# 3D radiation – why, when and how?

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# Introduction

- cornerstones of 1D radiative transfer in NWP were set back in 1970s:

  **1976:** delta-scaling within the two-stream framework
  (Joseph, Wiscombe and Weinman)

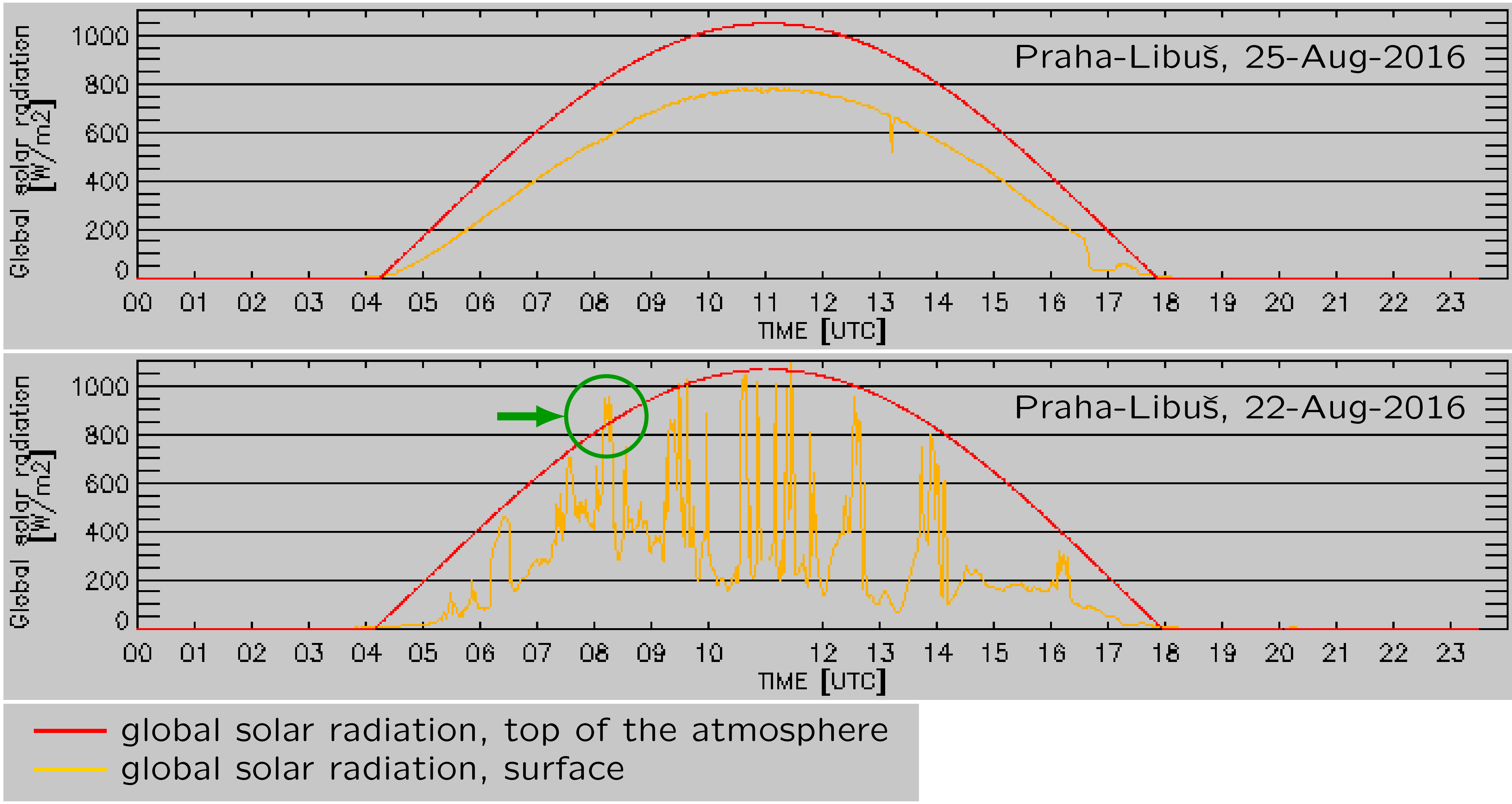
  **1979:** treatment of partial cloud cover and cloud overlap geometry
  (Geleyn and Hollingsworth)

- 1D approach employing **independent column approximation** (ICA) has been celebrating its success for 40 years, making radiative transfer calculations **parallelizable** and thus feasible in GCM and NWP models

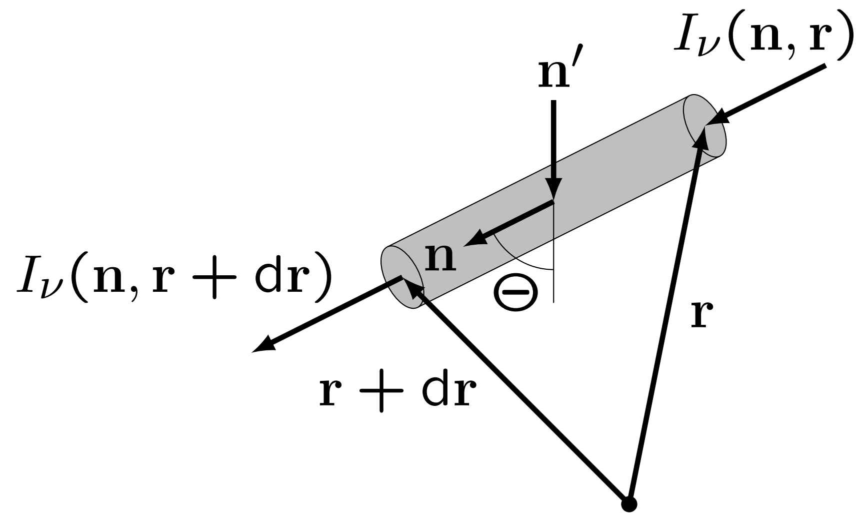
- during those years, however, horizontal resolution of NWP models increased by two orders of magnitude (200 km $\rightarrow$ 2 km)

- how relevant is 1D framework, when the NWP models start to resolve **cumuliform clouds** causing noticeable **3D effects**?

