Single-band approach – a way to full cloud-radiation interaction

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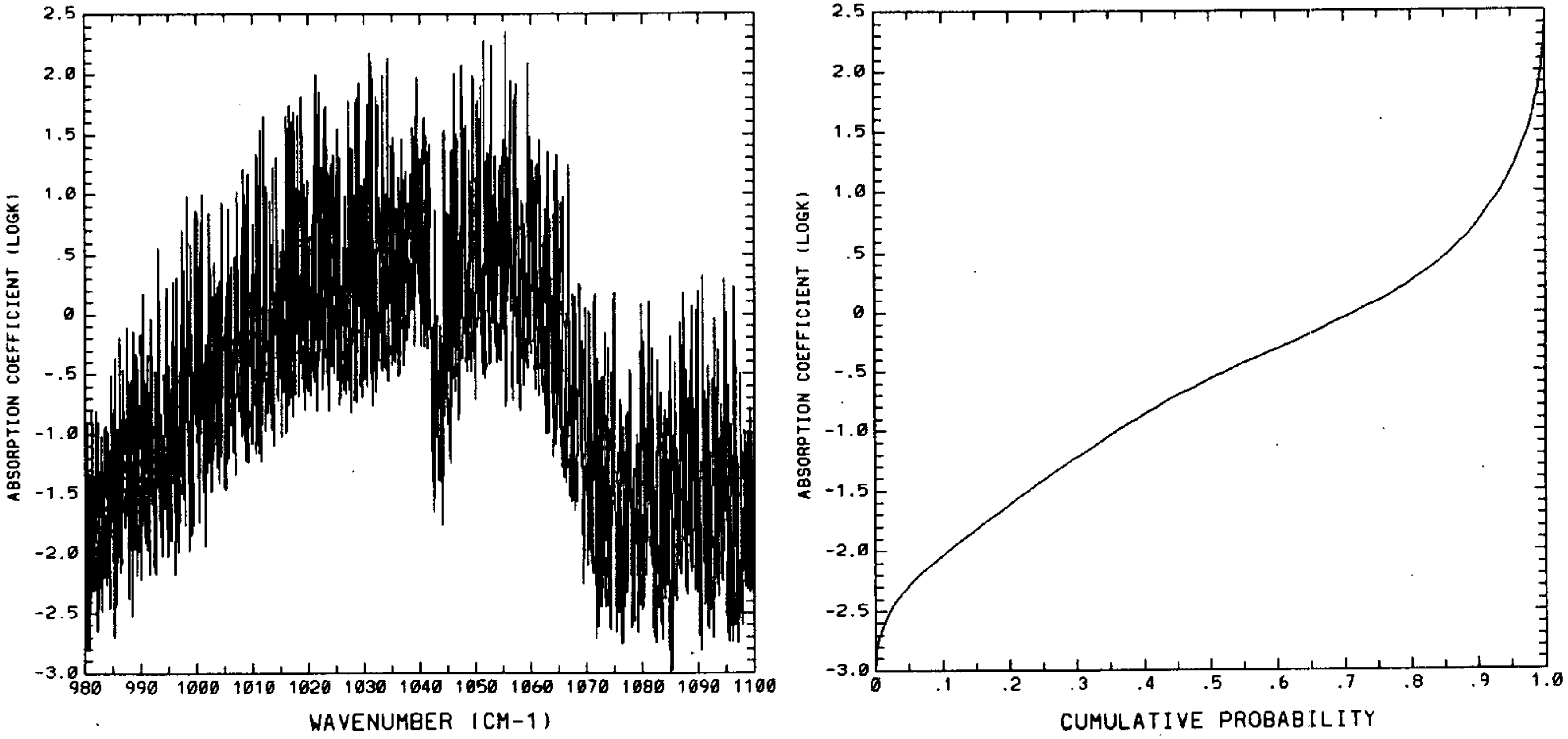
Introduction

- Contemporary numerical weather prediction (NWP) models predominantly use the radiation schemes based on the **correlated k-distribution (CKD) method.**
- Radiative fluxes and heating rates delivered by the CKD method have **outstanding accuracy.**
- However, the method is **too expensive** to be used in every model grid-point and time-step.
- A common way how to make the computational cost affordable for NWP is to perform radiation calculations with **reduced update frequency** and/or on **coarser grid**.
- Such approach **undersamples cloud-radiation interaction** for quickly evolving or highly variable model cloud field.
- Is there a feasible alternative that would **capture the cloud-radiation interaction fully?**

Central problem – spectral integration

Band transmission in the absence of scattering: $\tau(u,p,T) = \int_{\Delta\nu} w_\nu \exp[-k_\nu(p,T)u]\,\mathrm{d}\nu$.



Log of absorption coefficient k as a function of (left) wavenumber ν, and (right) cumulative probability g for the ozone 9.6 μm band, $p = 25$ hPa, and $T = 220$ K. Source: Fu and Liou (1992).

Two basic NWP approaches to spectral integration

1) Broadband approach (historically older):

- band transmission obtained by **analytical integration** of k_ν, constructed as a superposition of spectral lines with **idealized distribution** of line positions and strengths, e.g.:

