Radiation: basic concepts and NER

followed by

Radiation: gaseous-statistics- & cloud-saturation models

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(*with many thanks to Neva Pristov, Jan Mašek, Richard Fournier* (Laboratoire d'Energétique, UPS, Toulouse), *Pierre Bénard, Yves Bouteloup, Maria Derkova and Gwenaelle Hello*)

Presentation at TCA0, Radostovice, CZ, 27-3-07

The context

The challenge:

How to give to the ALARO radiative computations a good cost/efficiency ratio?

How to do it in a framework that allows bridges with other projects of similar goals?

The aim:

To best define a long ‘radiative time step’ and intermediate optimised recomputations for each ‘model time step’.

To treat this in a multi-purpose spirit: while the problem is currently rather neglected in NWP, it seems to attract theoretical (Pauluis & Emanuel, 2004) as well as non-NWP interest (IPSL+LE). The NER formalism is particularly well tailored to this goal.

The problem (1/2)

- Our problem is here the unbalance between the sophistication to be put in the thermodynamic description of the clouds and the fact that, in principle, the monitoring of their evolving radiative influence should be sacrificed, if one aims at having the most precise possible clear sky surface fluxes.
- The crucial point is indeed that of the pharaonic computing cost of the complete schemes (if called everywhere at every time-step) or that of the prohibitive memory burden of reconstitutions by the Curtis matrix method ($\sigma.T^4$ => flux) for the thermal spectrum (2 L**2 complete fields to store if one wants to recompute only the cloudy influence at each time step).

The problem (2/2)

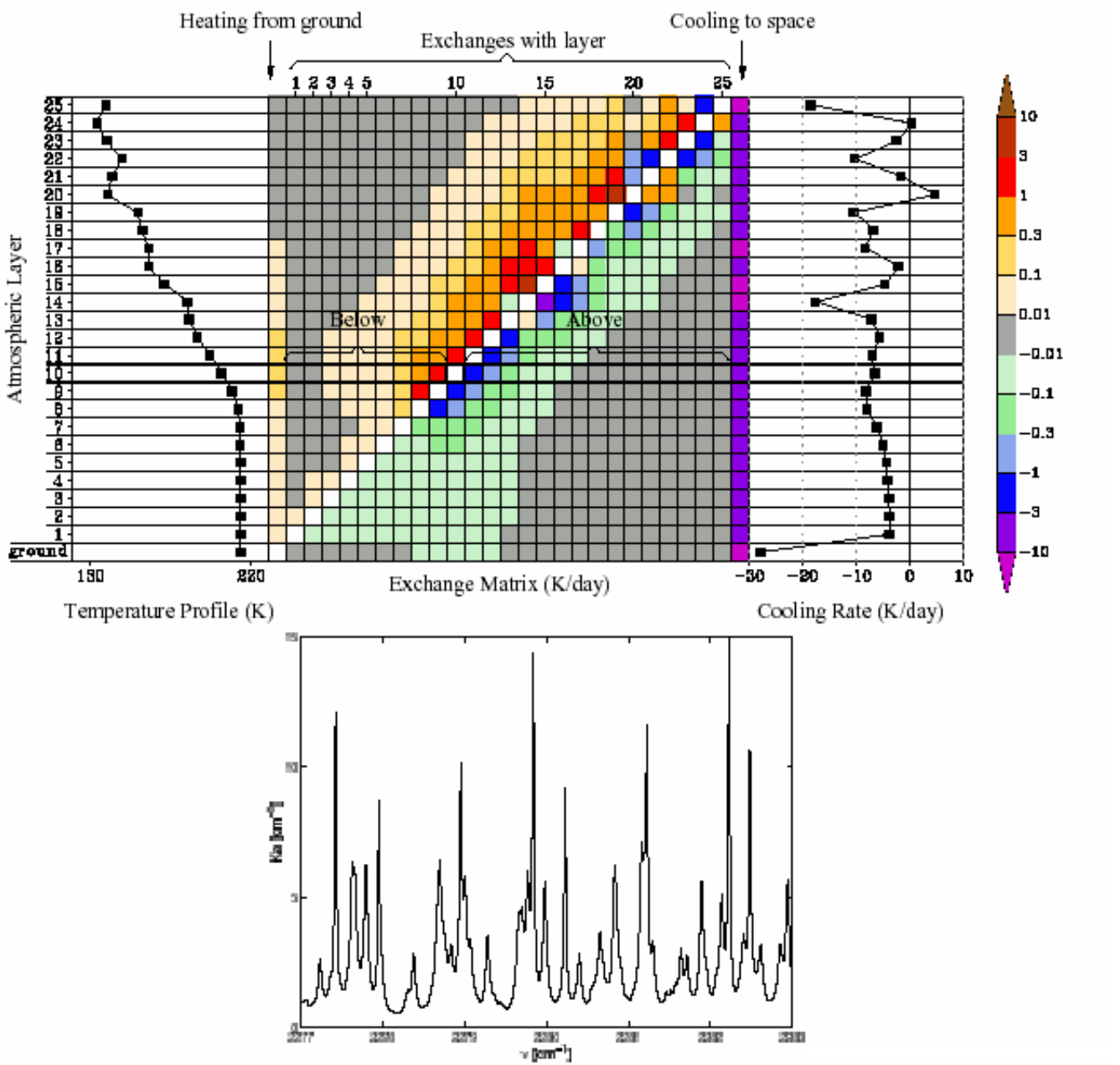
- The current compromise solutions are:
  - computations of intermediate complexity everywhere at each time-step (ex-ARPEGE-NWP, ALADIN) => one sacrifices accuracy to efficiency;
  - The IFS (=> ARPEGE-NWP) method of complex computations at an initial time followed by a time constant horizontally interpolated forcing during a dozen of time steps (ARPEGE-Climat, 2L fields to store) => 'static' and 'smoothed' clouds;
  - a partially selective recomputation whenever clouds 'move' (Meso-NH) => cumbersome and not too economical.
- What do we need to do better ? A good calibration of the clear-sky part with respect to the results of a sophisticated calculation, the possibility to add an 'interactive' radiative cloud model to a cheap recomputing of this clear sky part at each time step, and this to the price of a modest storage burden. Trying to square the circle ?

The Net Exchange Rate formulation (NER)

- One divides the atmosphere in ‘bodies’ (layers for us) and, considering each pair of them, one directly computes the net balance of exchanged photons.
- Contrary to all flux computation methods, this allows to neglect a lot of symmetrically exchanged photons => **simplicity**.
- It also leads to a principle of reciprocity: the warmer body will always heat the colder one => **realism**.
- It ensures energy conservation => **accuracy**.

Litterature on the NER formulation

- Green, J.S.A., Quart. J. Roy. Met. Soc., 93 (**1967**) 371-372.
- Hottel, H.C. and A.F. Sarofim. Radiative Transfer, McGraw-Hill (**1967**).
- Joseph, J.M. and R. Bursztyn, Journal of Applied Meteorology, 15 (**1976**) 319-325.
- Cherkaoui, M. , J.-L. Dufresne, R. Fournier, J.-Y. Grandpeix and A. Lahellec, JHT, 118 (**1996**) 401-407.
- De Lataillade, A., J.-L. Dufresne, M. El Hafi, V. Eymet and R. Fournier, JQSRT, 74 (**2002**) 563-584.
- Eymet, V. , J.-L. Dufresne, R. Ricchiazzi, R. Fournier and S. Blanco, Atmospheric Research, 72 (**2004**) 239-261.
- Hourdin, C., J.-L. Dufresnes, R. Fournier, F. Hourdin, **2005**: Net exchange reformulation of radiative transfer in the CO2 15µm band on Mars. In preparation.


Heating from ground
Exchanges with layer
Cooling to space
Atmospheric Layer
Below
Above
Temperature Profile (K)
Exchange Matrix (K/day)
Cooling Rate (K/day)

'Side advantages' of the NER formulation

- The 'natural' distinction between important and secondary terms gives a hint to a strategy of 'two frequencies' for **CPU savings**. The problem of clouds looks however like making the realisation cumbersome.
- Since (for isothermal layers) the 'i-to-j' exchange terms are proportional to $\sigma.(T_i^4-T_j^4)$, one may linearise their evolution equation with terms like $4.\sigma.(T_i^3.[\partial T_i/\partial t]-T_j^3.[\partial T_j/\partial t])$ in order to obtain a **stable** split-implicit time-step.

A new way to look at radiative calculations in NWP (1/2)

- **The method**:
  - Transform what currently makes the ACRANEB computation economical into a way to compact the information saved for future cheap computations.
  - Take advantage of this step to split radiative computations in three separate entities:
    - ***(I)*** A complex computation of gaseous transmissions in conditions of no scattering (‘clear-sky’);
    - ***(II)*** A way to compact (interpolations) and decompact (solver) this information;
    - ***(III)*** A model for ‘grey’ optical thicknesses (Rayleigh scattering, clouds, aerosols, falling precipitations?).

A new way to look at radiative calculations in NWP (2/2)

- **The associated avenues of progress**:
  - ***(I)*** Working with radiation specialists on the clear-sky gaseous problem.
  - ***(II)*** Improving the accuracy and efficiency of the 'solver'.
  - ***(III)*** Making the work on cloud optical properties closer to the one on microphysics.
- **The flexibility issue**:
  - If the problems are well separated, it is easier to progress.
  - The 'gaseous issue' is more important in climate research mode, the 'cloud' one in specific meso-scale work and the economy side is paramount in NWP => there should be space for a consensus.

The question of the vertical temperature profile (1/2)

- The choice to have a ‘computational’ atmosphere built as a piling-up of isothermal layers:
  - Is not a necessity if one wants to work in the NER framework (contrary to first intuition);
  - Is not the most physical solution;
  - Can however be used selectively, when one does not need the details of the intermediate path to get an accurate solution;
  - Will anyhow be used below to explain the proposed method (in all generality).

The question of the vertical temperature profile (2/2)

- In the following, one will work with three different profiles:
  - $I\!\!\Pi B = 1$ at the ground and everywhere in the atmosphere => allows to suppress all other exchanges than 'cooling to space' (CTS) – Profile A
  - $I\!\!\Pi B = 1$ at the ground et $I\!\!\Pi B = 0$ everywhere in the atmosphere => allows to suppress all other exchanges than 'exchange with surface' (EWS) – Profile B
  - The one corresponding to the physical truth => it mixes CTS, EWS with the 'exchanges between layers' (EBL) – Profile C

«Two-stream-type» monochromatic computations for a single model layer

One assumes having to compute only three fluxes: S for the solar parallel radiation, $F\downarrow$ for the downward diffuse radiation and $F\uparrow$ for the upward diffuse radiation. ΠB is the black-body flux associated to the temperature of the layer (supposed isothermal) from which diffuse radiation exits. One performs the change of variable $F^*=F-\Pi B$. τ is the optical thickness (growing downwards) and μ_0 the cosine of the sun's zenith angle. The «α» coeffients are considered constant across each layer.

$$\frac{\partial S}{\partial \tau} = -S/\mu_0$$

$$\frac{\partial F_*^{\downarrow}}{\partial \tau} = -\alpha_1 . F_*^{\downarrow} + \alpha_2 . F_*^{\uparrow} + \alpha_3(\mu_0) . S$$

$$\frac{\partial F_*^{\uparrow}}{\partial \tau} = -\alpha_2 . F_*^{\downarrow} + \alpha_1 . F_*^{\uparrow} - \alpha_4(\mu_0) . S$$

The trick with F* reduces the thermal 'source terms' to δs at the layers' interfaces, i.e. where fluxes are computed

The «adding-method» for the atmosphere from top to bottom (1/2)

One obtains readily, with indices '***t***' & '***b***' for top and bottom of the relevant layer, the following linear relationships:

$$\begin{vmatrix} S_b \\ F^{*\downarrow}_b \\ F^{*\uparrow}_t \end{vmatrix} = \begin{vmatrix} a_1 & 0 & 0 \\ a_2 & a_4 & a_5 \\ a_3 & a_5 & a_4 \end{vmatrix} . \begin{vmatrix} S_t \\ F^{*\downarrow}_t \\ F^{*\uparrow}_b \end{vmatrix}$$

with

$$a_1 = e(-\delta\tau/\mu_0) \quad a_{2/3} = a_{2/3}(\delta\tau, \alpha_{1/2/3/4}, \mu_0) \quad a_{4/5} = a_{4/5}(\delta\tau, \alpha_{1/2})$$

& $BCs\ S(\tilde{0}) = \mu_0 . I_0 \quad F^{\downarrow}(\tilde{0}) = 0$

\+ $BCs\ F^{\uparrow}(\tilde{N}) = A(\mu_0).S(\tilde{N}) + \overline{A}.F^{\downarrow}(\tilde{N}) \quad F^{\uparrow}_*(\tilde{N}) = (1-\varepsilon).F^{\downarrow}_*(\tilde{N})$

The «adding-method» for the atmosphere from top to bottom (2/2)

- Once the previous system of equations is known its extension from the monochromatic to the spectral case ‘only’ suffers from the fact that transmissivities are not additive (the so-called ‘saturation effect’).
- In case of a single source (like for solar radiation) or single pseudo-source (like for the photons lost to space or going from the surface for the thermal case), one can trace-back with a method of ‘idealised paths’ before solving (equivalent gaseous optical depths are computed in a situation without scattering and reused as such when scattering is introduced).
- Our main problem (for economy of CPU as well as of storage-space) is the multi-source case of thermal radiative exchange between layers.

CTS+EWS+EBL decomposition of the thermal radiative exchange terms in absence of scattering (1/2)

$$F_{\tilde{n}} = -\sigma.T_{N+1}^4.\tau(\tilde{n},\tilde{N}) - \sum_{i=n+1}^{i=N} \sigma.T_i^4.(\tau(\tilde{n},\tilde{i}-1) - \tau(\tilde{n},\tilde{i})) + \sum_{j=1}^{j=n} \sigma.T_j^4.(\tau(\tilde{j},\tilde{n}) - \tau(\tilde{j}-1,\tilde{n}))$$

$$F_{\tilde{n}-1} = -\sigma.T_{N+1}^4.\tau(\tilde{n}-1,\tilde{N}) - \sum_{i=n}^{i=N} \sigma.T_i^4.(\tau(\tilde{n}-1,\tilde{i}-1) - \tau(\tilde{n}-1,\tilde{i})) + \sum_{j=1}^{j=n-1} \sigma.T_j^4.(\tau(\tilde{j},\tilde{n}-1) - \tau(\tilde{j}-1,\tilde{n}-1))$$

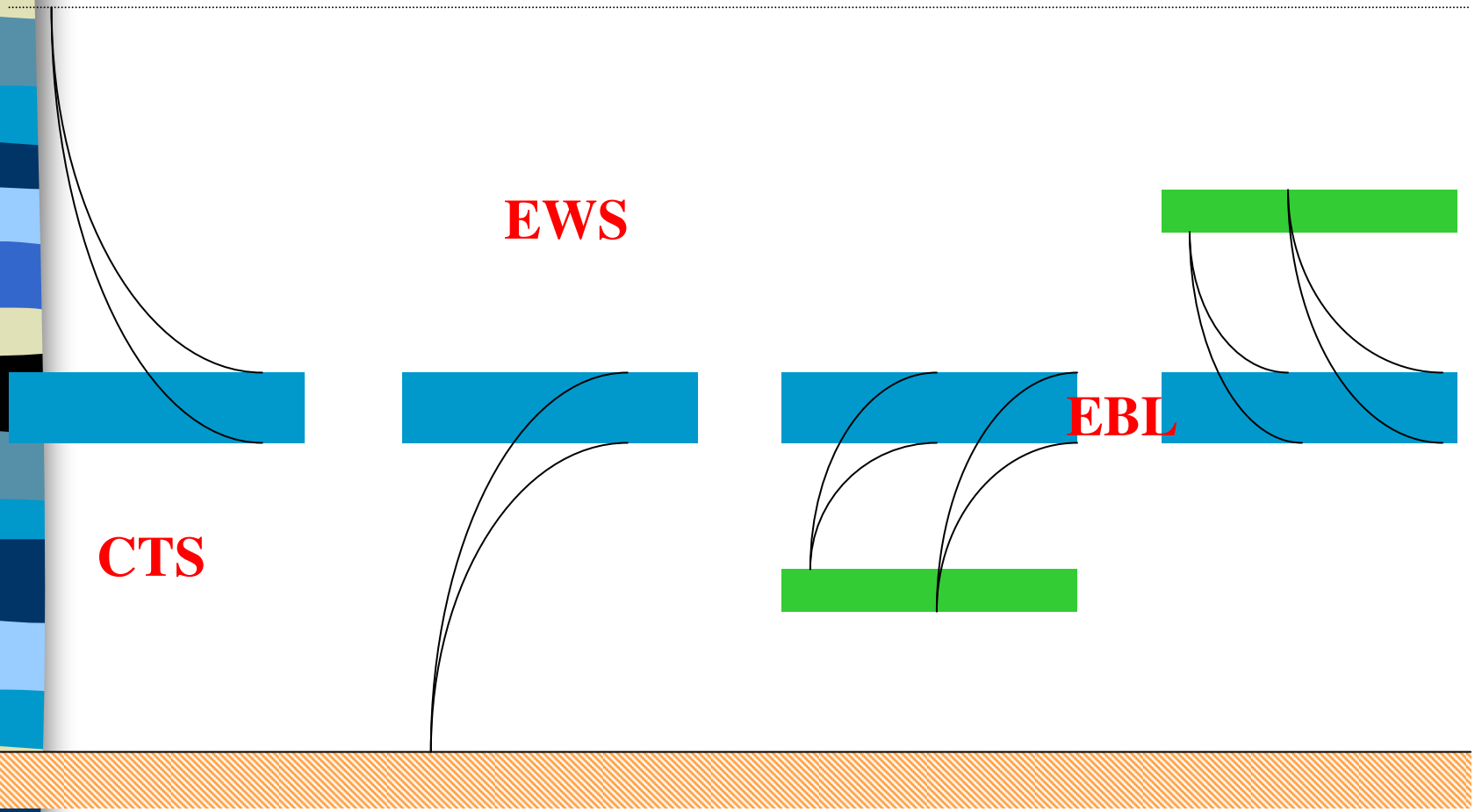
$$Rthr = F_{\tilde{n}} - F_{\tilde{n}-1} = \sigma.T_n^4.\left\langle \tau(\tilde{0},\tilde{n}) - \tau(\tilde{0},\tilde{n}-1) \right\rangle \qquad \text{CTS}$$

$$+\left(\sigma.T_{N+1}^4 - \sigma.T_n^4\right).\left\langle \tau(\tilde{n},\tilde{N}) - \tau(\tilde{n}-1,\tilde{N}) \right\rangle \qquad \text{EWS}$$

$$+\sum_{i=n+1}^{i=N} \left(\sigma.T_i^4 - \sigma.T_n^4\right).\left\langle \tau(\tilde{n},\tilde{i}-1) - \tau(\tilde{n}-1,\tilde{i}-1) - \tau(\tilde{n},\tilde{i}) + \tau(\tilde{n}-1,\tilde{i}) \right\rangle$$

$$+\sum_{j=1}^{j=n-1} \left(\sigma.T_n^4 - \sigma.T_j^4\right).\left\langle \tau(\tilde{j},\tilde{n}) - \tau(\tilde{j},\tilde{n}-1) - \tau(\tilde{j}-1,\tilde{n}) + \tau(\tilde{j}-1,\tilde{n}-1) \right\rangle \qquad \text{EBL}$$

