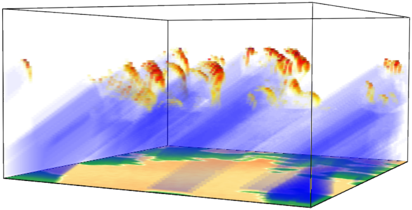
A 3D Radiative Transfer Solver for Atmospheric Heating Rates – powered by PETSc

Fabian Jakub

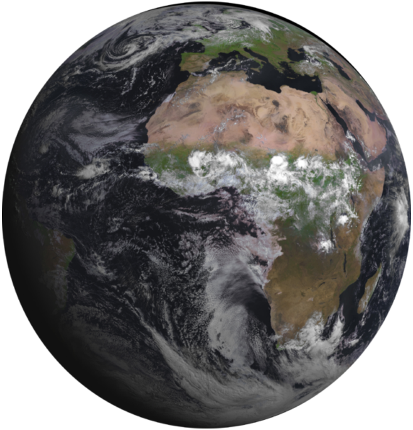
LMU - Meteorological Institute Munich



June 16, 2015

Radiative Transfer in atmospheric models

Why bother with Radiative Transfer in atmospheric models?



Earth fulldisk scan from SEVIRI (EUMETSAT)

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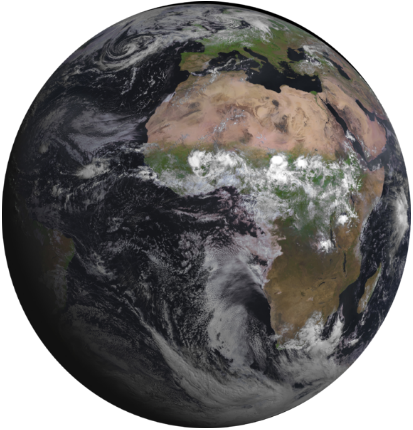

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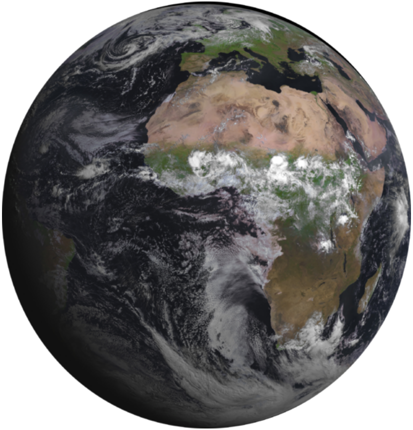

Earth fulldisk scan from SEVIRI (EUMETSAT)

- Sun heats surface and atmosphere
- Earth emits to space
- Radiation ultimately drives flow
  - .. on large scales
  - .. and on small scales

History of Radiative Transfer

Radiative Transfer theory well established

- radiative transfer equation (1960 Chandrasekhar)

$$\frac{\mathrm{d}L}{k_{\mathrm{ext}} \cdot \mathrm{d}s} = -L + \frac{\omega_0}{4\pi} \int_{4\pi} p(\Omega', \Omega)\, L(\Omega')\, \mathrm{d}\Omega' + (1-\omega_0) B_{\mathrm{Planck}}(T)$$

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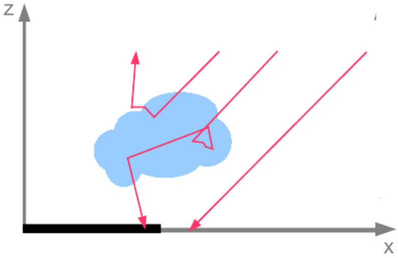
- surprisingly well working 1D approximations
- sophisticated 3D models since the 90's (e.g. MonteCarlo)
- ... but orders of magnitude too slow to run in atmospheric models

Approximations for Radiative Transfer

Radiative transfer describes photon interactions with atmosphere.
MonteCarlo modelling of scattering and absorption:



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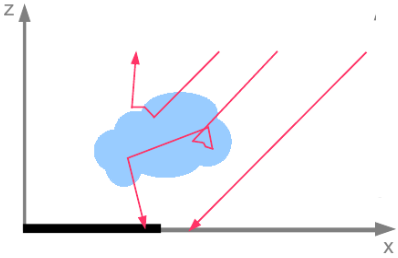

