Strahlungs-Seminar

A new Radiative Transfer Solver for fast computation of 3D Heating Rates for use in LES models

Fabian Jakub

5. Juni 2014

Does 3D Radiative Transfer impact cloud evolution?

Very likely:

- Schumann [2002]
- Frame et al. [2009]
- Wapler & Mayer [2007]
- O'Hirok [2005,ARM Meeting]

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Why bother with 3D RT for Heating Rates?

As a consequence of efficiency:

- all NWP/LES models use Independent Pixel Approximation
- usually employ two-stream solver
- sparse temporal sampling

If model resolution $<$ 1km need 3D RT!

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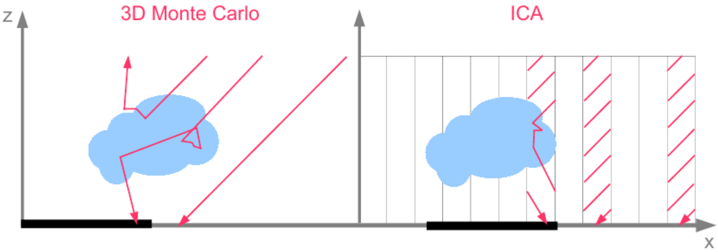
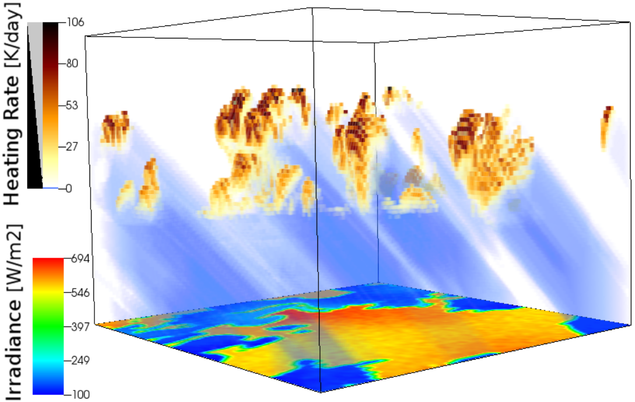
IPA vs. 3D RT



Exemplary cloud field

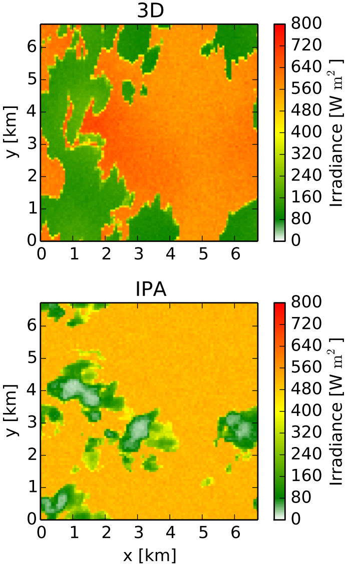
- solar zenith: 60°
- resolution: $\mathrm{dx} = 70m, \mathrm{dz} = 40m$



IPA compared to 3D calculation

Main differences at ground:

- Shadows translated
- Irradiance locally bigger than in clear sky
- RMSE: 62%
- Bias: $+4\%$
  (IPA $\rightarrow$ more Irradiance at ground)



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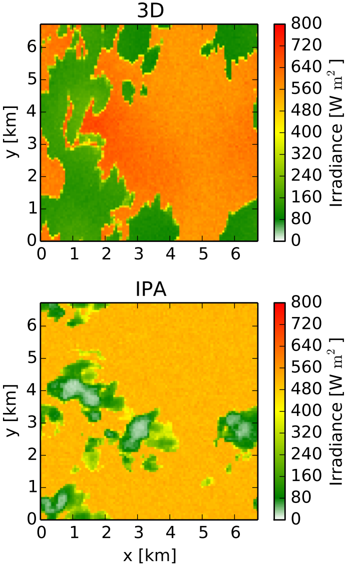