CTS+EWS+EBL decomposition of the thermal radiative exchange terms in absence of scattering (2/2)



What about the interaction with scattering?

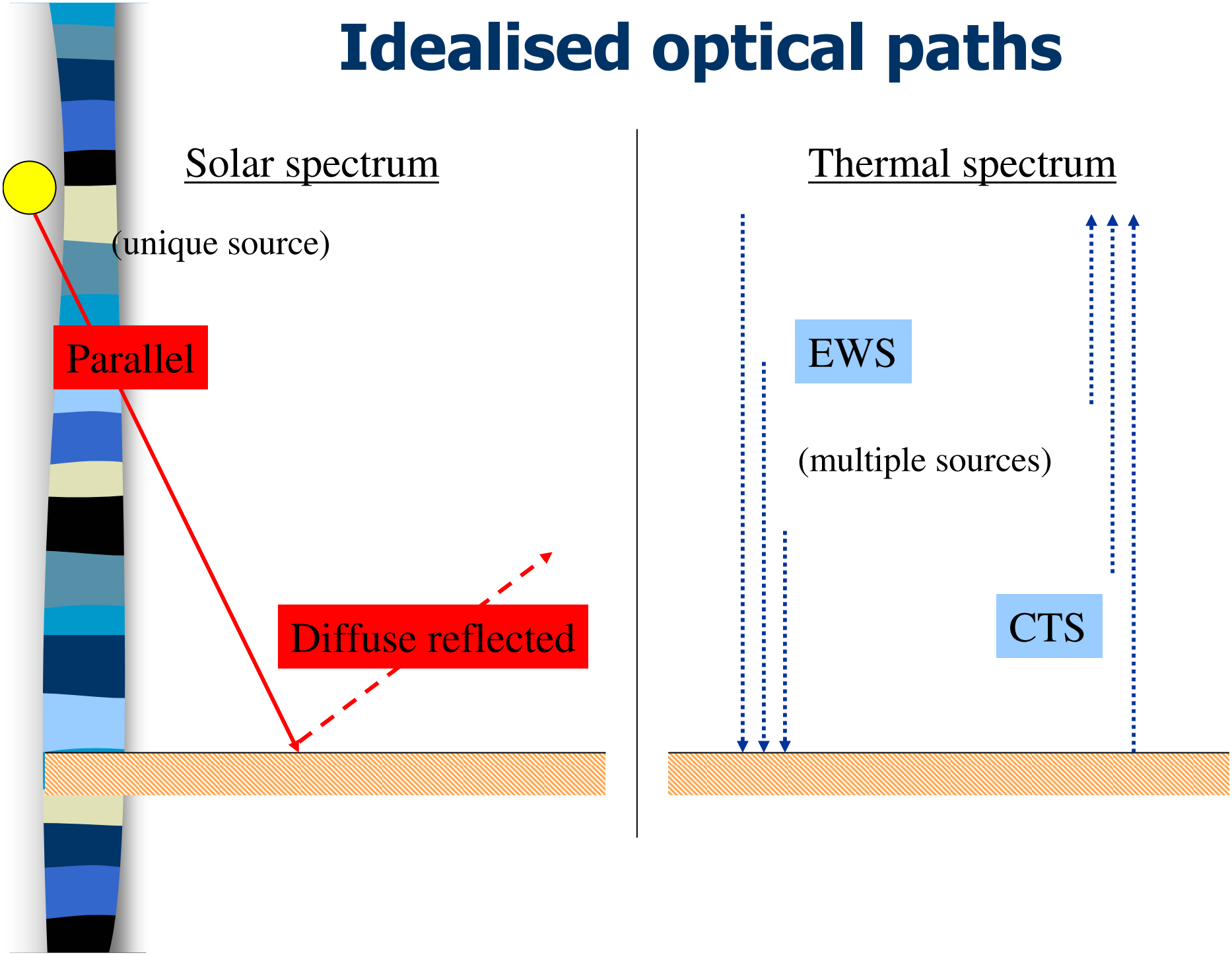
Method of idealised optical paths (1/3)

The basis of this method is very simple. One computes exactly the optical depths of gaseous absorption for every layer in a simplified geometry and one reinjects them as such in the «two-stream + adding» formalism, together with the ‘grey body’ effects.

For the solar part, the computation for S is straightforward and that for $F\downarrow$ and $F\uparrow$ relies on the absorption during the return path of a photon reflected at the surface but never scattered.

For the thermal part, the «CTS» and «EWS» computations rely on obvious direct optical paths. There remains, like always, the ‘CPU barrier’ for the «EBL» calculations.

Idealised optical paths



Method of idealised optical paths (2/3)

For this multiple sources' problem, the old trick used was to say that it is always preferable to under-estimate the radiative exchange between two layers than to risk triggering an instability through an over-estimation.

Each layer got thus assigned, for the sole «EBL» calculation, the smallest optical depth under which it can be seen from any position along the vertical.

But, owing to the saturation effect, the latter could only be that seen from the top of the atmosphere or that seen from the surface. One therefore simply did the approximation (rather «daring» but very economical):

$$\delta\tau_{gas}(EBL) = \min(\delta\tau_{gas}(CTS), \delta\tau_{gas}(EWS))$$

Method of idealised optical paths (2/3)

For this multiple sources' problem, the old trick used was to say that it is always preferable to under-estimate the radiative exchange between two layers than to risk triggering an instability through an over-estimation.

The 'anti-overestimation' approximation is indeed meant for cheap computations, but it also (and here primarily) corresponds to a strong compression of the information going from the 'transmission' part towards the solution of linear systems !!!

But, owing to the saturation effect, the latter could only be that seen from the top of the atmosphere or that seen from the surface. One therefore simply did the approximation (rather «daring» but very economical):

$$\delta\tau_{gas}(EBL) = \min(\delta\tau_{gas}(CTS), \delta\tau_{gas}(EWS))$$

Method of idealised optical paths (3/3)

- In practice, for the thermal spectrum, this corresponds to the following algorithm (Monsieur Jourdain's NER):
  - One does a calculation [I] with profile A and $\delta\tau_{gaz}(CTS)$
  - One does a calculation [II] with profile B and $\delta\tau_{gaz}(EWS)$
  - On does three calculations [III, IV, V] with profiles A, B & C and $\delta\tau_{gaz}(EBL) = \delta\tau_{min}$

After remultiplying the results (except 'V') by the ΠB values, one recombines [I] + [II] - [III] - [IV] + [V] in order to obtain the 'right' result.

Modifications suggested by Richard Fournier

- Nothing changes for solar fluxes;
- For the thermal part, one does not compromise on the CTS et EWS parts, that are done '100% true';
- For the EBL part, the dominating term is the one corresponding to exchanges between immediately adjacent layers; it is now treated independently (like CTS and EWS) and with special care (temperature profile, non-linearities);
- The corresponding $\delta\tau_{prox}$ can fortunately be obtained as easily as those for CTS and EWS;
- For all 'exactly computed' terms, one linearises the $\sigma.T^4$ time evolution in order to stabilise potential numerical oscillations.

One decisive change of perspective

- $\delta\tau_{prox}$ is also the '$\delta\tau_{max}$' for the whole atmosphere. Hence the central idea is to bracket the true result for EBL between 'min' (like up to now) and 'max' computations.
- This will be more expensive (8 inversions instead of 5) but the precision will be dramatically increased, without hampering the 'time intermittency strategy'.

Modified method (*ACRANEB*)

- One gets now the following algorithm:
  - One does a calculation [I] with profile A and $\delta\tau_{gaz}(CTS)$
  - One does a calculation [II] with profile B and $\delta\tau_{gaz}(EWS)$
  - On does three calculations [III, IV, V] with profiles A, B & C and $\delta\tau_{gaz}(EBL) = \delta\tau_{min}$
  - One does three calculations [VI, VII, VIII] with profiles A, B & C and $\delta\tau_{gaz}(EBL) = \delta\tau_{max} = \delta\tau_{prox}$

After remultiplying the results (except 'V' and 'VIII') by the relevant ΠB values, one recombines:

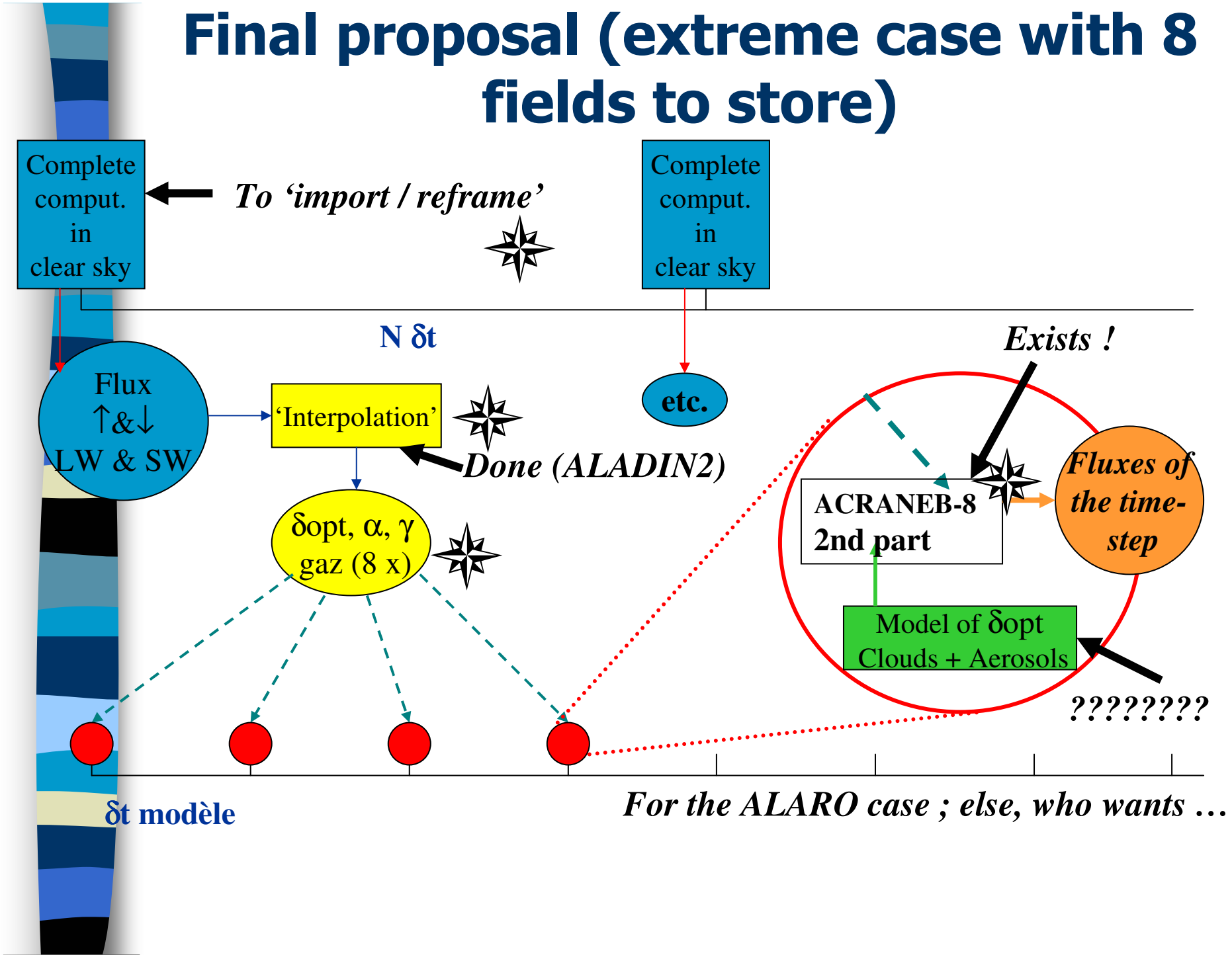
$$[I] + [II] - \alpha.([III]+[IV]-[V]) - (1-\alpha).([VI]+[VII]-[VIII]) + [\gamma]$$

in order to obtain the 'even righter' result. Just a 'small' problem: how to calibrate α and γ ?!

First consequences (to be developped in the presentation of the results)

- For the time storage one even gets now two variants of the method (and probably some intermediate offsprings):
  - To store everything (8 arrays) and to recompute nothing (original idea);
  - To store α and γ and to recompute, like up to now, the various $\delta\tau_{gaz}$.
- The 'I to VIII computations' method can already be applied in the current framework if one knows how to 'parameterise' α (with γ equal to zero).

Final proposal (extreme case with 8 fields to store)



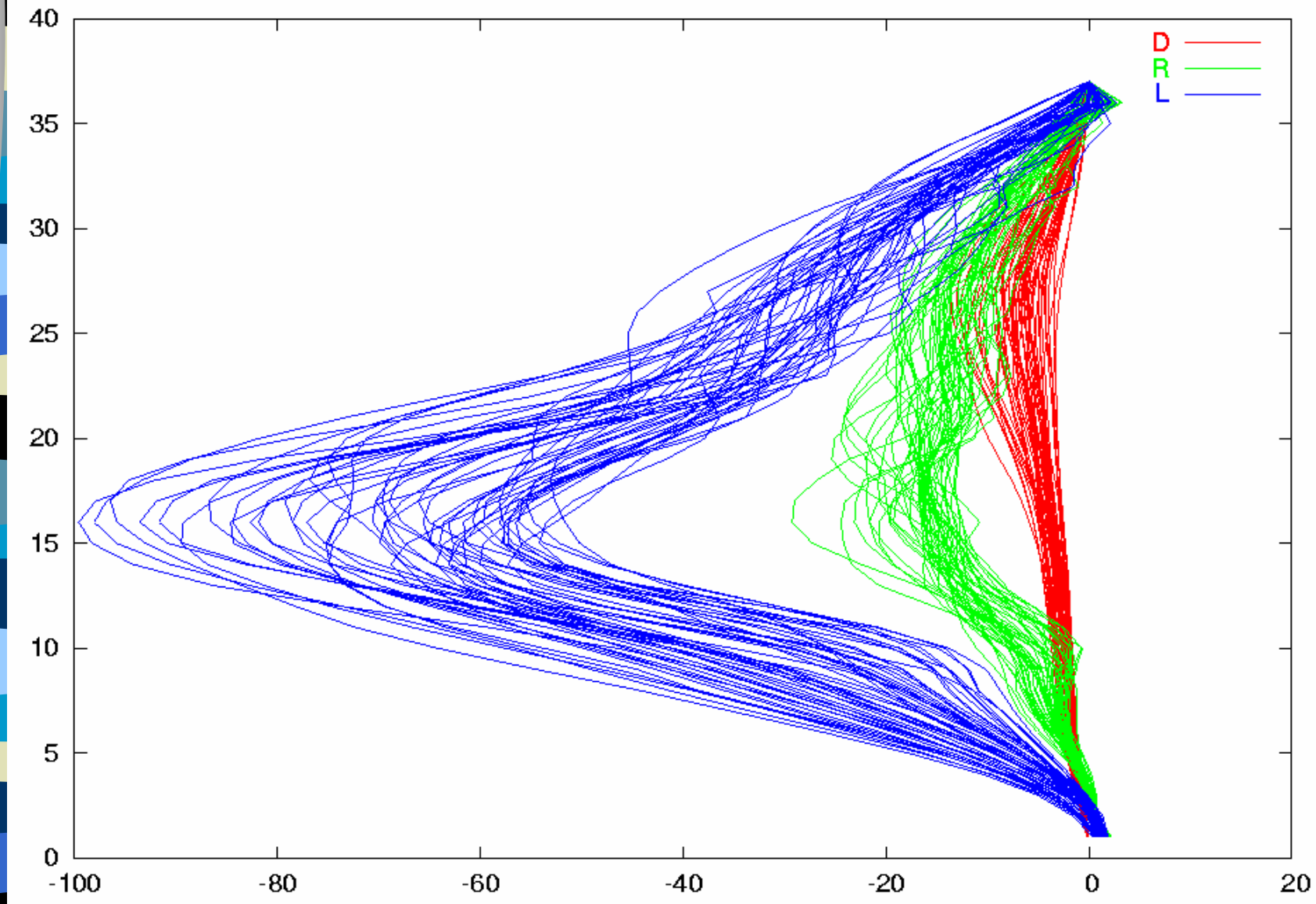
Advantages of the proposal

- It relies on well-proven approximations.
- It follows the simplifying principle of constant gaseous optical depths for $N.\delta$.
- It only requires a moderate storage space (between $8.L$ and $2.L$ fields, depending on the chosen options).
- It is simple and relatively cheap.
- It is 'physical' in the sense that clear-sky fluxes at the beginning of each 'updating' period can be exact and that one can put sophistication (without excessive CPU burden) in the clouds- and aerosols (or even precipitation ?) 'models'.
- It alllows extensions for who would like to go further (other cloud overlapping assumption, even more sophisticated schemes in input, …).
- It is potentially 'adjointable'.
- It is modular, didactic and of very general scope.

