3D radiation:
Possible approaches and preliminary IFS results

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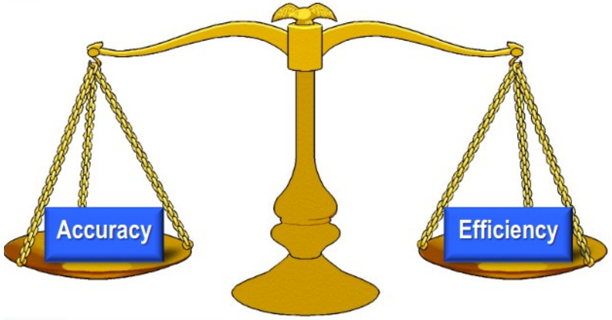

3D radiation:
Possible approaches and preliminary IFS results

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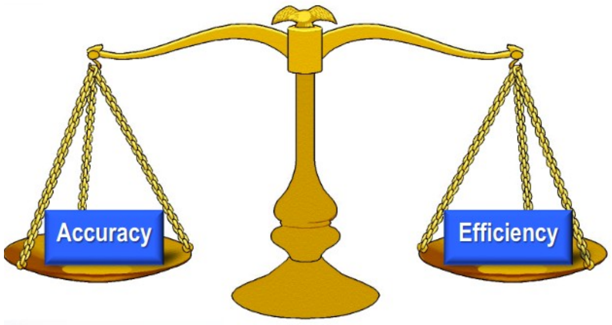
With thanks to Robin Hogan, Bernhard Mayer and Ján Mašek for making excellent presentations from which I shamelessly stole



Overview

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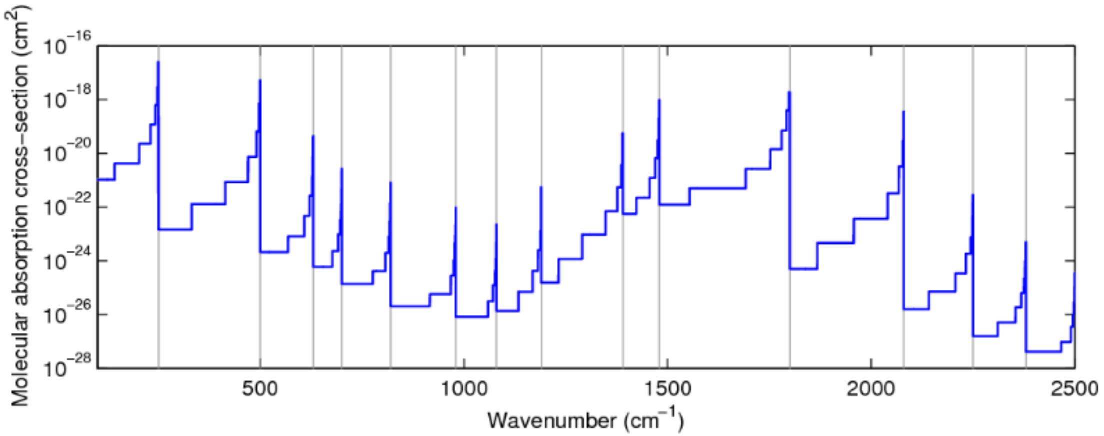
- Introduction: sources of error in radiation parameterizations
- Possible approaches for 3D radiation in (VHR) NWP that are cheap enough
  1) Run ecRAD-SPARTACUS (intra-column 3D radiative effects) on coarser radiation grid (for physical reasons, not computational)
  2) “Dynamically computed” true 3D radiation (not yet available for NWP)
- Preliminary IFS results using SPARTACUS and varying horizontal/temporal frequency of radiation computations

Accuracy & efficiency

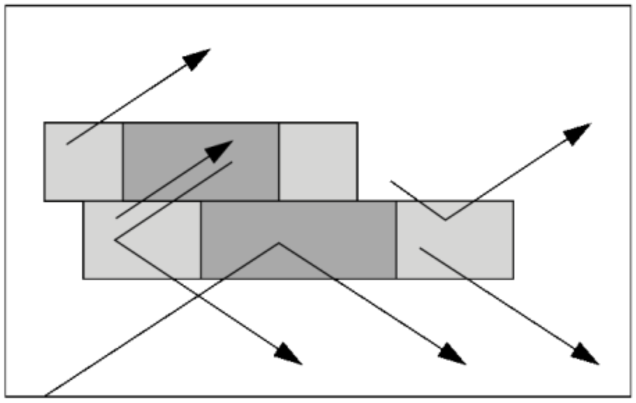
$$F = \int\int\int\int\int I(\lambda, x, X, t, \theta)\, d\lambda\, dx\, dX\, dt\, d\theta$$

- Scheme numerically integrates instantaneous monochromatic radiances I to get broadband fluxes F
- Accuracy and efficiency depend on number of quadrature points used in each dimension



Wavelength λ

- At ECMWF we use "RRTMG" to approximate gas spectrum: **252** spectral points (solar+infrared)
- Testing new "ecCKD" gas optics at ECMWF: similar accuracy with **64** points



Sub-grid horizontal distance *x*

- "Tripleclouds" solver uses **3** quadrature points (only in cloudy layers)
- "McICA" solver presents each spectral interval with a different stochastic cloud profile: no additional quadrature points, but some noise if too few spectral intervals
- Large uncertainty in sub-grid cloud structure, so more quadrature points probably not justified

Slide by Robin Hogan

Accuracy & efficiency

$$F = \int \int \int \int \int I(\lambda, x, X, t, \theta)\, d\lambda\, dx\, dX\, dt\, d\theta$$

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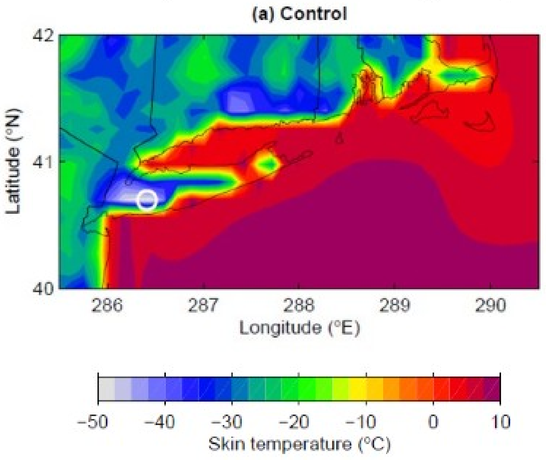
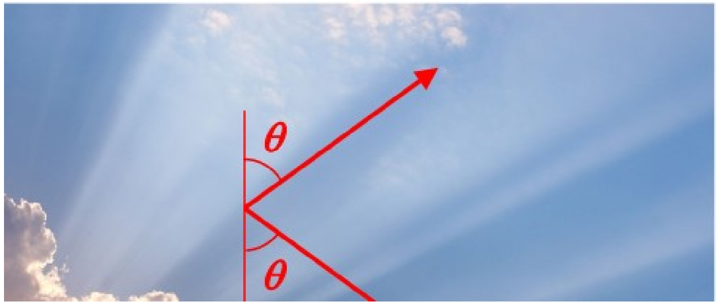


Sub-sampling model points in space *X* and time *t*

In IFS:

- Radiation called every hour (better than 3-hourly) with 10x fewer spatial gridpoints
- Little detectable improvement when more frequent in time or space!
- Partly due to "approximate updates" (Hogan & Bozzo 2015) every gridbox/timestep



Zenith angle θ

- Virtually all atmospheric models assume diffuse radiation propagates with **2** zenith angles: the two-stream approximation (Schuster 1905), although solar radiation adds the direct beam so effectively **3** zenith angles
- Cost of *N*-stream scheme: no scattering O(*N*), with scattering O(N^3)!
- *What is the accuracy gain of more streams, and how can we do it cheaply?*