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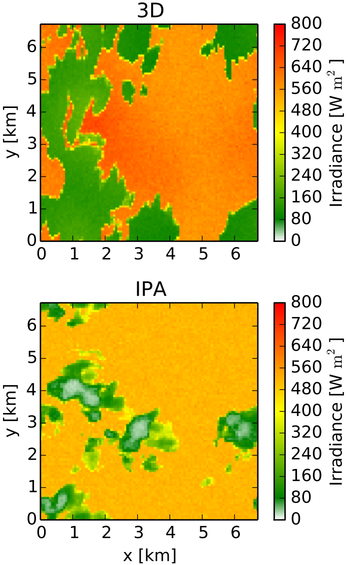

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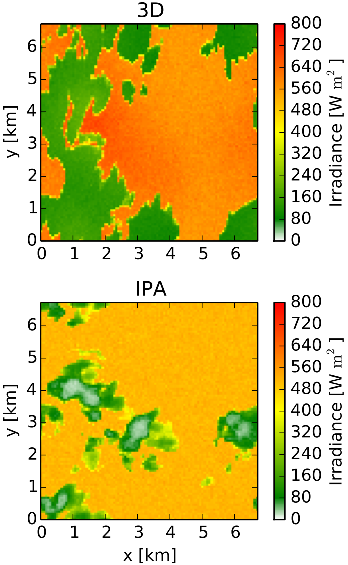

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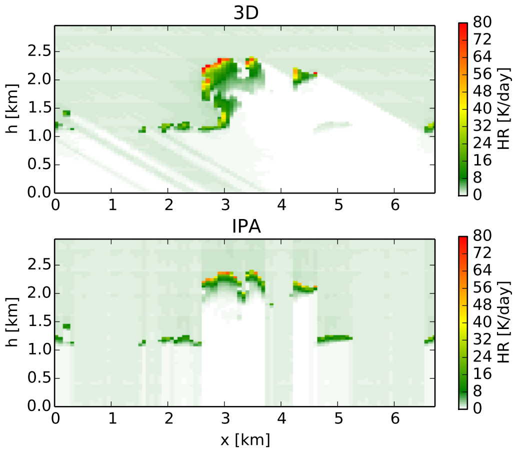
Main differences in atmosphere:

- Heating on cloud side faces
- Elongated cloud shadows
- RMSE: 74%
- Bias: −12%

  (3D → more absorption)



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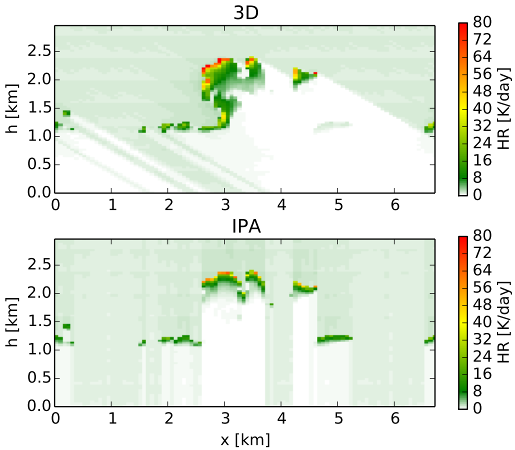

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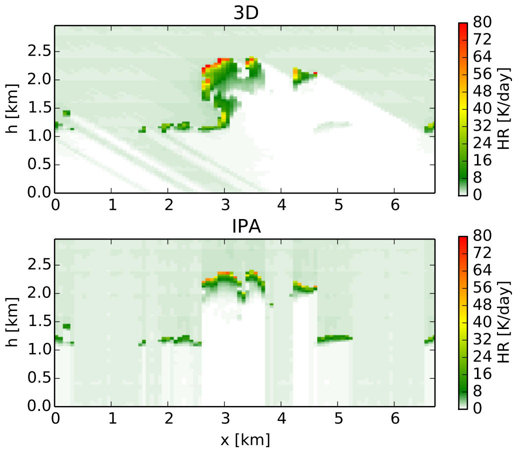