# Observed 3D effect of cumulus clouds



# 3D radiative transfer equation




$$\mathbf{n}\cdot\boldsymbol{\nabla} I_\nu(\mathbf{n},\mathbf{r}) = \overbrace{-k_\nu^{\text{abs}}(\mathbf{r})\rho(\mathbf{r})I_\nu(\mathbf{n},\mathbf{r})}^{\text{absorption}} + \overbrace{k_\nu^{\text{abs}}(\mathbf{r})\rho(\mathbf{r})B_\nu(T(\mathbf{r}))}^{\text{emission}} +$$

$$+\underbrace{k_\nu^{\text{scat}}(\mathbf{r})\rho(\mathbf{r})\left[-I_\nu(\mathbf{n},\mathbf{r}) + \frac{1}{4\pi}\oint_{4\pi} P_\nu(\mathbf{n}\cdot\mathbf{n}',\mathbf{r}) I_\nu(\mathbf{n}',\mathbf{r})\,\mathrm{d}\Omega'\right]}_{\text{scattering}}$$

$$\frac{1}{4\pi}\oint_{4\pi} P_\nu(\mathbf{n}\cdot\mathbf{n}',\mathbf{r})\,\mathrm{d}\Omega' \qquad \mathbf{n}\cdot\mathbf{n}' = \cos\Theta$$

# Plane parallel approximation

- central quantity in radiative transfer – spectral radiance $I_\nu$ – depends on 2 angles and 3 spatial coordinates

- dimensionality of the problem can be greatly reduced by assuming horizontally homogeneous, **plane-parallel atmosphere:**

$$I_\nu(\theta, \phi, x, y, z) \rightarrow I_\nu(\theta, z)$$

- radiative transfer can then be formulated for azimuthally averaged radiance, depending only on zenith angle $\theta$ and vertical coordinate $z$

- 1D radiative transfer equation is solved in every model column, **neglecting lateral exchanges** between columns $\Rightarrow$ **ICA**

- ICA fits into the framework of 1D physics, enabling efficient parallelization of NWP codes

# 1D radiative transfer solvers

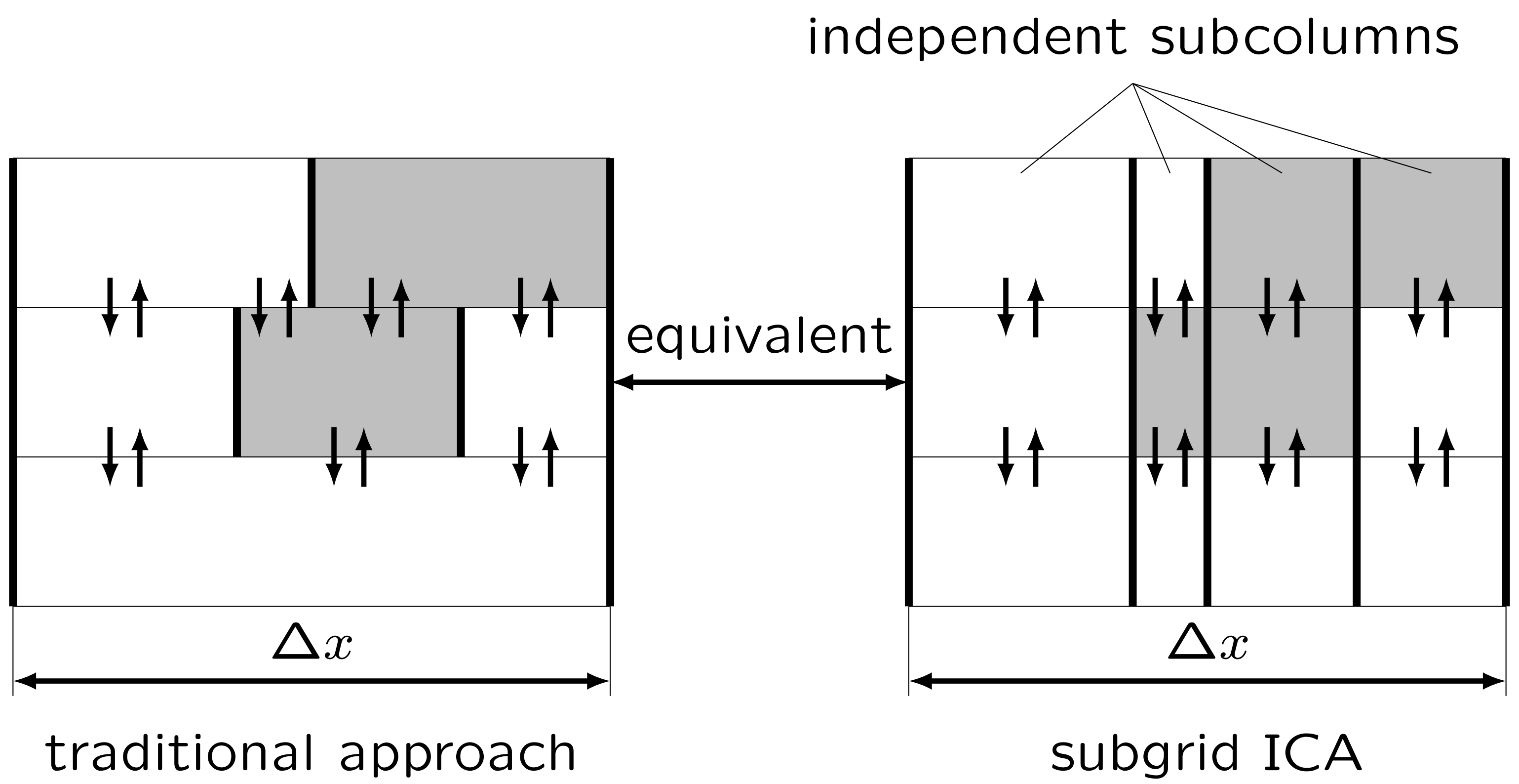
- majority of current NWP models further simplify 1D radiative transfer by **two-stream approximation** combined with **adding method**
- dependency on zenith angle is addressed by two point quadrature, replacing radiance by upward and downward fluxes $F^{\uparrow}$, $F^{\downarrow}$
- atmosphere is sliced into $L$ homogeneous layers characterized by their transmissions $T$ and reflectivities $R$
- for each layer there are 2 equations relating incoming and outgoing fluxes:

$$\begin{pmatrix} F^{\downarrow}_{\text{bot}} \\ F^{\uparrow}_{\text{top}} \end{pmatrix} = \begin{pmatrix} T & R \\ R & T \end{pmatrix} \cdot \begin{pmatrix} F^{\downarrow}_{\text{top}} \\ F^{\uparrow}_{\text{bot}} \end{pmatrix} + \begin{pmatrix} J^{\downarrow}_{\text{bot}} \\ J^{\uparrow}_{\text{top}} \end{pmatrix}$$

- equating fluxes leaving one layer with fluxes entering the next layer results in a linear system for $2L+2$ fluxes, closed by 2 boundary conditions (in the simplest case with trivial cloud geometry)
- matrix to be inverted is $(2L+2) \times (2L+2)$ with 5 non-zero diagonals
- inversion can be done by Gaussian elimination and back-substitution, with the cost linear in $L$

# Dealing with cloud geometry

- incorporation of clouds into 1D radiative transfer is done by dividing each model layer into homogeneous **clearsky** and **cloudy** regions
- **lateral exchanges** between these regions are **not assumed**
- at the layer interfaces, fluxes leaving clearsky and cloudy regions are redistributed according to assumed **cloud overlap mode:**