Slide by Robin Hogan

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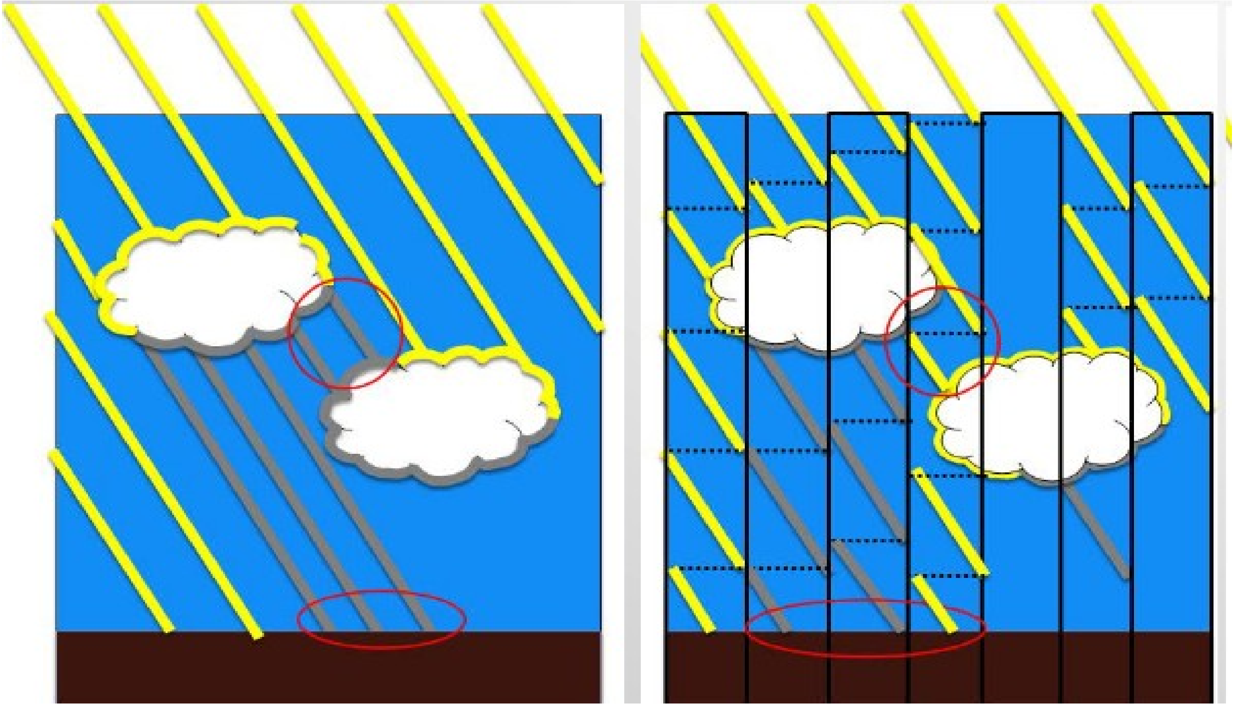


3D radiation
(real atmosphere)

NWP / GCM:
Two-stream approximation
+ independent column
approximation (ICA)

If we want to go beyond 1D radiative transfer, we need cost savings somewhere else

Recently it has been shown we can reasonably trade off **spectral resolution:**

While there is a positive correlation with accuracy, doing the spectral discretization in a smart way allows similar accuracy with fewer quadrature points (**ecCKD gas optics scheme by Robin Hogan**)

→ 3-8x saving in floating point operations

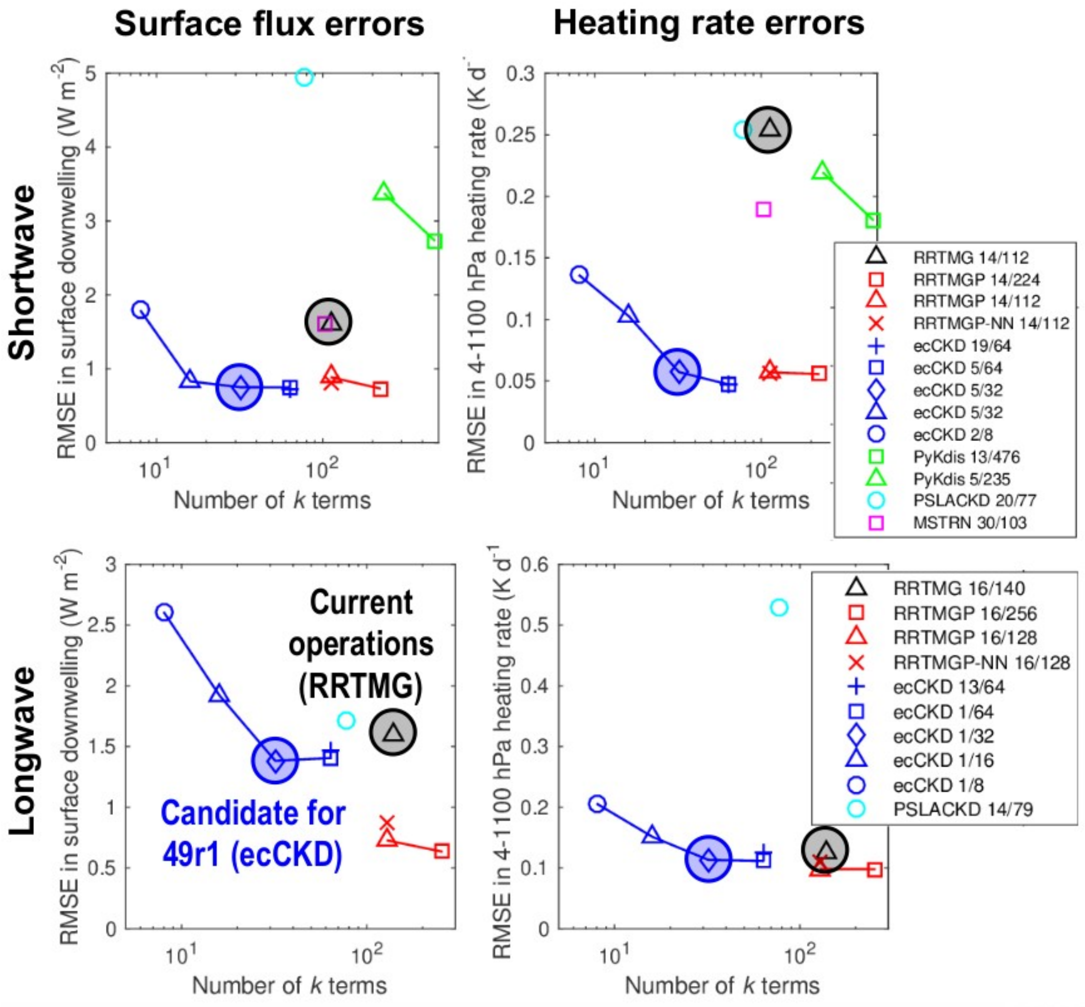
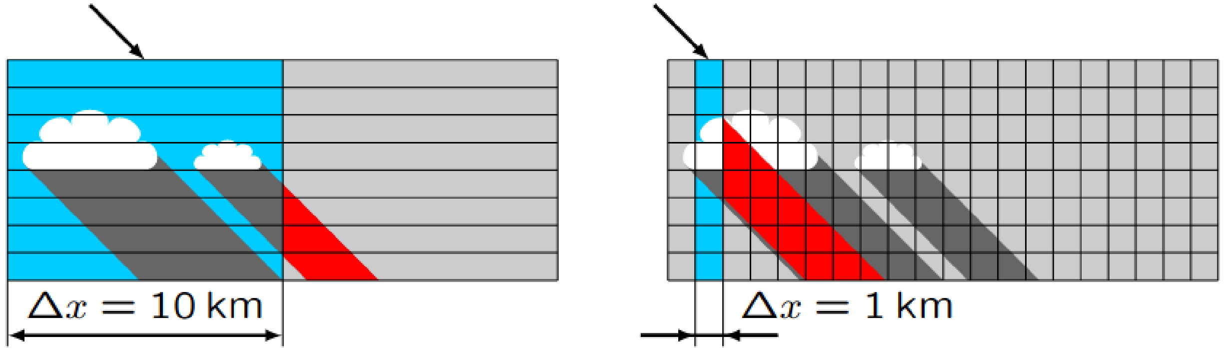


Figure by Robin Hogan

Subgrid or resolved?

- when the horizontal mesh size is much larger than horizontal dimension of individual clouds, 3D radiative effects are mostly subgrid and can be parameterized in ICA framework

- when the clouds start to be horizontally resolved, radiative exchanges between neighbouring model columns become significant

