A Dynamic Approach to 3D Radiative Transfer in NWP Models

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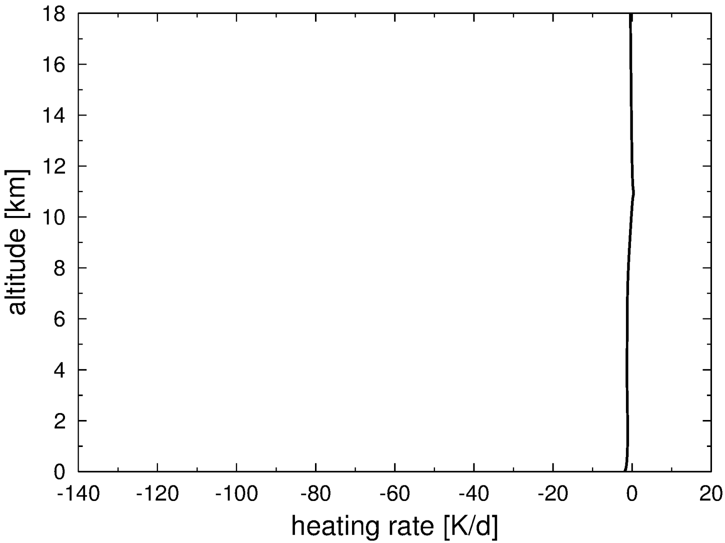
Radiative Heating and Cooling: Thermal (1D)



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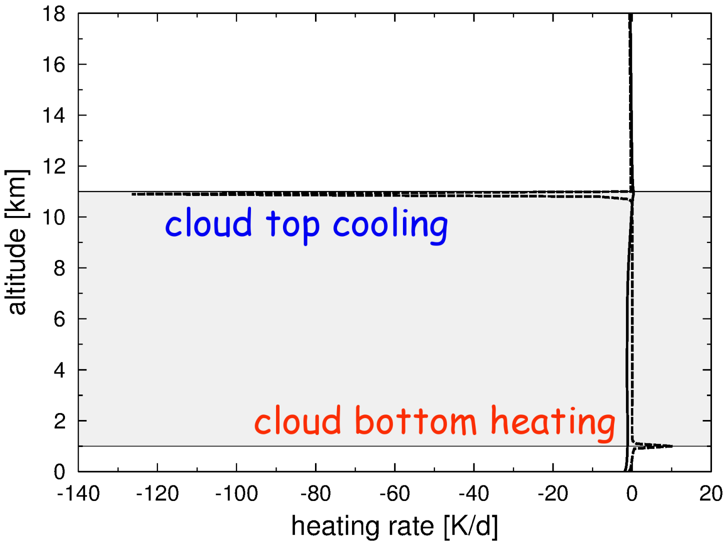
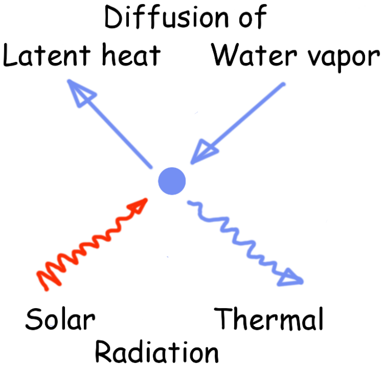


Potential Effects of Radiation on Clouds

- Droplet growth affected by absorption/emission of radiation
- Effect of heating/cooling rates on dynamics
- Differential heating of the surface (cloud shadows)

Radiative Heating and Cooling: Microscopic View



Analytical 3D Thermal Heating and Cooling Rates

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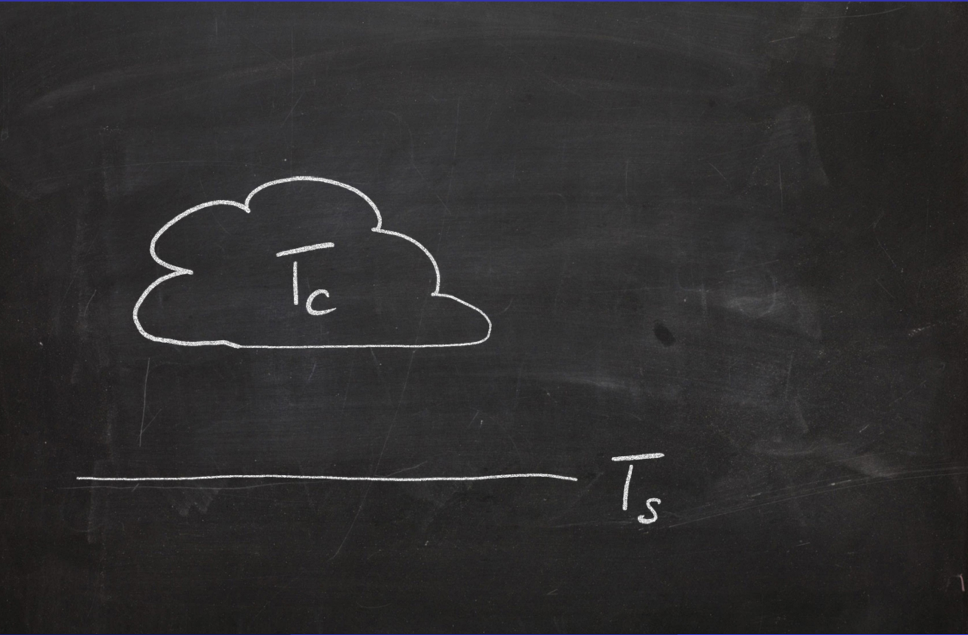

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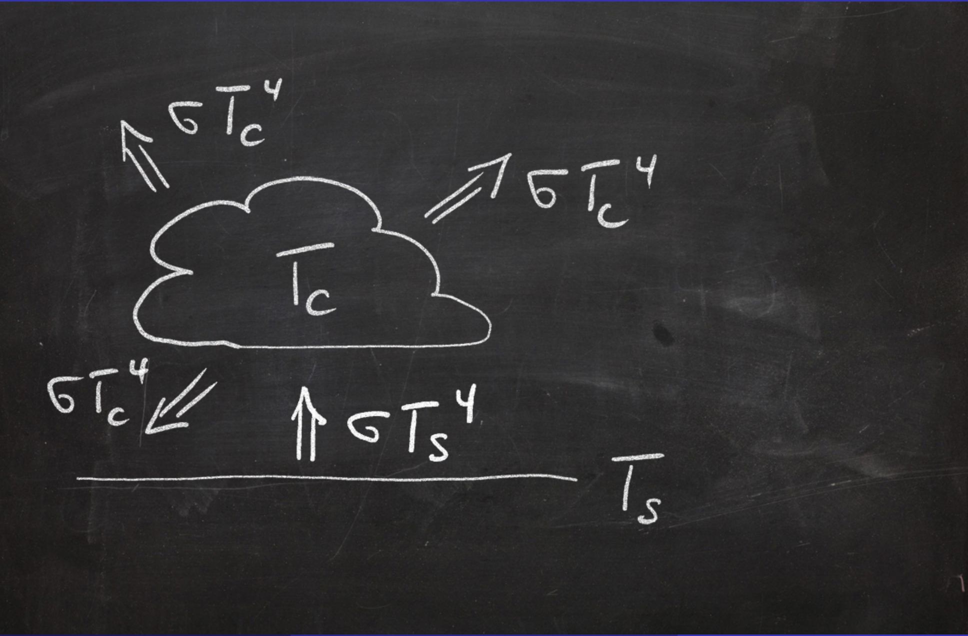