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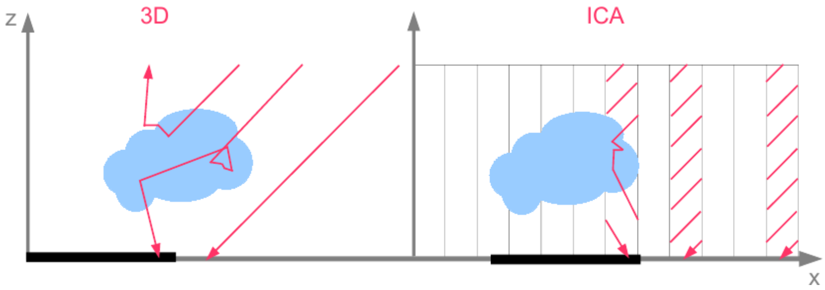


simplify to solve:

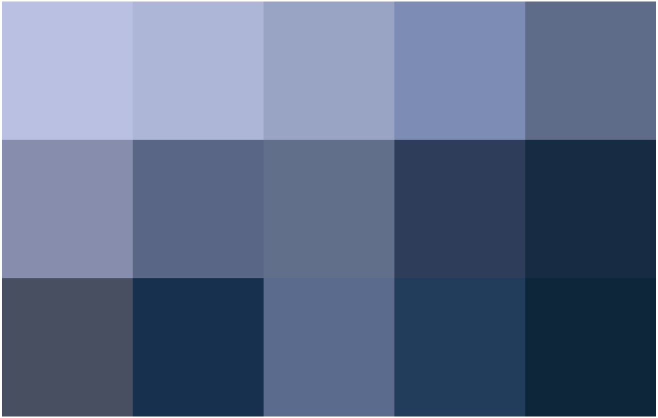
- Plane Parallel approx.
- Independent Column approx.
- Twostream solvers
- diagonal band-matrix (5)

Why care for 3D radiation now? – a matter of resolution

Complex cloud radiation interaction

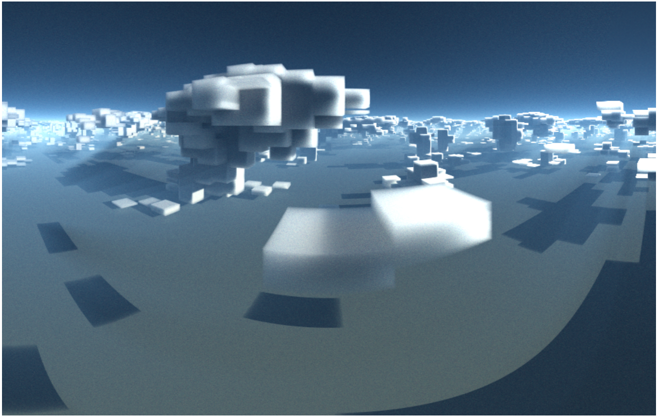
Why care for 3D radiation now? – a matter of resolution

Global models



Why care for 3D radiation now? – a matter of resolution

Weather models today

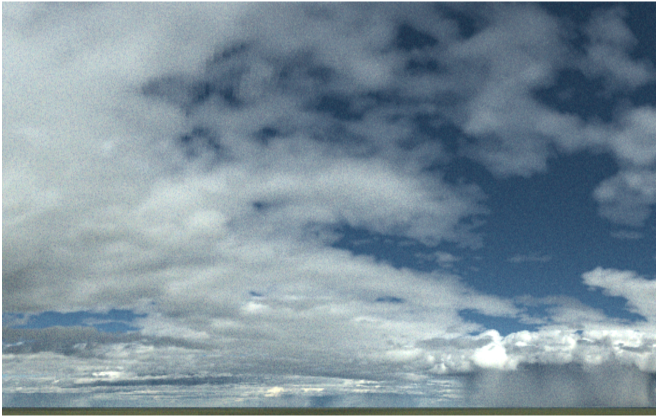


Visualization done with libRadtran.org/**MYSTIC** (Monte carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres)

Mayer, B., 2009. Radiative transfer in the cloudy atmosphere (EPJ Web of Conferences)