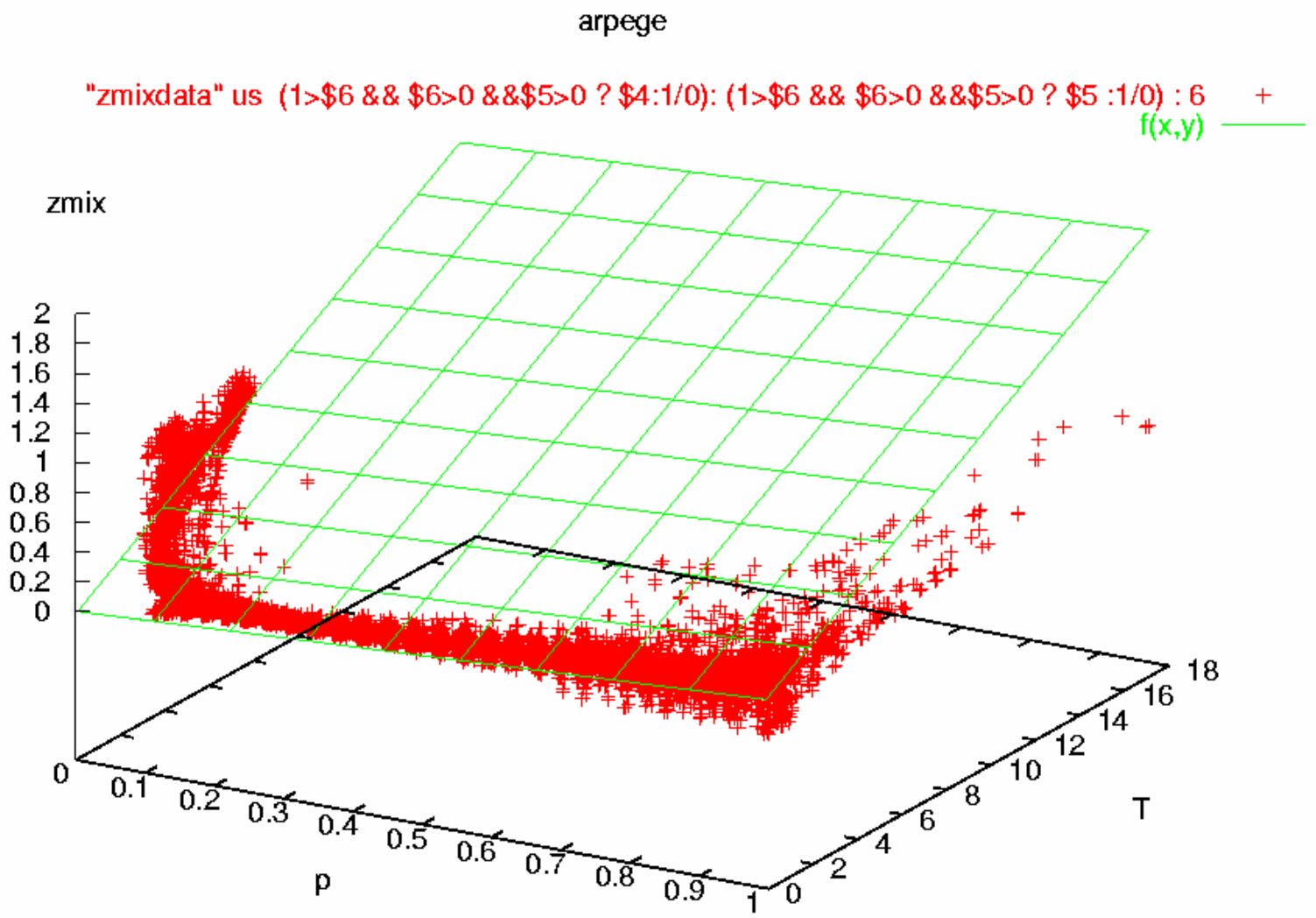
Disadvantages of the proposal

- It assumes a decorrelation between the respective extinction spectra of gases and clouds+aerosols. Only experimental work can tell whether this is a penalising problem or not.
- It fights against the dogma of radiative schemes ‘sub-contracted as a whole’.
- It requires to be able to economically split the gaseous parts of ‘cloned’ schemes into CTS + EWS + EBL. This ‘*economy*’ is in fact not so easy to reach for ‘hard-wired’ schemes (like FMR and RRTM).
- It requires a minimum of coordination for interfacing.

First results (parameterisation of α): 'EBL-fluxes' for max (L), min (D) and exact (R)

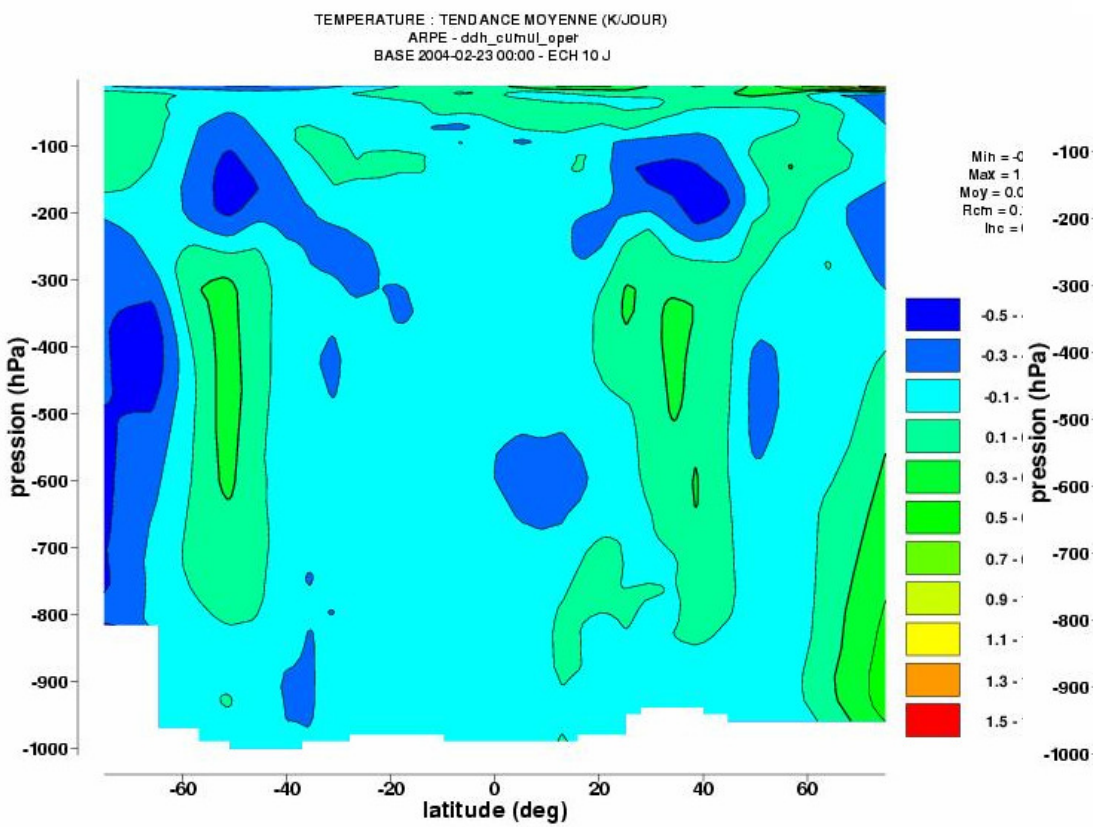


First results (parameterisation of α): two parameters fit



3D results (parameterised version, Part 1)

Temperature biases in zonal mean



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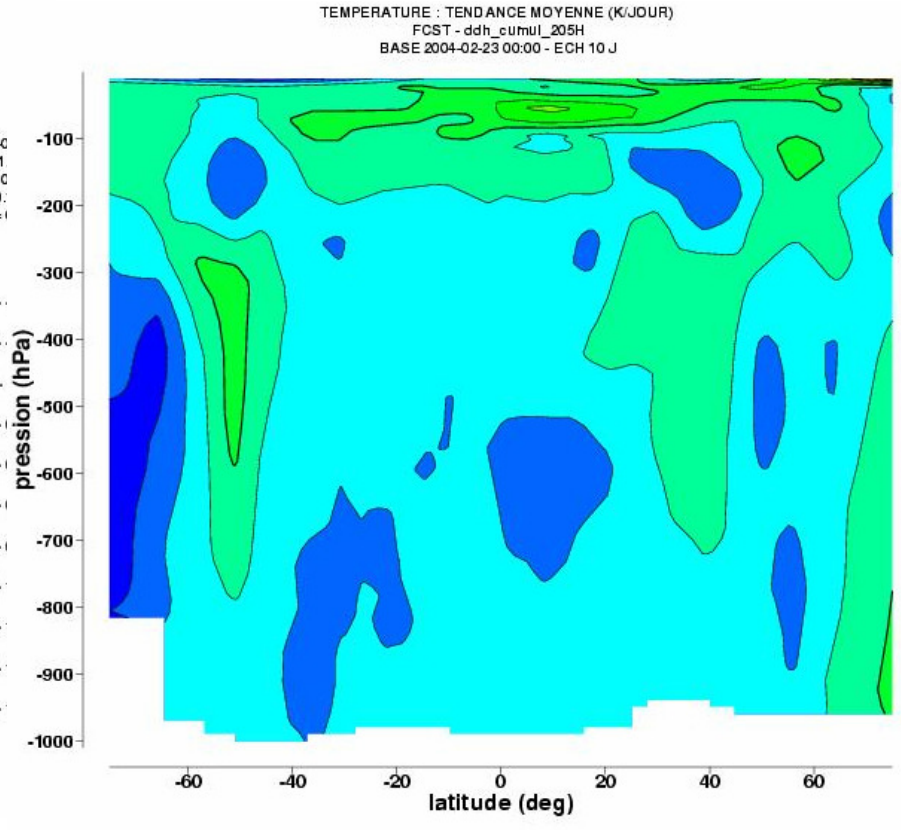
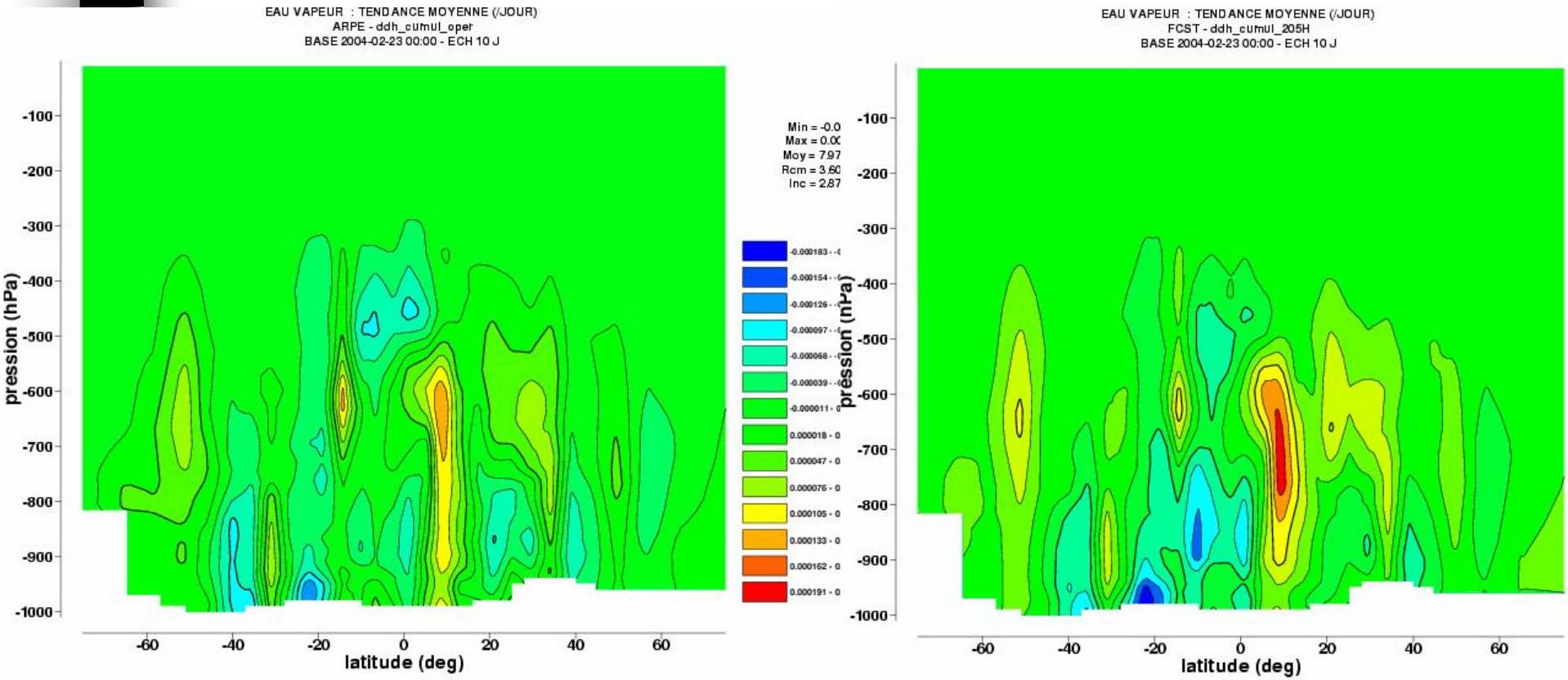


TEST

3D results (parameterised version, Part 1)