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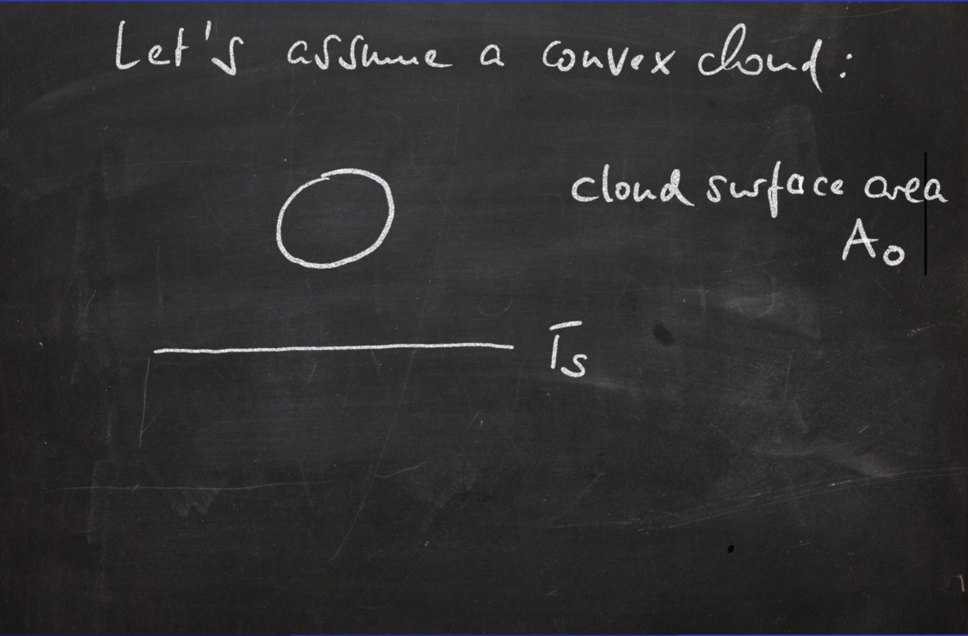
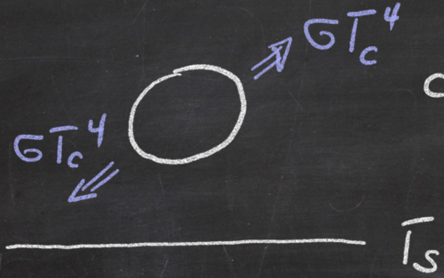


Analytical 3D Thermal Heating and Cooling Rates

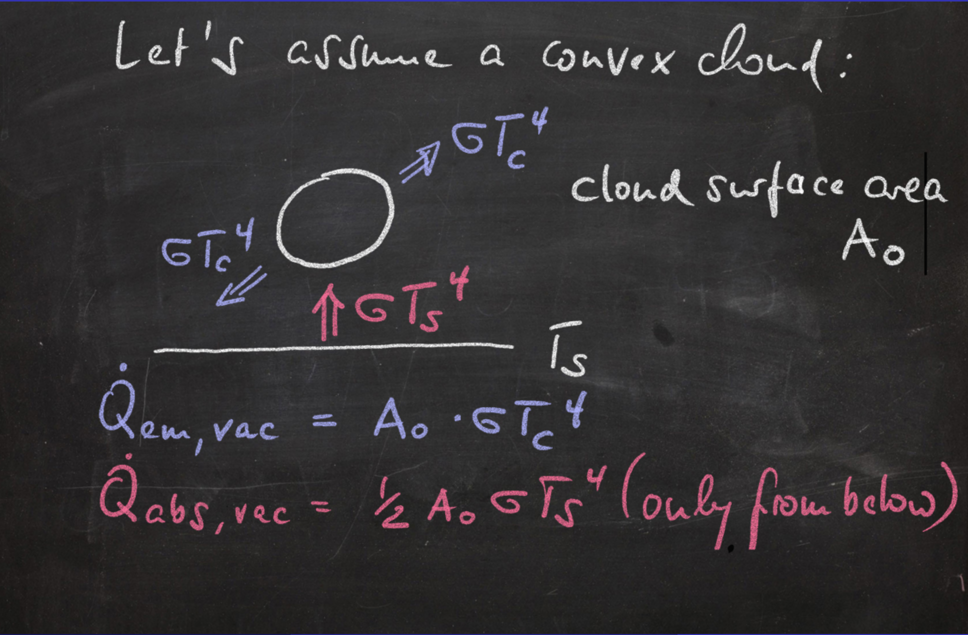
Let's assume a convex cloud:



cloud surface area A_0

$$\dot{Q}_{em,vac} = A_0 \cdot \sigma T_c^4$$

Analytical 3D Thermal Heating and Cooling Rates



Analytical 3D Thermal Heating and Cooling Rates

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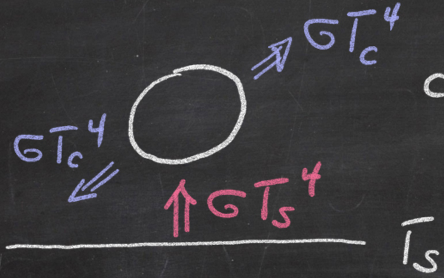


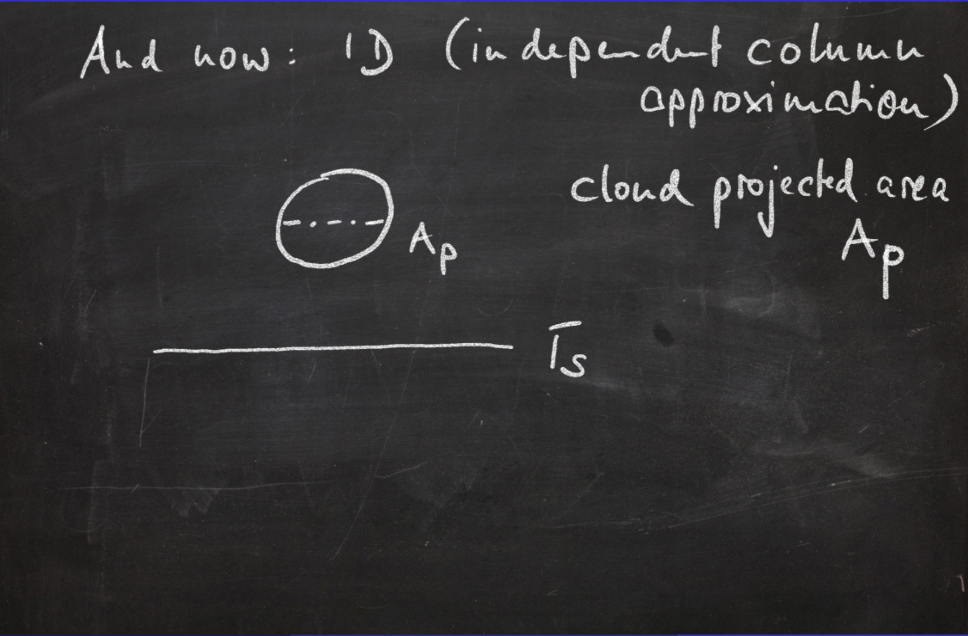
cloud surface area A_0

$$\dot{Q}_{em,vac} = A_0 \cdot \sigma T_c^4$$

$$\dot{Q}_{abs,vac} = \tfrac{1}{2} A_0 \sigma T_S^4 \text{ (only from below)}$$

$$\dot{Q}_{rad,vac} = \dot{Q}_{abs,vac} - \dot{Q}_{em,vac} = A_0 \sigma \left(\tfrac{1}{2} T_S^4 - T_c^4\right)$$