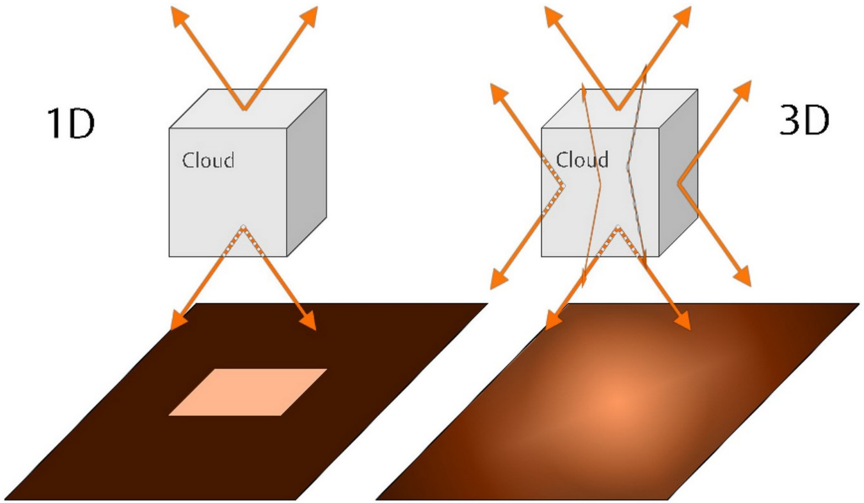


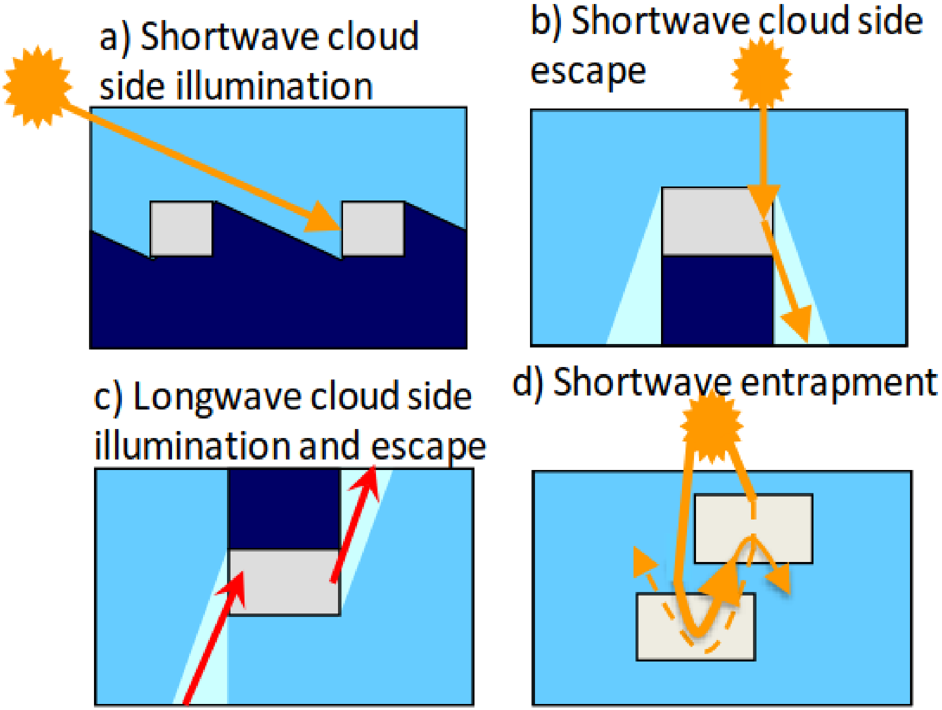
- some subgrid effects due to 3D cloud shape may still need to be parameterized

Slide by Ján Mašek

Approach 1: Run SPARTACUS on coarser grid

SPARTACUS (Speedy algorithm for radiative transfer through cloud sides), solver in ECMWF radiation scheme ecRad





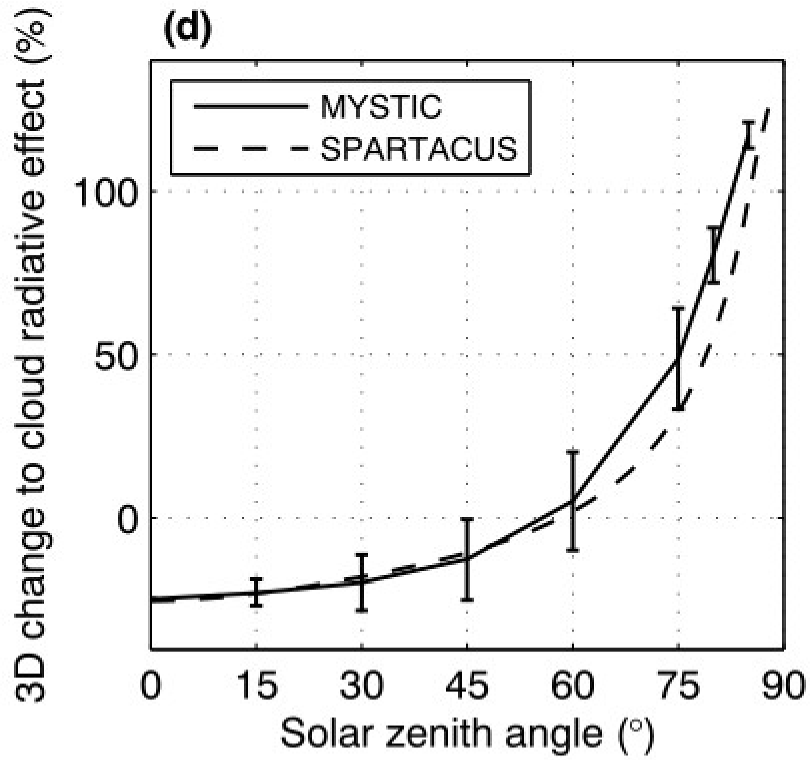
SPARTACUS computes **cloud 3D effects by adding extra terms to the two-stream equations**

→ ~5x increase in cost

→ **previously** too expensive for operations

Approach 1: Run SPARTACUS on coarser grid

SPARTACUS (Speedy algorithm for radiative transfer through cloud sides), solver in ECMWF radiation scheme ecRad



Shortwave cloud radiative effect

Approach 1:
Run SPARTACUS
on coarser grid

Improving efficiency

Ukkonen and Hogan (*in prep.*): By combining

1) Code refactoring to e.g. expose more parallelism (improving vectorization on CPUs)

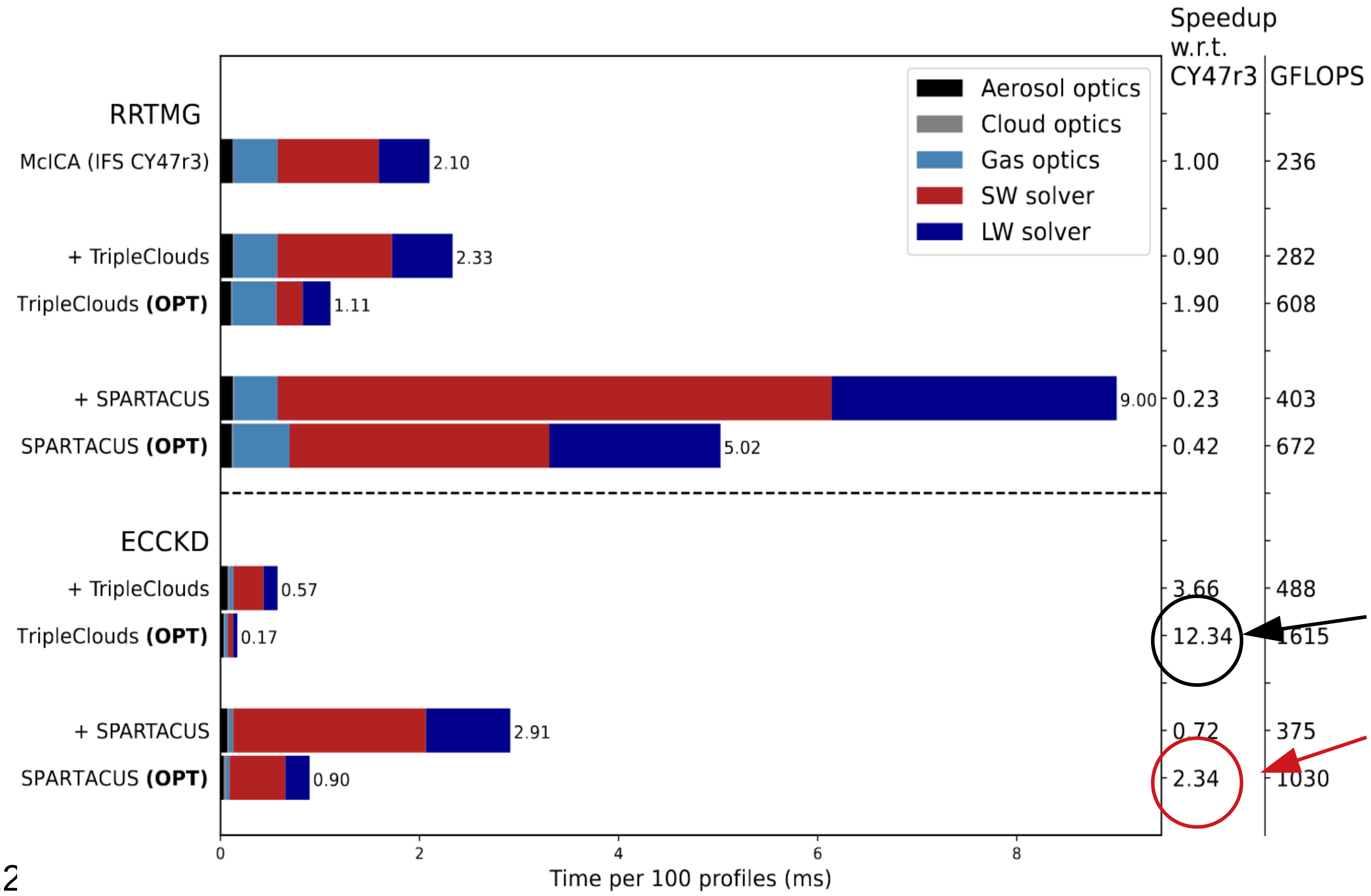
2) Innovations in algorithms (reducing the spectral dimension via new gas optics scheme)