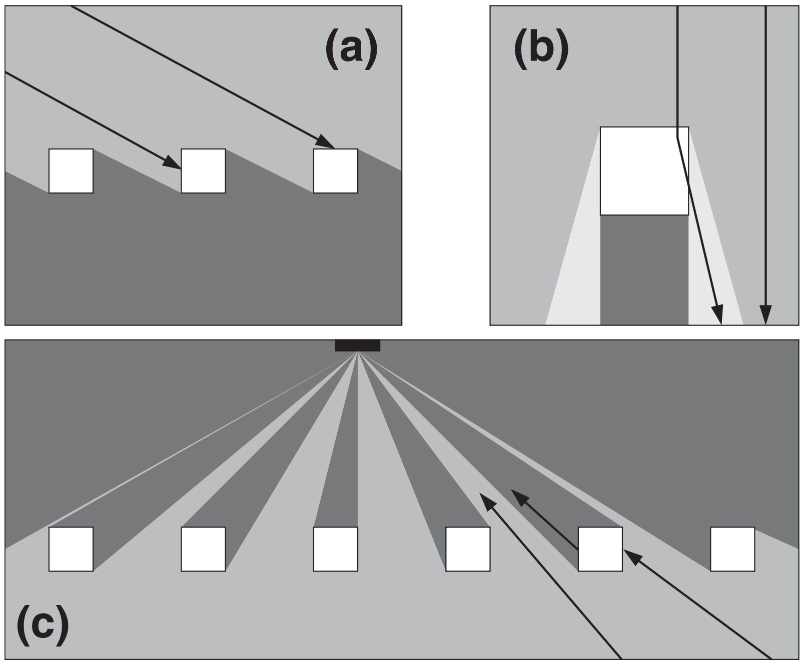
# Two common 1D treatments of cloud geometry

- **traditional approach** incorporates cloud geometry directly in the solver, increasing system matrix to $(4L+4)\times(4L+4)$ with 9 non-zero diagonals

- **Monte Carlo ICA** (McICA) divides model column into $N$ independent subcolumns, containing only **binary clouds** (clear–overcast)
  - subcolumns are filled by **cloud generator**, respecting layer cloud fractions, overlap mode and cloud condensates
  - simpler $(2L+2)\times(2L+2)$ solver is applied $N$ times $\Rightarrow$ costly
  - schemes performing many ($\gtrsim 100$) monochromatic calculations can distribute them randomly over cloudy subcolumns $\Rightarrow$ **significant cost reduction**
  - such simplification is bias free, but it contaminates radiative fluxes by **stochastic noise**
  - McICA combined with correlated $k$-distribution (CKD) method is a widely used solution

# 3D radiative effects of clouds

- nice schematic explanation of various 3D radiative cloud effects can be found in Hogan and Shonk (2013):



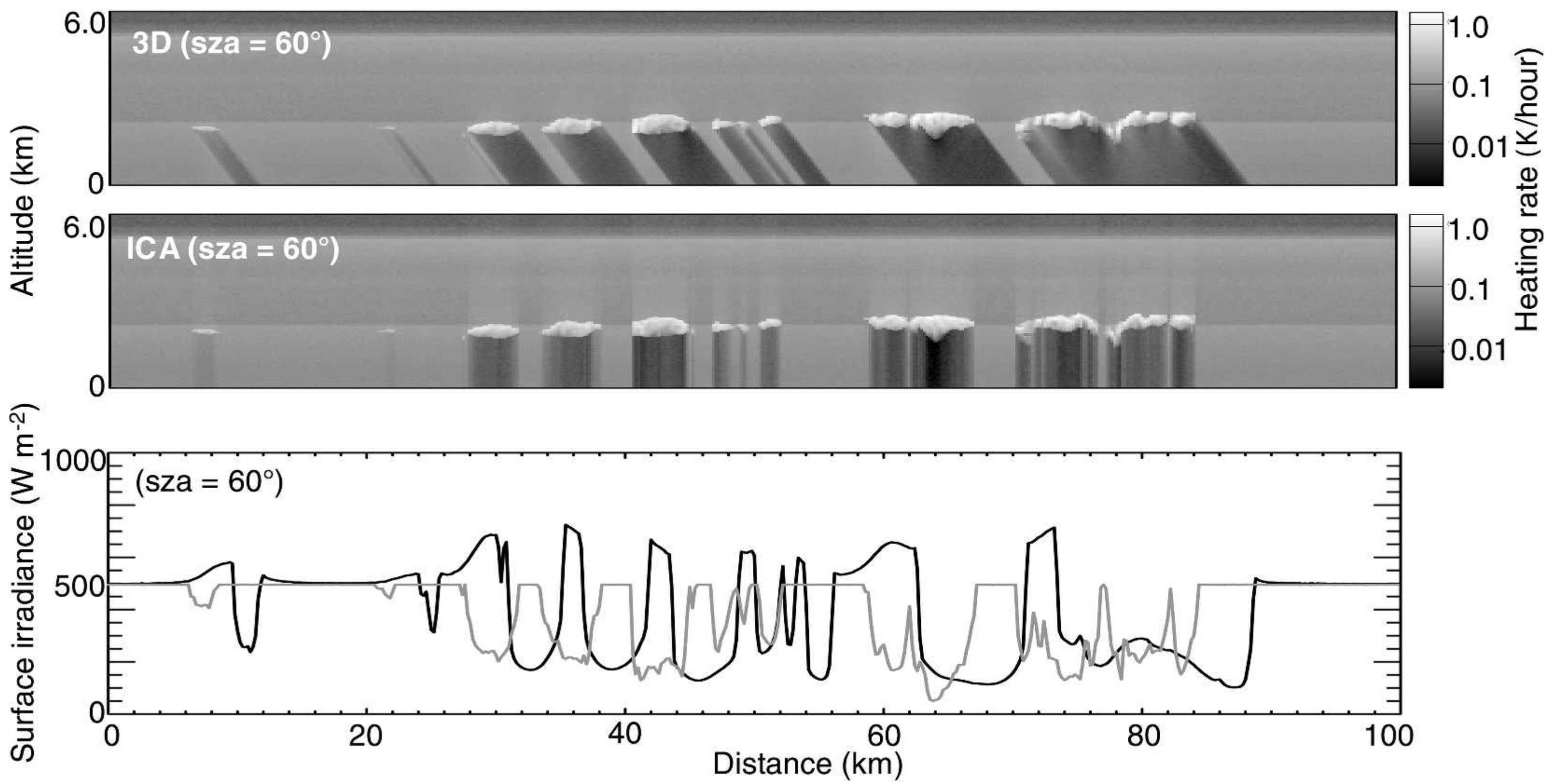

**(a)** shading by cloud sides, low sun
**(b)** focusing by cloud sides, high sun
**(c)** increased cloud radiative forcing due to higher apparent cloud fraction

- 3D cloud effects usually result in **smoothing** of radiation fields, but sometimes they can cause also their **sharpening**

# How significant?

- O'Hirok and Gautier (2005) demonstrate that neglecting 3D radiative cloud effects can cause local error in surface insolation 500 $\mathrm{W\,m^{-2}}$

- however, error averaged over 100 km wide domain is only 2 $\mathrm{W\,m^{-2}}$




Shortwave heating rate and surface insolation for cumulus cloud field ($\theta = 60^\circ$, $\Delta x = 200$ m, $\Delta z = 45$ m).