Analytical 3D Thermal Heating and Cooling Rates



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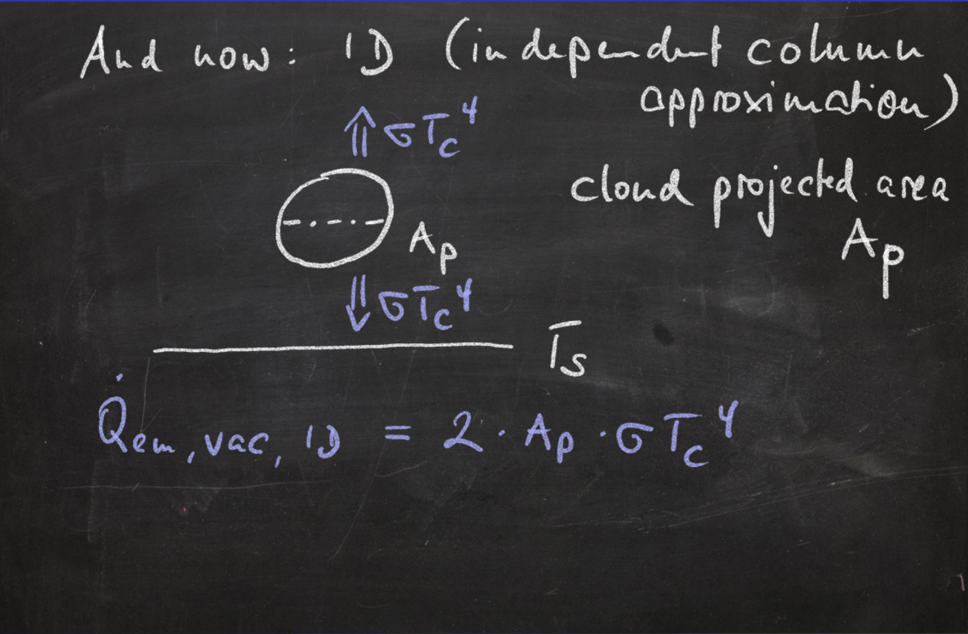
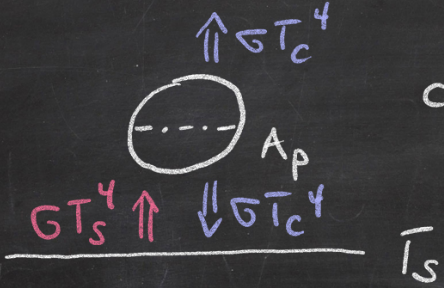


Analytical 3D Thermal Heating and Cooling Rates

And now: 1D (independent column approximation)



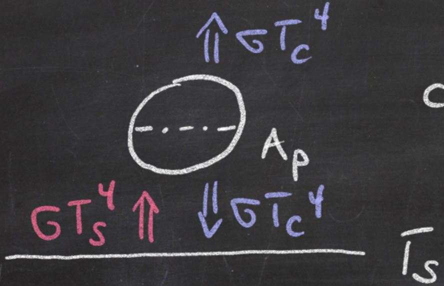
cloud projected area A_p

$$\dot{Q}_{em,vac,1D} = 2 \cdot A_p \cdot \sigma T_c^4$$

$$\dot{Q}_{abs,vac,1D} = A_p \cdot \sigma \cdot T_s^4$$

Analytical 3D Thermal Heating and Cooling Rates

And now: 1D (independent column approximation)



cloud projected area A_p

$$\dot{Q}_{em,vac,1D} = 2 \cdot A_p \cdot \sigma T_c^4$$

$$\dot{Q}_{abs,vac,1D} = A_p \cdot \sigma \cdot T_s^4$$

$$\dot{Q}_{rad,vac,1D} = A_p \cdot \sigma \cdot \left(T_s^4 - 2 T_c^4\right)$$

Analytical 3D Thermal Heating and Cooling Rates

For example: Cube with length d:

$$A_o = 6\,d^2$$

$$A_p = d^2 = \tfrac{1}{6} A_o$$

$$\Rightarrow \dot{Q}_{rad,3D} = 3 \cdot \dot{Q}_{rad,1D} \; !$$

Analytical 3D Thermal Heating and Cooling Rates

For example: Cube with length d:

|d|

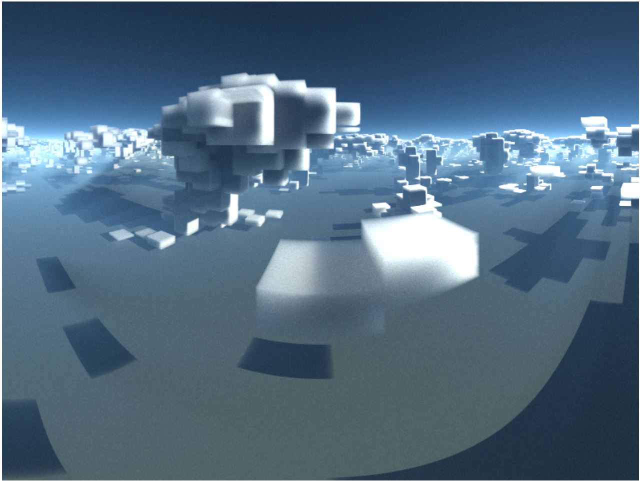
$$A_O = 6\,d^2$$

$$A_p = d^2 = \tfrac{1}{6} A_O$$

$$\Rightarrow \dot{Q}_{rad,3D} = 3 \cdot \dot{Q}_{rad,1D} \; !$$

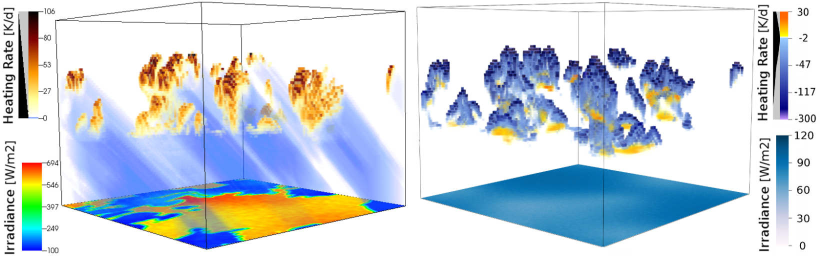
Sphere instead of cube:
Factor 2 instead of 3

Model clouds are often cubes!



MYSTIC visualization of 2km “convection-permitting” model output

Of course we can do much better than that!

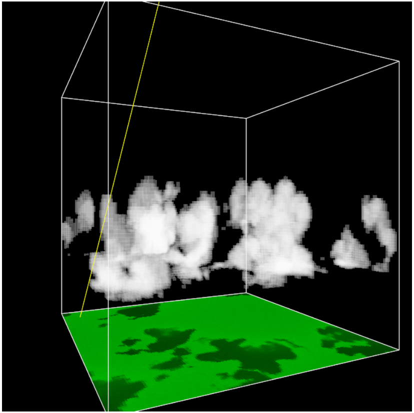


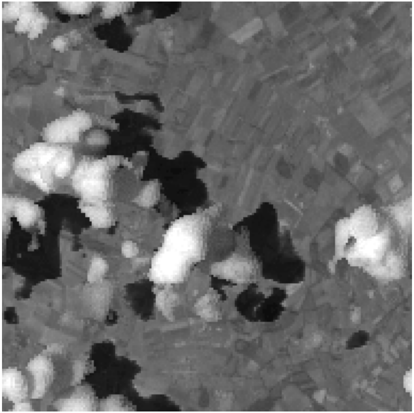
MYSTIC simulation: Carolin Klinger, Fabian Jakub, HD(CP)2

Monte Carlo Code for the physically correct tracing of photons in cloudy atmospheres, e.g. Mayer, 2009

Monte carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres

Mayer, 2009; Buras, Emde, Klinger, ...