we end up with

...~10x increase in speed for TripleClouds and SPARTACUS

...SPARTACUS now 2x cheaper than operational ecRad in IFS cy48

New gas optics + refactoring results in a very fast ecRad

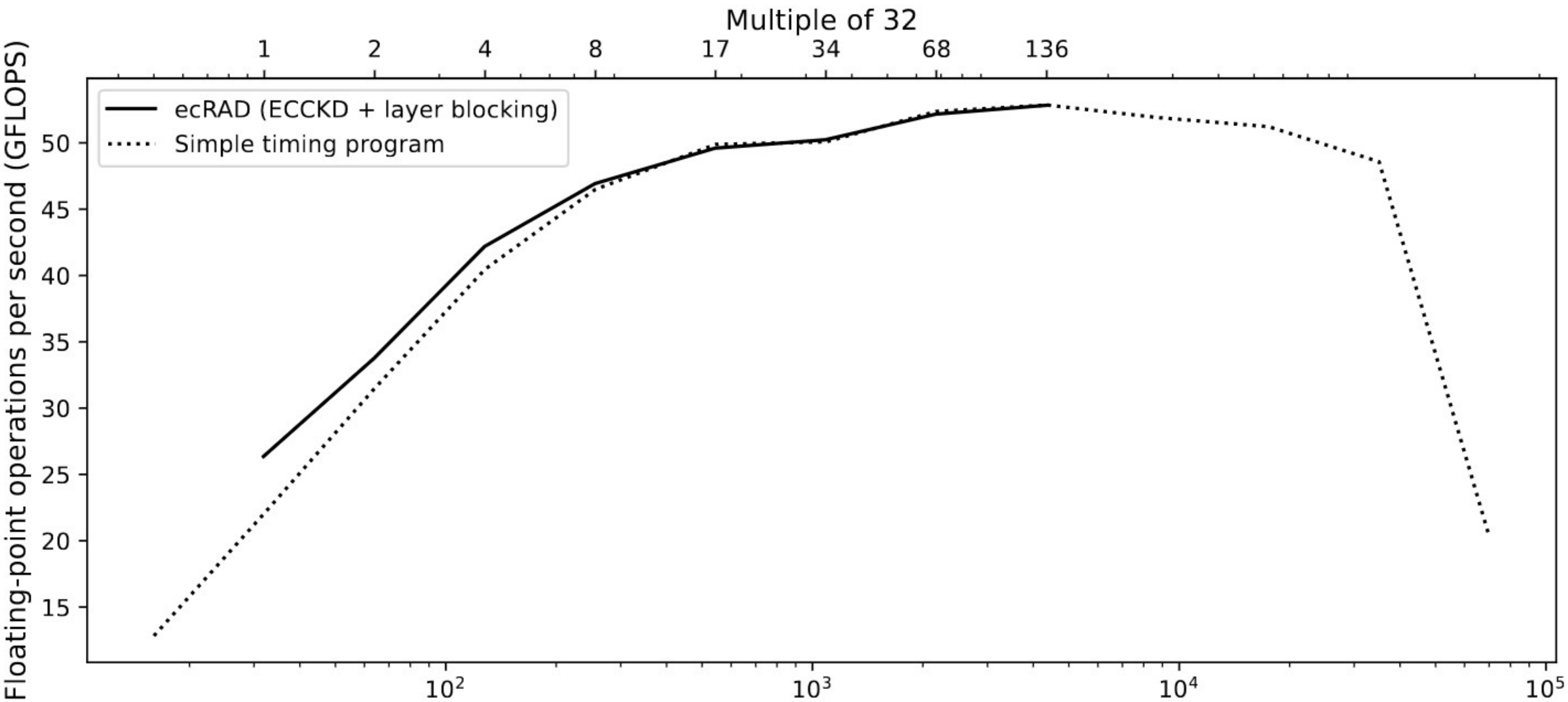


Reduced spectral space + Performance optimization = better accuracy at ~1/10 the cost of old radiation!

OR

3D cloud radiative effects, at ½ the cost of old radiation

Performance vs Length of SIMD-vectorized loop for arithmetically intense shortwave computations



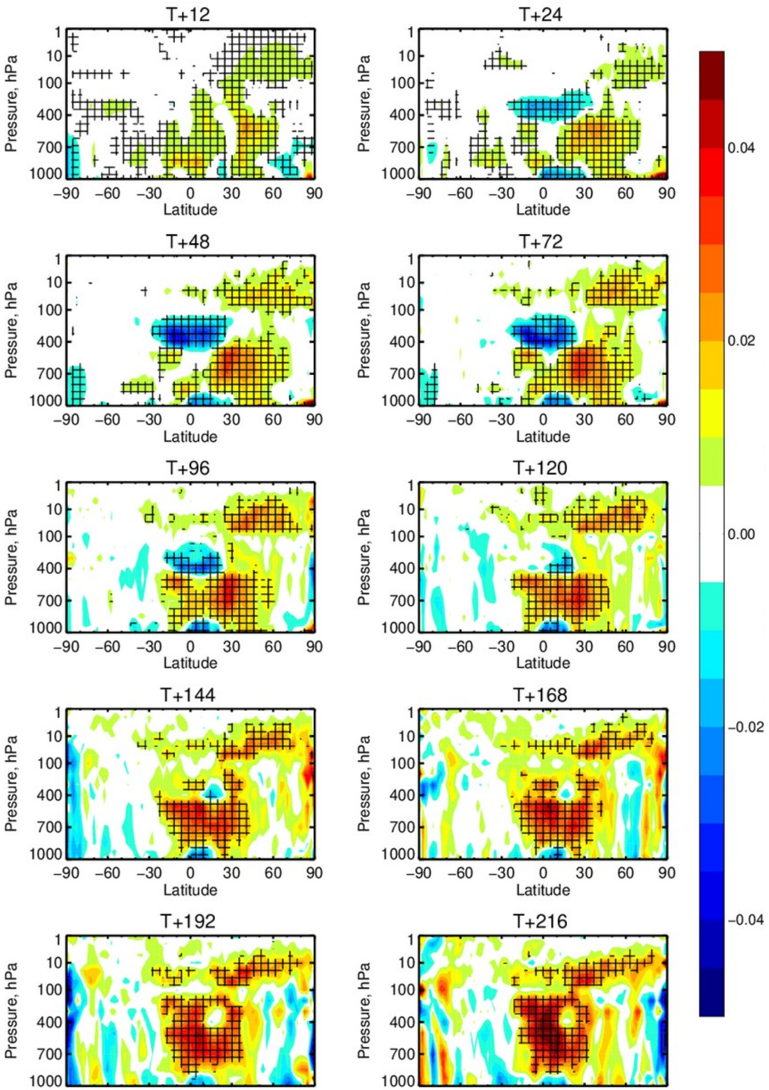
Performance almost doubled on an AMD CPU (AVX-256) when going from a loop length of N=32 to 320 (caveat: *N* not known at compile time).

Can we refactor other physics codes for longer inner loops?

Impact of cloud 3D radiative effects in the IFS

Increases IFS temperature RMSE (~bias) in the troposphere and stratosphere :(

But this is without model tuning!



Suite of June-July-August IFS runs at 9 km resolution, radiation grid 30 km

Blue = improvement

Red = degradation

Impact of cloud 3D radiative effects in the IFS

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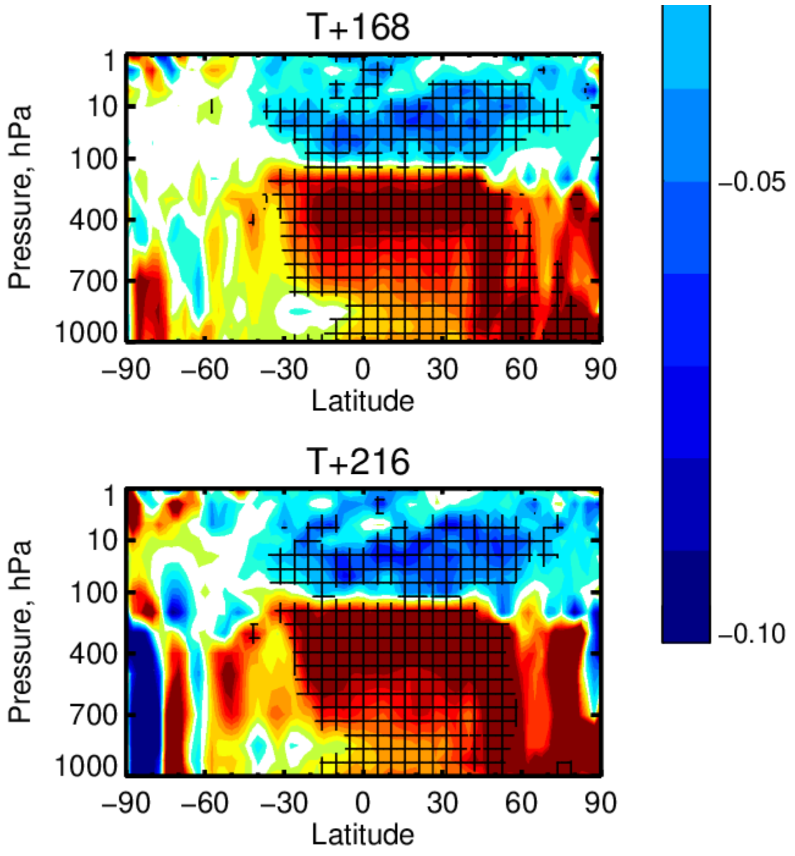
Suite of June-July-August IFS runs at 9 km resolution, radiation grid 30 km

Increases IFS temperature RMSE (~bias) in the troposphere and stratosphere :(

But this is without model tuning!