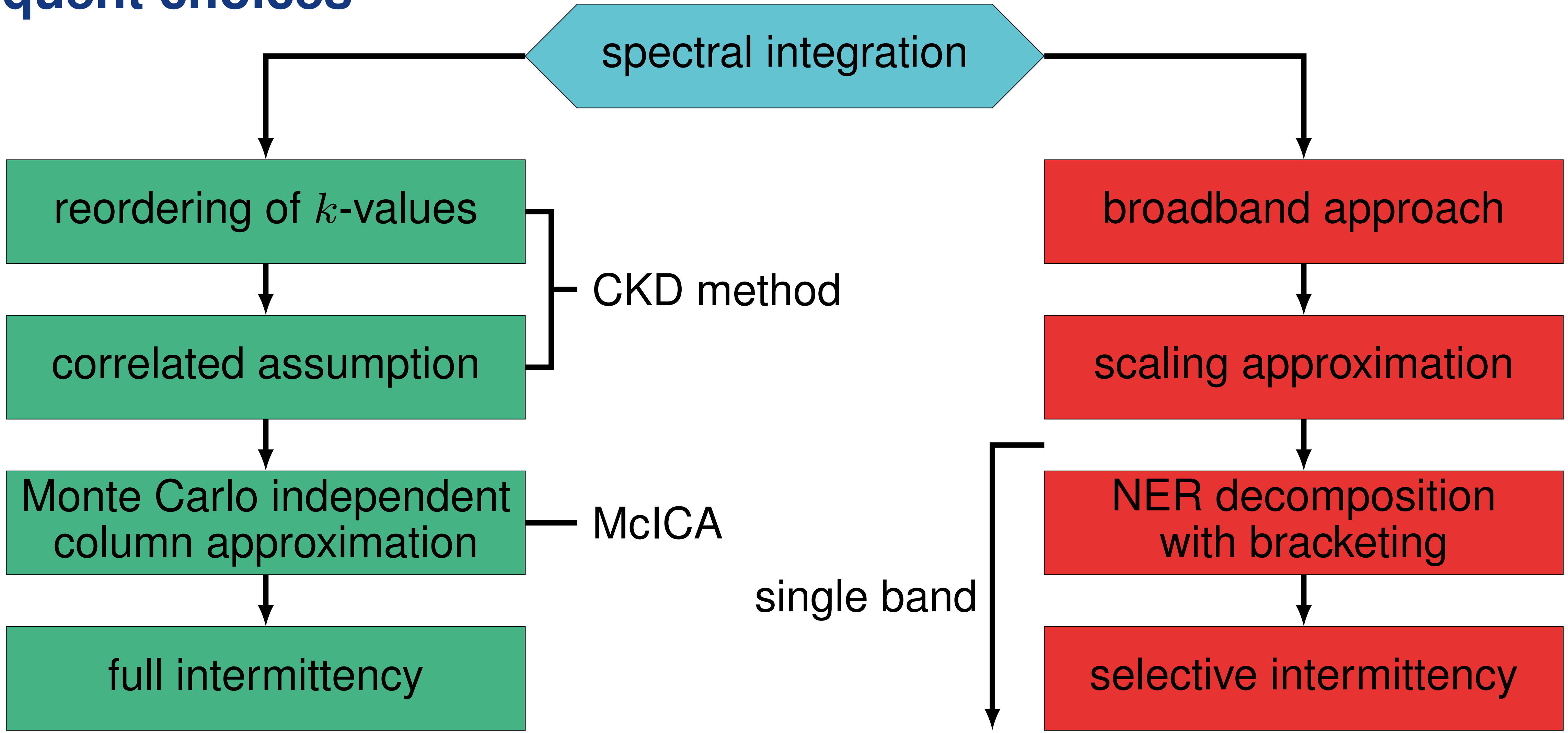
$$\tau_{\mathsf{malkmus}}(u,p,T) = \mathrm{exp}\{-a(T)[\sqrt{1+4b(p,T)u}-1]/[2b(p,T)]\};$$

- parameters $a(T)$, $b(p,T)$ either related to the actual mean line parameters, or determined by fitting the band model transmission to a line-by-line reference.

2) k-distribution method (present mainstream):

- k_ν values reordered according to their cumulative probablity g;
- band transmission obtained by **numerical integration** of $k(g)$, using a **small number** of quadrature points: $$\tau(u,p,T) = \sum_i \mathrm{exp}[-k(g_i,p,T)u]\,\Delta g_i.$$

Subsequent choices



spectral integration

reordering of k-values

correlated assumption

CKD method

Monte Carlo independent column approximation

McICA

full intermittency

broadband approach

scaling approximation

NER decomposition with bracketing

single band

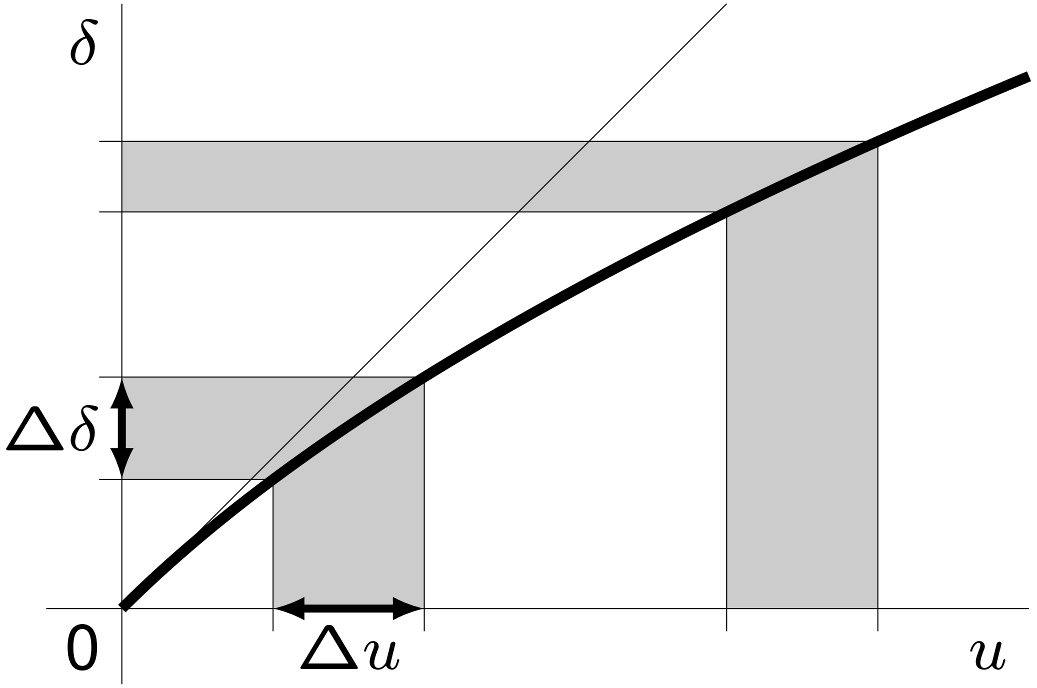
selective intermittency

RRTMG scheme
(14 SW and 16 LW bands)

ACRANEB2 scheme
(1 SW and 1 LW bands)

Optical saturation – the main troublemaker

- Band radiative transfer in **non-grey media** has to deal with **optical saturation.**
- For small absorber amounts, band optical depth δ grows linearly with absorber amount u.
- For bigger absorber amounts, radiation at strongly absorbing wavelengths is spent, and the band optical depth grows with slower than linear rate.
- The more distant is the layer from the source, the more transparent it appears: $\Delta\delta = \delta(u + \Delta u) - \delta(u)$.
- Each emission source implies its own set of band optical thicknesses $\Delta\delta$.
- Optical saturation **strongly penalizes the LW band approach,** where an exact solution with L atmospheric layers would require $L + 1$ solvings of the radiative transfer equation.