Why care for 3D radiation now? – a matter of resolution

Next-gen models



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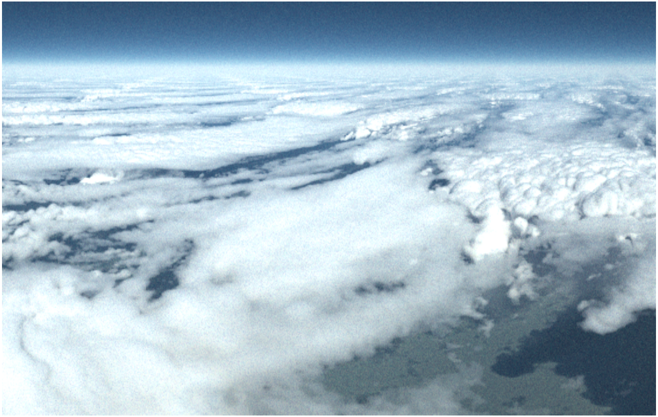

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Does 3D Radiative Transfer impact cloud evolution?

3D radiative transfer may affect

- cloud evolution and lifetime
- microphysical processes (condensation, nucleation)
- precipitation onset/amount
- convective organization

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Can we answer this by high resolution modelling?

$HD(CP)^2$ project (www.hdcp2.eu)

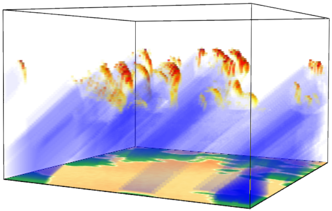
HD(CP)²

High definition clouds and precipitation
for advancing climate prediction

- run hindcasts over Central Europe
- 100m horizontal resolution
- grids consisting of 10.000 x 15.000 x 300 voxels
- first develop a model capable of running it (ICON)
- . . . with the goal to develop improved parametrizations for weather and climate predictions

The Tenstream solver

A new concept for a solver – what do we want?

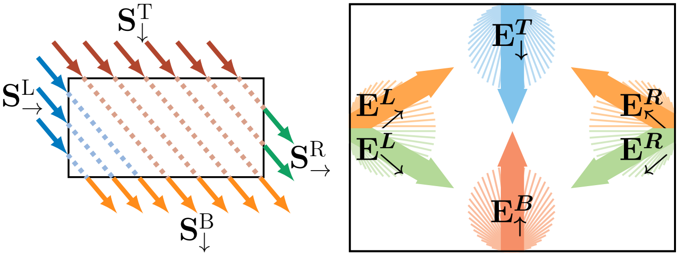


I3RC cloud scene, benchmark heating rate calculation with MYSTIC (MonteCarlo code)

- accurately approximate 3D effects
- has to be several orders of magnitude faster than state of the art 3D solvers
- parallelizable on modern machines

The TenStream solver

Finite Volume formalism:
Discretize energy transport – spatially and by angle



(a) direct streams (θ=40°) (b) diffuse streams

Fabian Jakub and Bernhard Mayer, 2015. A three-dimensional parallel radiative transfer model for atmospheric heating rates for use in cloud resolving models – The TenStream solver (JQSRT)

The TenStream solver

Setup equation system for one voxel:

$$\begin{bmatrix} E^{T}_{\uparrow} \\ E^{B}_{\downarrow} \\ E^{L}_{\swarrow} \\ E^{R}_{\searrow} \\ E^{L}_{\nwarrow} \\ E^{R}_{\nearrow} \\ S^{B}_{\downarrow} \\ S^{R}_{\rightarrow} \end{bmatrix} = \begin{bmatrix} \gamma_1 & \gamma_2 & \gamma_3 & \gamma_3 & \gamma_4 & \gamma_4 & \beta_{01} & \beta_{11} \\ \gamma_2 & \gamma_1 & \gamma_4 & \gamma_4 & \gamma_3 & \gamma_3 & \beta_{02} & \beta_{12} \\ \gamma_5 & \gamma_6 & \gamma_7 & \gamma_8 & \gamma_9 & \gamma_{10} & \beta_{03} & \beta_{13} \\ \gamma_5 & \gamma_6 & \gamma_8 & \gamma_7 & \gamma_{10} & \gamma_9 & \beta_{04} & \beta_{14} \\ \gamma_6 & \gamma_5 & \gamma_9 & \gamma_{10} & \gamma_7 & \gamma_8 & \beta_{05} & \beta_{15} \\ \gamma_6 & \gamma_5 & \gamma_{10} & \gamma_9 & \gamma_8 & \gamma_7 & \beta_{06} & \beta_{16} \\ 0 & 0 & 0 & 0 & 0 & 0 & \alpha_{00} & \alpha_{10} \\ 0 & 0 & 0 & 0 & 0 & 0 & \alpha_{01} & \alpha_{11} \end{bmatrix} \begin{bmatrix} E^{B}_{\uparrow} \\ E^{T}_{\downarrow} \\ E^{R}_{\swarrow} \\ E^{L}_{\searrow} \\ E^{R}_{\nwarrow} \\ E^{L}_{\nearrow} \\ S^{T}_{\downarrow} \\ S^{L}_{\rightarrow} \end{bmatrix}$$

Couple voxels in 3 dimensions. . .

The TenStream solver

Setup equation system for one voxel:

$$
\begin{bmatrix} E^T_\uparrow \\ E^B_\downarrow \\ E^L_\swarrow \\ E^R_\searrow \\ E^L_\nwarrow \\ E^R_\nearrow \\ S^B_\downarrow \\ S^R_\rightarrow \end{bmatrix}
=
\begin{bmatrix}
\gamma_1 & \gamma_2 & \gamma_3 & \gamma_3 & \gamma_4 & \gamma_4 & \beta_{01} & \beta_{11} \\
\gamma_2 & \gamma_1 & \gamma_4 & \gamma_4 & \gamma_3 & \gamma_3 & \beta_{02} & \beta_{12} \\
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0 & 0 & 0 & 0 & 0 & 0 & \alpha_{00} & \alpha_{10} \\
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\end{bmatrix}
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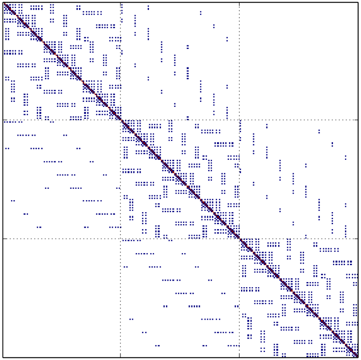
$$

Couple voxels in 3 dimensions...

...gives huge but sparse matrix.

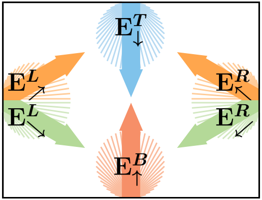


$\Longrightarrow$ solve with PETSc!

Energy transport coefficients

We need to determine the energy transport

from one stream to another:



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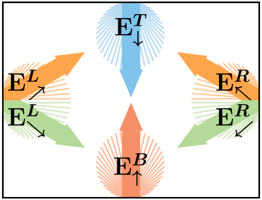
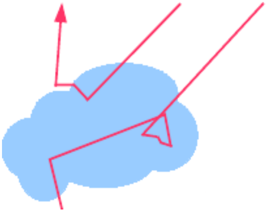


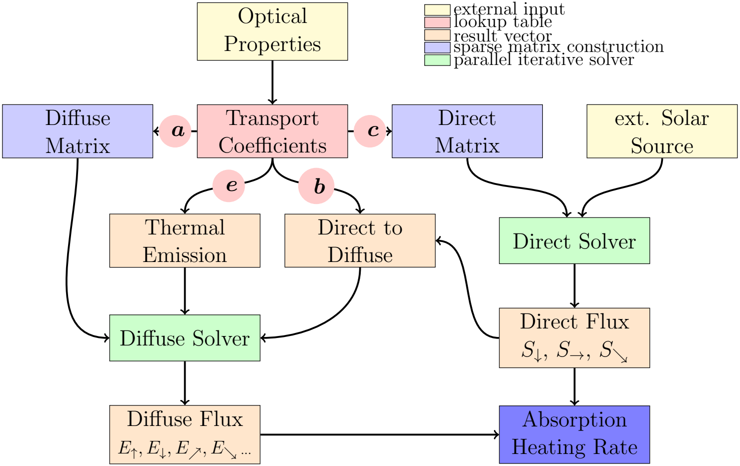
$\rightarrow$ solve radiative transfer equation