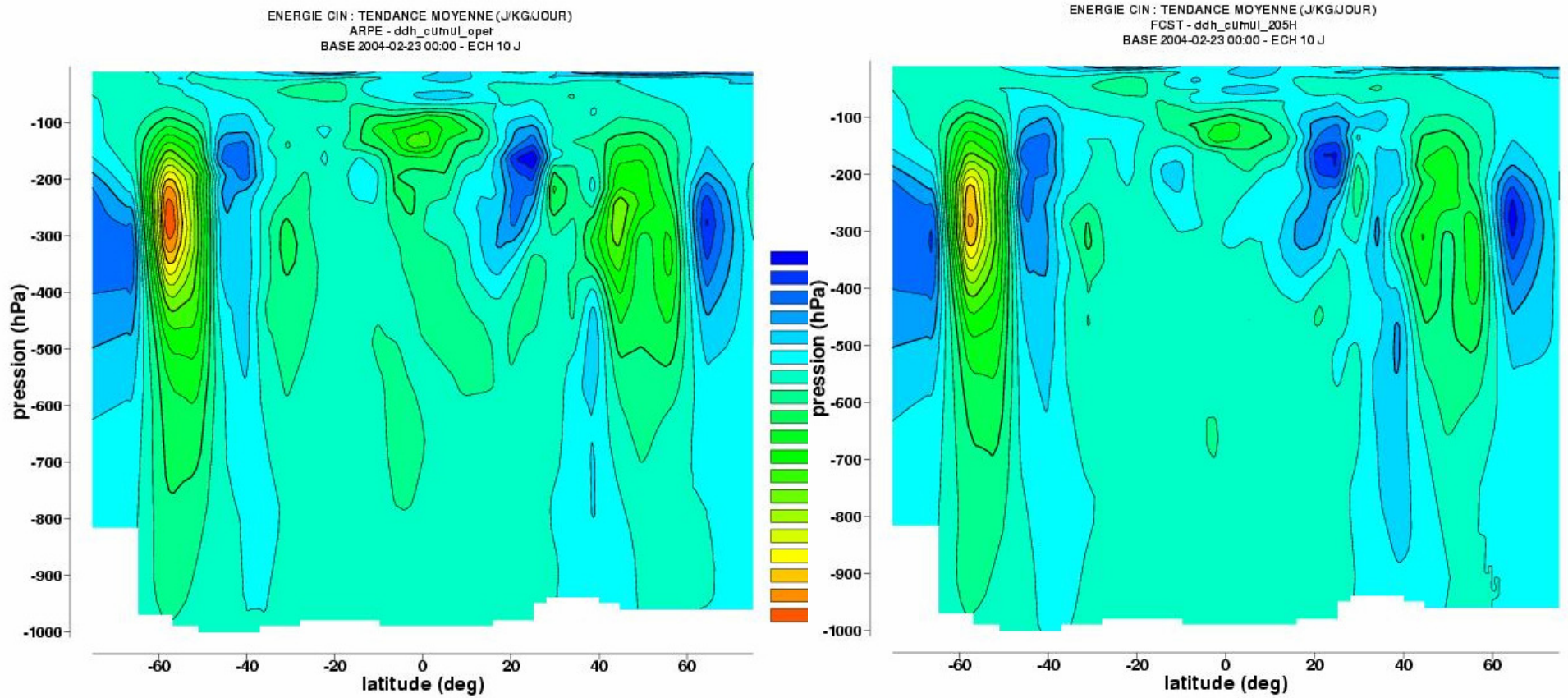
Specific humidity biases in zonal mean



OPER **TEST**

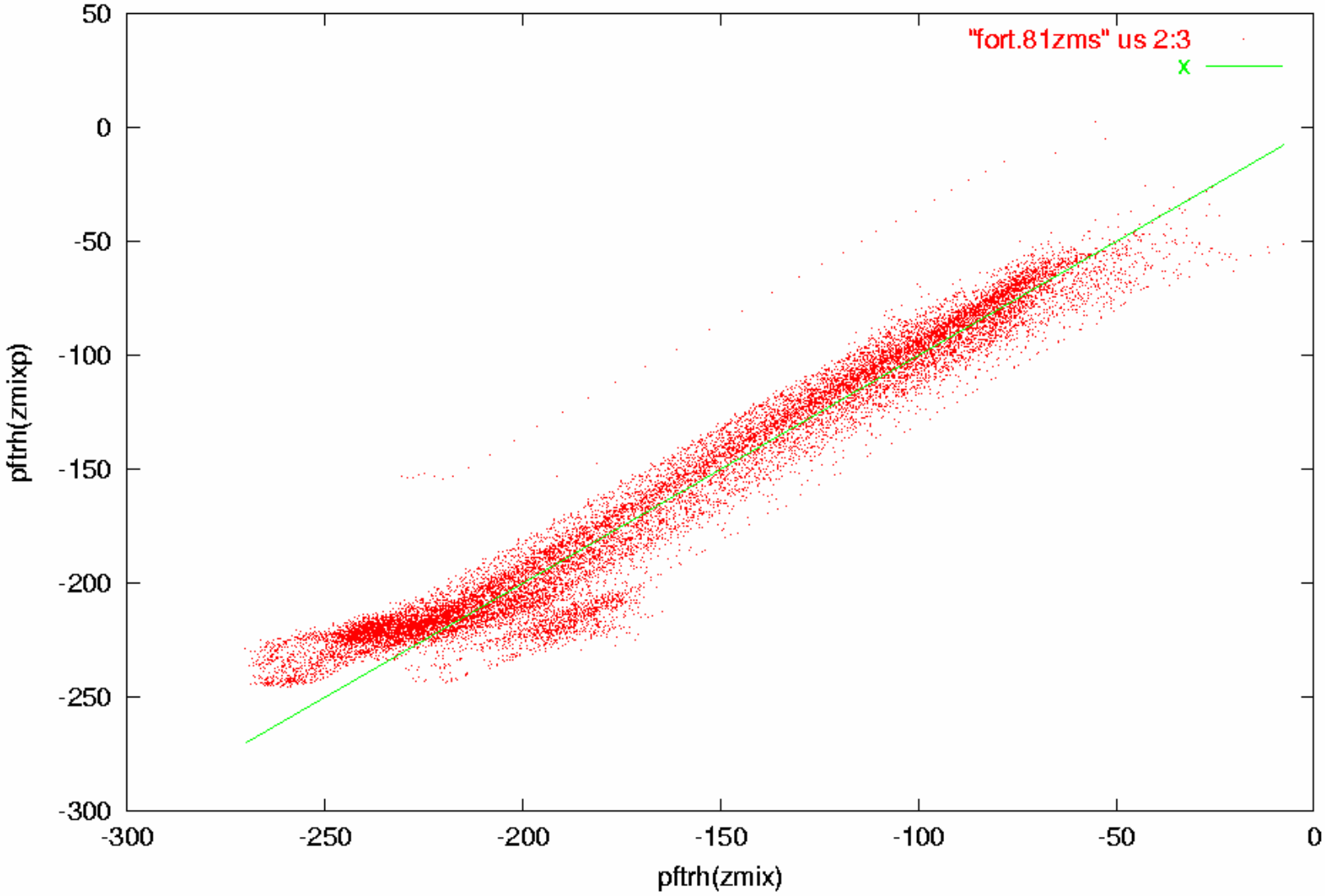
3D results (parameterised version, Part 1)

Kinetic energy biases in zonal mean

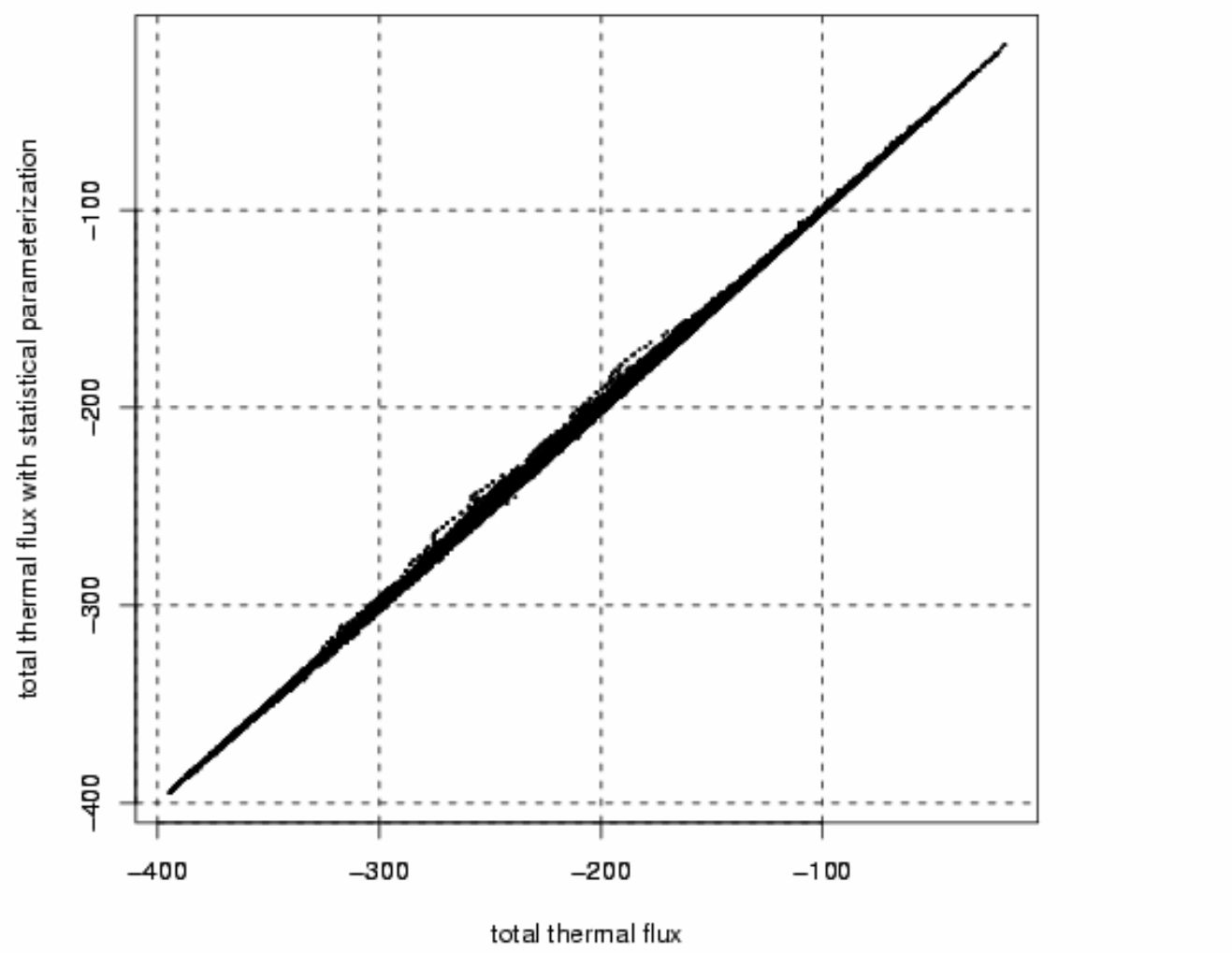


OPER **TEST**

Old results (parameterisation of α): dispersion diagram for total fluxes



New results (parameterisation of α): dispersion diagram for total fluxes (recent work by Neva Pristov)



Which difference(s) improves so dramatically the fit? (1/2)

- Correction of an ‘off-line’ bug: the previous statistical fits were done while still considering the part of the fluxes corresponding to the exchange between adjacent layers but used with the other choice (LRPROX=.T.) => now we have two sets of statistics and automatically use the right one.
- Differenciation of the influence of the static stability on α => it now varies with height.
- The fit to this profile and to the one of the ‘sigma-type’ dependency are more complex => there are now two APLPAR pre-computed profiles for the standard atmosphere.
- This fit includes a filter near both edges for the recommended case of ‘LRPROX’.

Which difference(s) improves so dramatically the fit? (2/2)

case of approximate treatment (`LRPROX=.FALSE.`) it sets:

$$\texttt{ZMAN(JLEV)} = 0.29 \tanh(2.0\sigma_j^*)$$
$$\texttt{ZMAK(JLEV)} = 0.07\sigma_j^{*1.5} + 0.14(1-\sigma_j^*)^{20}$$

For exact treatment (`LRPROX=.TRUE.`) tuning of `ZMAN` is different:

$$\texttt{ZMAN(JLEV)} = 0.14 \tanh(3.5\sigma_j^*)$$
$$\texttt{ZMAK(JLEV)} = 0.07\sigma_j^{*1.5} + 0.14(1-\sigma_j^*)^{20}$$

Moreover, in this case values `ZMAK` close to the edges of atmosphere must be pushed toward zero in order to prevent double accounting of 'local' effect:

```
IF ( LRPROX ) THEN
  DO JLEV = KTDIA, KTDIA+3
    ZMAK(JLEV) = ZMAK(JLEV) / 2**(KTDIA+4-JLEV)
  ENDDO
  DO JLEV = KLEV-4, KLEV-1
    ZMAK(JLEV) = ZMAK(JLEV) / 2**(5-KLEV+JLEV)
  ENDDO
ENDIF
```

Going back to the gaseous transmission functions

- In order to be a full ‘minimum-cost reference’, the ACRANEB computations (old and new) were extended to the Voigt line-profile (from the Lorenzian one) in order to cope with high model tops.
- Some work on more accurate transmission functions started in the contrasting direction of the RRTM ‘super multi-parameter abacus’ (because it is the rather expensive solution used in AROME).
- One will now see that there is probably room for a compromise between 1 and 140 spectral intervals!

Computation of optical depths for ACRANEB using the gaseous RRTM transmission functions

- **Purpose**: To use new kind of basic input for ACRANEB in order to
  - (a) help getting « exact » clear sky fluxes;
  - (b) get more accurate transmission functions (consistency with AROME & latest knowledge on gaseous amounts).
- The functions used in this example are taken from the RRTM database
- **Strategy**:
  1. To import RRTM transmission functions
  2. To evaluate their impact on ACRANEB
  3. To fit those functions to improve efficiency (if possible … although highly wishable !)

RRTM database for LW computations [10-3000 cm^{-1}]

- RRTM is using a correlated-*k* method or ESFT (Exponential Sum Fitting Technique), without accounting for scattering
- **Principle**: $\tau_r(u, p, T) = \sum_{i=1}^{N} w_i e^{-k_i u \left(P/P^*\right)^{ai} \left(T/T^*\right)^{bi}}$

1. For each layer and spectral sub-interval:

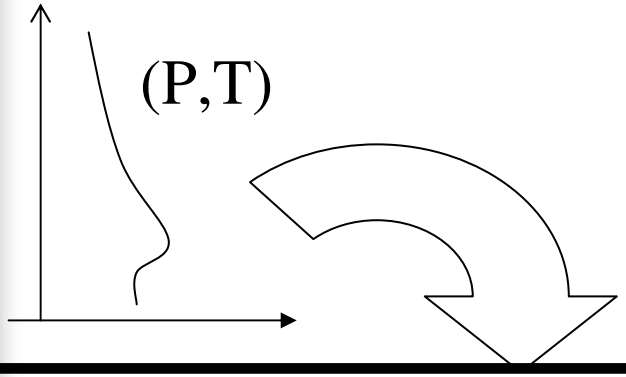
$$R_i^+ = R_i^0 + \left(B_i^{eff} - R_i^0\right).(1-\tau_i)$$

2. Then for each layer : $R^+ = \sum_i w_i R_i^+$

RRTM database for LW computations

- 16 spectral intervals, each one divided into sub-intervals (from 2 to 16)➔140 spectral sub-intervals.
- Absorbers: H2O, CO2, O3, CH4, N2O, CFC11, CFC12
- Ref: Mlawer et al. 1997
- Acraneb : 1 spectral interval, 3 absorbers (H2O, $CO2^{+}$, O3)