Pros and cons of the CKD method

- $\oplus$ **Optical saturation is escaped** by performing a set of quasi-monochromatic calculations.
- $\oplus$ Even the small number of quadrature points guarantees **outstanding accuracy.**
  (∼10 quadrature points per band)
- $\oplus$ Treatment of inhomogeneous optical paths by **correlated assumption is quite accurate.**
- $\ominus$ **Width of bands is limited** by the variation of spectral weights and of scattering coefficient.
  (∼10 bands needed to cover SW or LW spectra $\Rightarrow$ ∼100 quadrature points in total)
- $\ominus$ Solving radiative transfer equation once for each quadrature point is **expensive.**
- $\ominus$ Radiative update due to clouds implies full or partial **recalculation of the gas optics:**
  - radiative update in every model time-step is too costly (redundant gaseous calculations);
  - intermittent radiative update compromises accuracy (undersampled cloud evolution).

Pros and cons of the single-band approach

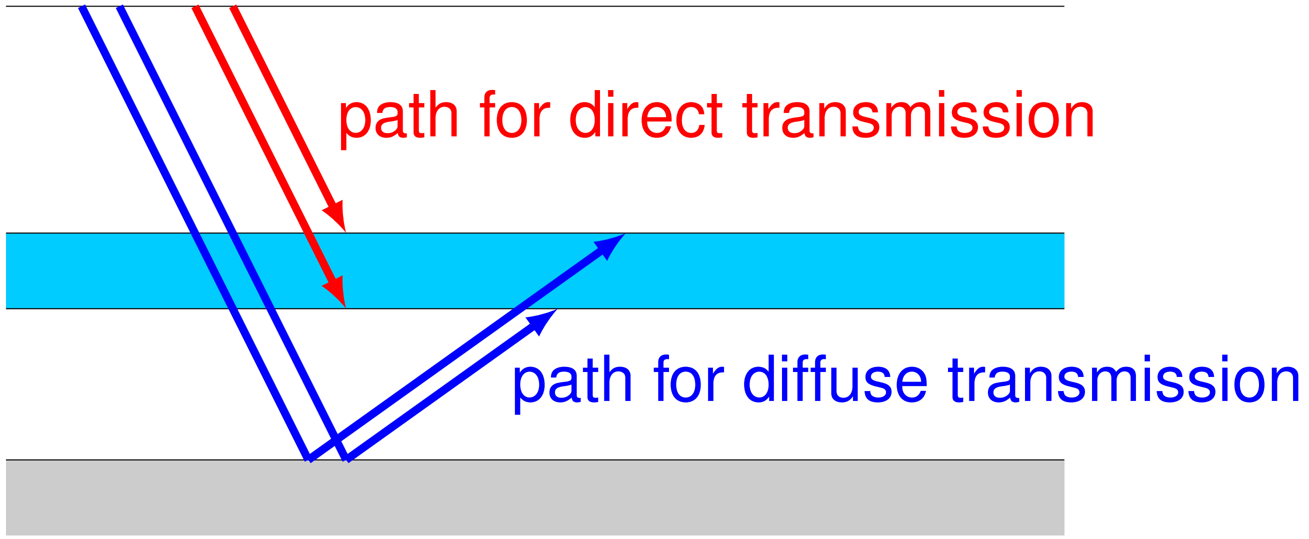
- ⊖ Important spectrally unresolved phenomena have to be **parameterized,** including all kinds of **optical saturation.**
- ⊖ Treatment of inhomogeneous optical paths by the 2-parametric **Curtis-Godson scaling approximation** has a limited accuracy.
- ⊖ Another accuracy limitation comes from an assumption of **spectrally flat surface albedo.**
- ⊖ With L atmospheric layers, computational **cost of LW calculations is proportional to L^2.**
- ⊕ Radiative update due to clouds can be done **without recalculating the gas optics.**
- ⊕ **Selective intermittency is affordable** thanks to a manageable memory size needed for the transfer of single-band gaseous optical thicknesses between the model time-steps.
- ⊕ Computational cost of LW calculations essentially linear in L can be achieved by the **net exchanged rate (NER) decompostion with bracketing.**

Necessary improvements of the single-band scheme

- To extend the broadband approach to single SW and LW bands, **several improvements were necessary** to achieve accuracy sufficient **for the short-range NWP:**
  - broadband correction of the Malkmus band model & incorporation of Voigt line shape;
  - parameterized optical saturation of Rayleigh scattering;
  - dependence of LW gaseous transmissions on the temperature of emitting body;
  - parameterized non-random LW overlaps between gases;
  - parameterized SW cloud optical saturation;
  - parameterized non-random SW overlaps between gases and clouds.
- **Increased computational cost** of the improved scheme can be **reduced by selective intermittency** without significant accuracy loss.

Method of idealized optical paths – SW gaseous absorption

- How to evaluate **optical saturation** in the presence of **scattering?**
- For gases, **idealized optical paths** can be taken, giving exact saturation in the absence of Rayleigh scattering, aerosols and clouds:
  - the source is direct solar radiation incoming at the top of the atmosphere;
  - scattered radiation is generated only by reflection from Lambertian surface.



Idealized SW gaseous optical paths.

- Obtained **saturated gaseous optical properties** are combined with those of remaining radiatively active species, and they **are used in a system with scattering.**
- Idealized optical paths are applicable also to Rayleigh scattering, but not to clouds.