with MonteCarlo method

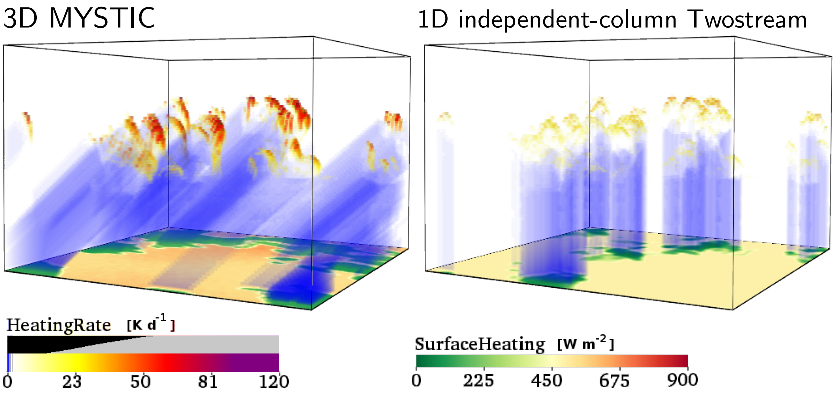


. . . and put them into LookUpTable

Algorithm Flowchart



Does it work?



Computations done with libRadtran (Library for Radiative Transfer, libradtran.org)

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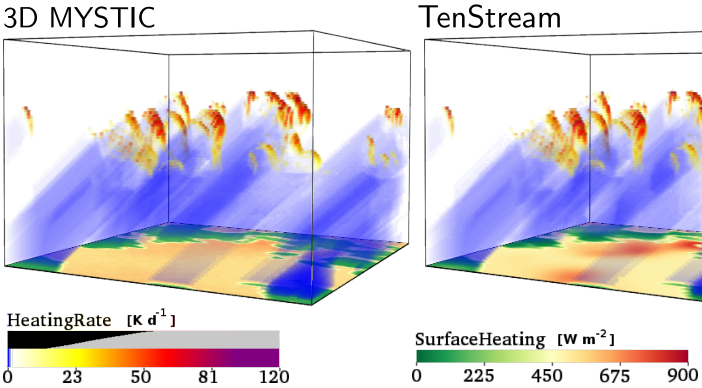

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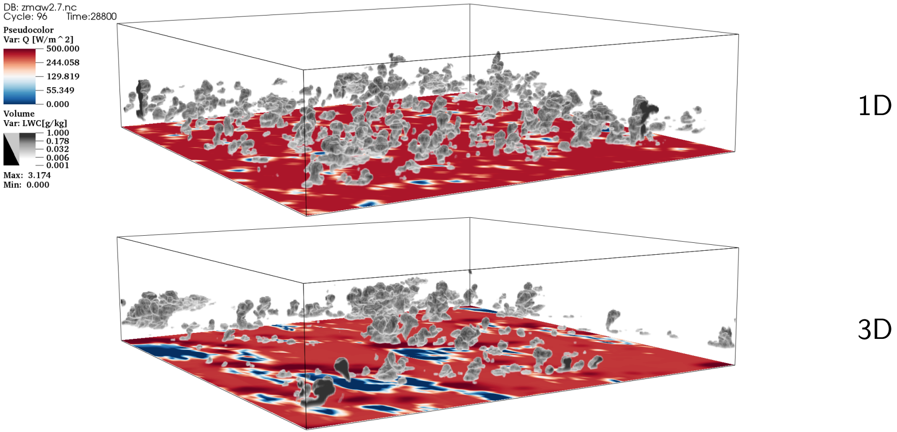
Couple Tenstream to atmospheric model

We coupled the TenStream solver to the UCLA - Large Eddy Simulation (LES)

- LES model atmospheric flow with resolutions from 10m to 1km
- includes dynamics, turbulence, microphysics and radiation
- TenStream solver factor 5-10 more expensive compared to 1D solver

Impact on convective organization

Simulate 30 km $\times$ 30 km domain with different radiative transfer



Current state and a glimpse at whats to come..