Tuning or other model changes needed since **SPARTACUS warms the troposphere**

→ **candidate for reducing long-standing cold biases?**



Blue = cooling

Red = warming

Impact of cloud 3D radiative effects in the IFS

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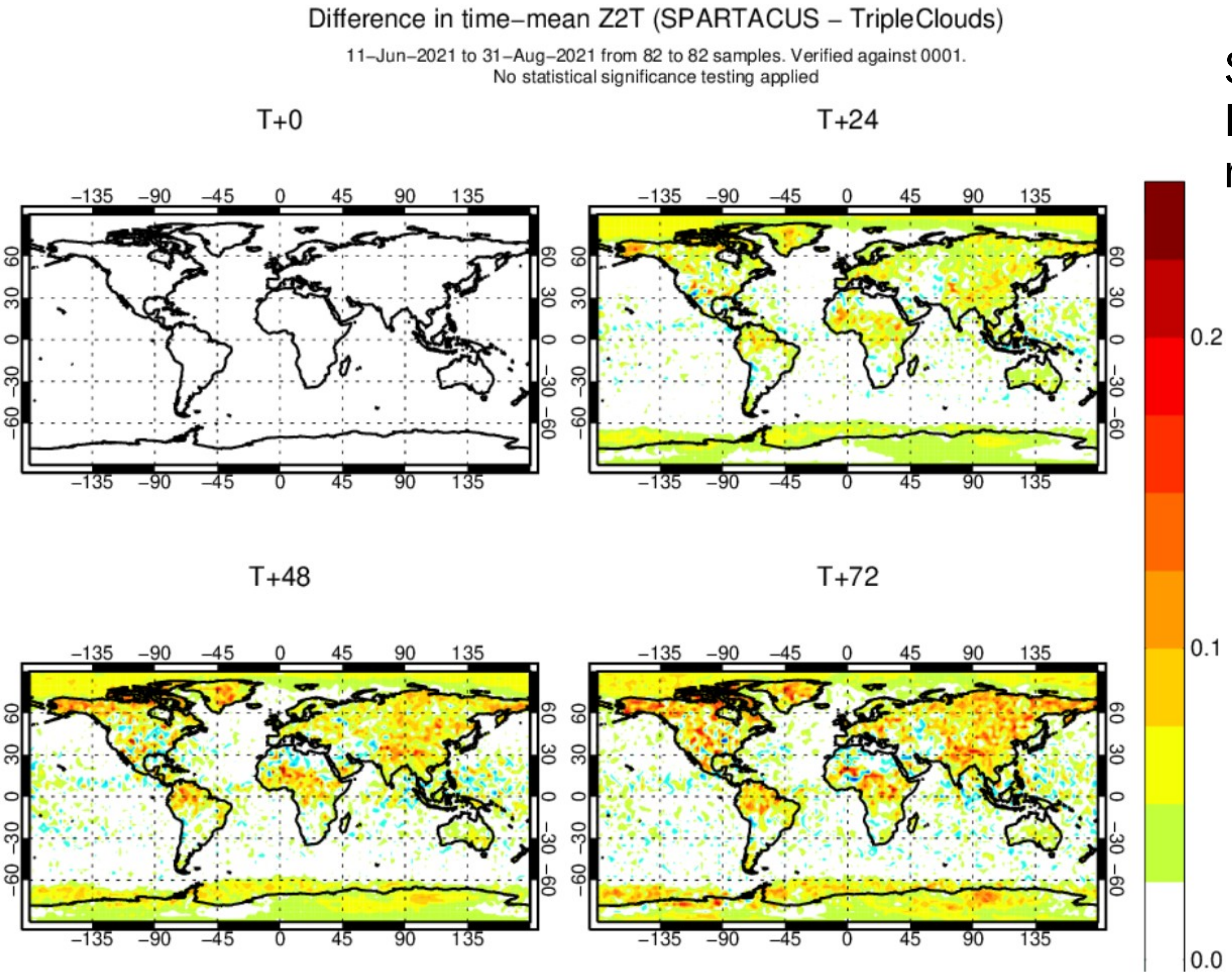
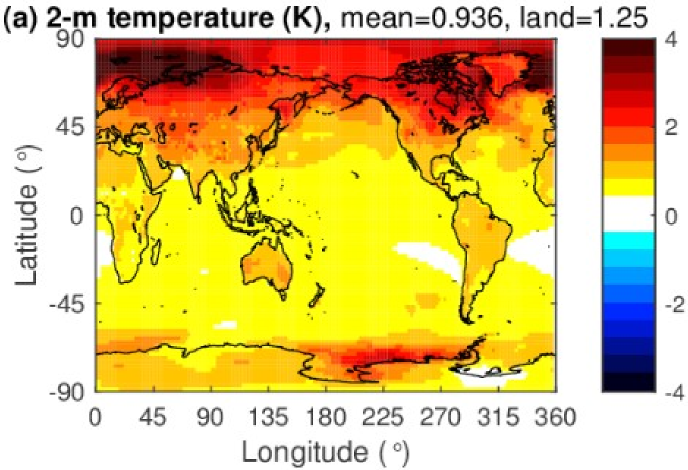
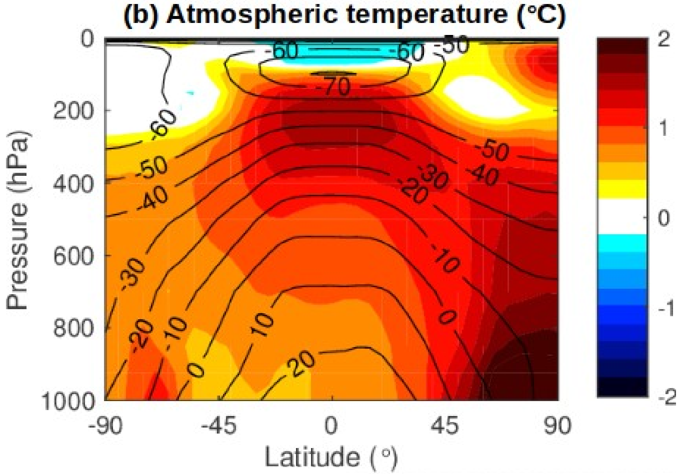


Suite of June-July-August IFS runs at 9 km resolution, radiation grid 30 km

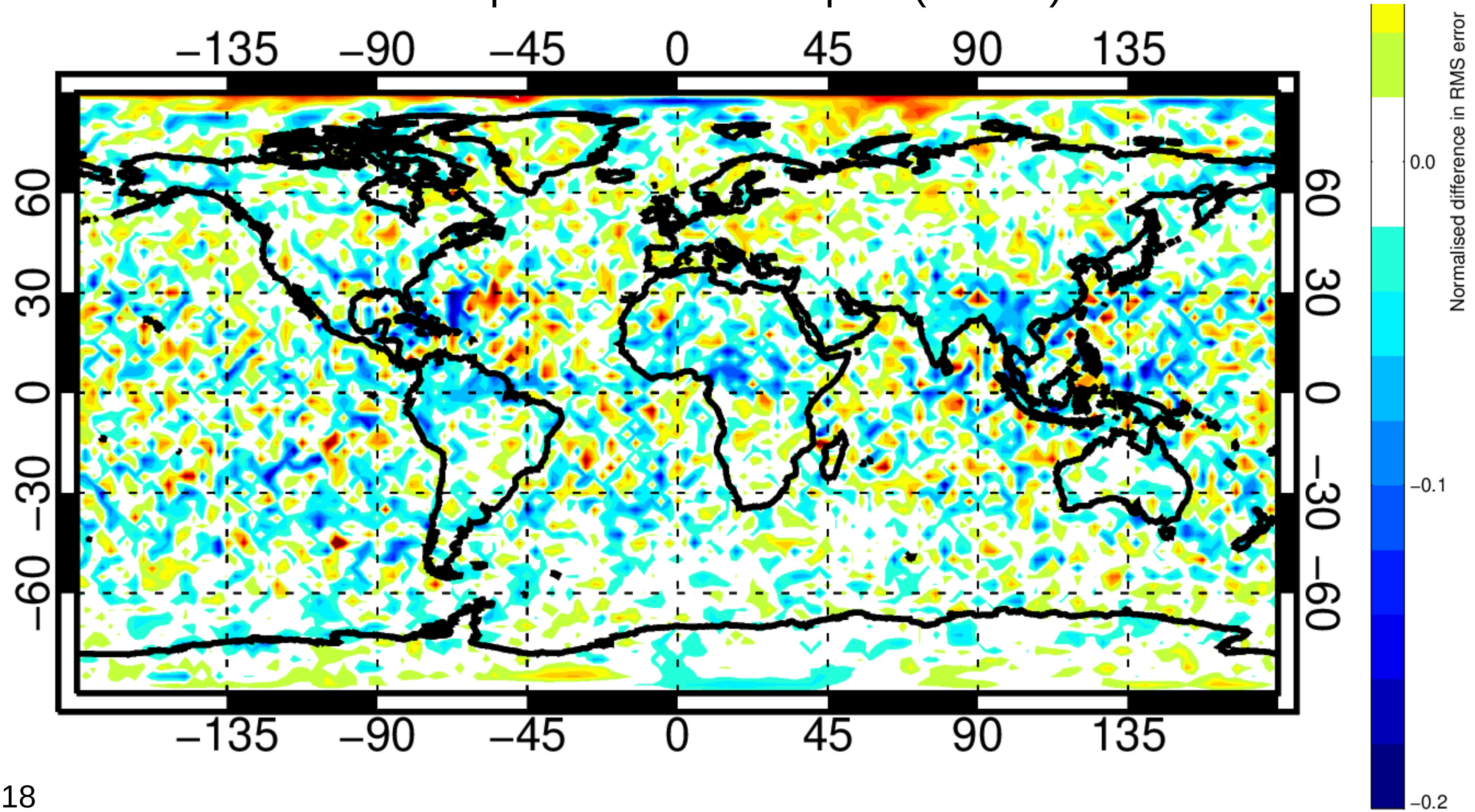
SPARTACUS climate impacts

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*





Up to ~15% better 5-day forecast of 2-metre temperature in the tropics (RMSE)