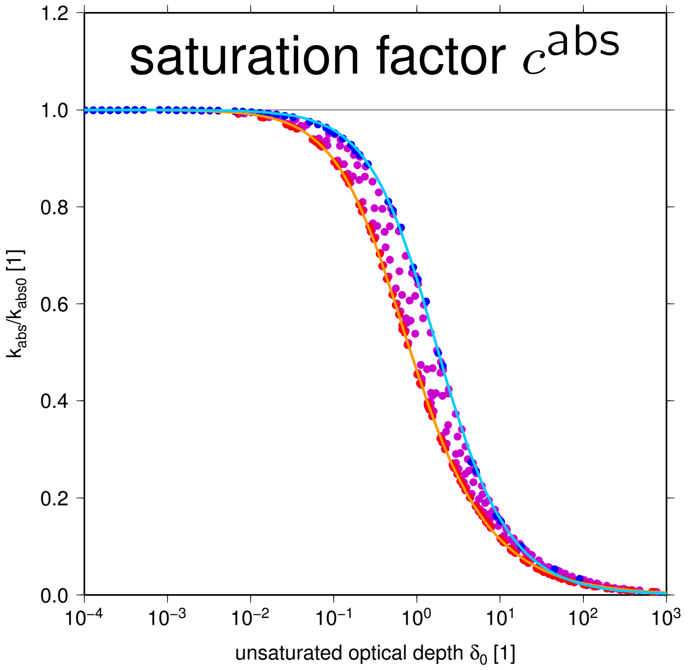
Beyond idealized optical paths – SW cloud optical saturation

- In the single SW band, **clouds cannot be treated as grey bodies.**
- SW cloud optical saturation must be evaluated with an inclusion of **multiple scattering,** accounting for the influence of the cloud layers above and below:

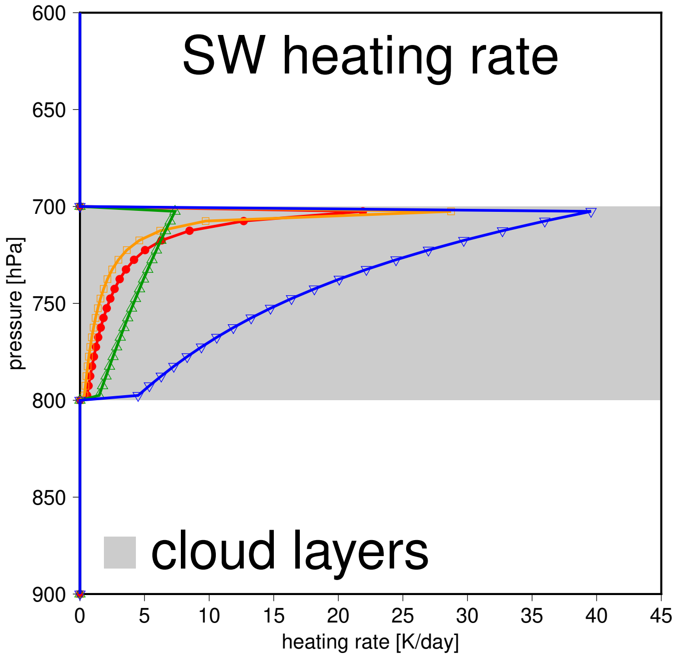
$$c^{\text{scat}}(\delta_0) = k^{\text{scat}}/k_0^{\text{scat}} \approx 1,$$

$$\begin{aligned} c^{\text{abs}}(\delta_0) &= k^{\text{abs}}/k_0^{\text{abs}} \\ &= 1/[1+(\delta_0/\delta_0^{\text{crit}})^m]^n, \end{aligned}$$

$$\begin{aligned} \Delta\delta_{0l}^{\text{eff}} &= \sum_{k=1}^{l-1} B^{\text{above}} n_k \Delta\delta_{0k} + \Delta\delta_{0l} \\ &+ \sum_{k=l+1}^{L} B^{\text{below}} n_k \Delta\delta_{0k}. \end{aligned}$$

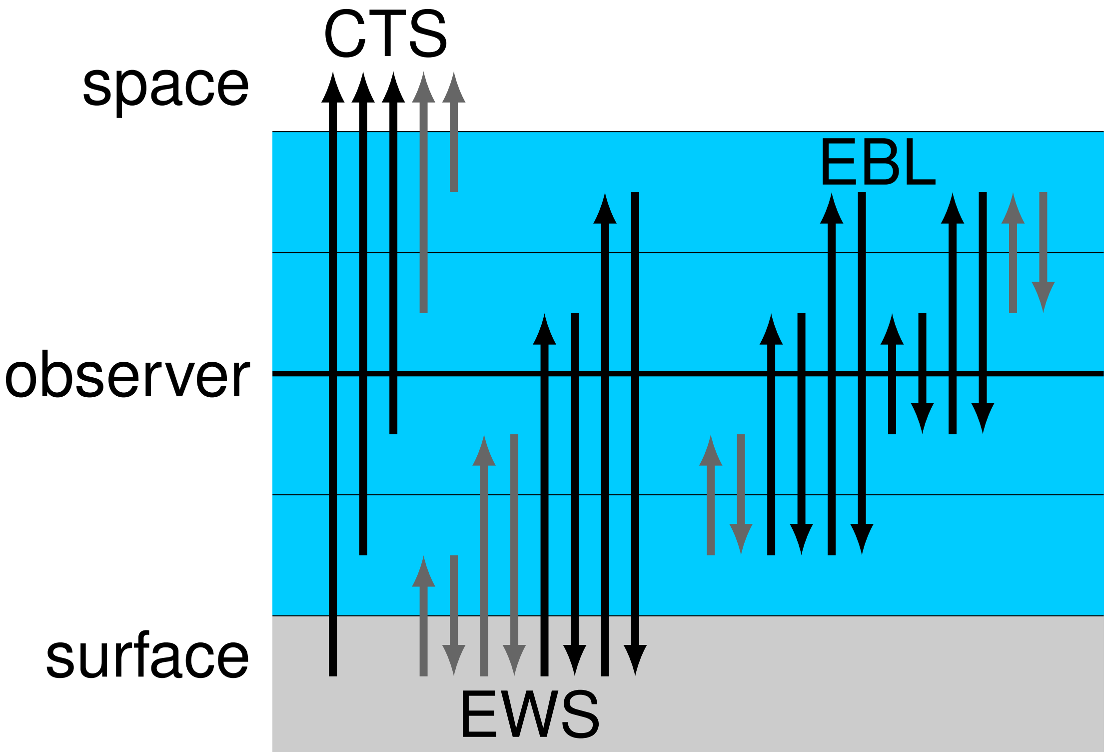


- liquid clouds
- ice clouds
- mixed clouds



narrowband reference
no saturation
static saturation
vertically varying saturation