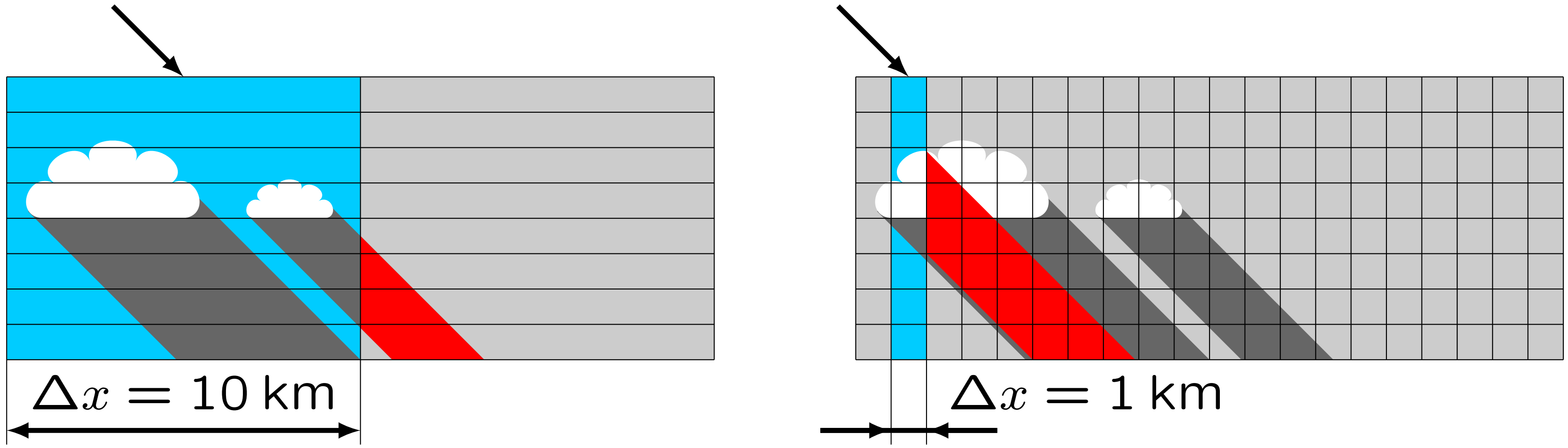
# When important?

- O'Hirok and Gautier (2005) conclude that:
  - ICA can be safely used for $\Delta x \geq 5\,\mathrm{km}$, with error in surface insolation staying below $100\,\mathrm{W\,m^{-2}}$ in almost all model columns
  - for $\Delta x \leq 2\,\mathrm{km}$, ICA can produce error locally reaching $500\,\mathrm{W\,m^{-2}}$
  - still the 3D radiative effects tend to average out on larger domains
  - for non-stationary cloud fields also time averaging tends to smooth the 3D effects out
  - due to high heat capacities of most underlying surfaces, any 3D effects are likely to be transitory and insignificant
- so far so good – but what about cloud-radiation feedback?
- this can only be evaluated with the 3D radiation scheme embedded in cloud resolving model $\Rightarrow$ Monte Carlo codes are too expensive for that

# 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



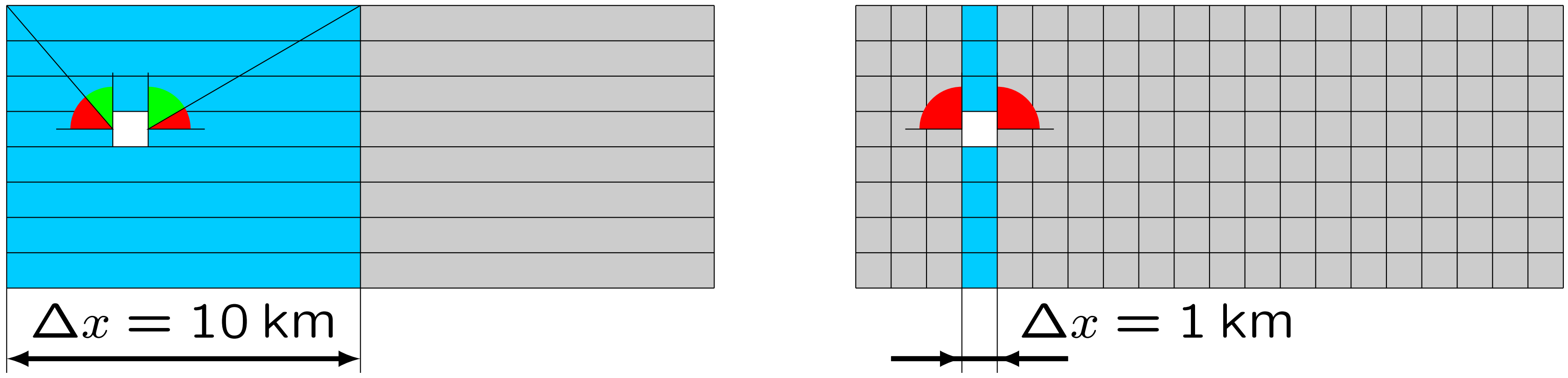

- some subgrid effects due to 3D cloud shape may still need to be parameterized

# Longwave 3D effects

- 3D radiative effects are most obvious in the shortwave case, but they are equally important in the longwave one

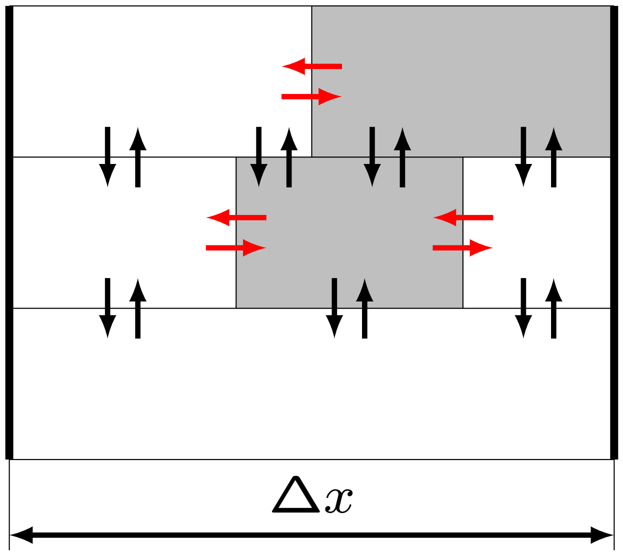
- this can be illustrated using an idealized example of isolated homogeneous and isothermal cubic cloud in vacuum (Schäfer et al. 2016):
  - cloud sides emit 4 times more energy than cloud top
  - $\frac{1}{2}$ of energy escaping from cloud sides is directed upward
  - effect of cloud sides increases energy reaching space by factor 3