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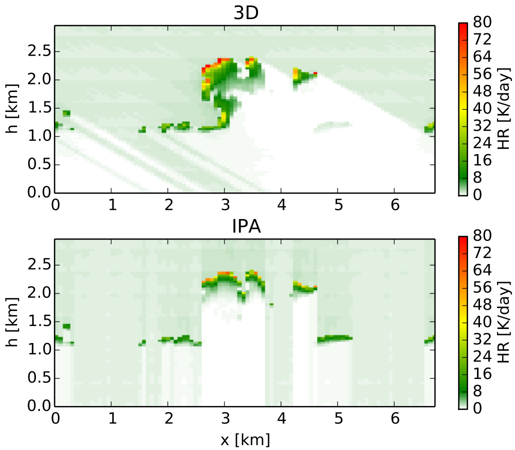
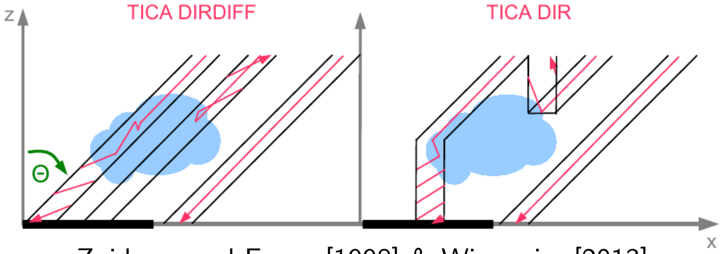


A trip down memory lane

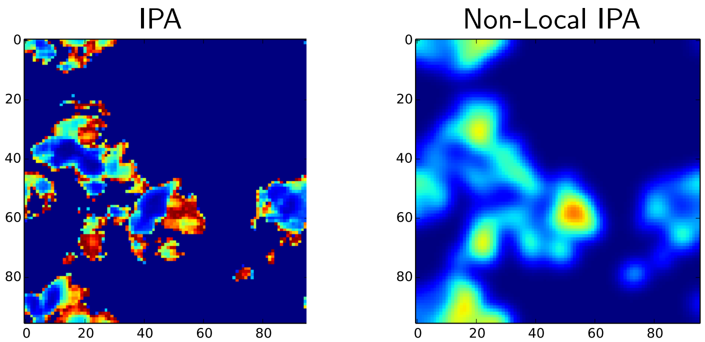
Tilted Independent Pixel Approx.



Zuidema and Evans [1998] & Wissmeier [2013]

A trip down memory lane

Diffuse Downward Irradiance at Ground



Marshak et al. [1998] & Wissmeier [2013]

Master Thesis

- combine TIPA and NIPA (Wissmeier)
- physically parametrize smoothing width
- apply to atmosphere

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Good for fluxes.

Not so for Absorption!

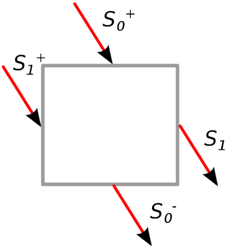
Parallelizes poorly!

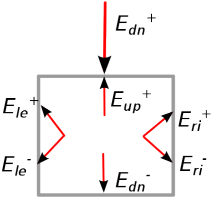
PhD Thesis

Time for a new concept!

Concept for a new Solver

- two-stream $\rightarrow$ N-stream
- Minimum
  - 3 for direct radiation $\rightarrow \mathrm{S_0, S_1, S_2}$
  - 10 for diffuse radiation $\rightarrow \mathrm{E_{dn}, E_{up}, E_{le}} \ldots$
- Transport coefficients from MonteCarlo model
- Couple boxes in linear equation system





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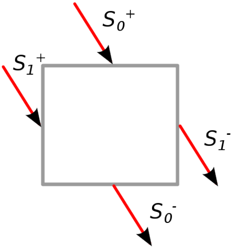

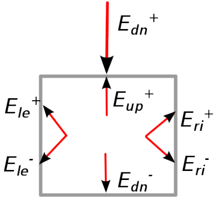

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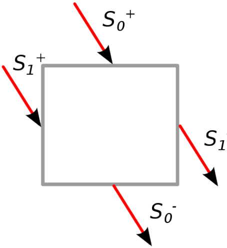