RRTM database for LW computations



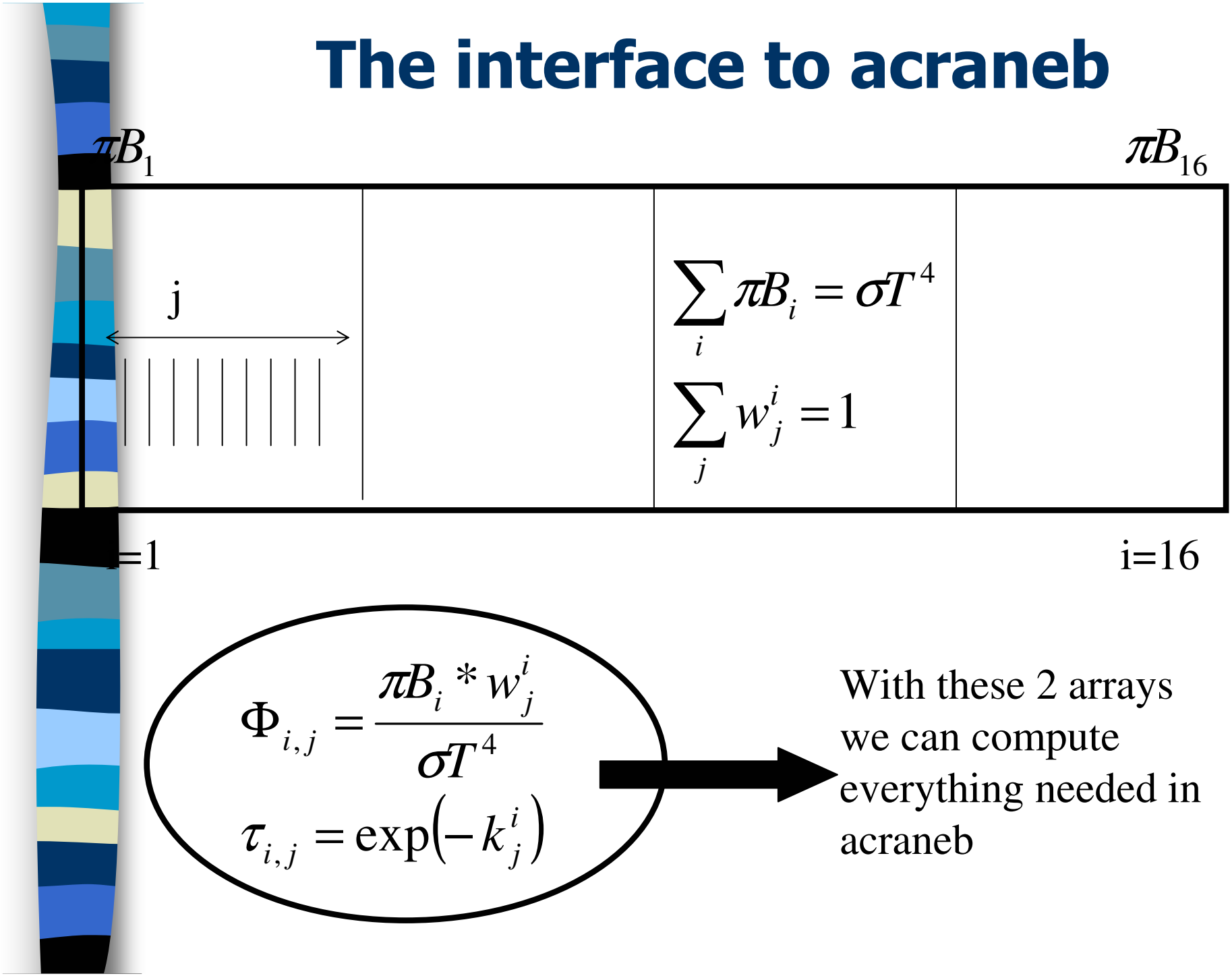
Tabulations of

59 P x 5 T x 140 i abs coeff & Planck fractions

4 points interpolations

140 ki & 140 weights of Planck function : $w_j^i \quad k_j^i$

The interface to acraneb

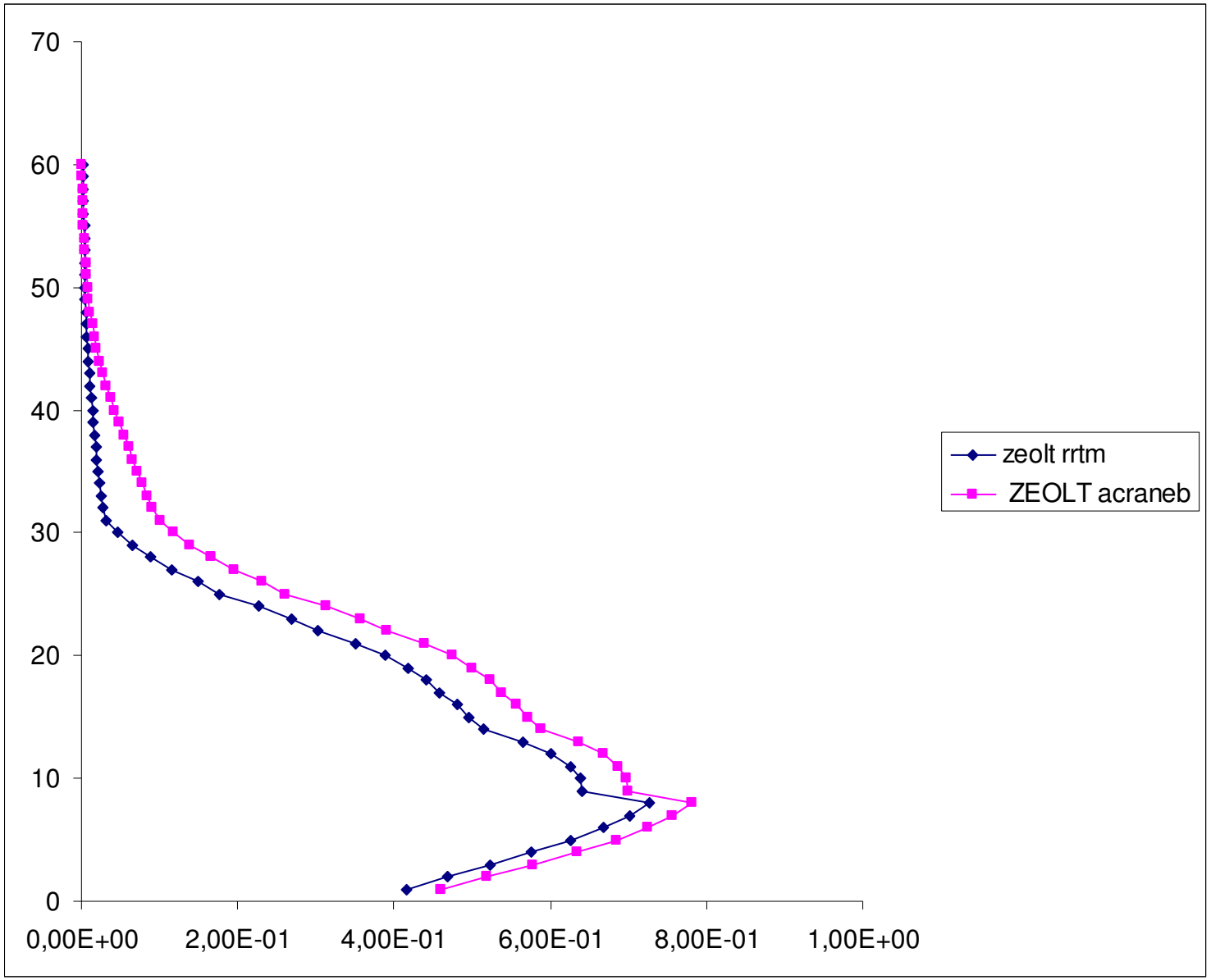


Evaluation of optical depths

- 1) For the local effect (EBL term)

$$e^{-\delta_l} = \sum_i \Phi_i^l \tau_i^l \longrightarrow \delta_l$$

l: vertical level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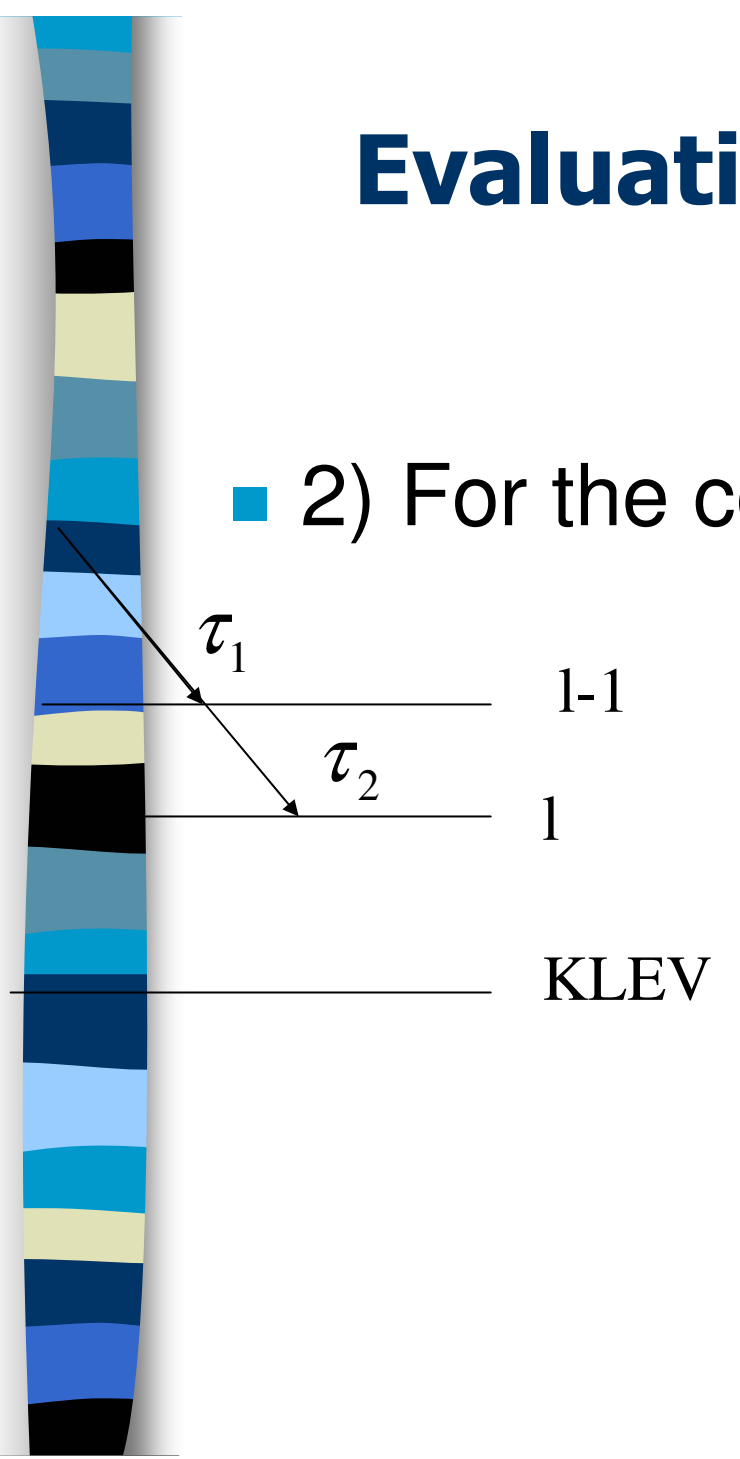
6,00E-01
8,00E-01
1,00E+00
zeolt rrtm
ZEOLT acraneb

Evaluation of optical depths

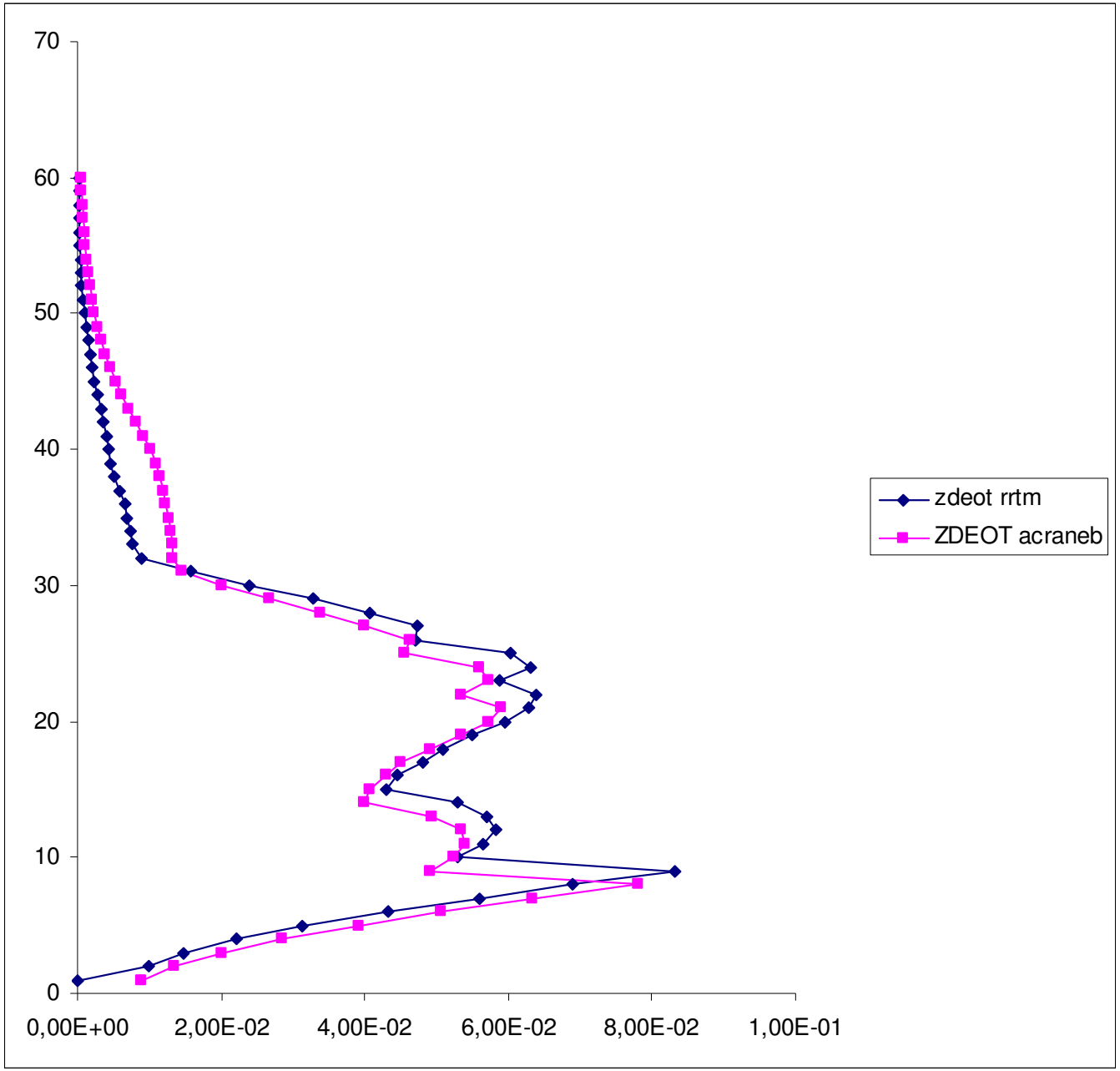
- 2) For the cooling to space (CTS term)



$$\tau_1 = \sum_i \Phi_i^{l-1} \prod_{k=0,l-1} \tau_i^k$$

$$\tau_2 = \sum_i \Phi_i^{l} \prod_{k=0,l} \tau_i^k$$

$$\delta_{CTS} = \ln \frac{[\ ]}{[\ ]}$$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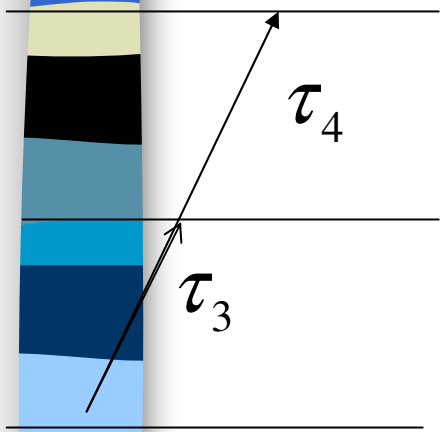
zdeot rrtm
ZDEOT acraneb

Evaluation of optical depths

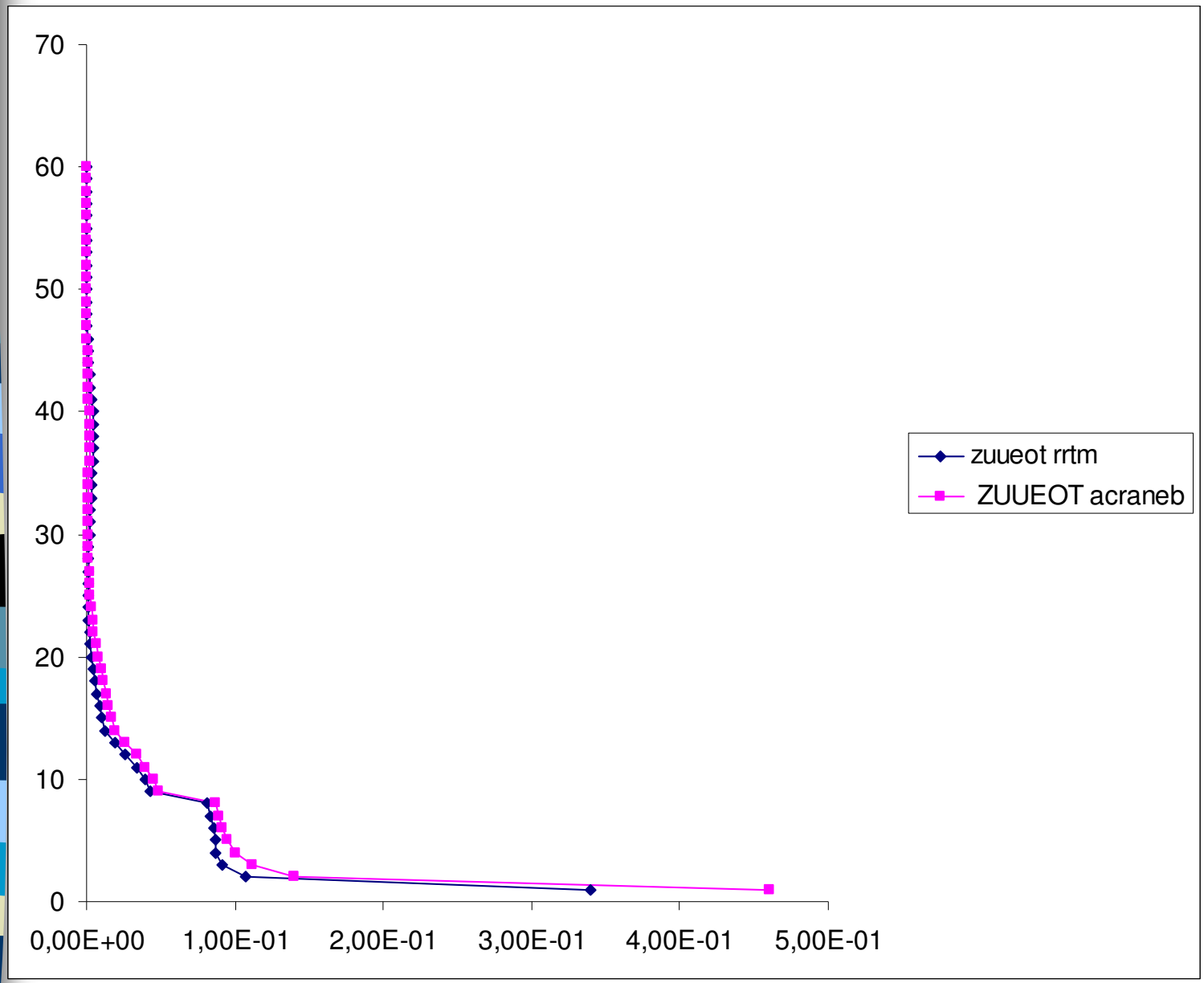
- 3) For the exchange with surface (EWS term)