Effects: Cloud Streets (Jakub and Mayer, 2017)

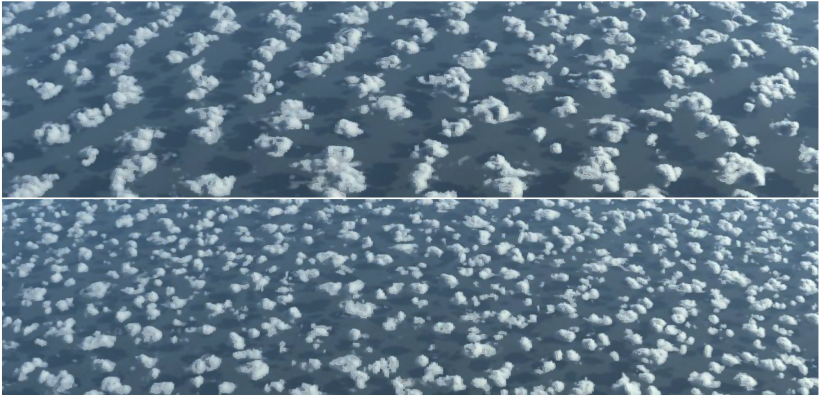
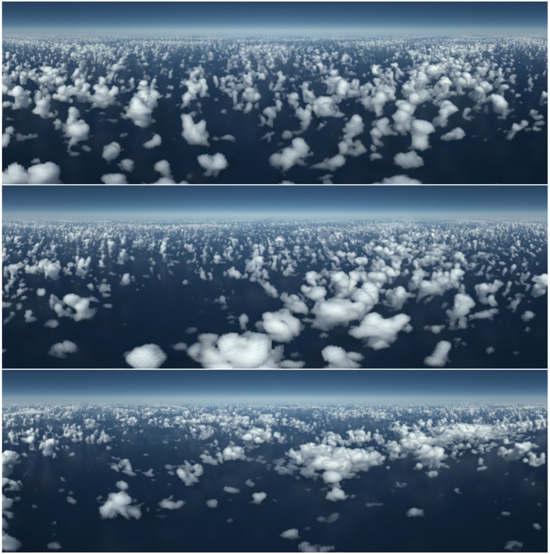


Figure 1. Virtual photograph of LES simulations at a cruising altitude of 15 km. Top panel: cloud formation of a simulation driven by 3D radiation (TenStream with sun in the east, i.e. right ($\varphi = 90°$)). Lower-panel: cloud formation of a simulation which was performed with 1D radiation (Two-stream). The specific model setup is the same as referenced in fig. 2 i.e., no background wind and a continental land surface. The simulations differ with respect to cloud size distributions and the organization in cloud streets, the cloud fraction though is the same (27 %). The visualization was performed with a physically correct rendering with MYSTIC (MonteCarlo solver in libRadtran (Mayer, 2009, Emde et al. 2015)). SZA = 60°

Effects: Cloud Organization (Klinger et al, 2017)



const. cooling

3D avg

3D

Radiative Transfer in NWP Models

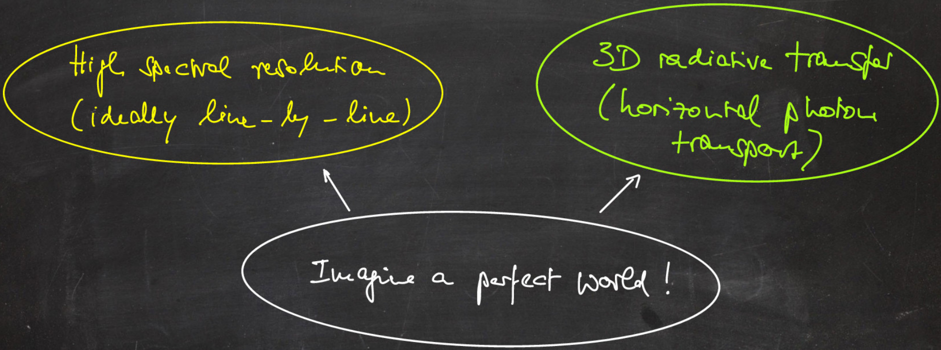
Imagine a perfect world!

Radiative Transfer in NWP Models

High spectral resolution
(ideally line-by-line)

Imagine a perfect world!

Radiative Transfer in NWP Models



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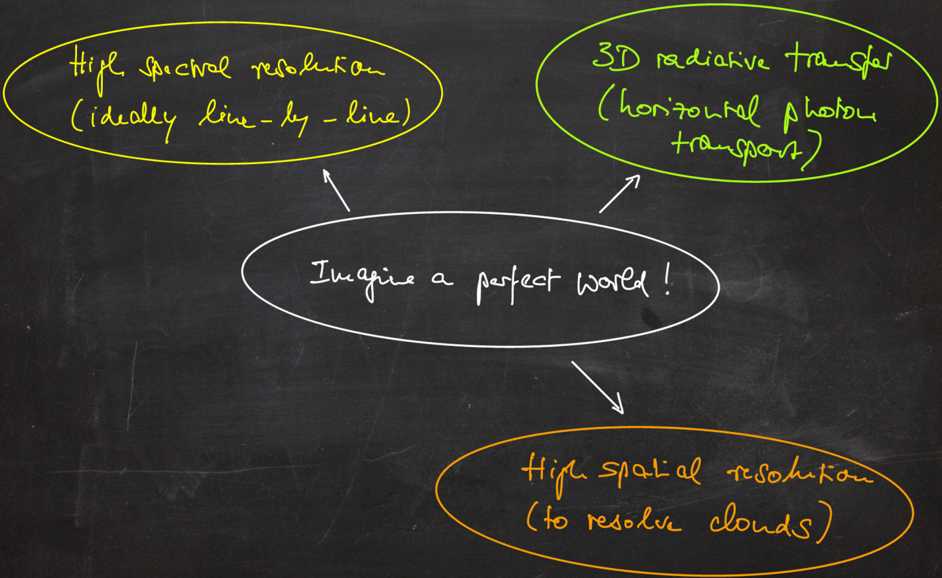

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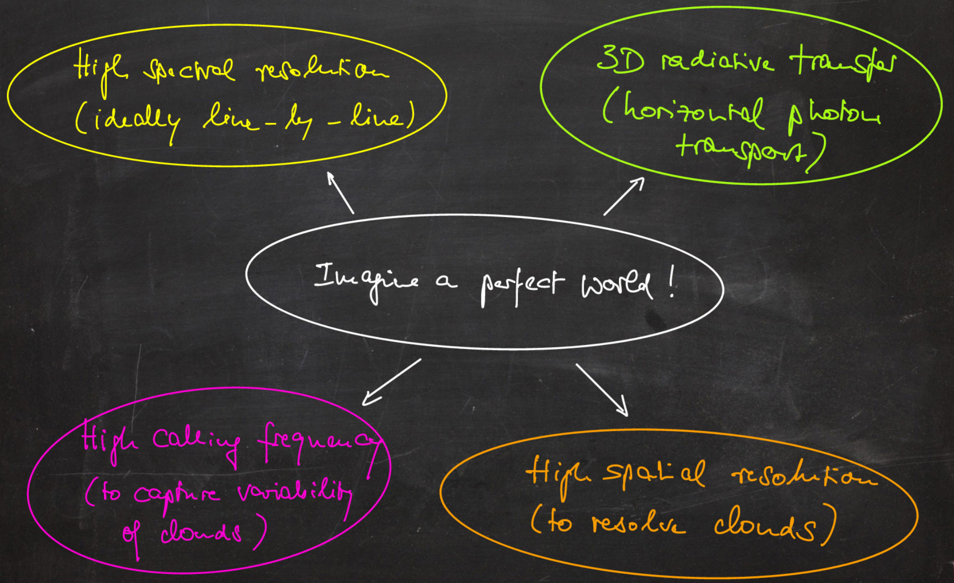