Conclusions

- Rapid development of parallel solver with PETSc
- Solve rad. transfer eq. in voxel with MonteCarlo methods
- Successfull integration in LES model

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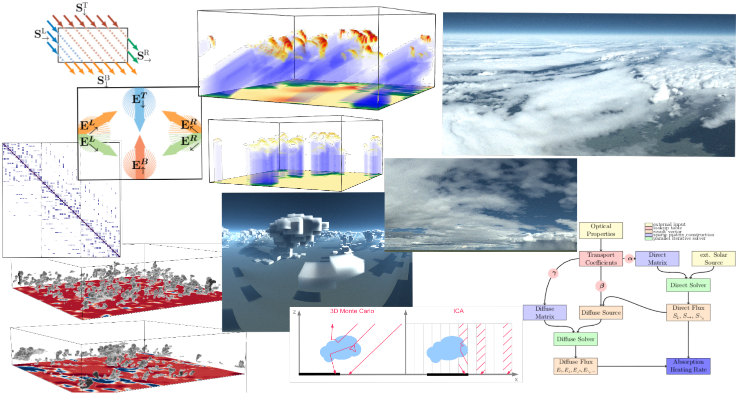
Outlook

- Determine 3D-radiation $\leftrightarrow$ cloud interaction
- Implement in icosahedral model ICON
- Make algorithm ready for large scale computations – $\mathrm{HD(CP)}^2$-Project

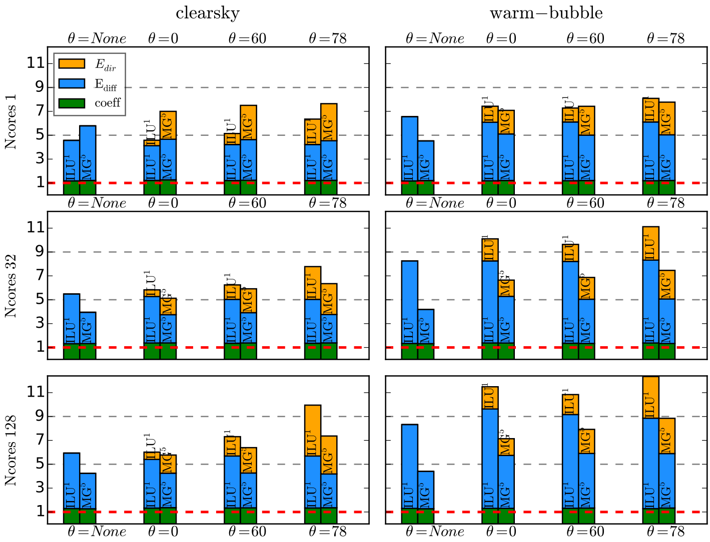
Thank you!



TenStream available at github.com/tenstream

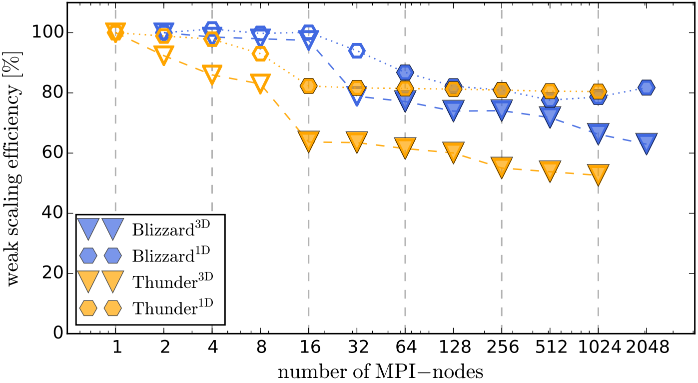
UCLA-LES with 3D interface available at github.com/uclales#jakubfabian