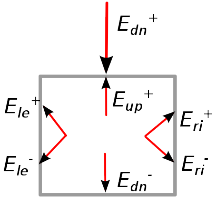

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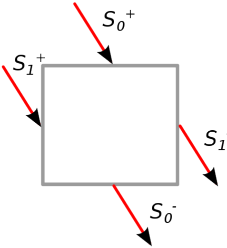

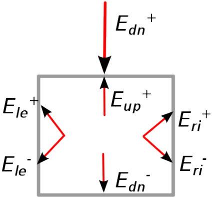

Recalling the two-stream form

$$\begin{pmatrix} \mathrm{E}_{up}^{+} \\ \mathrm{E}_{dn}^{-} \\ \mathrm{E}_{dir}^{-} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{11} & a_{23} \\ 0 & 0 & a_{33} \end{pmatrix} \begin{pmatrix} \mathrm{E}_{up}^{-} \\ \mathrm{E}_{dn}^{+} \\ \mathrm{E}_{dir}^{+} \end{pmatrix}$$

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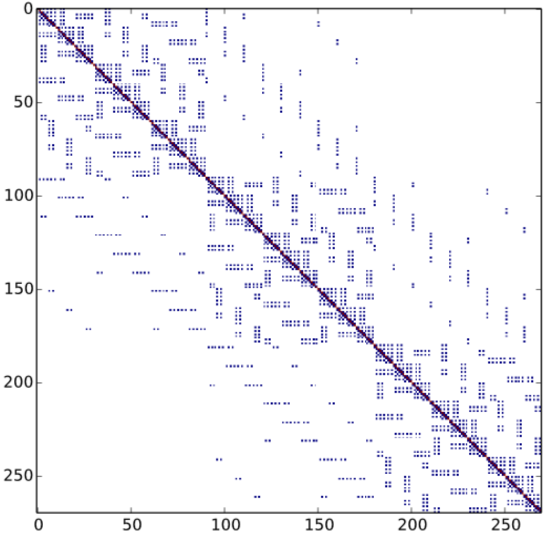
Non-zero pattern of 3x3x3 10-stream Matrix

- Matrix is huge but very sparse
- Direct Solver requires too much memory
- → Solve iteratively
- Parallelization results in non-local product (PETSc library)



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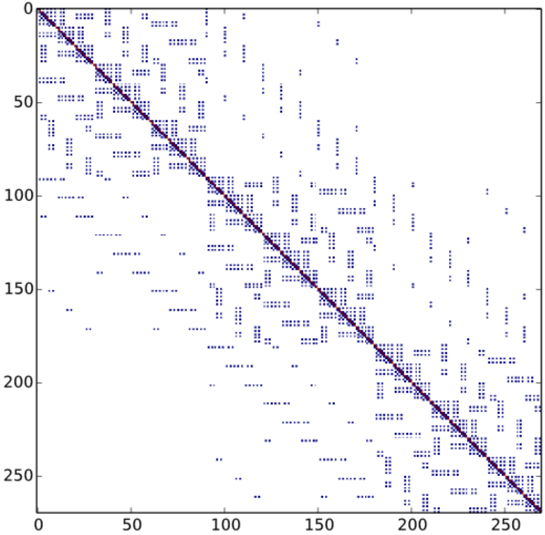

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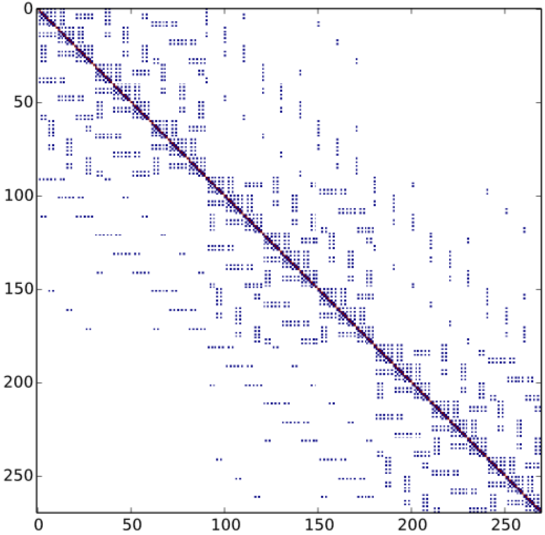