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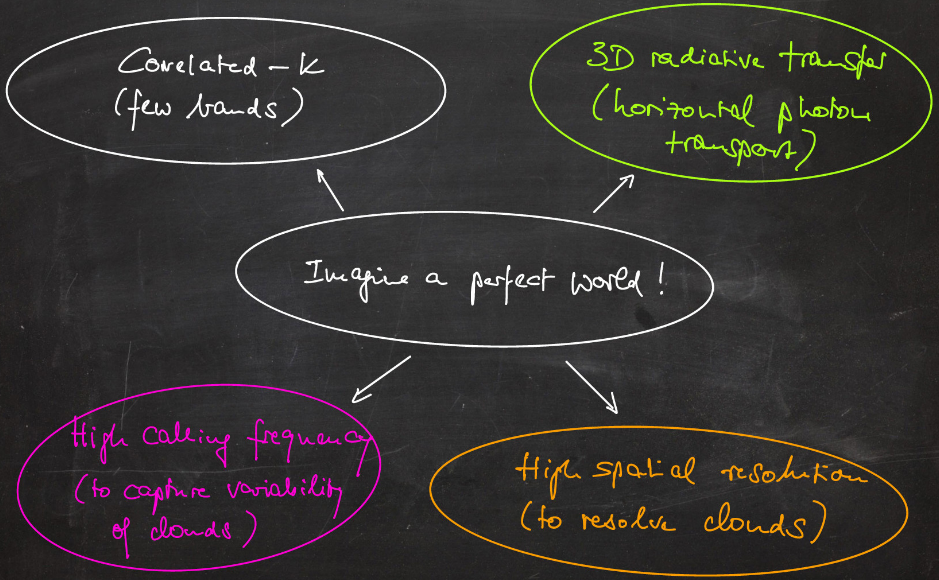

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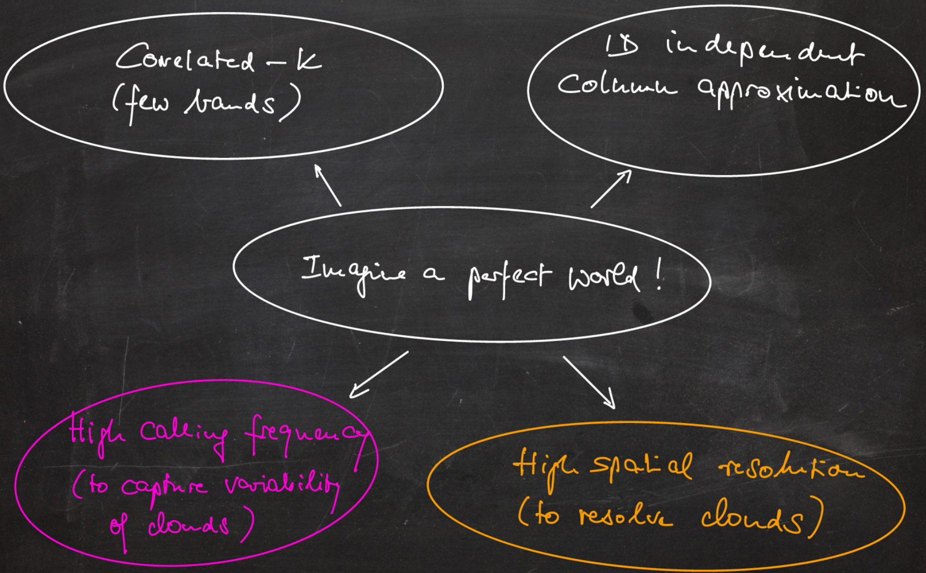

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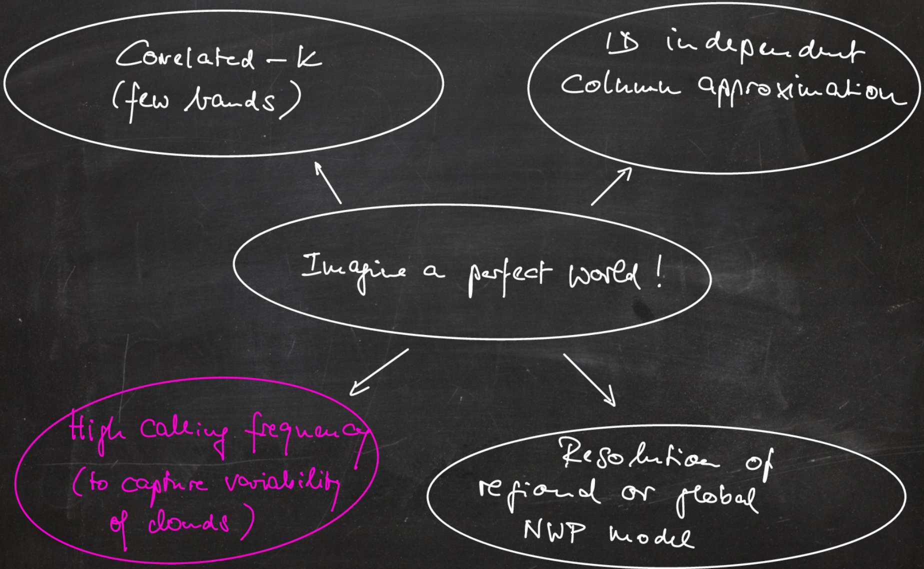

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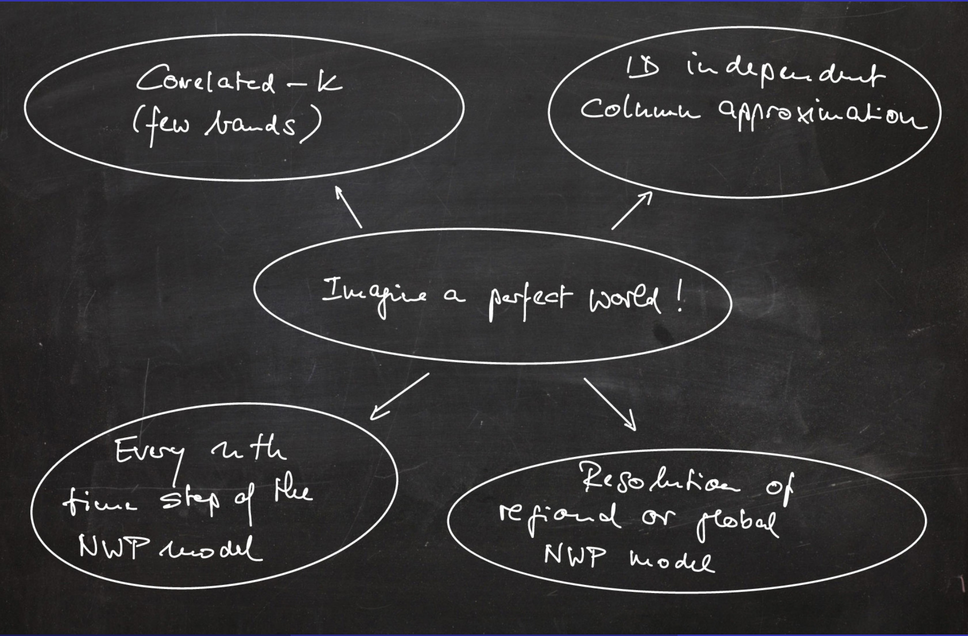