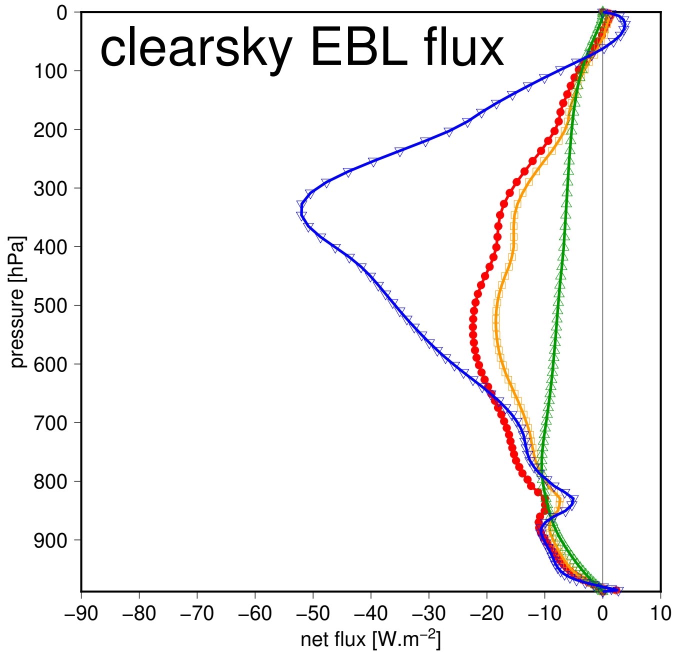
Breaking the LW barrier – NER decomposition



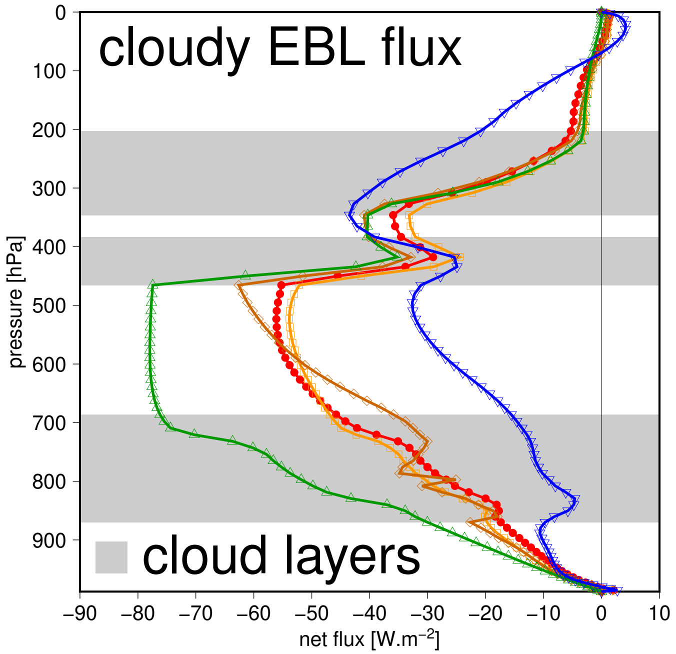
- **Net LW flux** across any atmospheric level can be split into **three components:**
  - **cooling to space (CTS);**
  - **exchange with surface (EWS);**
  - **exchange between** atmospheric **layers (EBL).**
- By clever manipulation with the source term, **CTS flux** can be obtained by **single solving** of the radiative transfer equation ⇒ **cost linear in L.**
- A set of **equivalent grey gaseous optical thicknesses** can be constructed, giving exact CTS flux in the absence of scattering.
- The same holds for **EWS flux.** A blocking point is **EBL flux,** where the exact calculation requires L solvings with L sets of gaseous transmissions ⇒ **cost quadratic in L.**

Breaking the LW barrier – bracketing technique

- Optically thin layers exchange less than optically thick ones.
- The most costly **EBL flux** can be interpolated between its **cheap min/max estimates.**
- Interpolation weights α are obtained in a **clearsky case.**
- They are filtered and applied with offsets β in a **cloudy case.**



narrowband reference
minimum estimate
maximum estimate
absorptivity-emissivity calculation



narrowband reference
minimum estimate
maximum estimate
interpolated flux / no filtering

$$\mathrm{EBL} = (1-\alpha)\mathrm{EBL}_{\mathrm{min}} + \alpha \mathrm{EBL}_{\mathrm{max}} + \beta$$

$$\alpha = \left\langle \frac{\mathrm{EBL}^{\mathrm{clear}} - \mathrm{EBL}^{\mathrm{clear}}_{\mathrm{min}}}{\mathrm{EBL}^{\mathrm{clear}}_{\mathrm{max}} - \mathrm{EBL}^{\mathrm{clear}}_{\mathrm{min}}} \right\rangle_{\mathrm{filter}} \qquad \beta = \mathrm{EBL}^{\mathrm{clear}} - (1-\alpha)\mathrm{EBL}^{\mathrm{clear}}_{\mathrm{min}} - \alpha \mathrm{EBL}^{\mathrm{clear}}_{\mathrm{max}}$$