Strong scaling experiment



Weak scaling experiment

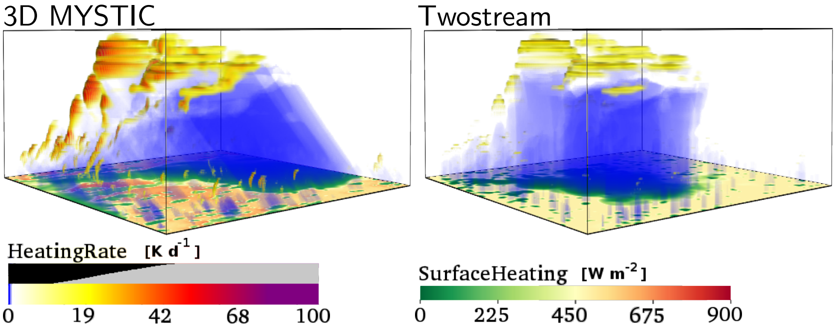
Problem size per compute node is constant ($\approx$ 100 k unknowns)



GAMG Settings

```
-ksp_type fgmres
-ksp_reuse_preconditioner
-pc_type gamg
-pc_gamg_type agg
-pc_gamg_agg_nsmooths 0
-pc_gamg_threshold 2e-1
-pc_gamg_sym_graph true
-pc_gamg_reuse_interpolation true
-mg_levels_ksp_type richardson
-mg_levels_pc_type sor
-mg_levels_pc_sor_its 5
```

Benchmark scenarios



Computations done with libRadtran (Library for Radiative Transfer, libradtran.org)

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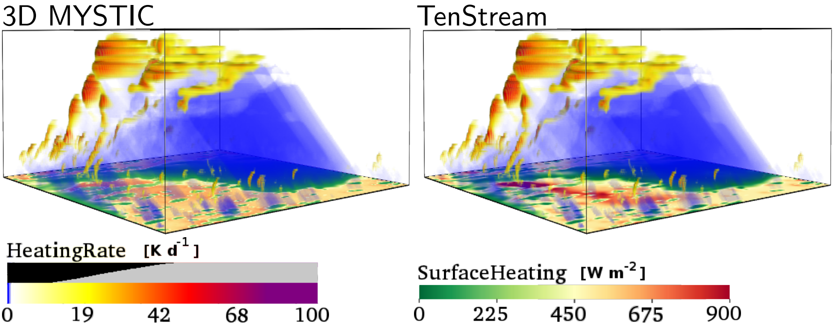

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RMSE of benchmark scenarios

	θ	I3RC TwostrICA		I3RC Tenstr		Cb TwostrICA		Cb Tenstr		ASTEX TwostrICA		ASTEX Tenstr	
Heating Rates in atmosphere	—	263	(-12.1)	85	(-1.2)	120	(-0.9)	65	(2.4)	100	(9.5)	75	(14.1)
	0	45	(-1.3)	16	(-0.7)	35	(-0.6)	19	(0.0)	11	(-1.0)	7	(-0.3)
	20	61	(-3.2)	20	(-0.5)	52	(-1.7)	20	(0.0)	14	(-1.4)	8	(-0.4)
	40	103	(-7.0)	23	(-0.5)	88	(-4.5)	22	(-0.1)	21	(-2.1)	12	(-0.2)
	60	176	(-12.8)	31	(-0.4)	138	(-9.3)	28	(-0.3)	40	(-1.1)	20	(2.0)
	80	389	(-17.0)	64	(1.8)	261	(-15.0)	48	(-0.2)	124	(-0.0)	33	(3.4)
Surface Heating	—	36	(6.5)	20	(-3.2)	28	(12.4)	11	(-2.4)	25	(-3.3)	14	(-12.3)
	0	20	(-2.3)	11	(-1.6)	24	(-4.3)	14	(-3.1)	10	(-0.6)	8	(-4.5)
	20	42	(-1.6)	14	(-1.7)	45	(-3.8)	15	(-3.0)	15	(-0.3)	9	(-4.1)
	40	55	(-0.1)	13	(-1.4)	66	(-2.5)	17	(-2.5)	15	(0.9)	9	(-2.4)
	60	62	(4.4)	18	(-1.0)	92	(1.1)	25	(-1.6)	16	(4.0)	11	(1.1)
	80	65	(24.2)	44	(0.4)	96	(27.6)	71	(-0.2)	18	(11.7)	10	(5.6)