$$\tau_3 = \sum_i \prod_{k=klev,l+1} \tau_i^k \left[\Phi_i^{l+1} \sigma T_{l+1}^4 - \Phi_i^{klev} \sigma T_{klev}^4 \right]$$

$$\tau_4 = \sum_i \prod_{k=klev,l} \tau_i^k \left[\Phi_i^{l} \sigma T_{l}^4 - \Phi_i^{klev} \sigma T_{klev}^4 \right]$$

$$\delta_{EWS} = \ln \frac{[\ ]}{[\ ]}$$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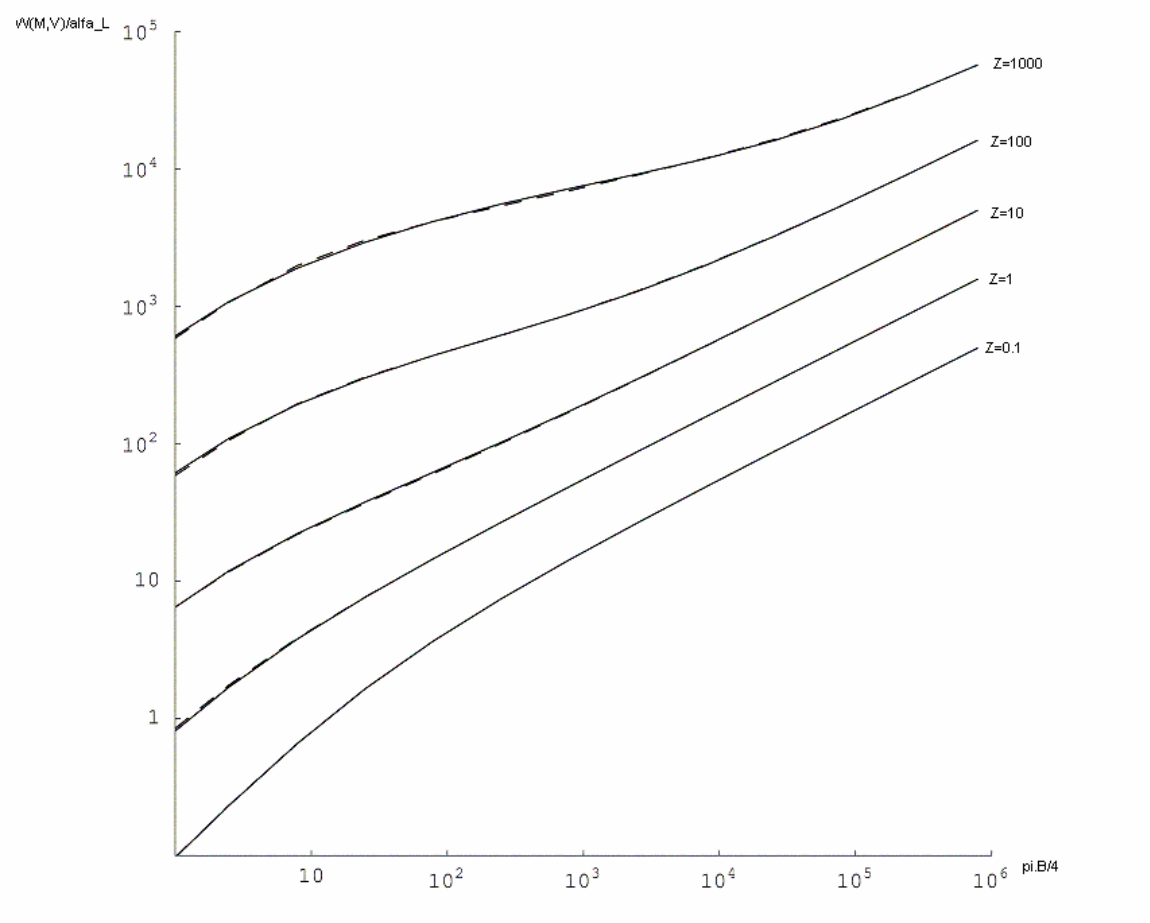
5,00E-01
zuueot rrtm
ZUUEOT acraneb

NER-related summary

- The NER method is particularly fruitful and well suited to the flexibility-modularity character sought for the ALARO-0 radiative computations.
- Combined to the strong points of ACRANEB, it offers two avenues of progress:
  - A set of basic improvements (at unchanged transmission functions), the main one being a ‘parameterisation’ of the interpolation weights between two ‘bracketing’ solutions;
  - Two ways (at least) of attacking the problem of intermittent radiative computations (balance: CPU ⇔ Memory).
- Surprisingly, the most difficult remaining task might well be to find the right level of complexity for a (NER oriented) accurate gaseous absorption evaluation, even if first ‘RRTM-like’ results are encouraging.

Addendum 1: cheap solution for putting the upper altitude Doppler broadening in ACRANEB



Simplified formula vs. exact numerical computation

Addendum 2: specific broad-band treatment of the cloud saturation effect (work of Jan Masek)

The heart of the problem: the saturation effect (1/2)

$$\alpha.e^{-k_1.u} + (1-\alpha).e^{-k_2.u} \neq e^{-\alpha.k_1.u-(1-\alpha).k_2.u}$$

- k1 and k2 may symbolically represent the maximum and minimum absorption (scattering) coefficients of a medium interfering with atmospheric radiative transfer; if they differ a lot, one sees the impossibility to meaningfully use a monochromatic approach for the whole spectrum.
- For gases, one can either use so-called ‘band-model’ or ‘k-distribution’ decompositions.
- In the second case there is no reason to do differently for ‘grey-bodies’ computations (clouds, aerosols, etc.).

The heart of the problem: the saturation effect (2/2)

- In the first case, it would be very penalising to use a k-distribution method for the (relatively) more linear of the two problems while avoiding it for the very complex gaseous one.
- The previous solution of ACRANEB used compromise average ***k*** values. This was ***not satisfactory*** because it amounts to neglect the so-called 'saturation effect', i.e.:
  * In wavelengths with a strong ***k***, radiation already absorbed somewhere is not any more available for being absorbed elsewhere;
  * In wavelengths with a weak ***k***, there is still room for absorption;

  $\Rightarrow$ ***the longer the absorption path, the smaller the average absorption coefficient should be!***

Aims of the study

- To parameterise the saturation effect, if possible for very broad band considerations (1 solar interval, 1 thermal one).
- To do it not level-by-level like in most models (FMR for instance), but cloud-by-cloud.
- To take into account the overlapping assumption (*LRNUMX=.T./.F.*) for this generalisation.
- To do the job for potentially mixed liquid/ice clouds (the total effect is more than the sum of the individual ones).
- *To use the occasion to also parameterise the impact of the cloud water density on the abs/scat coefficients (the denser the cloud => the bigger the particles => the lesser their relative impact, since it is proportional to the droplets' surface).*

Chosen strategy (parameterisation)

Loops over spectral intervals and layers

- (1) For each layer, to first compute an unscaled optical depth δ_0.
- (2) For each pair of layers (one being in the 'reference' role) to find a geometrical weight of the other one.
- (3) To compute δ_0_tot as the weighted sum of all δ_0 values in the atmosphere.
- (4) To compute $c\_abs = k\_abs/k\_abs\_0 = f_a(\delta\_0\_tot)$ and $c\_scat = k\_scat/k\_scat\_0 = f_s(\delta\_0\_tot)$ for liquid and ice (to be applied only to the 'reference' layer.

Chosen strategy (validation)

- One starts from the individual 'observed' narrow-band-model data of ***Stephens*** (for 7 water cloud types) and ***Röckel et al.*** (for 16 ice cloud types), courtesy of B. Ritter. The assymetry values were empirically rescaled, accounting for 'cloud-shape'.
- One builds a delta-two-stream multi-layer multi-spectral multi-component complex cloud model for diffuse radiation on the basis of these data. The broad-band dependencies upon the water density (**for step N°1**) are Pade-fitted here after spectral averaging. This 'calibration' model is used only for diffuse fluxes.
- In the case of the homogeneous uniform cloud, inverting the spectrally averaged transmissivity (a_4) and reflectivity (a_5) into synthetic ***k_abs*** and ***k_scat*** helps doing the fit necessary **for step N°4**.
- In the case of non-homogeneous and/or multi-layer non-uniform clouds, the validation occurs on scatter plots ('observed' vs. 'parameterised') for the a_4 and a_5 values.

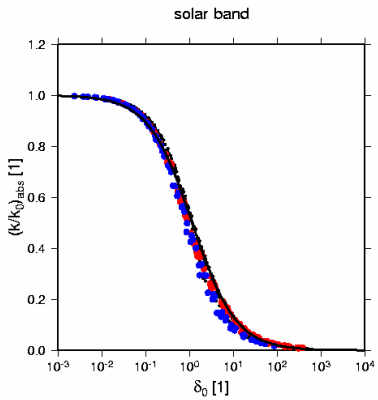
Central (unexpected) result

- **In the solar case, the dependency of c_abs and c_scat on the total optical depth hardly changes whether the cloud is liquid, ice or mixed, whether it is homogeneous or not, whether it is uniform or not !!!**
- In the thermal case, the situation is less clear-cut, but the dependency is sensitive only for optical depths that lead to quasi-black-body fluxes (also a saturation). **Hence the method remains OK.**
- The useful mathematical fit is simple:

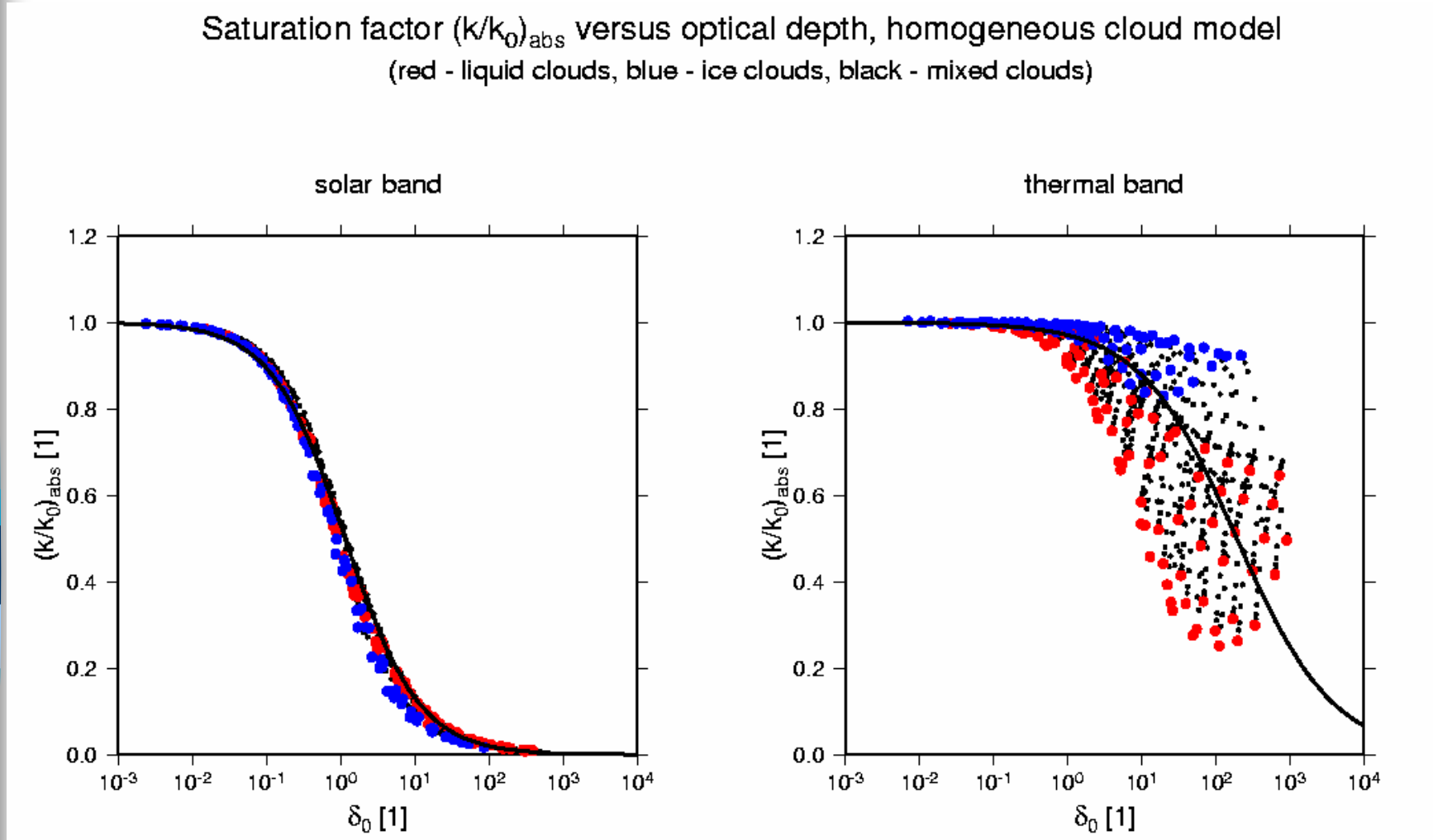
$$c = \frac{1}{1 + (\delta_0 / \delta_0^{crit})^{\nu}}$$

For abs/scat

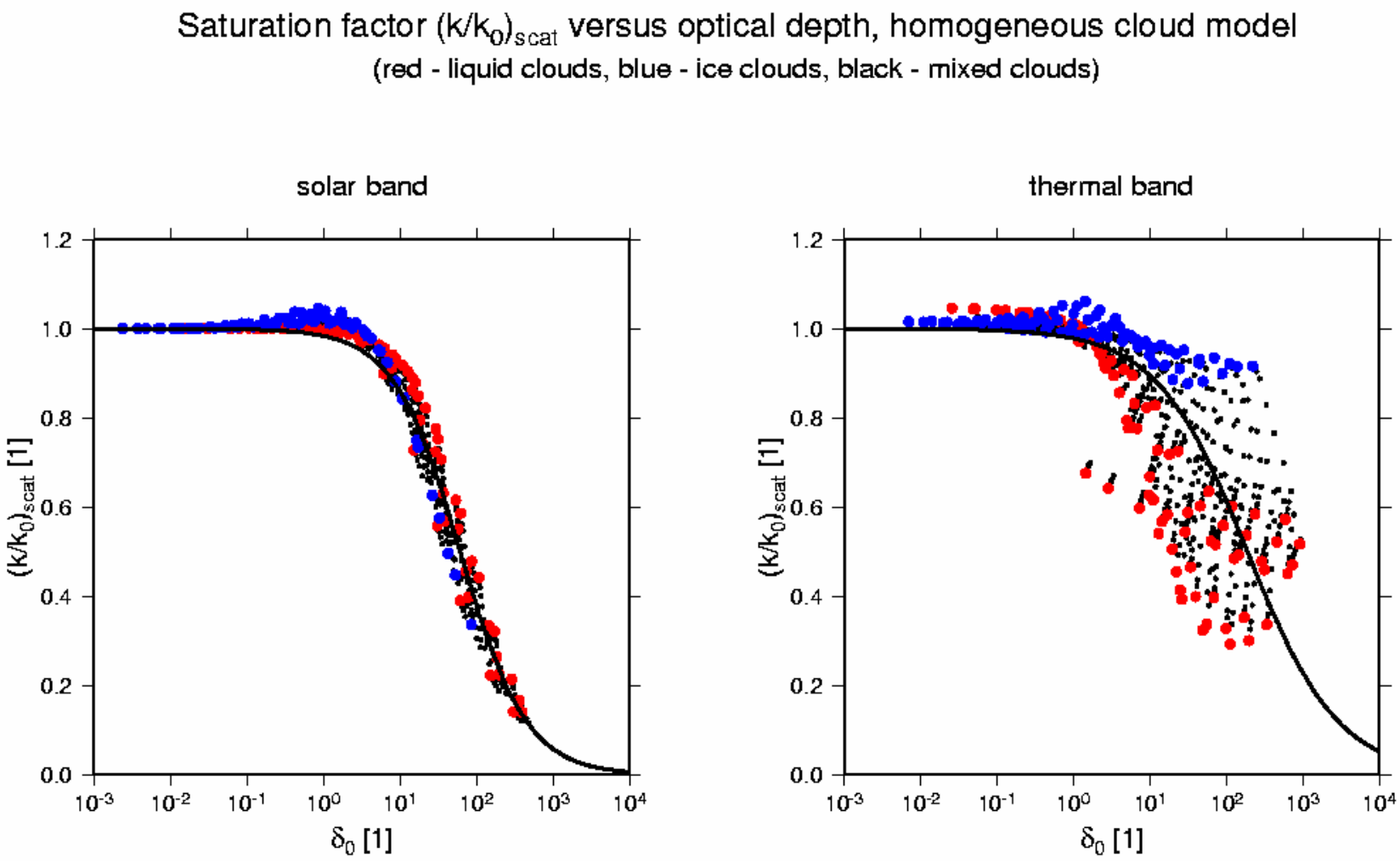
& solar/thermal



Results for the c(δ_0) fit (1/2)