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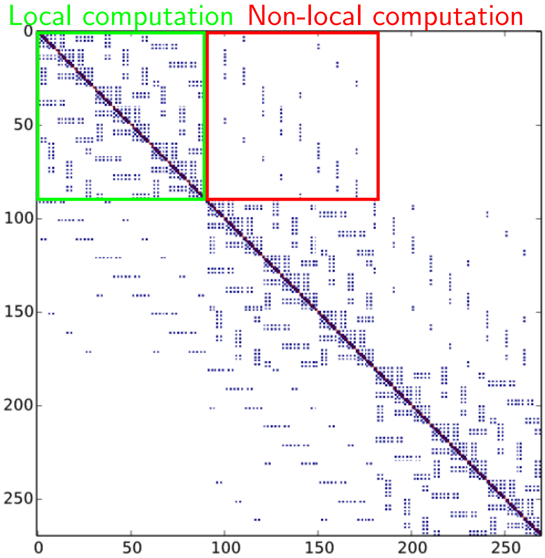

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- Use simple MonteCarlo Raytracer
- Transport Coefficients depend on:
  - dz/dx aspect ratio
  - $\beta_{scatter}$ scattering coefficient
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  - g asymmetry parameter
  - θ, ϕ sun angles
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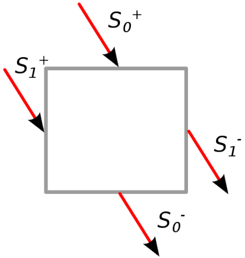