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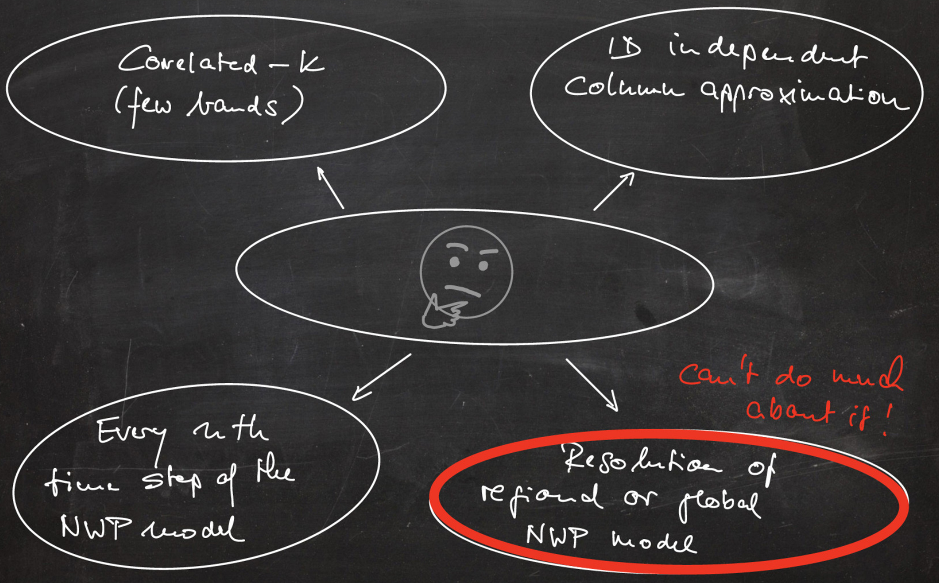

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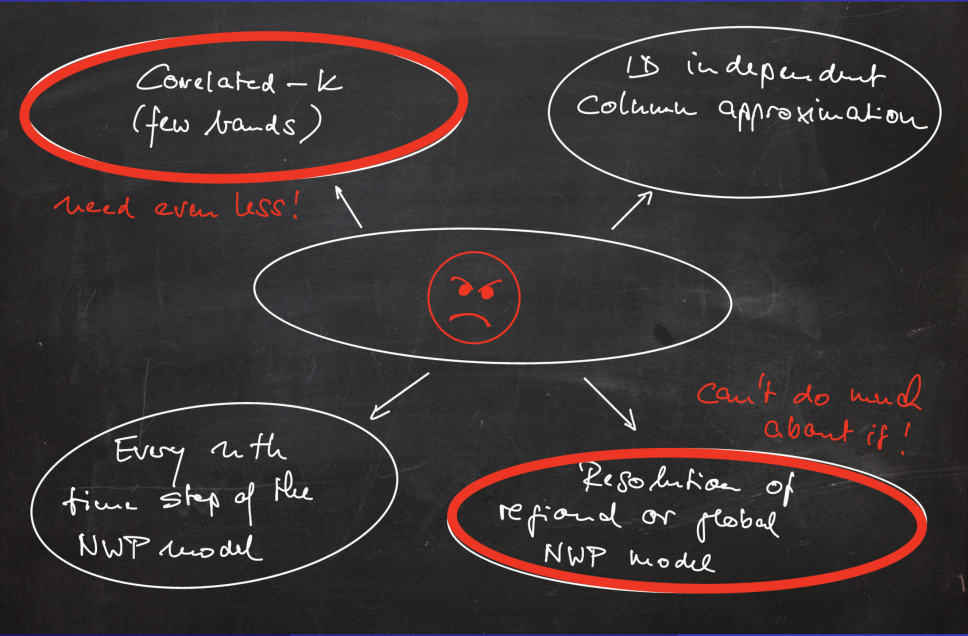

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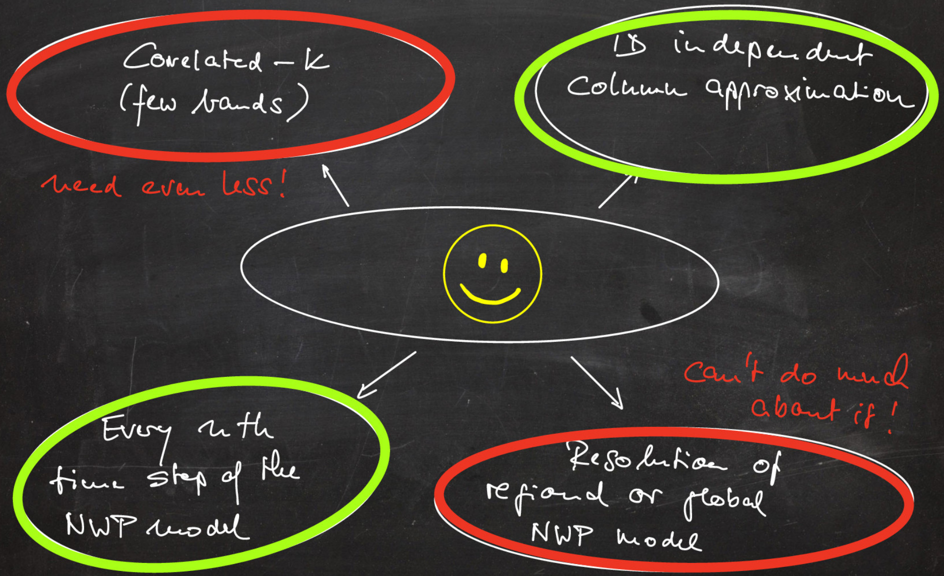

The Tenstream Solver (Mayer and Jakub, 2015 a,b)

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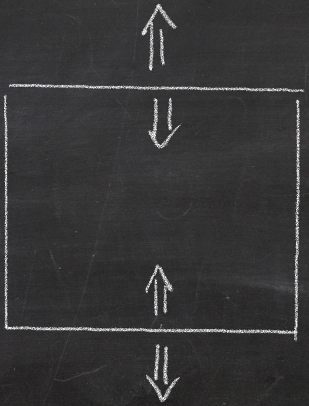

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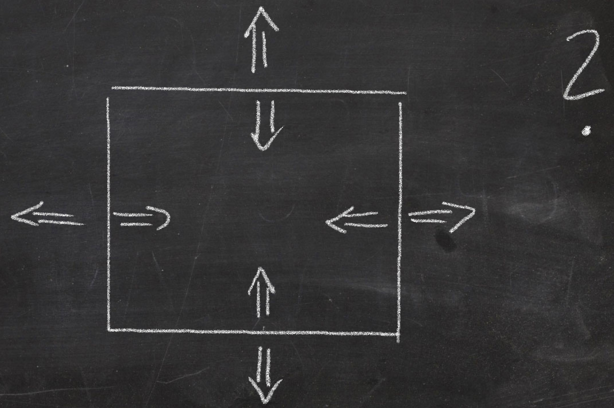

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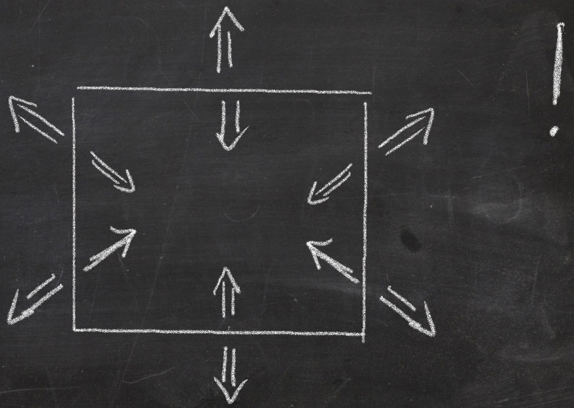