- when the horizontal mesh size is large enough, significant portion of radiation emitted by cloud sides remains in the model column and its 3D effect can be parameterized within ICA



# SPARTACUS solver (subgrid)

- current resolution of ECMWF deterministic forecast is about 9 km, with radiation grid reduced to 29 km ⇒ 3D effects mostly subgrid
- ecRad scheme (Hogan and Bozzo 2018) contains SPARTACUS solver that allows **subgrid transfer across the cloud sides:**




- two-stream equations are extended by the **extra terms** representing lateral transport between clearsky and cloudy regions, proportional to **effective cloud edge length**
- ecRad with SPARTACUS is 5.8 times slower than with McICA solver ⇒ unfeasible for operations, but **fast enough for research**

# 3D solvers (resolved)

- 3D radiative transfer solvers can be roughly divided in two groups:

  1) rigorous (very expensive, beyond the reach of NWP)
  2) approximate (cheaper, developed for NWP needs)

- first group has two important representatives:

| | |
|---|---|
| **MYSTIC**<br>(Monte Carlo) | stochastic, brute force, used as **3D reference**<br>physically straightforward<br>easily implementing complex geometries, etc. |
| **SHDOM** | deterministic, iterative on adaptive grid<br>resembling spectral transform method |

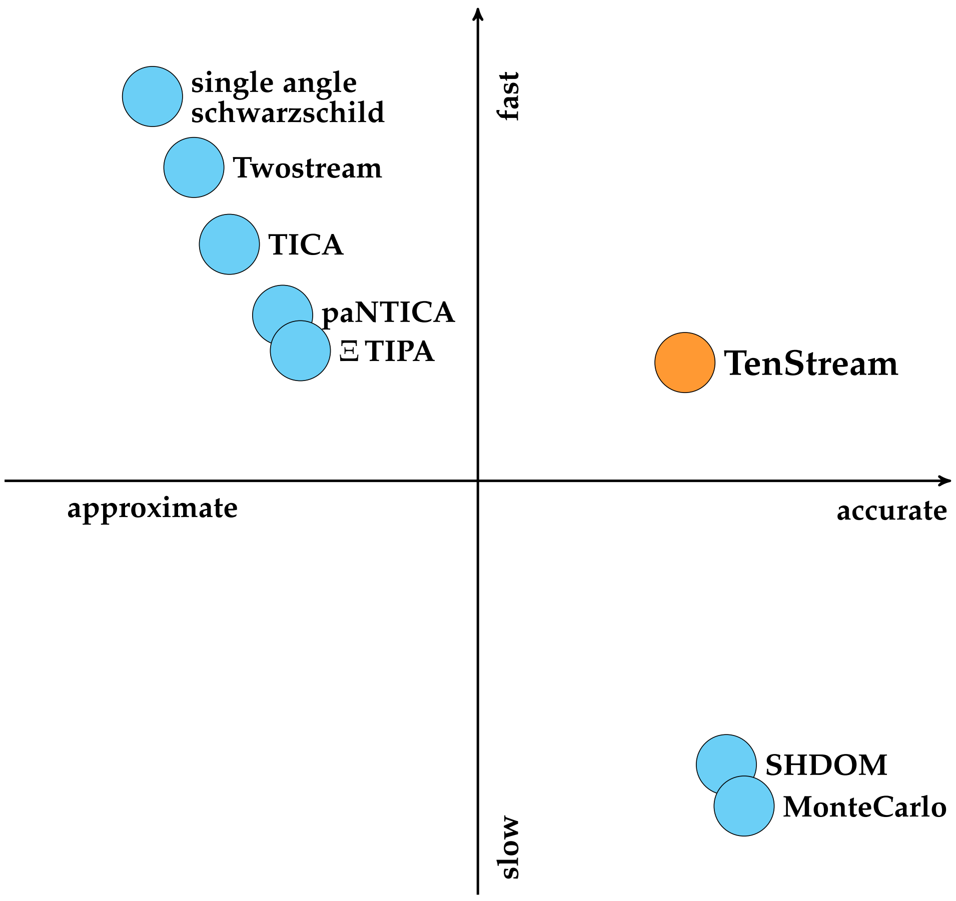
- second group contains quasi-3D improvements of the two-stream solver, overcoming some limitations of ICA:

**TICA, paNTICA, NCA, . . .**

- recently the **TenStream** solver appeared, claiming to be nearly as accurate as rigorous solvers, but for the first time affordable inside LES model (not yet NWP)

# Cost versus accuracy

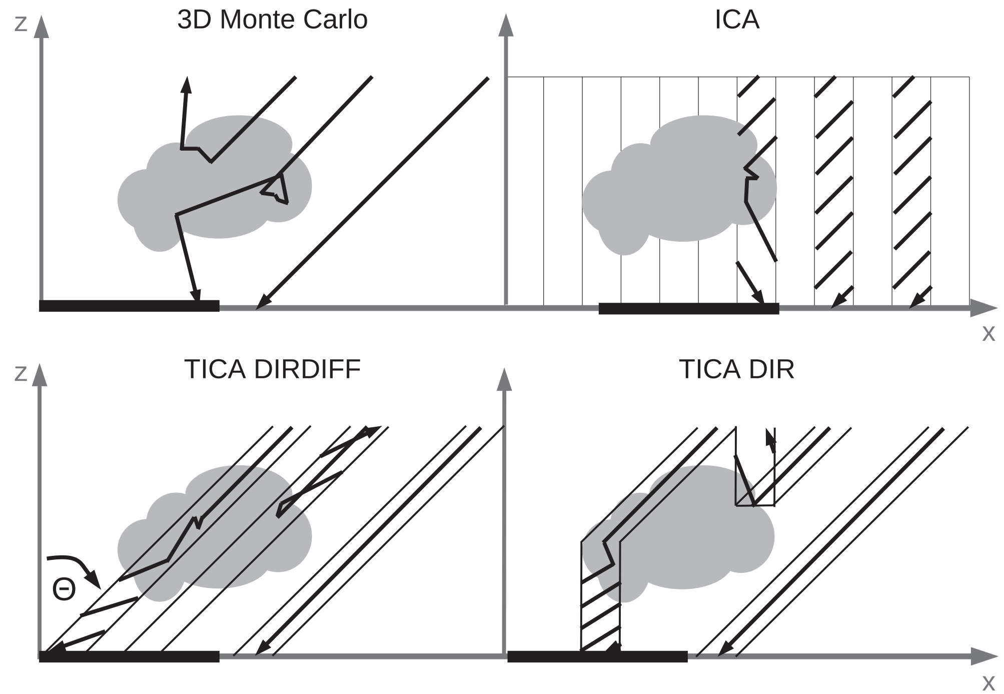
- dissertation of Jakub (2016) gives an instructive comparison of various 3D solvers in terms of cost and accuracy:




- rigorous solvers (Monte Carlo, SHDOM) are 4–5 orders of magnitude more expensive than the two-stream solver!