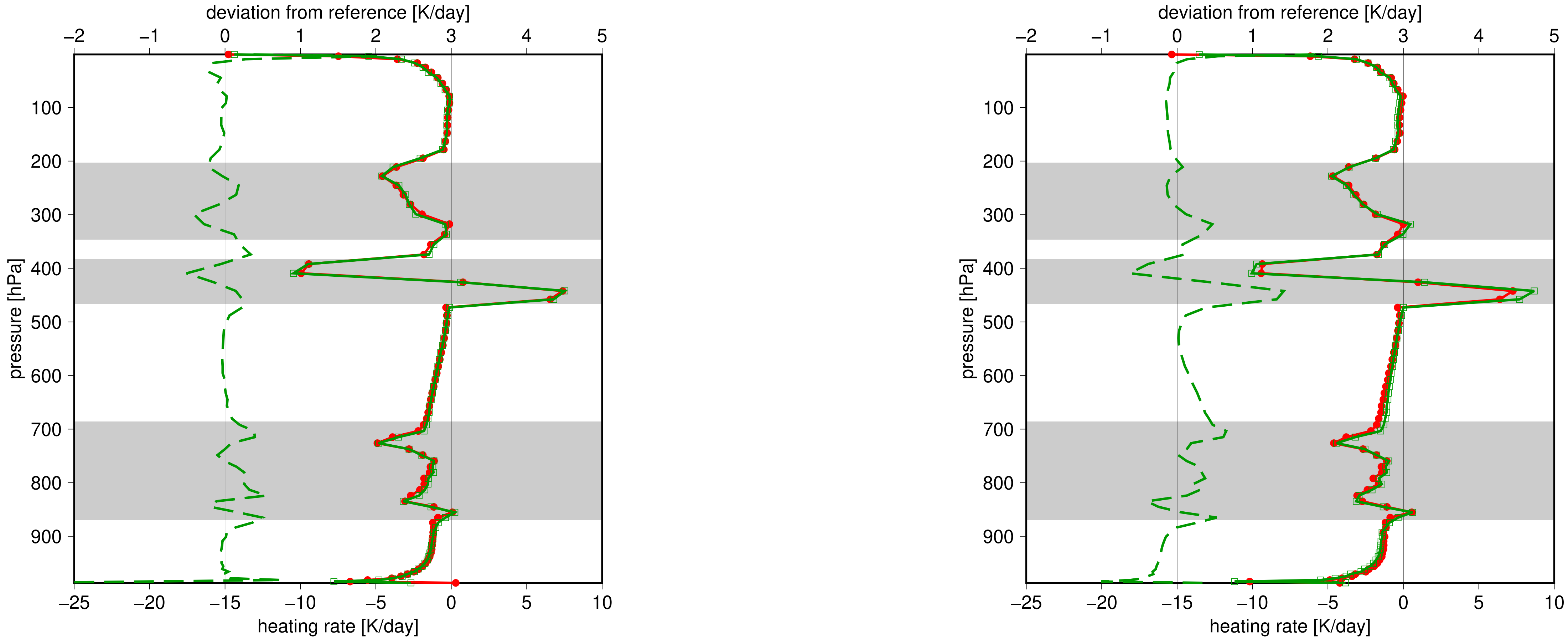
Breaking the LW barrier – final assembling

- **NER decomposition with bracketing** obtains the net LW flux by **8 solvings** of the radiative transfer equation:

$$F^{\mathrm{net}} = \mathrm{CTS} + \mathrm{EWS} + (1-\alpha)\overbrace{\left(F^{\mathrm{net}}_{\mathrm{min}} - \mathrm{CTS}_{\mathrm{min}} - \mathrm{EWS}_{\mathrm{min}}\right)}^{\mathrm{EBL}_{\mathrm{min}}} + \alpha\overbrace{\left(F^{\mathrm{net}}_{\mathrm{max}} - \mathrm{CTS}_{\mathrm{max}} - \mathrm{EWS}_{\mathrm{max}}\right)}^{\mathrm{EBL}_{\mathrm{max}}} + \beta.$$

- Computation employs **4 sets of equivalent grey gaseous optical thicknesses:** $\Delta\delta_{\mathrm{CTS}}$, $\Delta\delta_{\mathrm{EWS}}$, $\Delta\delta_{\mathrm{EBL\_min}}$ and $\Delta\delta_{\mathrm{EBL\_max}}$.
- Expensive calculation of clearsky bracketing weights α and offsets β can be done intermittently ⇒ **cost** of the scheme remains **essentially linear in L.**
- Scattering by **aerosols and clouds** is accounted for, situation is simplified by the fact that in the LW spectrum, they **can be treated as grey bodies.**

Stand-alone accuracy – LW heating rates



▨ cloud layers

narrowband reference (432 LW bands)
RRTMG scheme (16 LW bands)

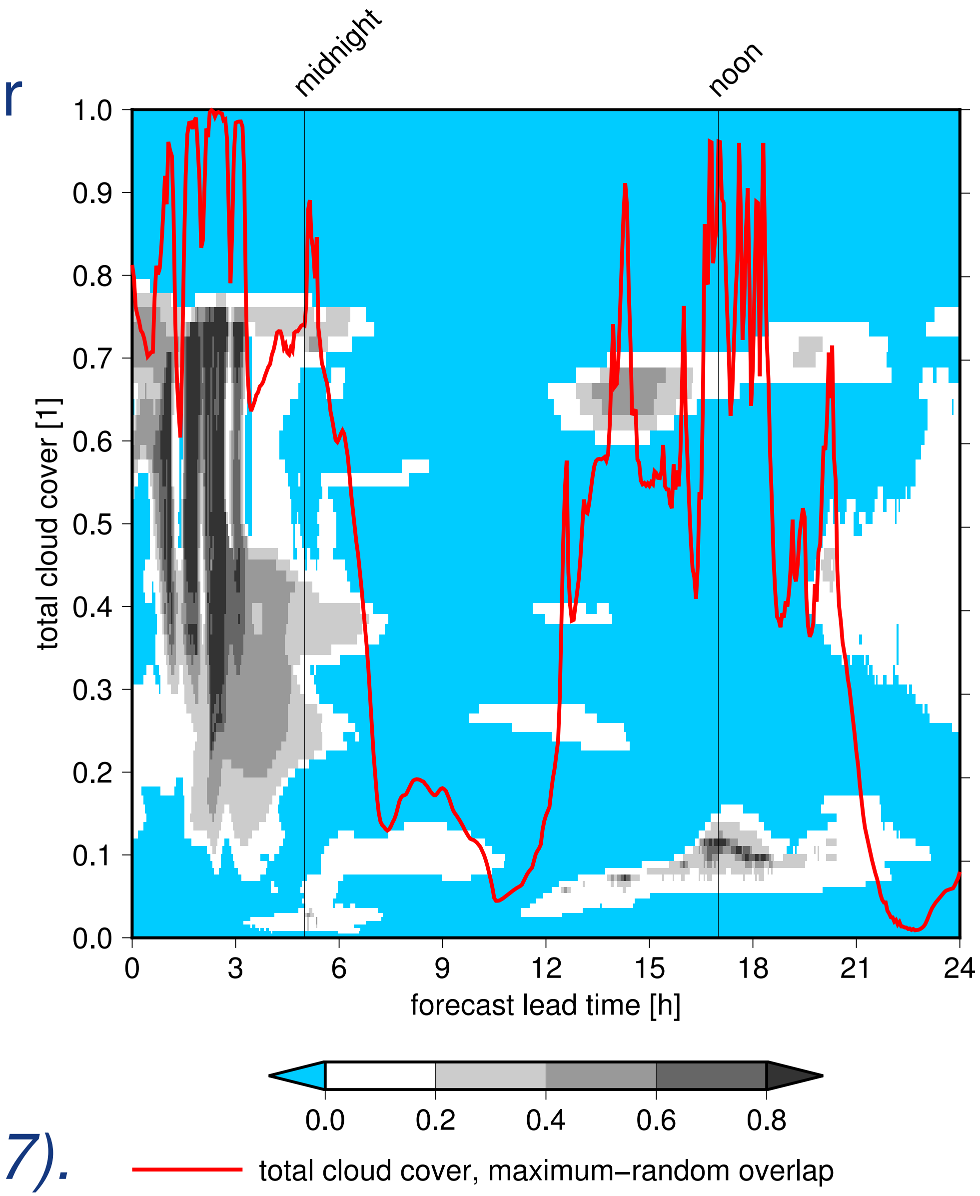
narrowband reference (432 LW bands)
ACRANEB2 scheme (1 LW band)