Standard deviation

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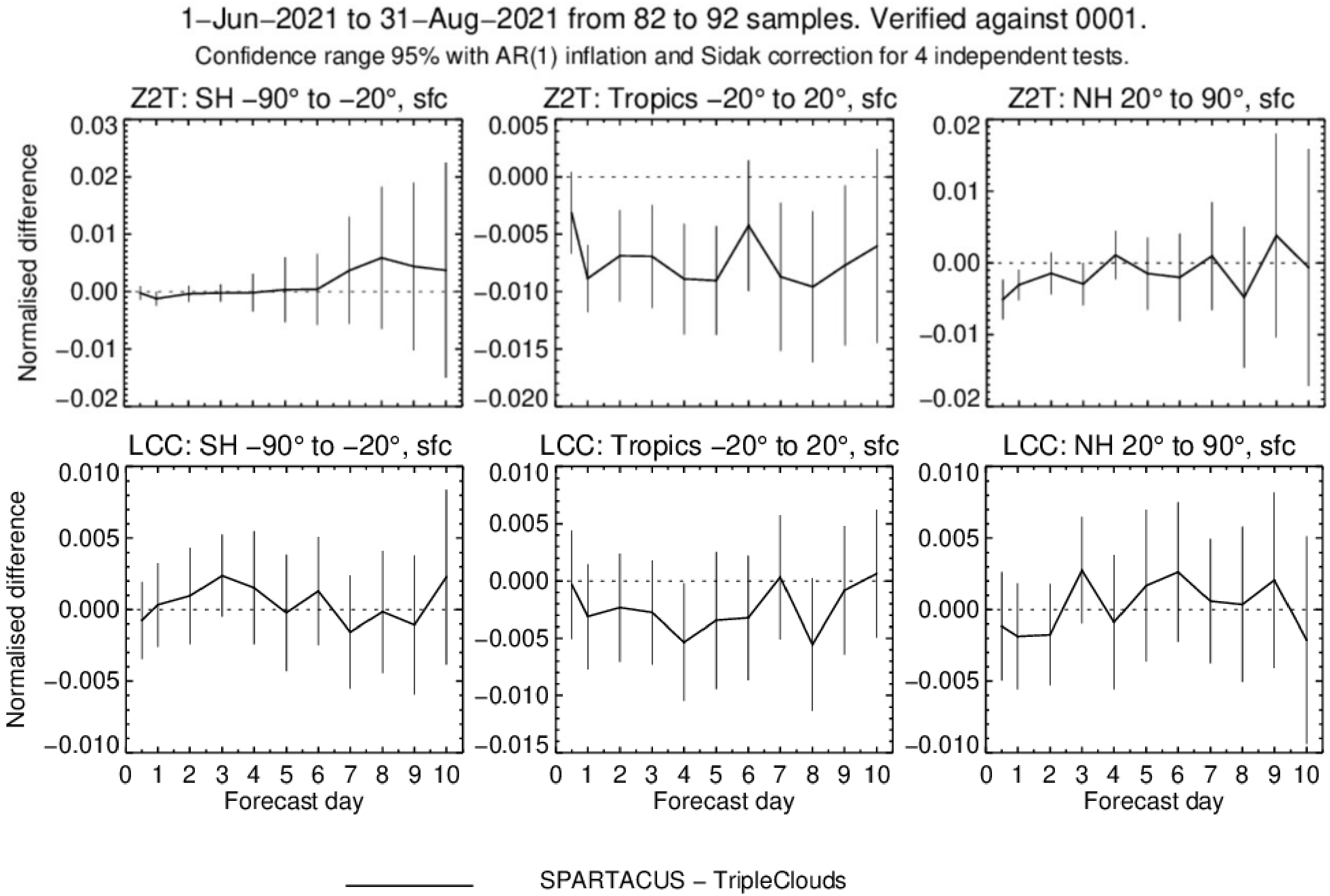
Suite of June-July-August IFS runs at ~9 km (TCo1279)



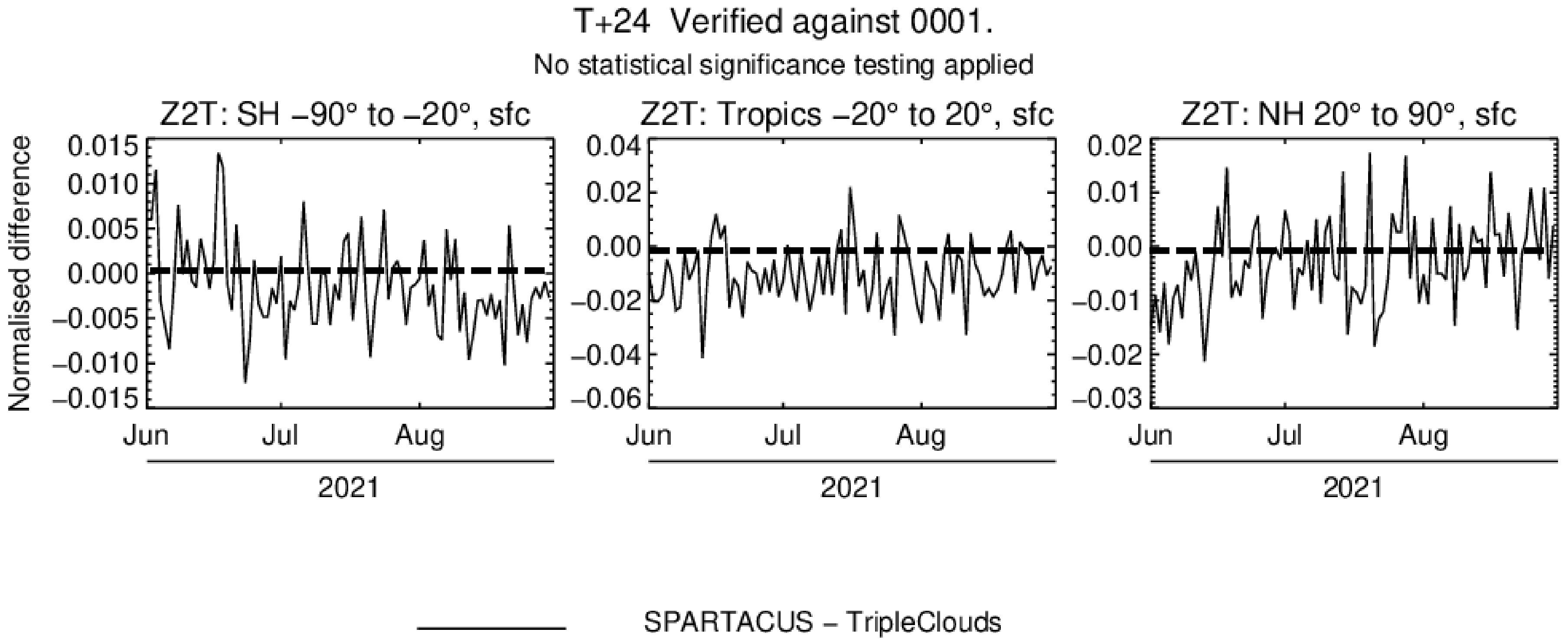
2-metre temperature:

0.5 - 1% overall improvement in the tropics

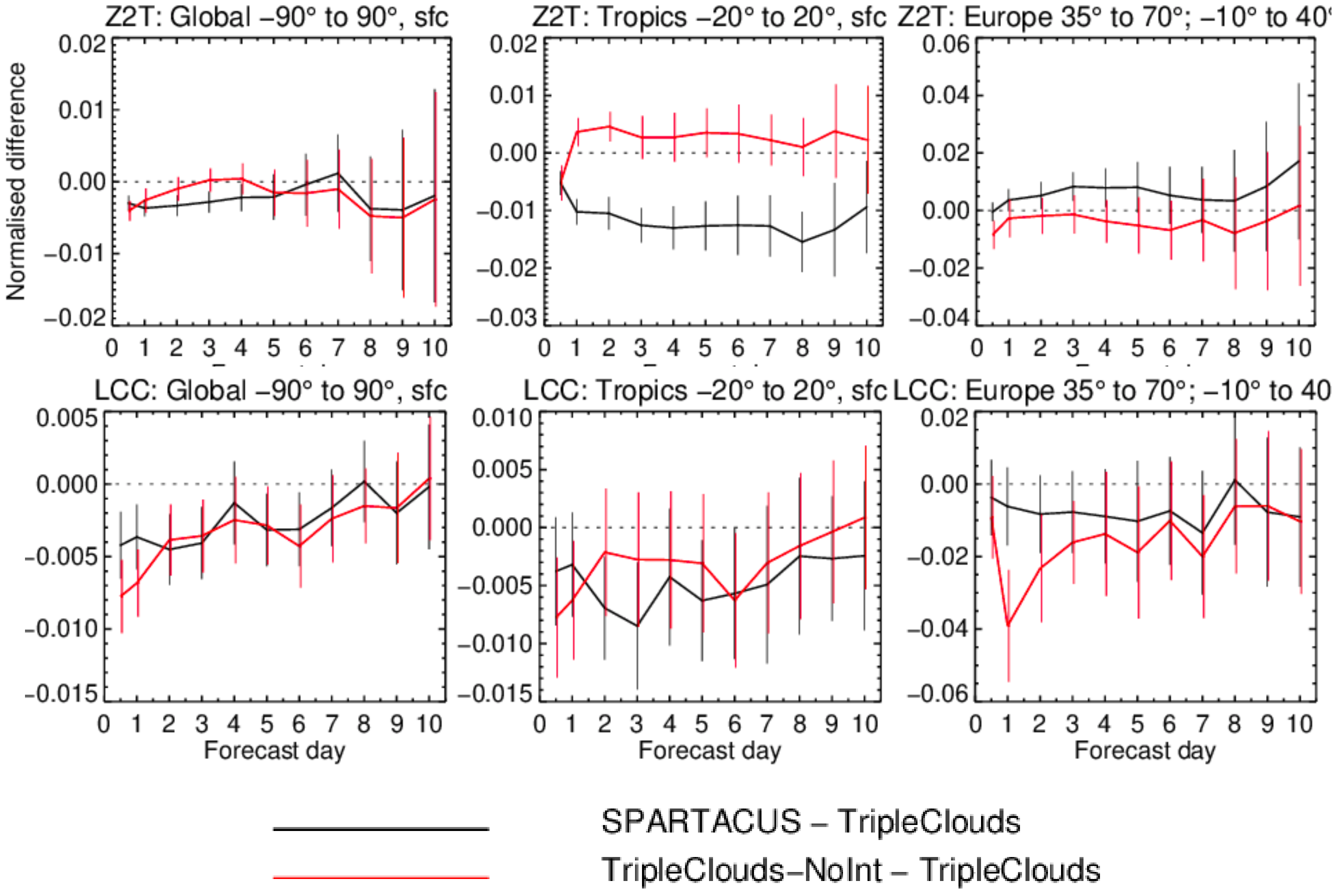
Low cloud cover in the tropics also has small reduction in standard deviation

RMSE of 1-day forecast of 2-metre temperature

Suite of June-July-August IFS runs at ~9 km (TCo1279)



Impact on RMSE when
1) turning on 3D effects
2) increasing horizontal resolution of radiation (80→25km) (turning off coarse radiation grid)



Suite of June-July-August IFS runs at ~25 km

2-metre temperature:

SPARTACUS increases forecast skill in the tropics

Low cloud cover:

SPARTACUS and higher spatial frequency both increase skill

Impact on RMSE when
1) turning on 3D effects
2) turning on 3D effects + 30-minute radiation instead of 1-hourly

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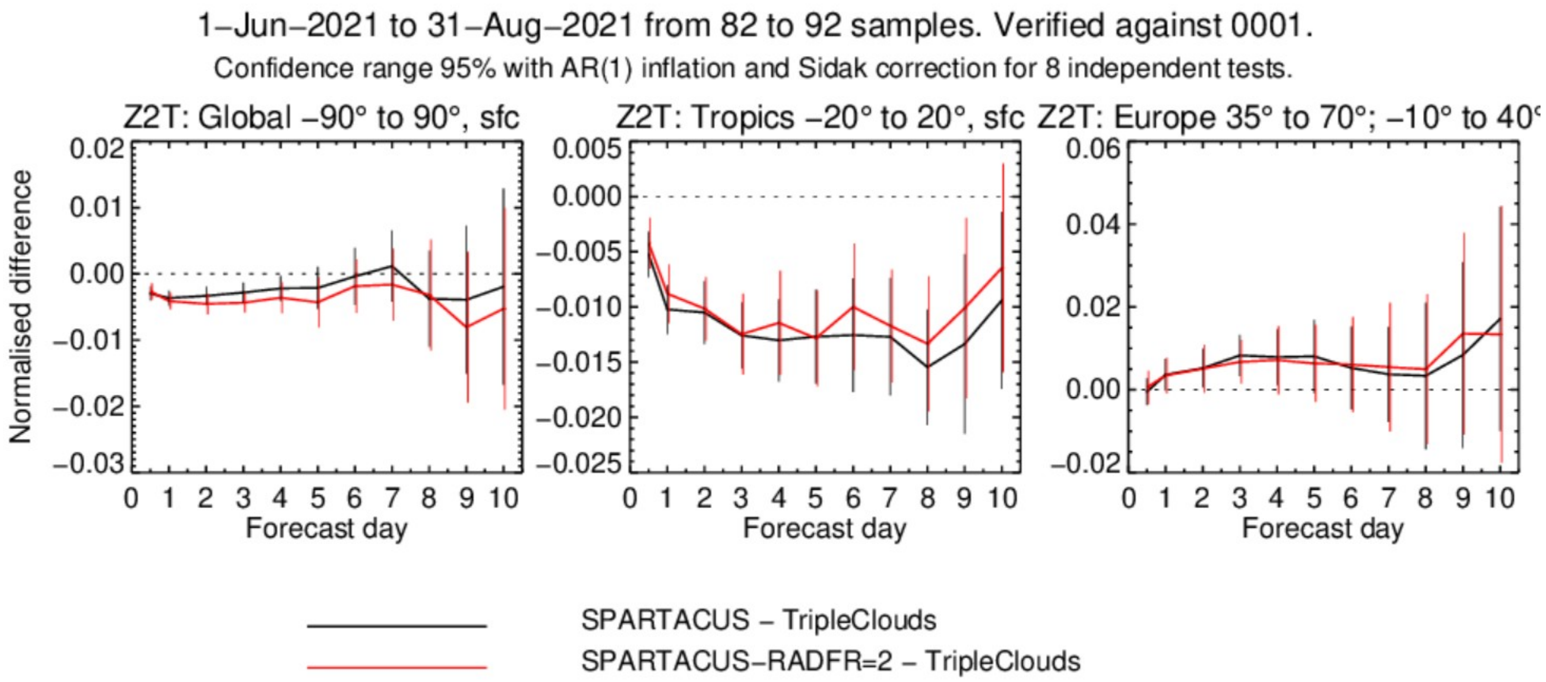
Suite of June-July-August IFS runs at ~25 km



No improvement in **2-metre temperature** from calling radiation more often

This is probably because IFS uses "approximate updates" for radiation at every model step!

Idea for using SPARTACUS in high-resolution NWP

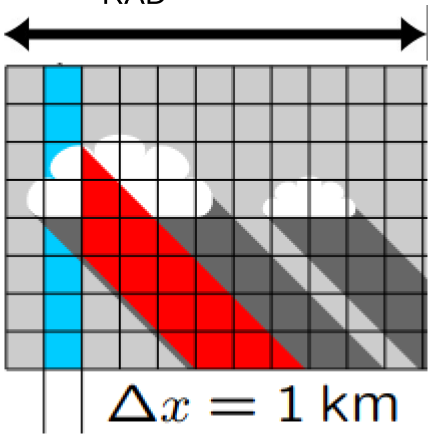
SPARTACUS..

- Represents **subgrid** radiative transfer across cloud sides
- Is not suitable for kilometer-scale simulations where radiative flows between columns becomes important
- Takes as input the **fractional standard deviation (FSD) of cloud water** (currently a constant) and effective cloud edge length (parameterized)

Best of both worlds: run SPARTACUS on coarser grid and compute cloud variability from fine grid?

$FSD = FSD_{resolved} + FSD_{sub\text{-}grid}$, where $FSD_{sub\text{-}grid} \rightarrow 0$ for VHR?

Δx_{RAD} = 10 km



Effects: Cloud Organization (Klinger et al, 2017)

const. cooling

3D avg

3D

Effects: Cloud Organization (Klinger et al, 2017)

const. cooling

3D avg

3D

← SPARTACUS?

Effects: Cloud Organization (Klinger et al, 2017)

const. cooling

3D avg ← SPARTACUS?

3D ← What if we want this?