# Family of TICA schemes (shortwave)

- basic idea of **tilted ICA** (TICA) is explained in Wissmeier et al. (2013):




- **direct beam** is independent of diffuse fluxes and its propagation can be calculated along **tilded column** ⇒ correct placement of cloud shadows
- primary scattering of exactly treated direct beam is a source of **diffuse radiation**, propagated in the **two-stream framework**
- column for diffuse radiation can be tilted or not (variants DIRDIFF and DIR, respectively)

# Inclusion of diffuse 3D effects – paNTICA

- TICA schemes do not account for radiation smoothing due to diffuse transport between the two-stream columns

- this effect can be simulated by applying **horizontal smoother** on diffuse fluxes delivered by TICA

- **non-local TICA** (NTICA) implements smoothing as a convolution with **Gaussian kernel**

- optimal kernel width depends on the scene and location

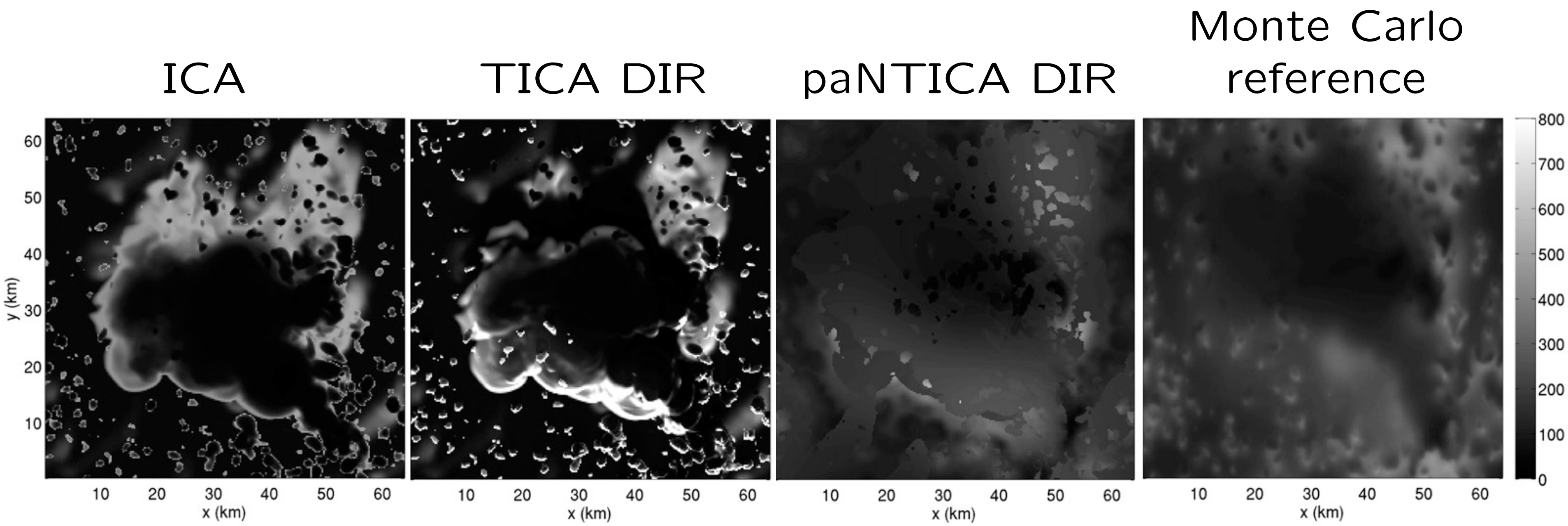
- **parameterized NTICA** (paNTICA; Wissmeier et al. 2013) expresses the kernel width for downward diffuse flux as a function of solar zenith angle and distance to the nearest cloud base

- non-constant kernel width **violates energy conservation** by 1–2%, but implied bias is negligible $\Rightarrow$ this is a **minor issue** given considerable improvement over ICA

- radiation scheme with paNTICA is about 2 times more expensive than with the two-stream solver

# ICA and TICA versus Monte Carlo reference

cumulonimbus case, diffuse downward solar flux at surface [$\mathrm{W\,m^{-2}}$]

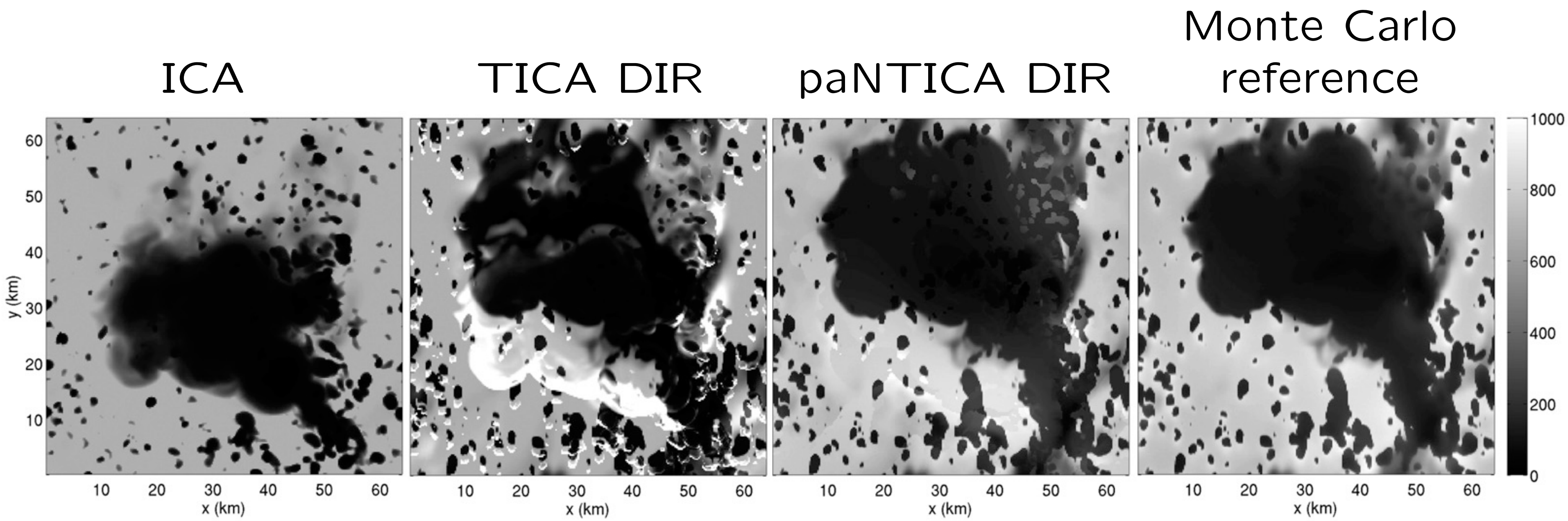



$\theta = 50^\circ$, $\Delta x = \Delta y = 250\,\mathrm{m}$, $\Delta z_{\mathrm{min}} = 200\,\mathrm{m}$
sun from the south, surface albedo 0.05

source: Wissmeier et al. (2013)