LW heating rate comparison with (left) no LW scattering, and (right) LW scattering included.

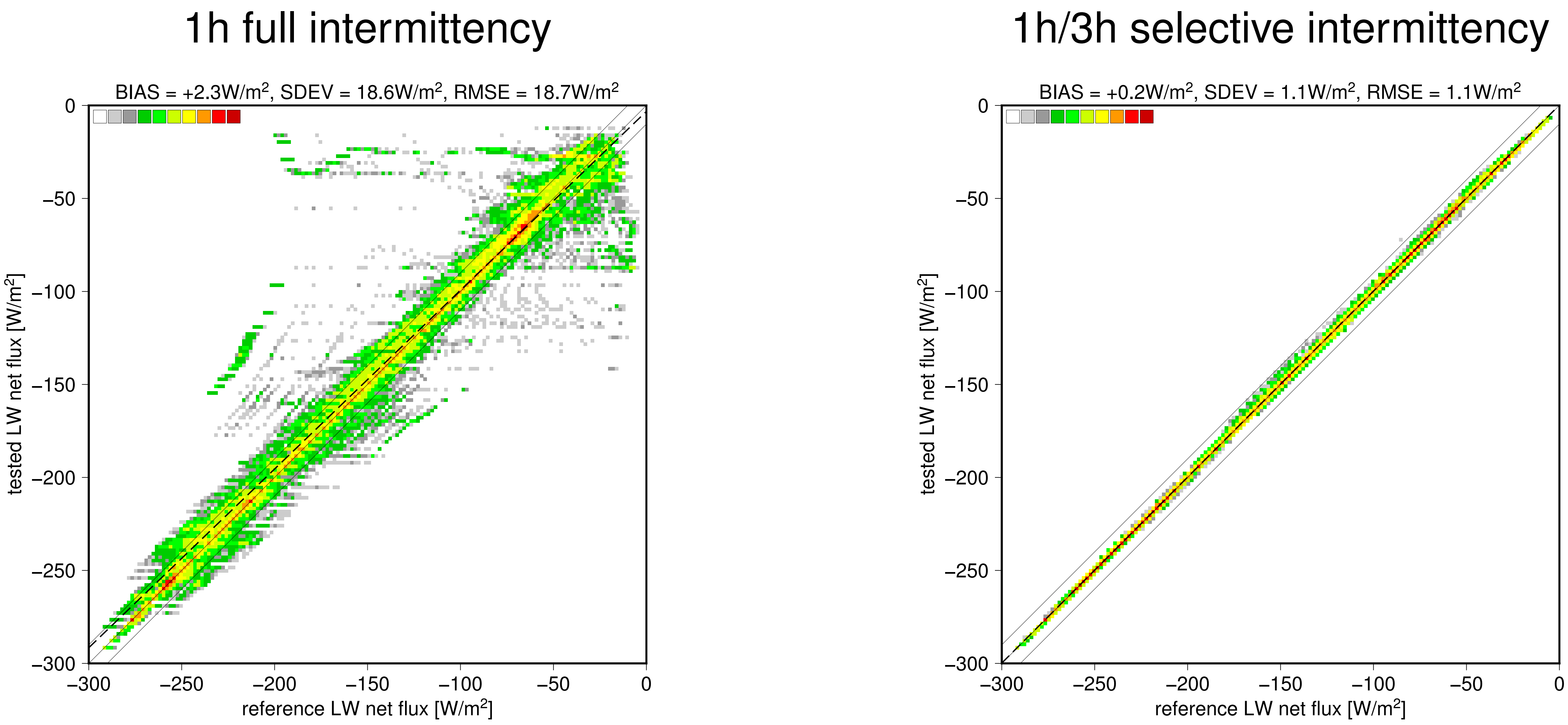
Full versus selective intermittency

- **Full intermittency** does not solve the radiative transfer equation in every model time-step (typically every **1h**).
- **Selective intermittency** solves the radiative transfer equation in every model time-step:
  - actual cloud optical properties are used;
  - **gaseous transmissions** / **bracketing weights** are updated less frequently (typically every **1h**/**3h**).