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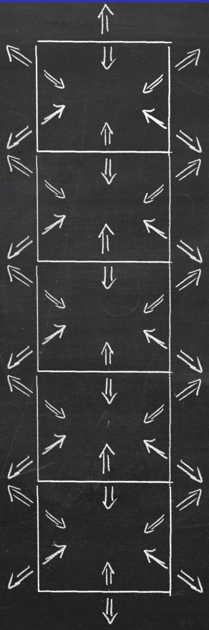

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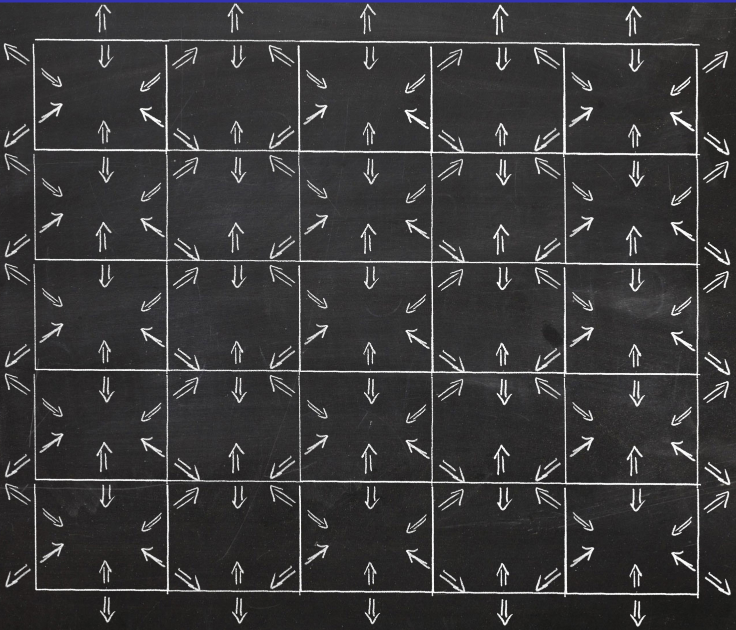
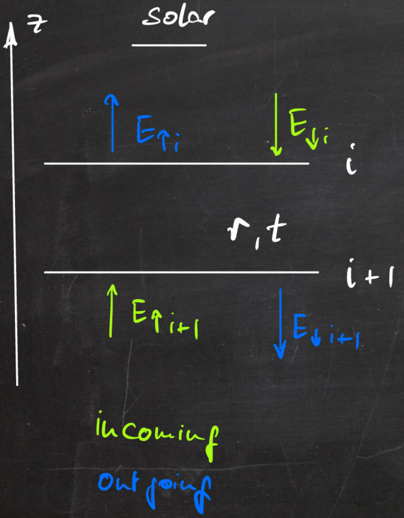


“Dynamic RT”



$$E_{\uparrow i} = r \cdot E_{\downarrow i} + t \cdot E_{\uparrow i+1}$$

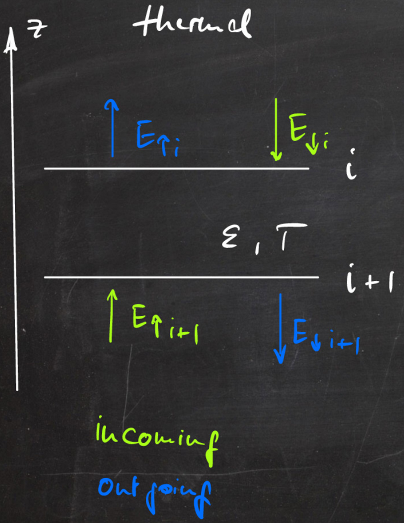
$$E_{\downarrow i+1} = t \cdot E_{\downarrow i} + r \cdot E_{\uparrow i+1}$$

for n model layers

→ linear equation system

alternatively iterative solution = “dynamic RT”

"Dynamic RT"



$$E_{\uparrow i} = (1-\varepsilon) E_{\uparrow i+1} + \varepsilon \sigma T^4$$

$$E_{\downarrow i+1} = (1-\varepsilon) E_{\downarrow i} + \varepsilon \sigma T^4$$

for n model layers:

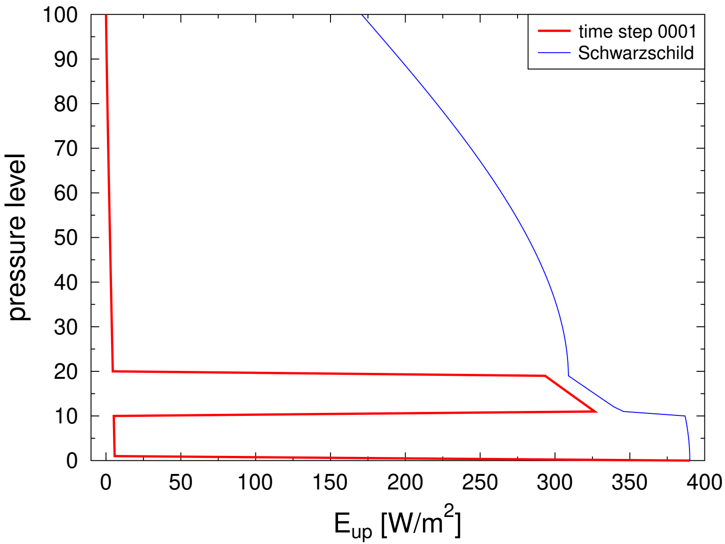
upward / downward recurrence

≡ iterative solution

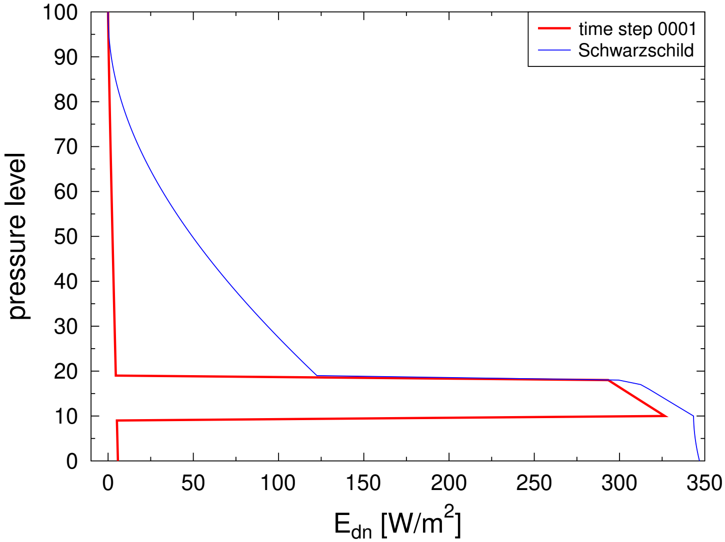
= "dynamic RT"

"Gauß – Seidel"

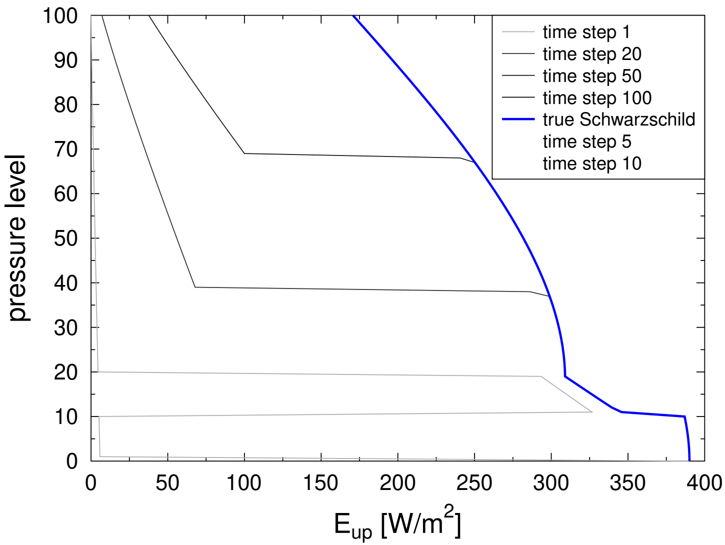
“Dynamic RT” – 1D , static cloud, upward flux