# ICA and TICA versus Monte Carlo reference

cumulonimbus case, total downward solar flux at surface [$\mathrm{W\,m^{-2}}$]

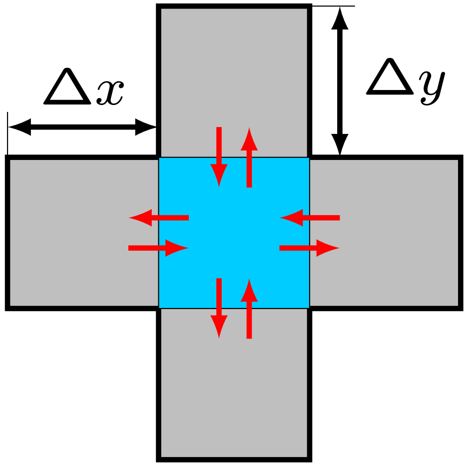



$\theta = 50^\circ$, $\Delta x = \Delta y = 250\,\mathrm{m}$, $\Delta z_{\mathrm{min}} = 200\,\mathrm{m}$
sun from the south, surface albedo 0.05

source: Wissmeier et al. (2013)

# NCA scheme (longwave)

- **neighboring column approximation** (NCA; Klinger and Mayer 2016) accounts for longwave radiative exchanges between given column and 4 neighboring columns:




- NCA neglects longwave scattering and it is best suited for $\Delta x \geq 100$ m, improving spatial distribution of heating and cooling considerably
- at finer resolution, exchanges between more distant columns become important
- solver involving only 5 columns does not break code parallelization
- NCA increases the cost of radiation scheme by factor 1.5–2 compared to 1D solution

# TenStream solver

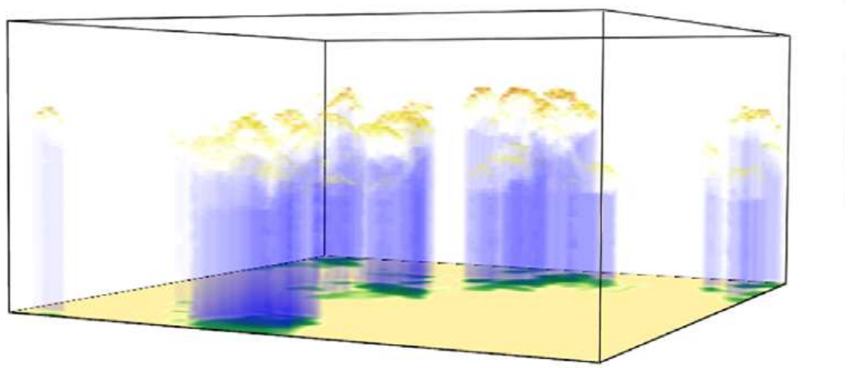
- recently, TenStream solver of Jakub and Mayer (2015) appeared as the first truly 3D solver embedded in cloud resolving model
- there are 10 diffuse streams assumed:
  - vertical transport is described by upward and downward fluxes through $xy$-plane (as in two-stream case)
  - horizontal transport is described by 4 fluxes through $xz$-plane and another 4 fluxes through $yz$-plane


- in 3D domain with $N_\mathrm{g}$ gridboxes, resulting **sparse matrix** $10N_\mathrm{g} \times 10N_\mathrm{g}$ is **huge** $\Rightarrow$ it must be **inverted iteratively**
- results in UCLA LES model are impressive, increasing the cost of radiation scheme 5–10 times $\Rightarrow$ still beyond reach of NWP

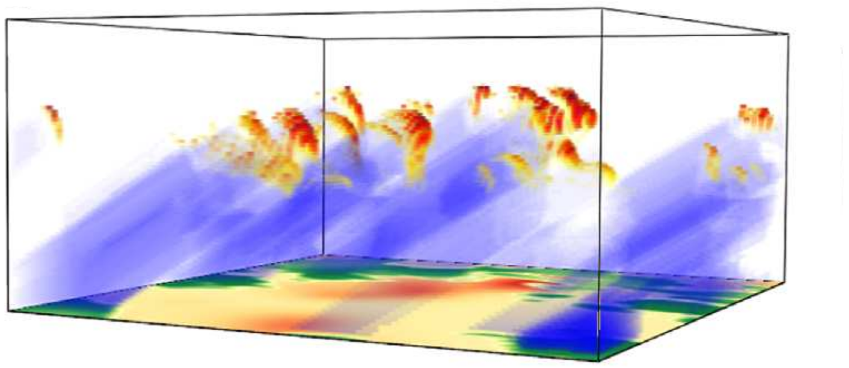
# ICA and TenStream versus Monte Carlo reference

cumulus case, shortwave atmospheric heating rate and surface insolation

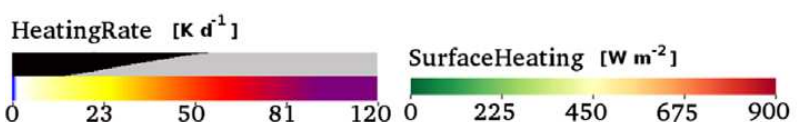
ICA (two-stream delta-Eddington)



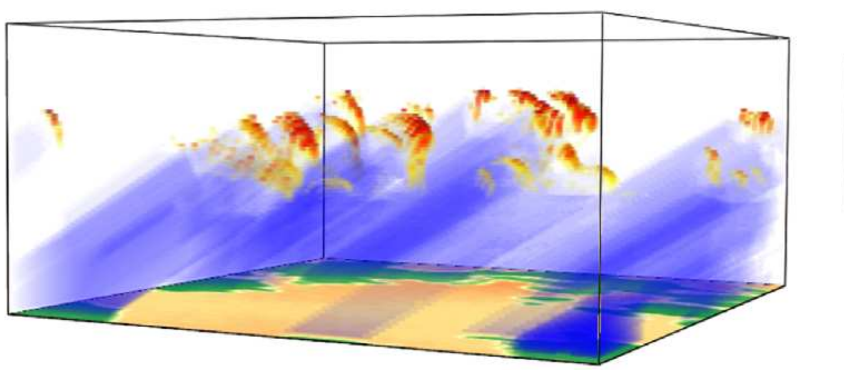
TenStream



$\Delta x = \Delta y = 70\,\text{m},\ \Delta z_{\text{min}} = 40\,\text{m}$




Monte Carlo reference

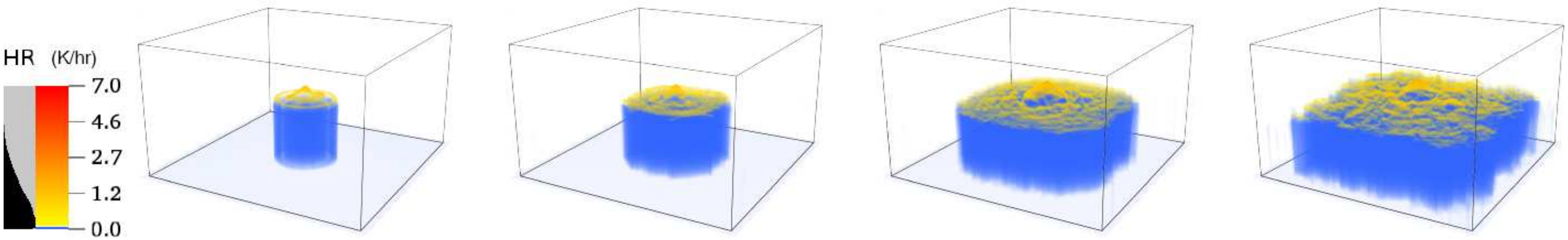


source: Jakub and Mayer (2015)