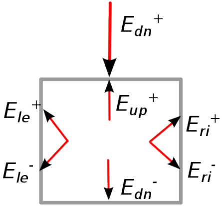

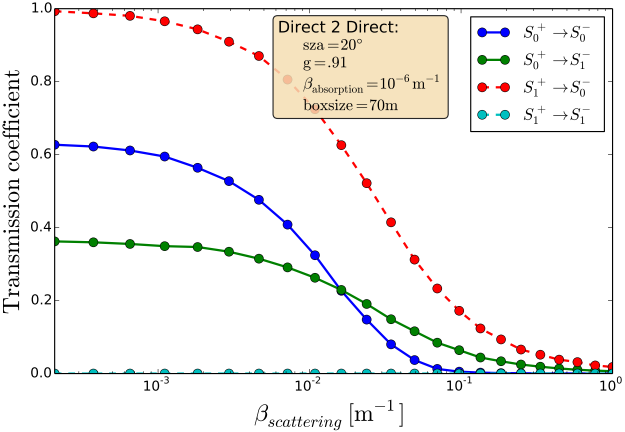

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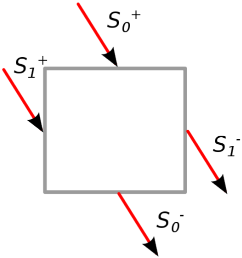
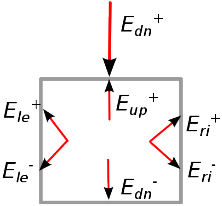
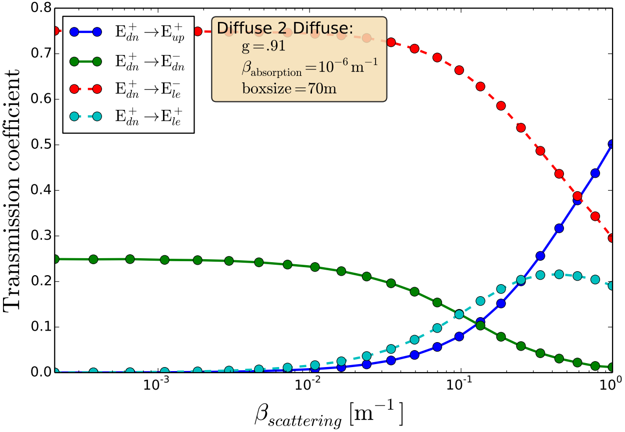
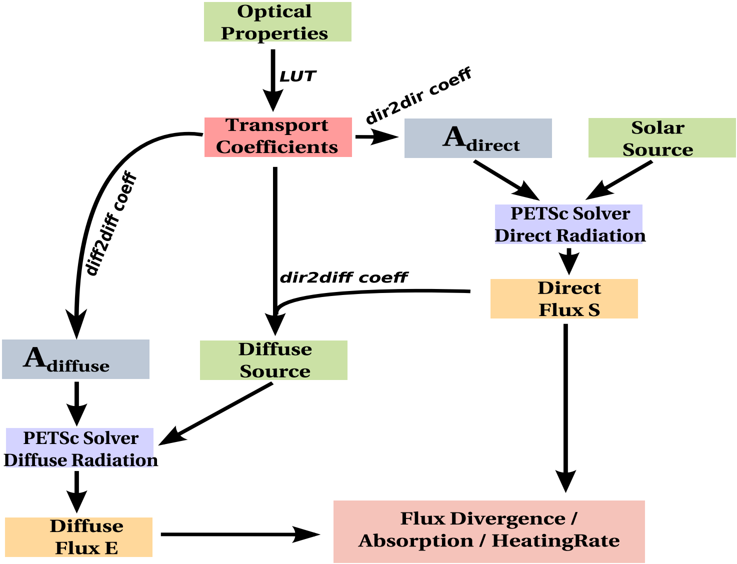


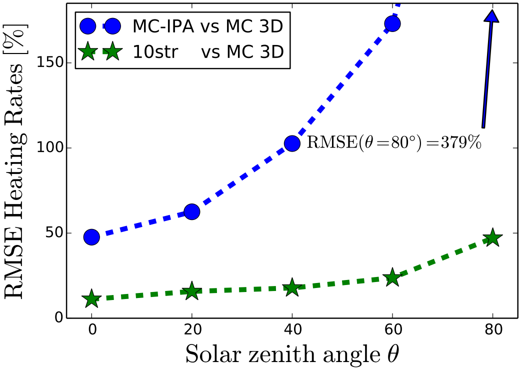




Algorithm Outline

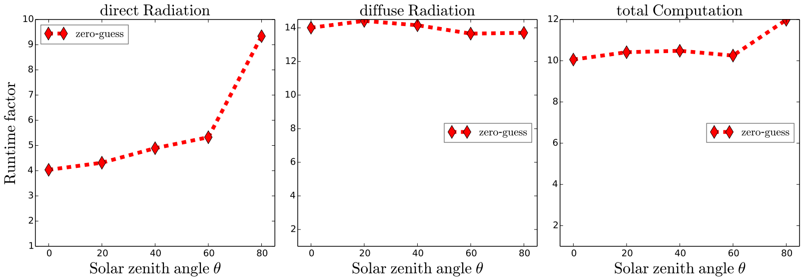


Algorithm Performance for I3RC cloud scene



What does it cost computationally?

Runtime increase compared to two-stream solver



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Ten-stream → worst case factor ≈3

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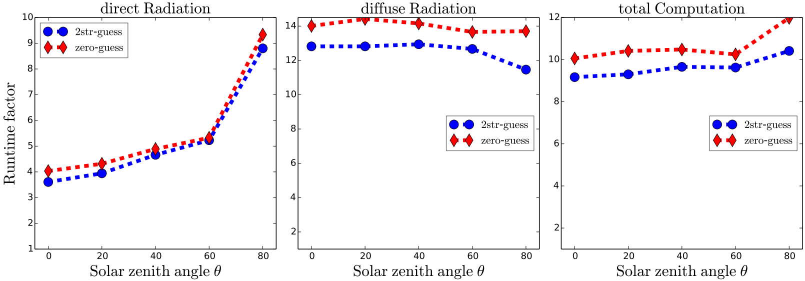