Demo case for comparing the two intermittent strategies: Passage of the waving cold front in Prague on 1st/2nd July 2012. Evolutions of layer cloud fractions and total cloud cover are shown, $\Delta t = 3$ *min. Source: Mašek (2017).*



Full versus selective intermittency – LW net flux error



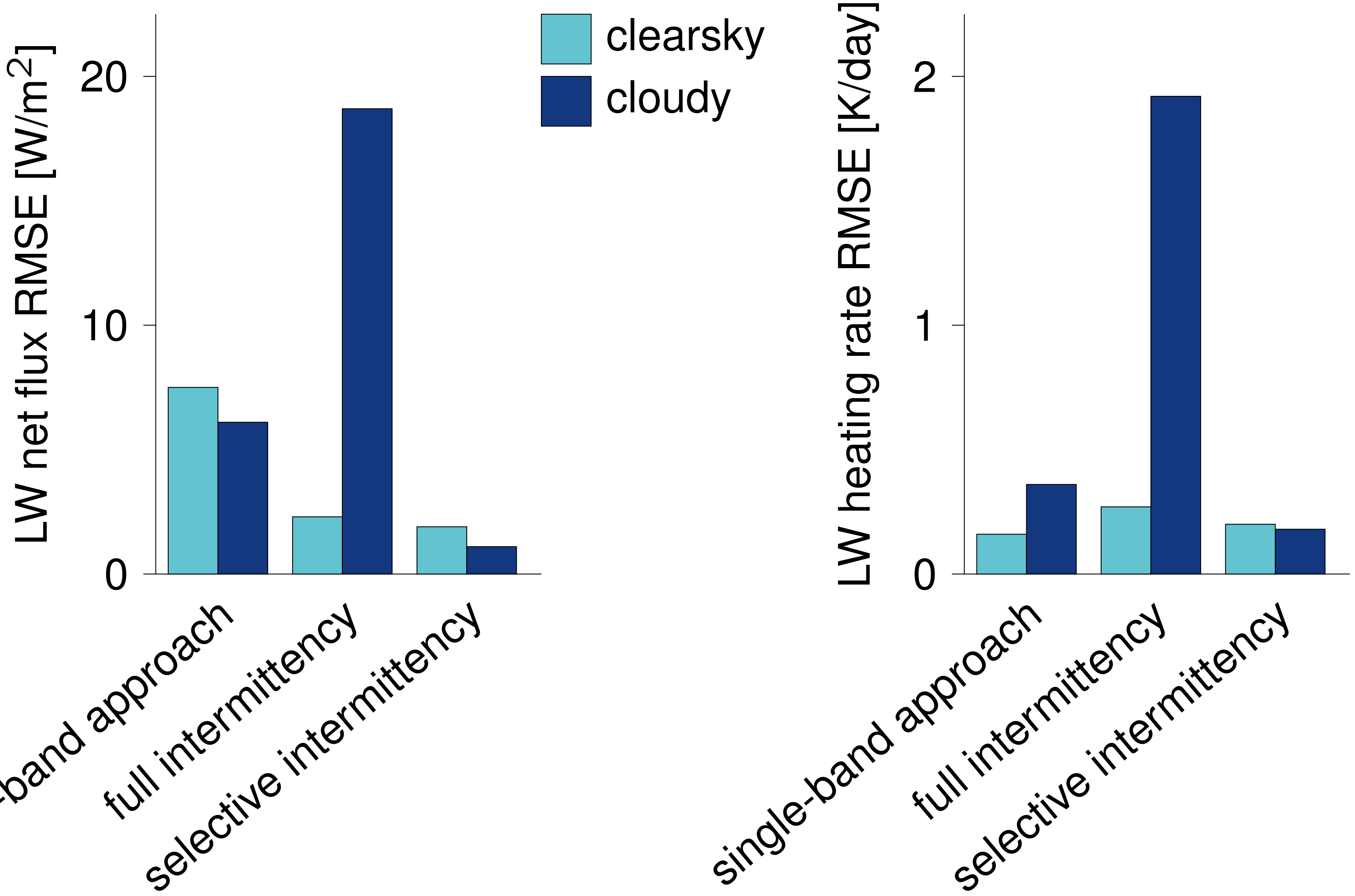
1h full intermittency

1h/3h selective intermittency

Intermittently updated LW net flux versus actual LW net flux. Offline mode.

Full versus selective intermittency – LW error balance

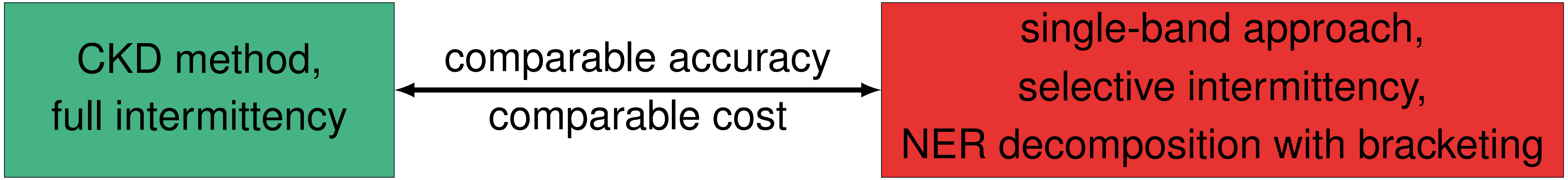
- In a cloudy case, error coming from full intermittency becomes **dominant.**
- Error of selective intermittency remains **comparable** to error of single-band approach.
- Error balance is important for **optimal use** of computational resources.



RMSE of (left) LW net flux, and (right) LW heating rate due to single-band approach, 1h full intermittency, and 1h/3h selective intermittency. Offline mode.

Conclusions

- In the context of **short-range NWP,** the single-band approach is no longer a poor relative of the noble CKD method.
- After substantial improvements, the radiation scheme using single SW and LW spectral bands became **competitive to the mainstream approach.**



CKD method,
full intermittency

comparable accuracy
comparable cost

single-band approach,
selective intermittency,
NER decomposition with bracketing

- Selective intermittency brings an advantage of the **full cloud-radiation interaction,** compensating for a lower stand-alone accuracy of the gaseous transmissions.
- Some accuracy limitations of the single band-approach are difficult to break. Could they be overcome by a **hybrid solution?**

References – ACRANEB2 scheme

- J. Mašek, J.-F. Geleyn, R. Brožková, O. Giot, H. O. Achom, and P. Kuma, 2016: Single interval shortwave radiation scheme with parameterized optical saturation and spectral overlaps. *Q. J. R. Meteorol. Soc.,* **142,** 304–326.
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- J. Mašek, 2017: Broadband radiation scheme fully interacting with clouds. *Doctoral Thesis, Charles University in Prague, Faculty of Mathematics and Physics,* 102 pp.

Thank you for your attention

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