# Impact of 3D radiation on cloud evolution

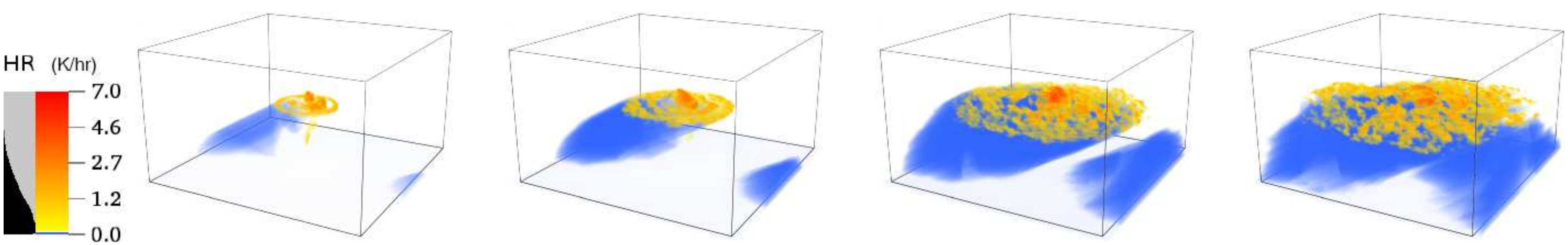
warm bubble experiment, shortwave atmospheric heating rate

ICA (two-stream delta-Eddington)




15 min 30 min 45 min 60 min

TenStream $\Delta x = \Delta y = \Delta z = 50\,\text{m}$



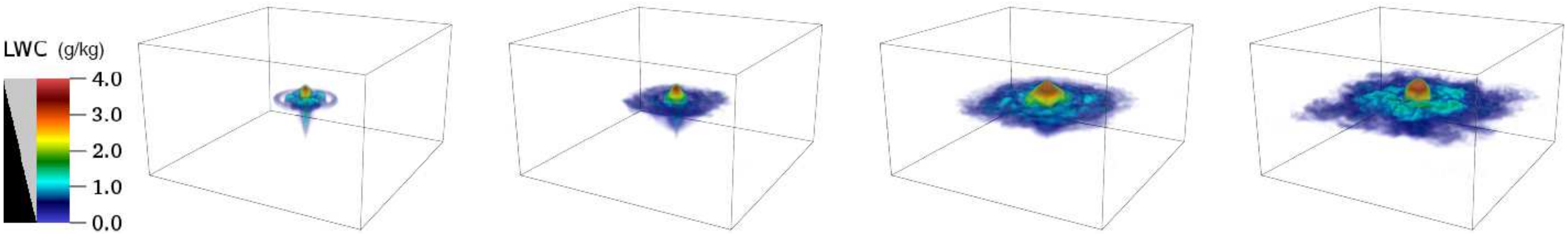

15 min 30 min 45 min 60 min

source: Jakub and Mayer (2016)

# Impact of 3D radiation on cloud evolution

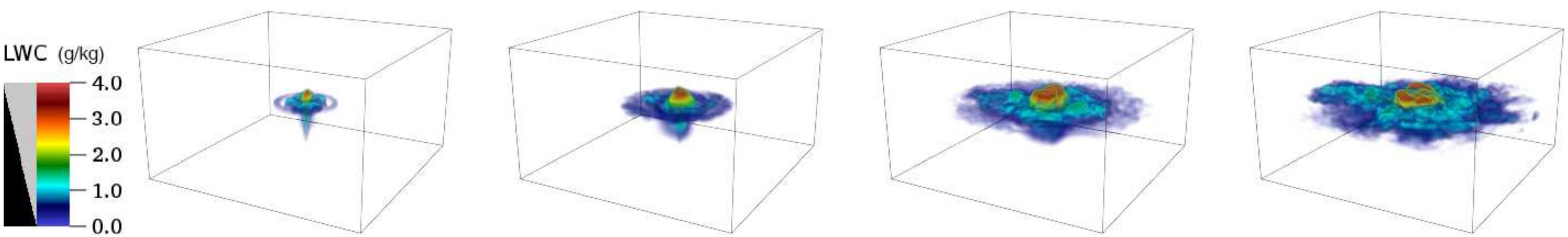
warm bubble experiment, cloud liquid water content

ICA (two-stream delta-Eddington)




15 min 30 min 45 min 60 min

TenStream $\Delta x = \Delta y = \Delta z = 50\,\text{m}$




15 min 30 min 45 min 60 min

source: Jakub and Mayer (2016)

# Relevance of LES results for kilometric NWP

- LES results obtained with TenStream solver are very recent
- impact of 3D radiative transfer on cloud dynamics has to be carefully analyzed and understood, we are still at the very beginning
- LES simulations are run with at least 20 times finer mesh sizes than current high resolution NWP $\Rightarrow$ relevance of some conclusions for NWP world is not obvious
- key question for short range NWP is following:

**How important for forecast evolution is radiative forcing on the shortest resolved scales?**

- future development of NWP radiative transfer schemes depends critically on a honest answer
- such answer cannot be obtained without testing impact of 3D radiative effects in realistic NWP setup (spatial resolution, forecast length, feedbacks, . . . )

# Conclusions

- ACRANEB2 scheme is currently used at its best, but with ALARO-1 entering **cloud resolving scales** use of ICA becomes problematic
- the only reasonable option for keeping ICA would be to use it on **reduced radiation grid** $\Rightarrow$ unreliable details not calculated, high resolution information lost
- still I believe that short range NWP should aspire for realistic cloud dynamics, including **resolved 3D radiative transfer**
- if there ever is ACRANEB3 scheme, “3” should stay for 3D effects
- development of 3D radiation scheme in the NWP model is beyond capability of single person
  - importing ideas, tools, and maybe even codes from 3D radiation community seems to be necessary $\Rightarrow$ **collaboration desirable**
  - ALADIN code implementation has to be designed in close cooperation with **experts in parallelization**
- being double optimist, I hope to have some 3D solution available in ALARO♥ by the year 2030 ☺