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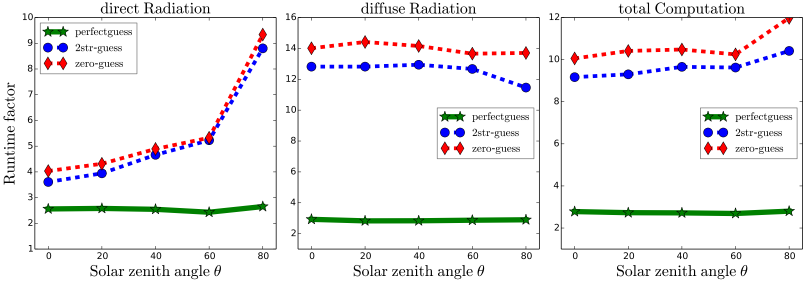

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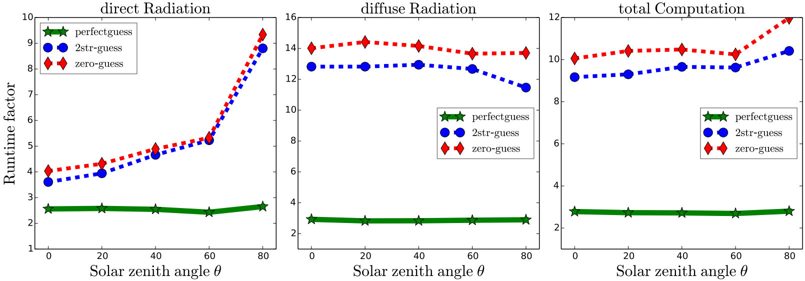

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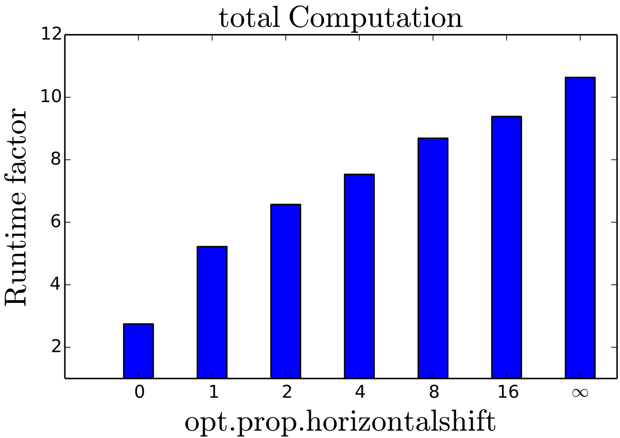
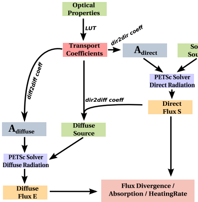
How does wind affect convergence?

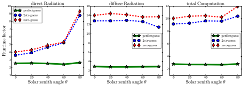


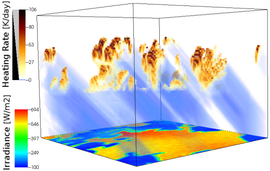
And a glimpse at what's to come...

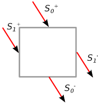
- Include algorithm in UCLA-LES / PALM
- Merge with thermal solver from Carolin Klinger
- Check if there are differences in cloud physics / evolution
- Ultimate goal is to include and test solver in ICON for HDCP^2 project

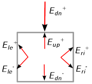
Thank you!

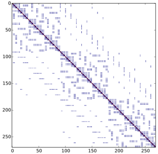

Optical Properties
LUT
Transport Coefficients
dir2dir coeff
A_direct
Solar Source
PETSc Solver Direct Radiation
Direct Flux S
diff2diff coeff
dir2diff coeff
A_diffuse
Diffuse Source
PETSc Solver Diffuse Radiation
Diffuse Flux E
Flux Divergence / Absorption / HeatingRate

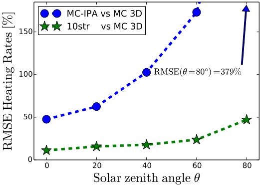

direct Radiation
diffuse Radiation
total Computation
Runtime factor
Solar zenith angle θ

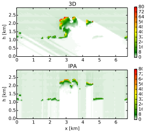

Heating Rate [K/day]
Irradiance [W/m2]