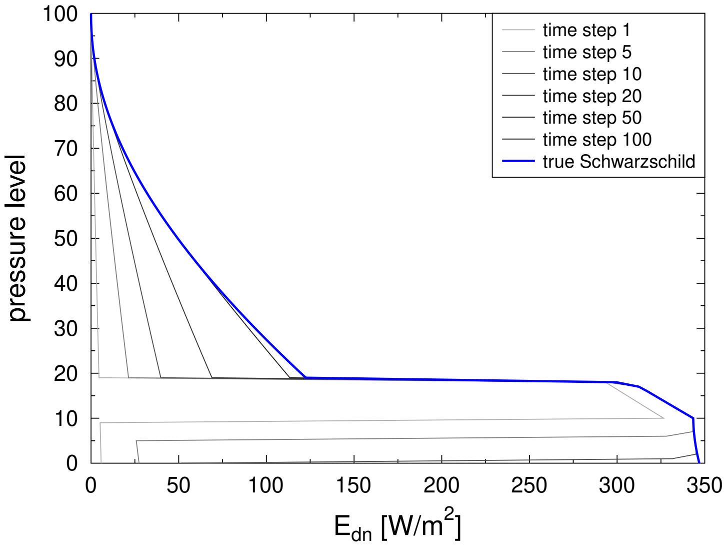
"Dynamic RT" – 1D, static cloud, downward flux



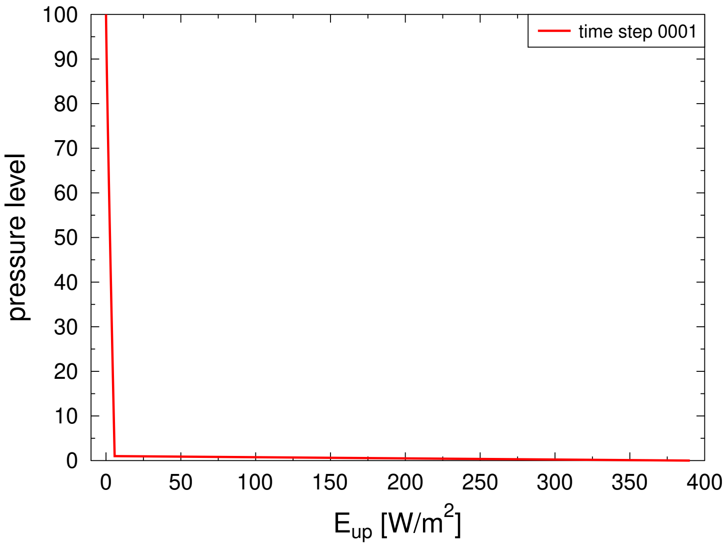
Dynamic RT – if the movies won't work



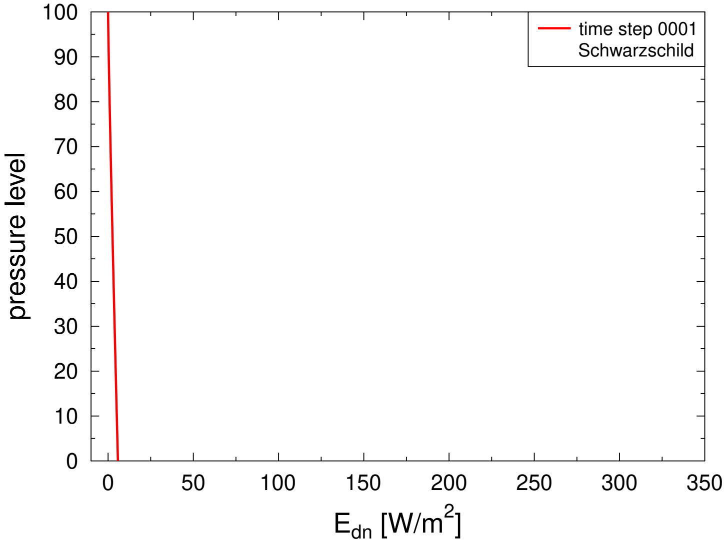
Dynamic RT – if the movies won't work



“Dynamic RT” – 1D , variable cloud, upward flux



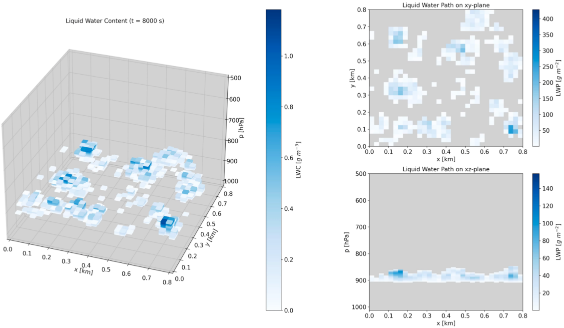
“Dynamic RT” – 1D , variable cloud, downward flux



Dynamic RT – how good is it?

Cloud and Model Setup

100 time steps of a precomputed LES cloud field with a temporal resolution of 10 s



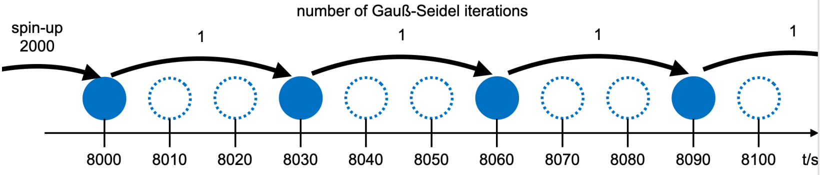
- shallow cumulus cloud field
- 149 vertical layers, 32 x 32 grid boxes in the horizontal
- grid boxes have the same shape and LWC as in the original 256 x 256 domain

Dynamic RT – how good is it?

Evaluation of the New Solver

Domain Average Solver Performance

Example: setup for Δt_{rad} = 30 s (about as expensive as a 1D delta Eddington-solver)



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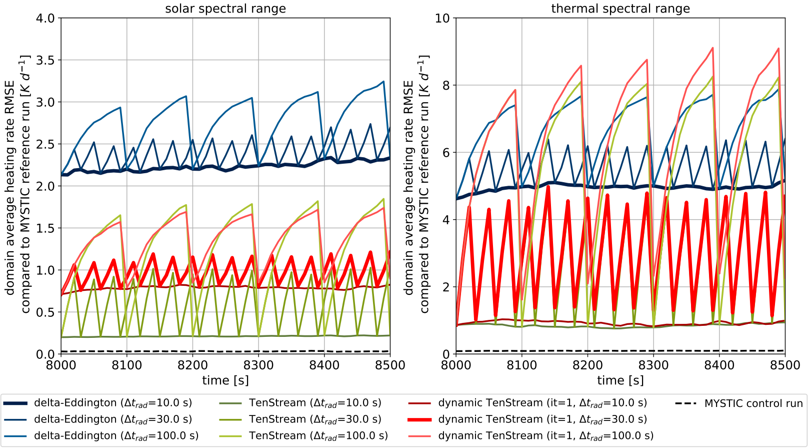

Summary

- Considerable differences between 3D and 1D heating rates in high resolution radiative transfer and cloud models
- Effect on clouds in high resolution models demonstrated
- There is hope for fast (dynamic) parameterizations of 3D radiation
- Even 1 km resolution is grey zone for radiation models!