at individual sites?

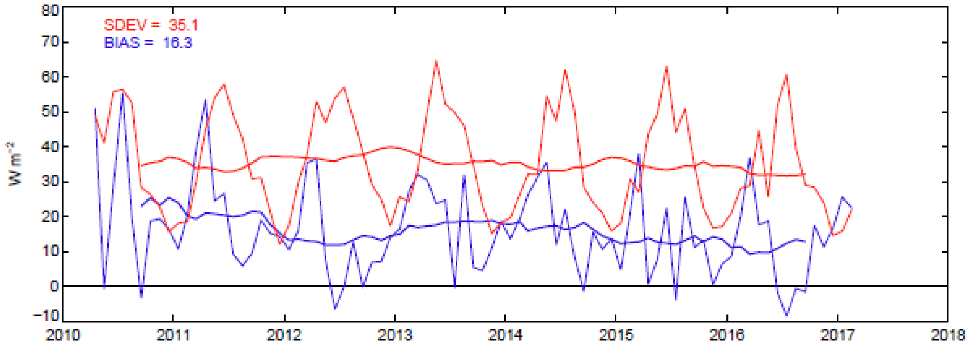
Cabauw December 2016 to February 2017



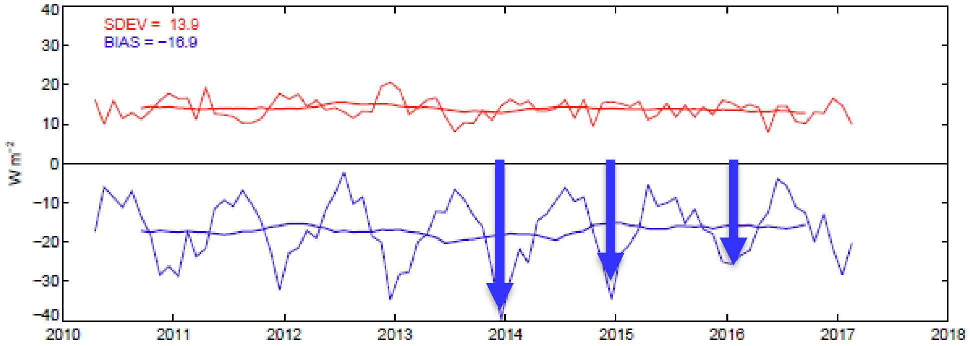
Sapporo December 2016 to February 2017



Sapporo shortwave



Sapporo longwave

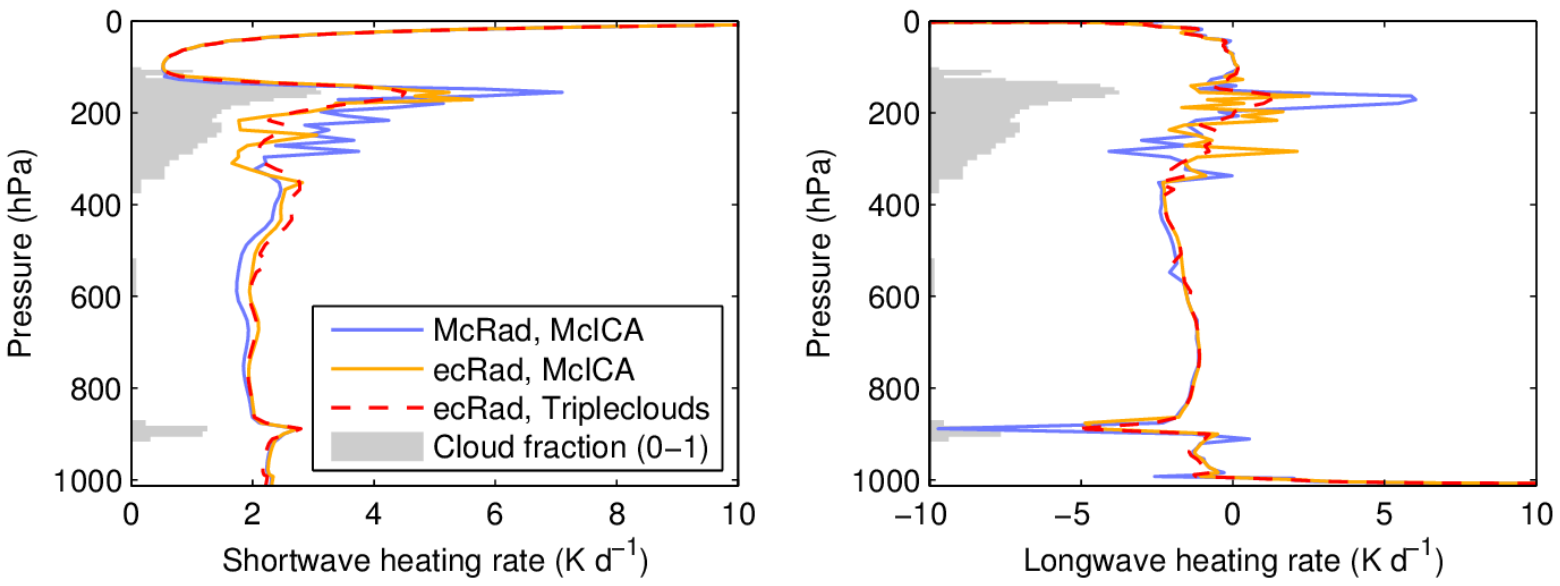


- Some locations are much more difficult than others!
  - Sapporo is a large city, by the coast, surrounded by mountains, with large annual snowfall
- ECMWF has a new task force to unpick the causes of surface temperature errors (including BL, clouds, surface schemes)
- *But there are obvious areas where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

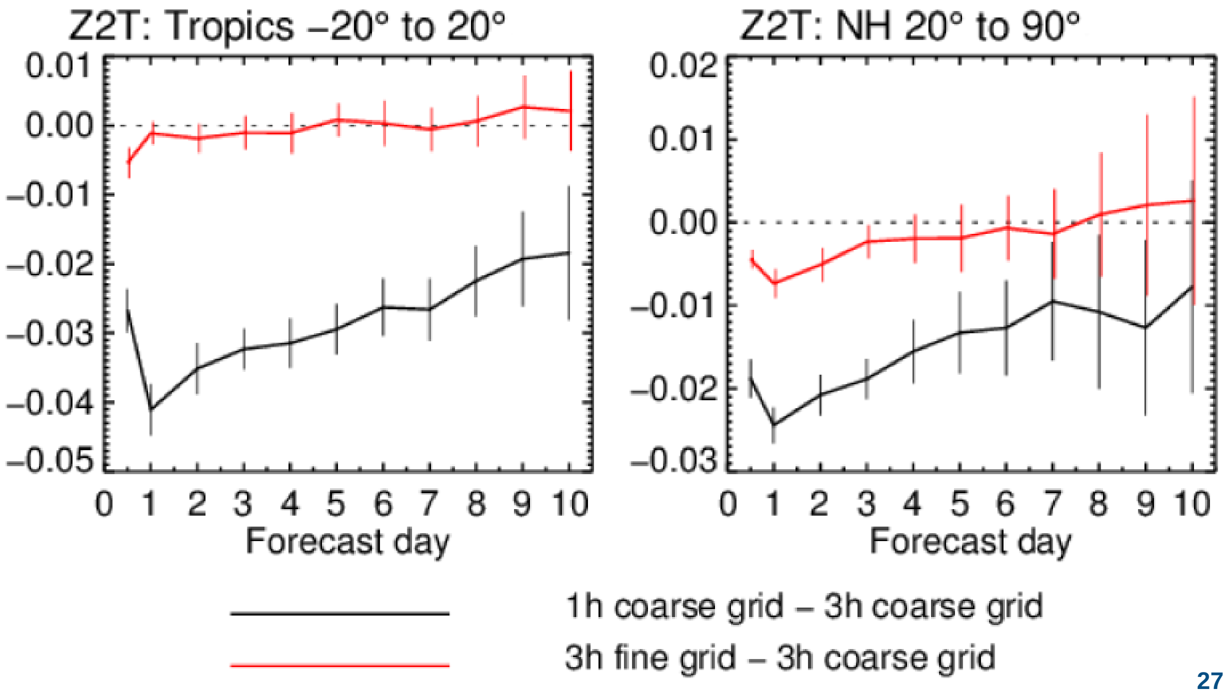
- Far too little downwelling LW: not enough cloud?
- Early evening error could also be signature of urban heat island (Oke 1982), not in model

Improved accuracy

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



- Calling radiation more frequently than 3 h has a much greater impact on forecast skill than calling it every model gridpoint



ECMWF

Test of 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
- In coupled climate runs, troposphere warms by ~0.5 K; 1 K over summer pole
- In forecasts, impact on RMSE for temperature and wind depends on existing small biases in these quantities

Impact on climate of coupled model