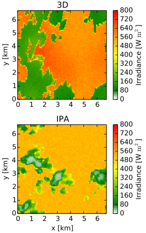

S_0^+
S_1^+
S_1^-
S_0^-

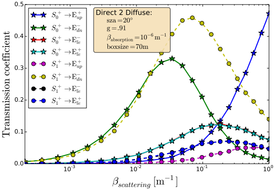

E_{dn}^+
E_{up}^+
E_{le}^+
E_{ri}^+
E_{le}^-
E_{ri}^-
E_{dn}^-

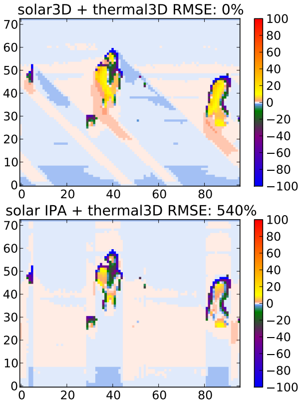



MC-IPA vs MC 3D
10str vs MC 3D
RMSE(θ=80°)=379%
RMSE Heating Rates [%]
Solar zenith angle θ

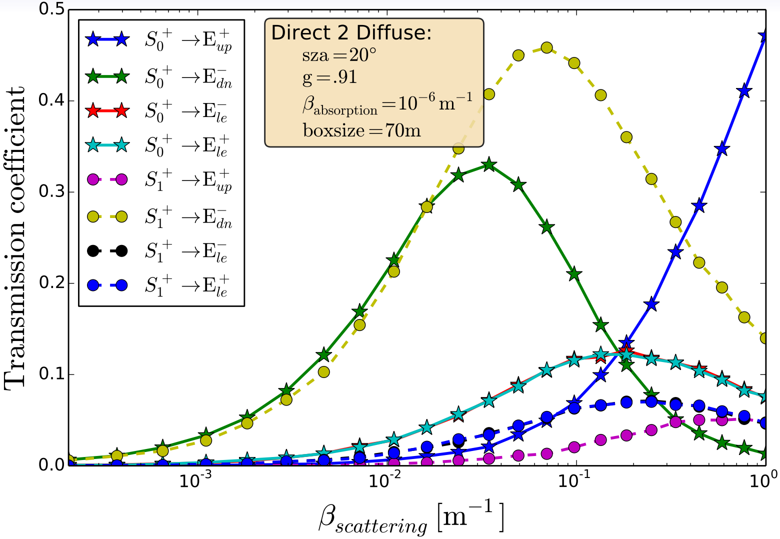

3D
IPA
h [km]
x [km]


3D
IPA
y [km]
x [km]
Irradiance [W m^{-2}]


Direct 2 Diffuse:
sza = 20°
g = .91
$\beta_{absorption} = 10^{-6}$ m^{-1}
boxsize = 70m
Transmission coefficient
$\beta_{scattering}$ [m^{-1}]



solar3D + thermal3D RMSE: 0%
solar3D + thermal IPA RMSE: 982%
solar IPA + thermal3D RMSE: 540%
solar IPA + thermal IPA RMSE: 866%



Direct 2 Diffuse:
sza = 20°
g = .91
$\beta_{\mathrm{absorption}} = 10^{-6}\,\mathrm{m}^{-1}$
boxsize = 70m
$S_0^+ \rightarrow \mathrm{E}_{up}^+$
$S_0^+ \rightarrow \mathrm{E}_{dn}^-$
$S_0^+ \rightarrow \mathrm{E}_{le}^-$
$S_0^+ \rightarrow \mathrm{E}_{le}^+$
$S_1^+ \rightarrow \mathrm{E}_{up}^+$
$S_1^+ \rightarrow \mathrm{E}_{dn}^-$
$S_1^+ \rightarrow \mathrm{E}_{le}^-$
$S_1^+ \rightarrow \mathrm{E}_{le}^+$
Transmission coefficient
0.0
0.1
0.2
0.3
0.4
0.5
10^{-3}
10^{-2}
10^{-1}
10^{0}
$\beta_{scattering}\ [\mathrm{m}^{-1}]$