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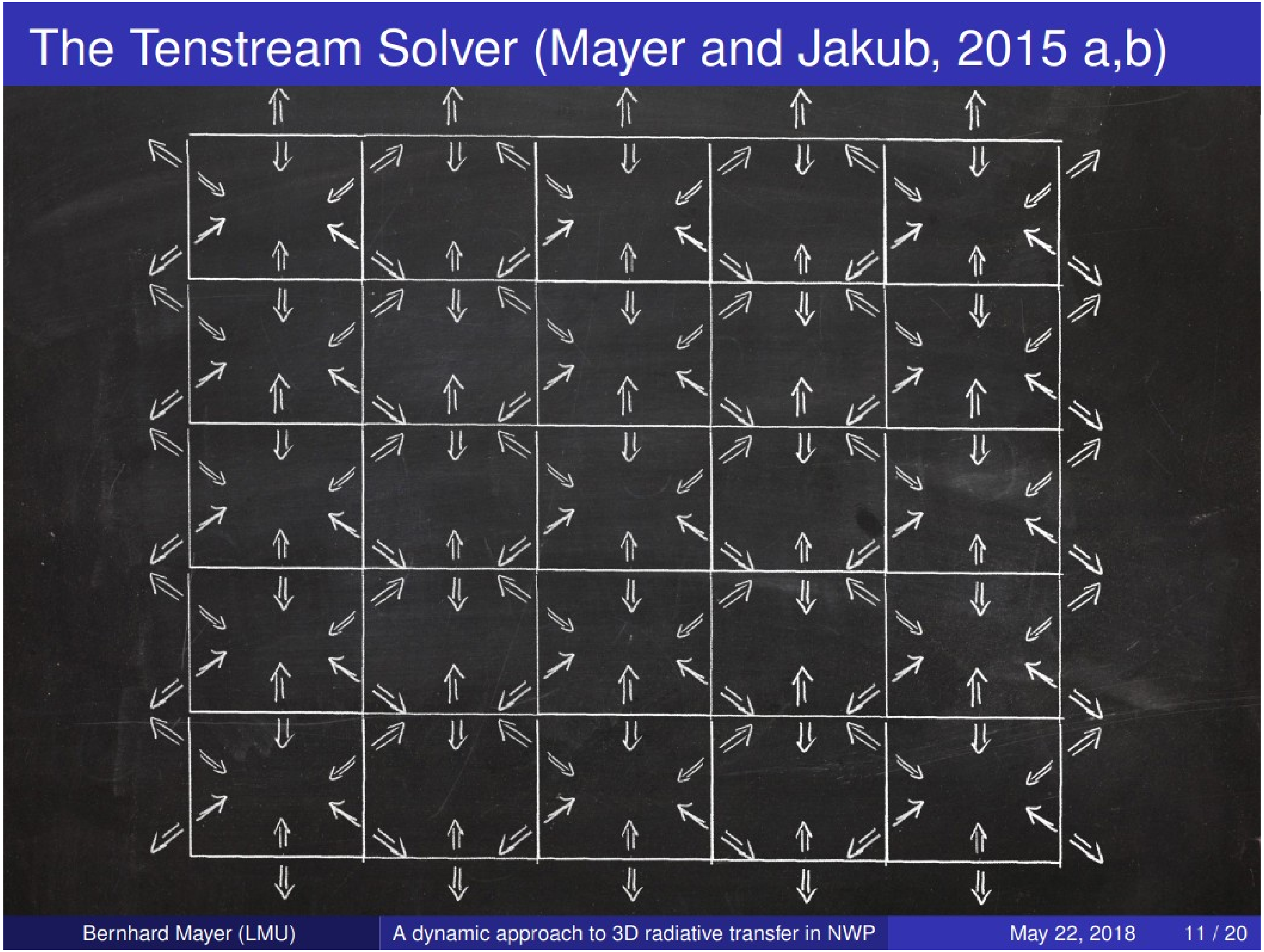


Approach 2: True 3D radiation dynamically

See intriguing talk “a **Dynamic Approach to 3D Radiative Transfer**” by Bernhard Mayer at ECMWF Annual Seminar 2022

events.ecmwf.int/event/300/timetable/

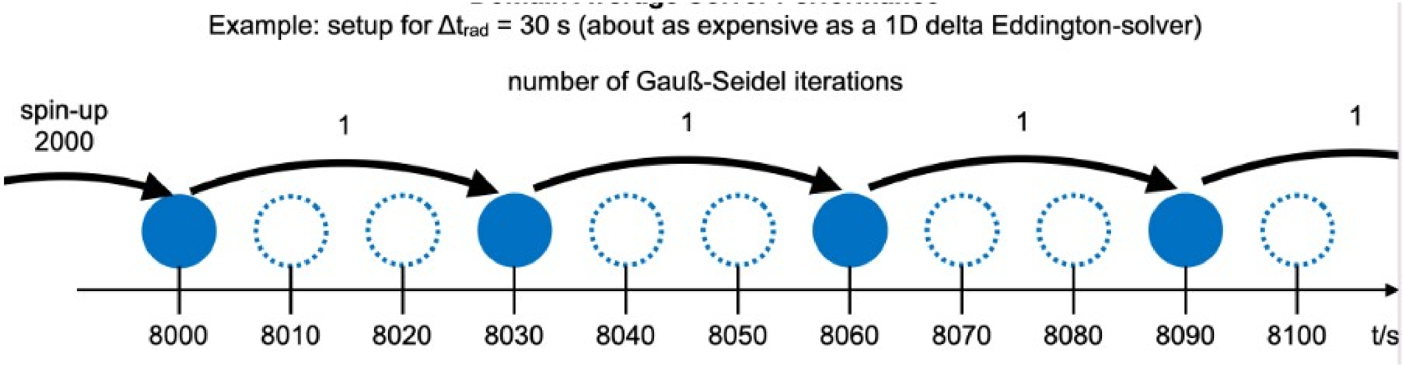
Approach 2: True 3D radiation dynamically

“TenStream” is a relatively fast 3D radiative transfer solver available for LES, **but still not fast enough for NWP**

Interesting idea presented by Bernhard Mayer, to be tested in ICON:

Treat radiation dynamically, computing radiative flows (only) to nearest grid cells in three dimensions at every (Nth) time step

Reduces cost, and converges to the true solution (after some time)



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Dynamic RT – how good is it?

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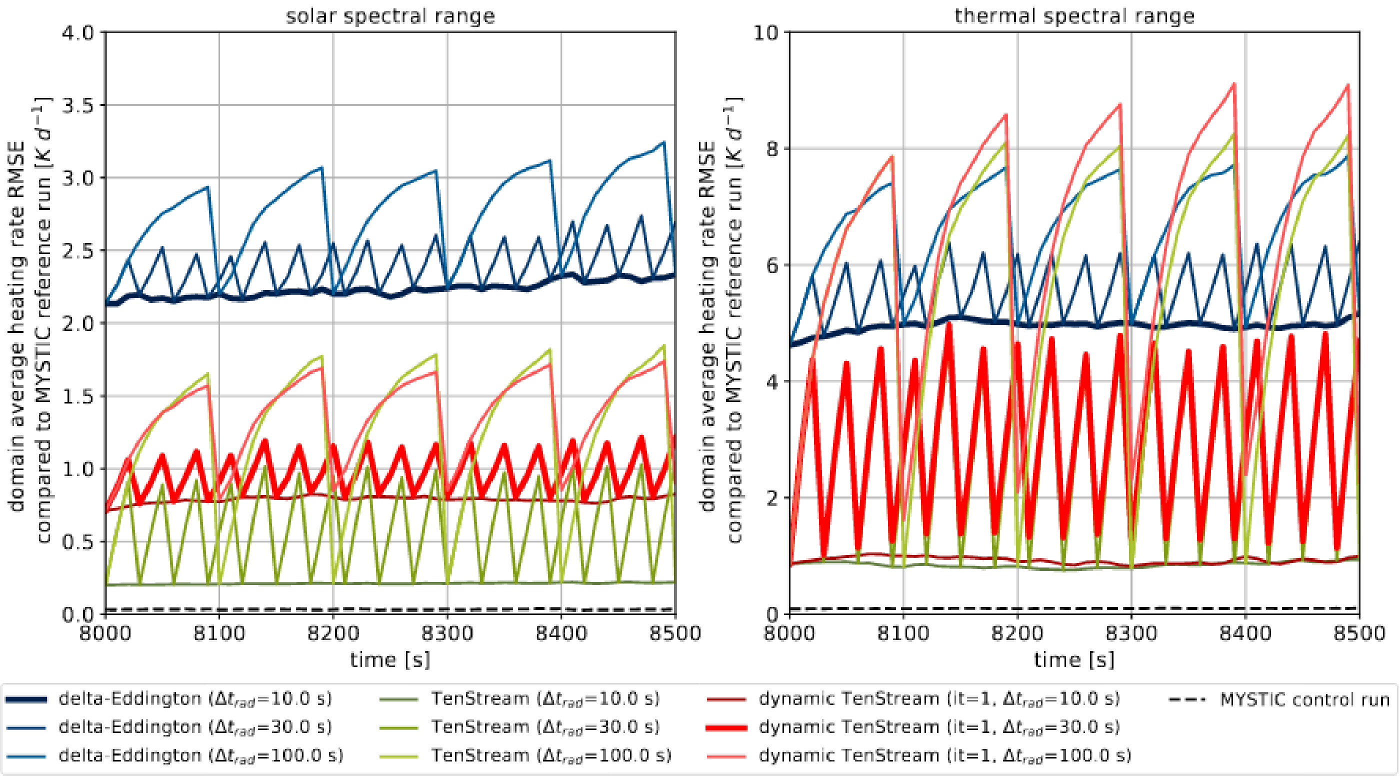
Approach 2:
True 3D radiation dynamically



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Summary

- The ecRad scheme developed at ECMWF now very fast
- SPARTACUS solver computes 3D cloud radiative effects and is now affordable
- For high-resolution regional models, a good idea might be to run SPARTACUS on a coarser grid, and use the fine-grid information to compute cloud variability
- Alternatively, approaches to make true 3D solvers more affordable are also being investigated but not yet available