Results for the c(δ_0) fit (2/2)



Special choices for the multi-level cloud geometry problem

The chosen solution for the weighting of distant clouds depend on the geometry choice:

- If LRNUMX=.F. => $f(n_j,n_k)=(n_k)^p$
- If LRNUMX=.T. => $f(n_j,n_k)=[min(1,n_k/n_j)]^p$

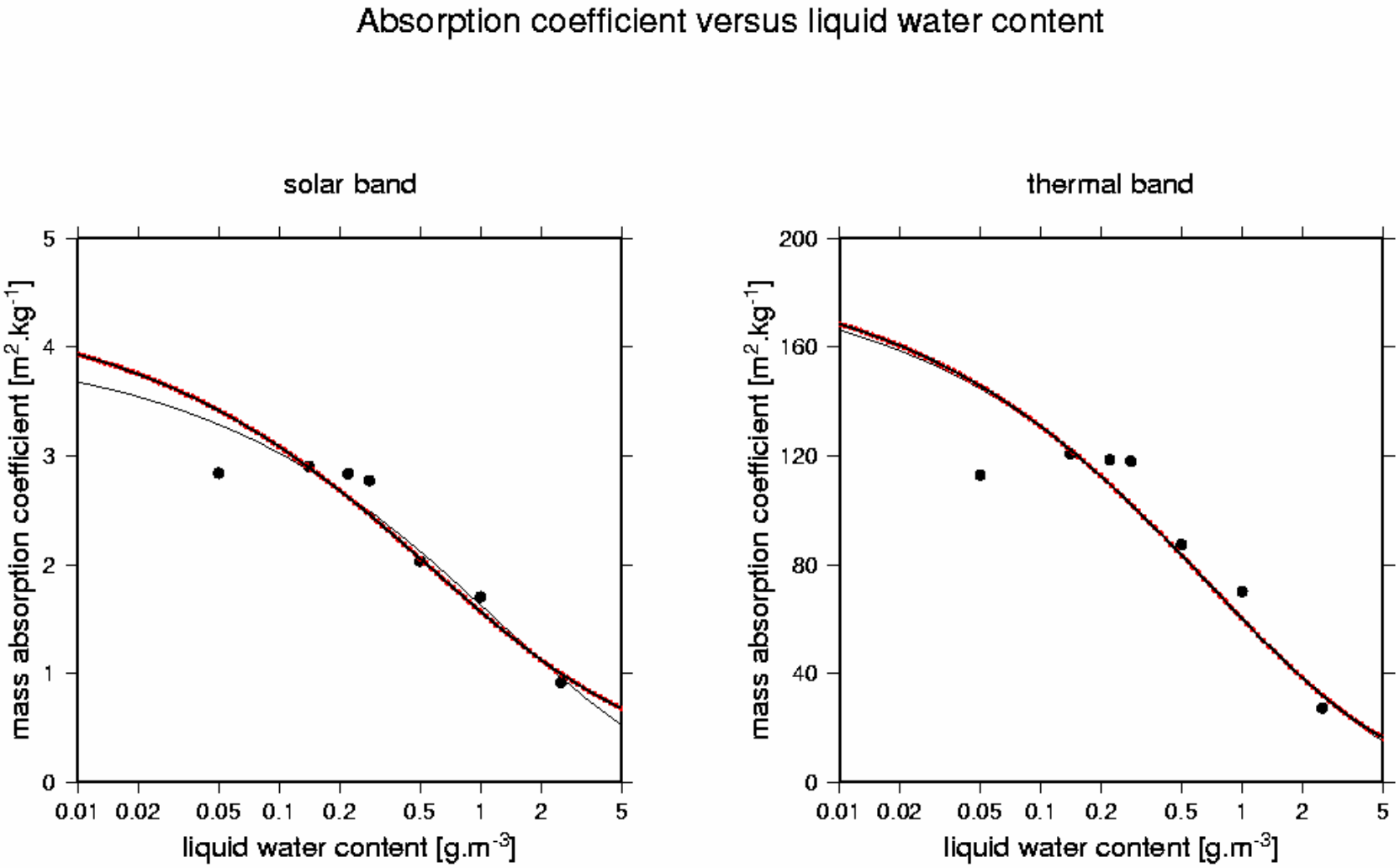
Special choices for the 'density fits'

- On the ensuing diagrams ***k(ρ)***, one gets:
  - Spectrally averaged individual 'cloud' values (7 - liquid=**dots**- or 16 -ice=**stars**- of them);
  - The direct fit of these points by a monotonic function (**thin continuous line**);
  - The result of the computation applied to a serial of fits at each wavelength (**red dots**);
  - The finally selected fit of the 'red dots' set (**thick continuous line**) by a function of the type:

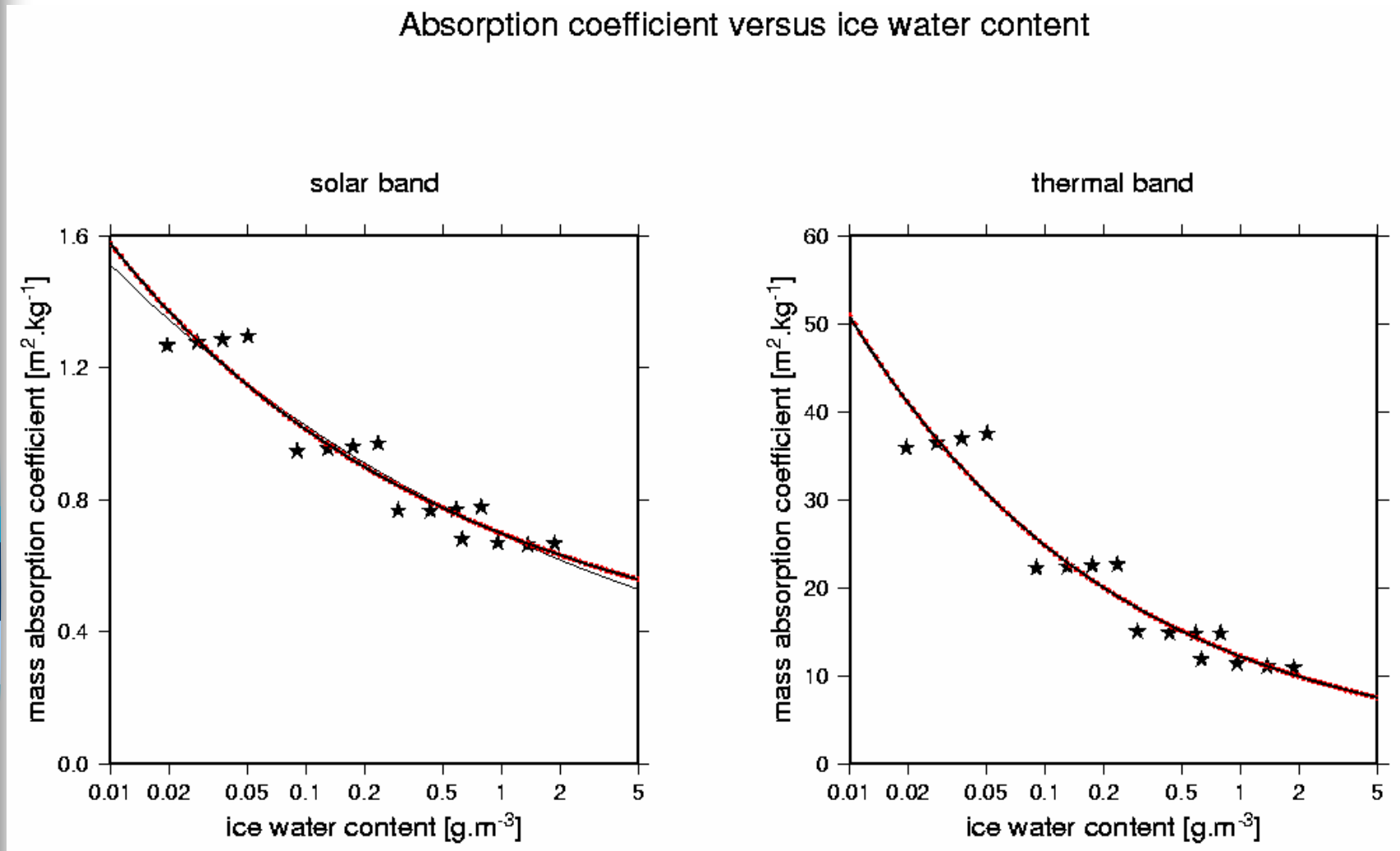
$$k = e^{-\frac{a_0 + a_1.\rho^{\mu} + a_2.\rho^{2\mu} + a_3.\rho^{3\mu}}{1 + b_1.\rho^{\mu} + b_2.\rho^{2\mu} + b_3.\rho^{3\mu}}}$$

- A similar procedure is applied for the density dependency of the asymmetry factor ***g*** (not shown).

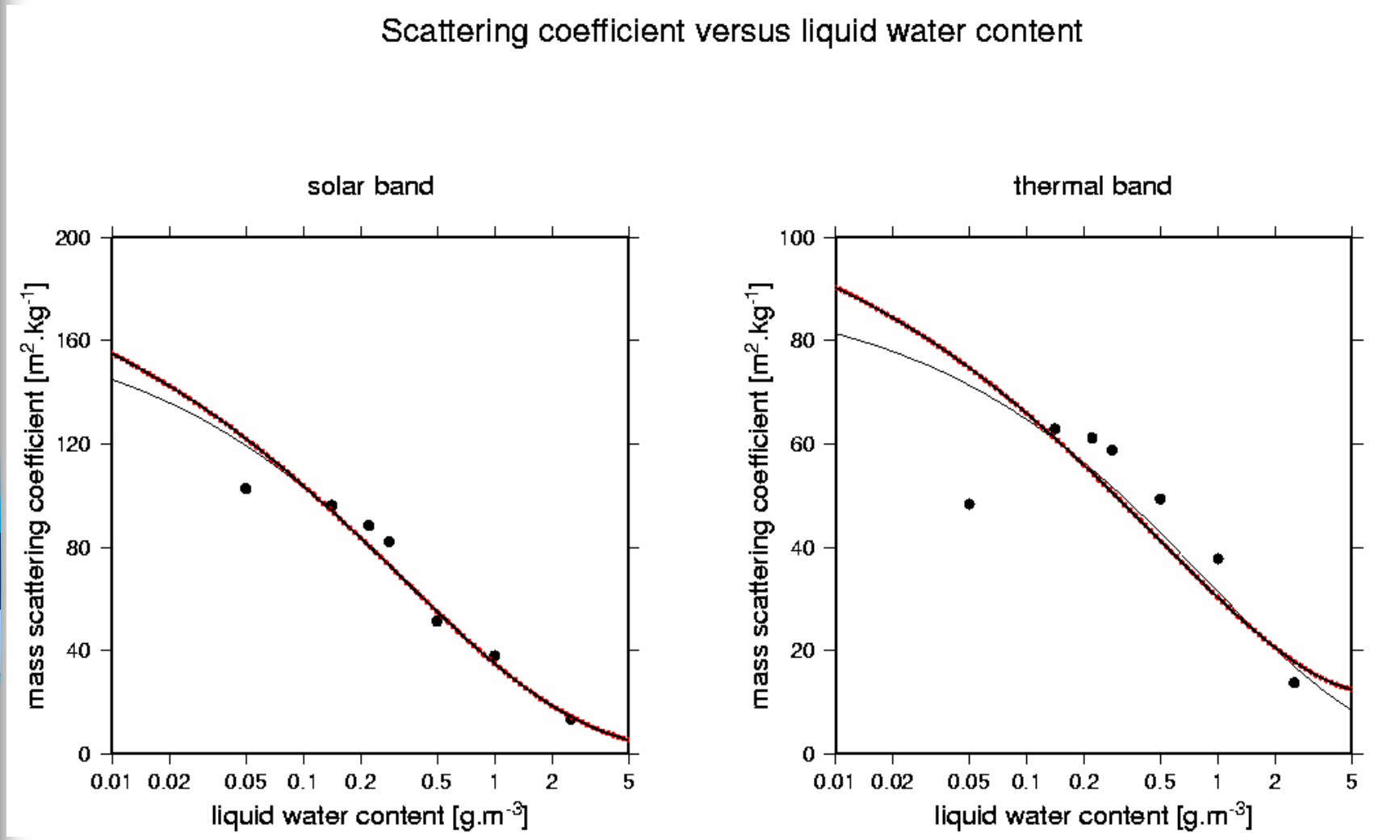
Results for the $k_{abs/scat}(\rho_{liq/ice})$ fit (1/4)



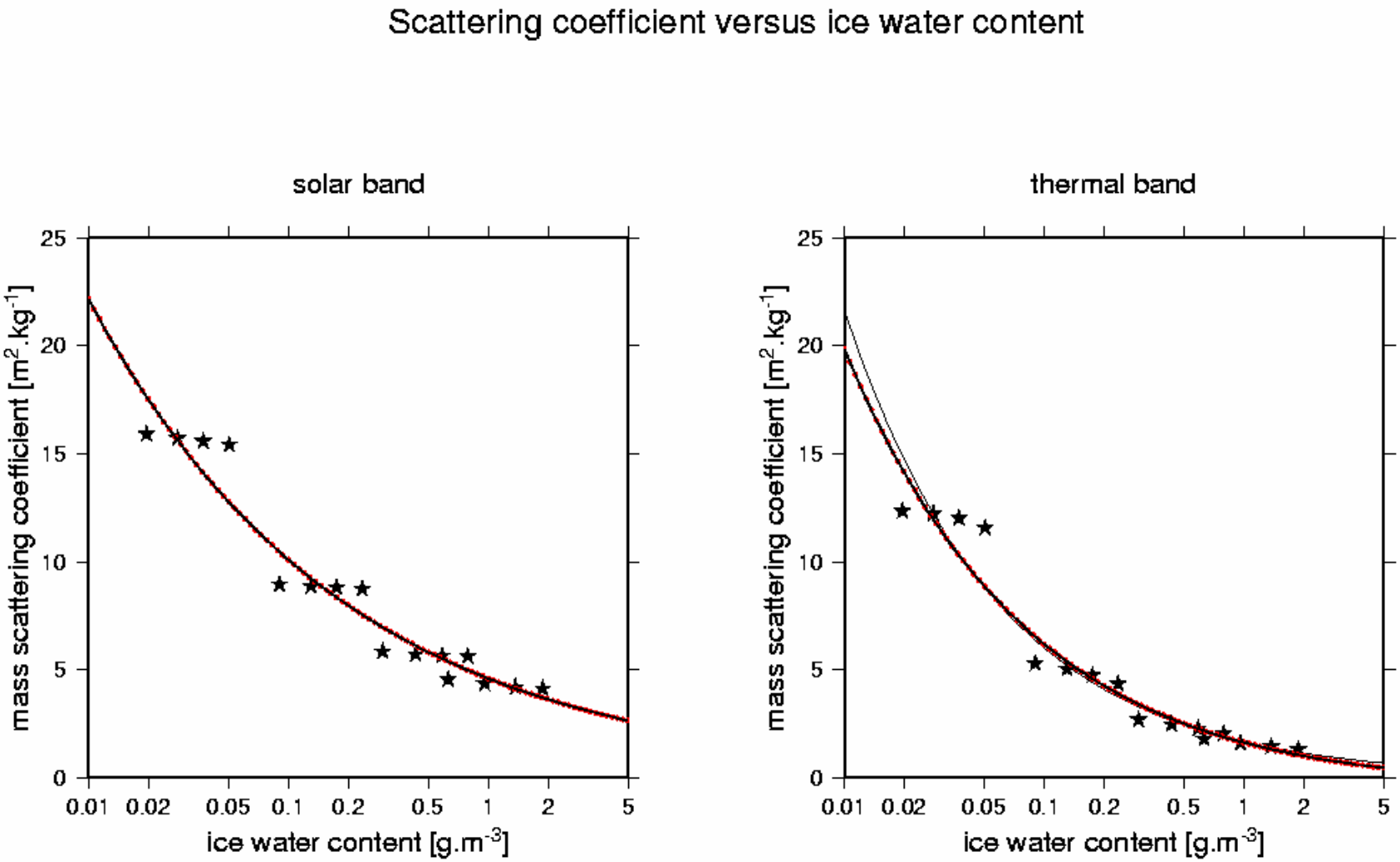
Results for the $k_{abs/scat}(\rho_{liq/ice})$ fit (2/4)



Results for the $k_{abs/scat}(\rho_{liq/ice})$ fit (3/4)



Results for the $k_{abs/scat}(\rho_{liq/ice})$ fit (4/4)



The solar path problem

- All what was said up to now works well for the thermal band and for the scattering in the solar band.
- For the absorption in the solar band one must take into account the asymmetry of propagation (the saturation in the higher clouds ‘masks’ the one in the lower clouds)
- The trick is to do the cloud summation only to the ‘reference level’ and to replace $c(\delta_0)$ by the expression $d[\delta_0 . c(\delta_0)]/d\ \delta_0$ (the reasons are a bit too complex to be explained here).

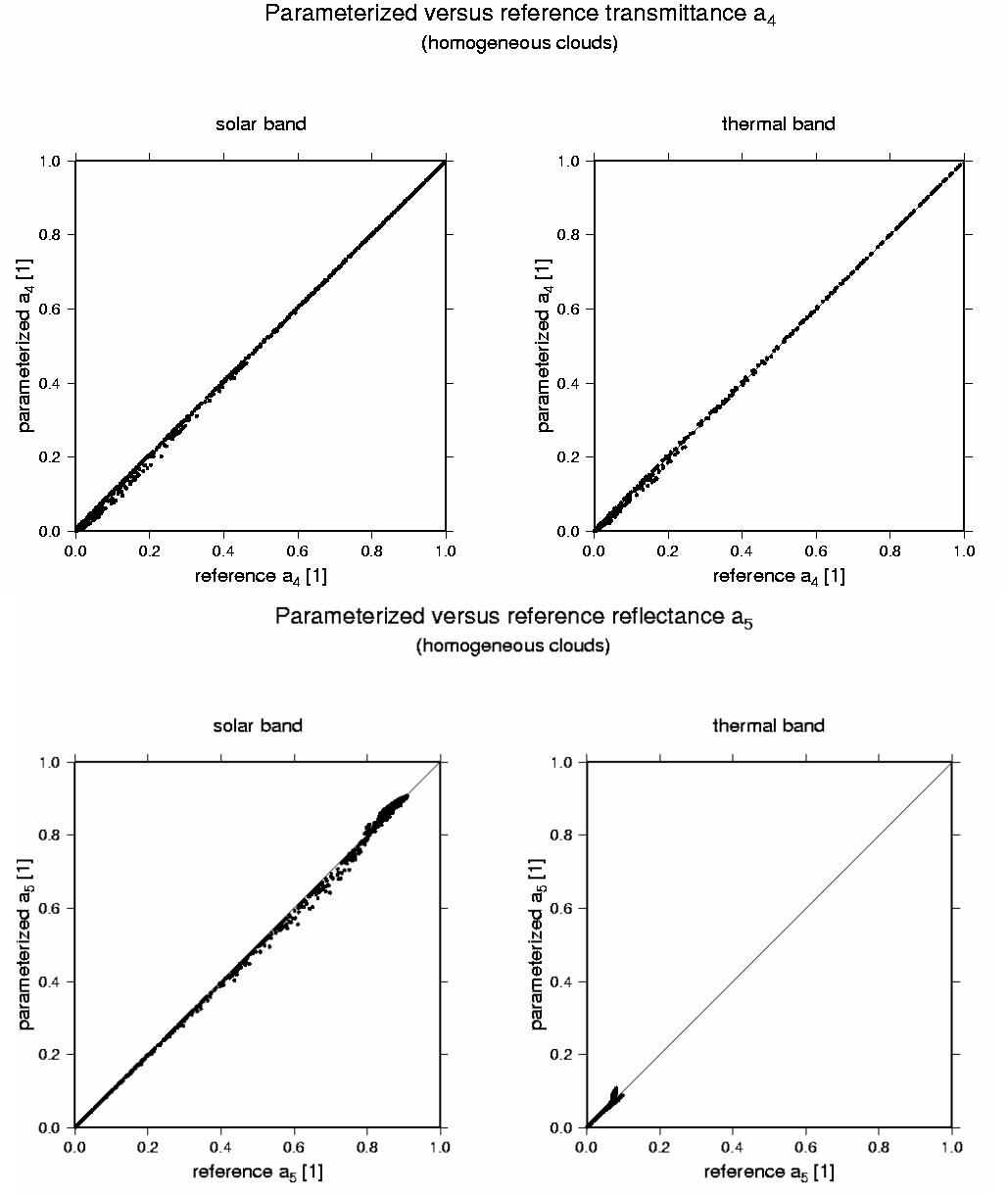
Synthesis

- We found, with a heuristic but rigorous method, a way to express the broadband cloudy optical properties as a kind of

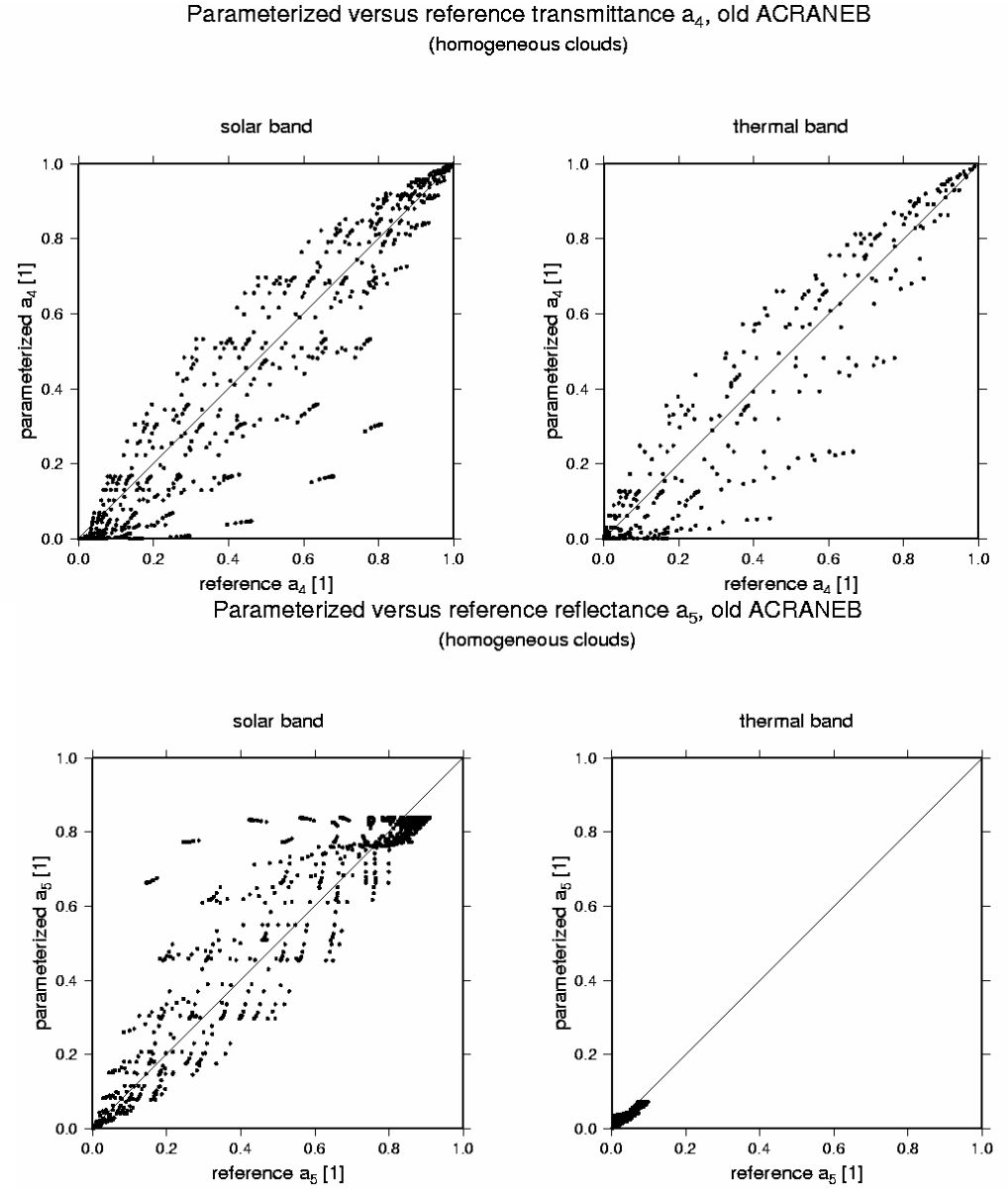
BAND MODEL (in the gaseous slang).

- The best way to validate this approach is to look at the final stand-alone products (***a4*** & ***a5***) for:
  - A homogeneous single cloud [2 plots: new/old];
  - The impact of non-homogeneity (3 layers);
  - The impact of non-uniformity (3 layers).

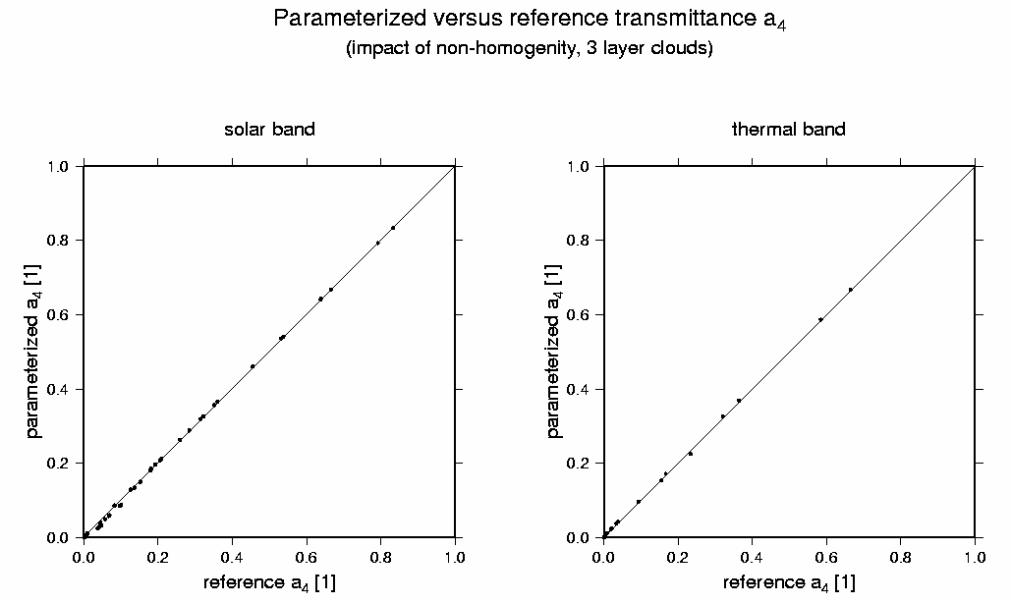
Scatter plots for transmissivities and reflectivities (1a/3)

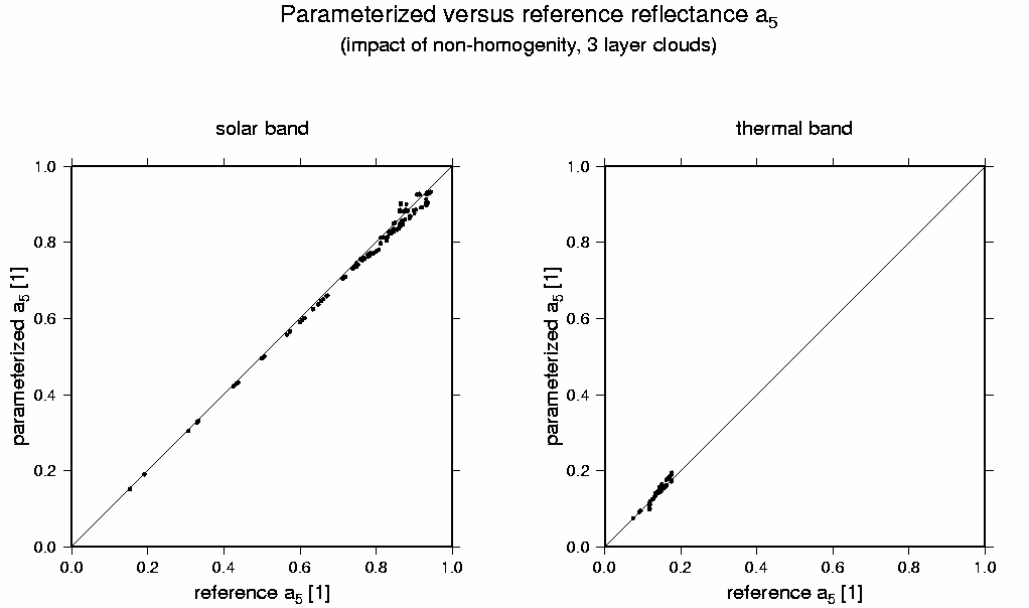


The same plots for the current code, still for a single cloud (1b/3)

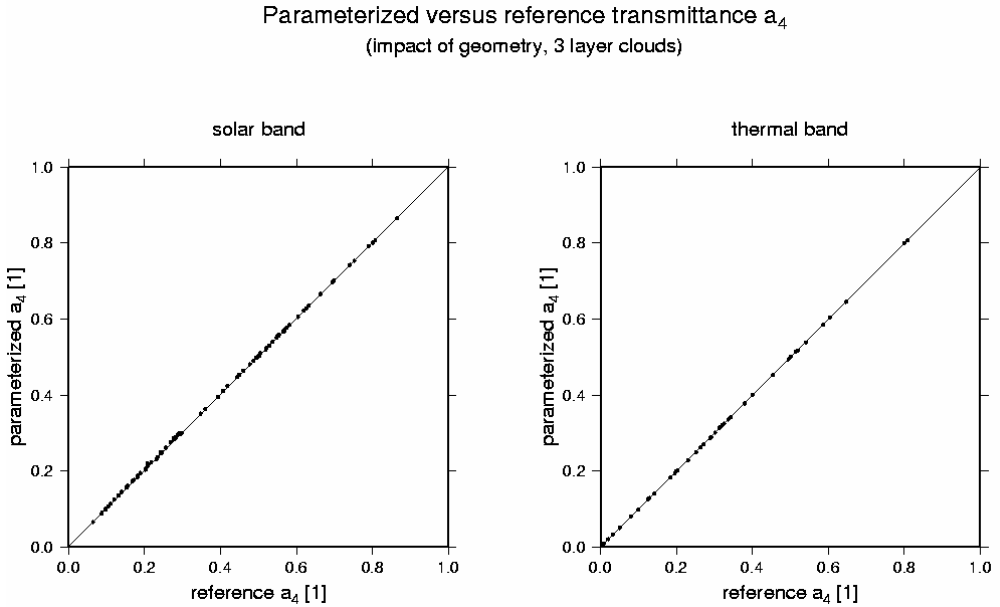


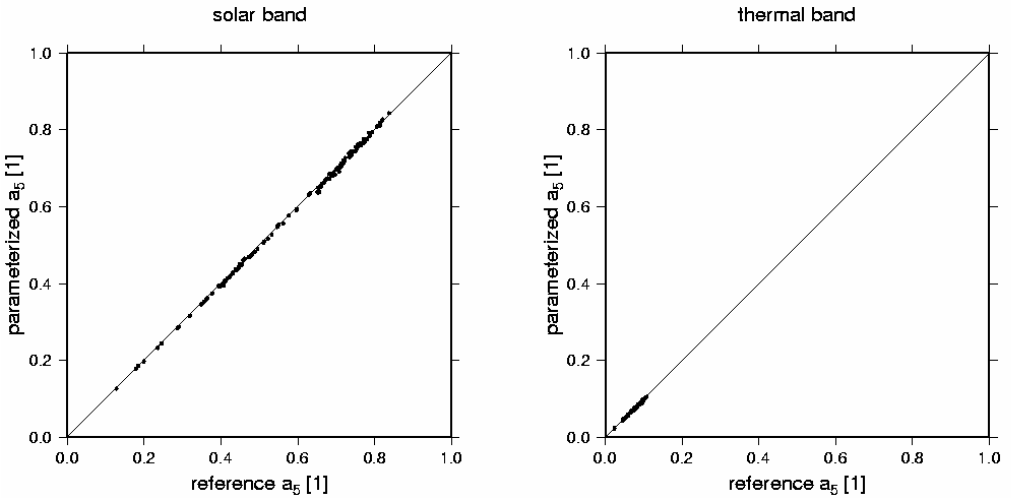
Scatter plots for transmissivities and reflectivities (2/3)





Scatter plots for transmissivities and reflectivities (3/3)





Conclusion (for the cloud part)

- The initial goal is reached. We had to compromise on the basic data and on the homogeneity in the case of solar absorption.
- There was a quite interesting discovery made along the path to it (***a relative saturation depending only on a total optical depth gives very accurate results***).
- Consequences:
  - The more precise model is ‘relatively’ cheap;
  - The ‘broad-band’ strategy for grey effects is perfectly acceptable and this helps not precluding what to use for the gaseous effects.

General conclusion

- There remain a lot to be done on radiation in ALARO-0 and post-ALARO-0.
- The workplan issue is complicated because we have converging but independent paths towards a long-term goal:
  - Modularisation of the code;
  - Improvement of gaseous transmission functions;
  - Work in the direction of ‘new’ intermittency;
  - Better aerosol model;
  - Intermediate price for the Voigt extension;
  - Improving the ‘multi-cloud’ aspect of the ‘cloud-band-model’.
- Coordination necessary, but between which workforces?