UPDATE ON THE PROPOSAL FOR A NEW CONCEPT IN RADIATIVE COMPUTATIONS FOR NWP

Jean-François GELEYN, Gwenaelle HELLO and Neva PRISTOV

(*with many thanks to Richard Fournier* (Laboratoire d'Energétique, Université Paul Sabatier, Toulouse), *Yves Bouteloup and Maria Derkova*)

The problem

- 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 (bis)

- 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, **2004**: Longwave radiative analysis of cloudy scattering atmospheres using a Net Exchange Formulation. Accepted in Atmospheric Research.
- Hourdin, C., J.-L. Dufresnes, R. Fournier, F. Hourdin, **2005**: Net exchange reformulation of radiative transfer in the CO_2 15μm band on Mars. In preparation.

Heating from ground · Exchanges with layer · Cooling to space

Exchange Matrix (K/day)

Temperature Profile (K) · 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

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.

A new way to look at radiative calculations in NWP

- **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

- **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 in principle be space for a consensus.

The question of the vertical temperature profile

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 NEP 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

In the following, one will work with three different profiles:

- $\Pi B = 1$ at the ground and everywhere in the atmosphere => allows to suppress all other exchanges than 'cooling to space' (CTS) – Profile A

- $\Pi B = 1$ at the ground et $\Pi B = 0$ 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

CTS+EWS+EBL decomposition of the thermal radiative exchange terms in absence of scattering

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

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

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

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

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

$$\text{EBL}$$

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

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

EWS

EBL

CTS
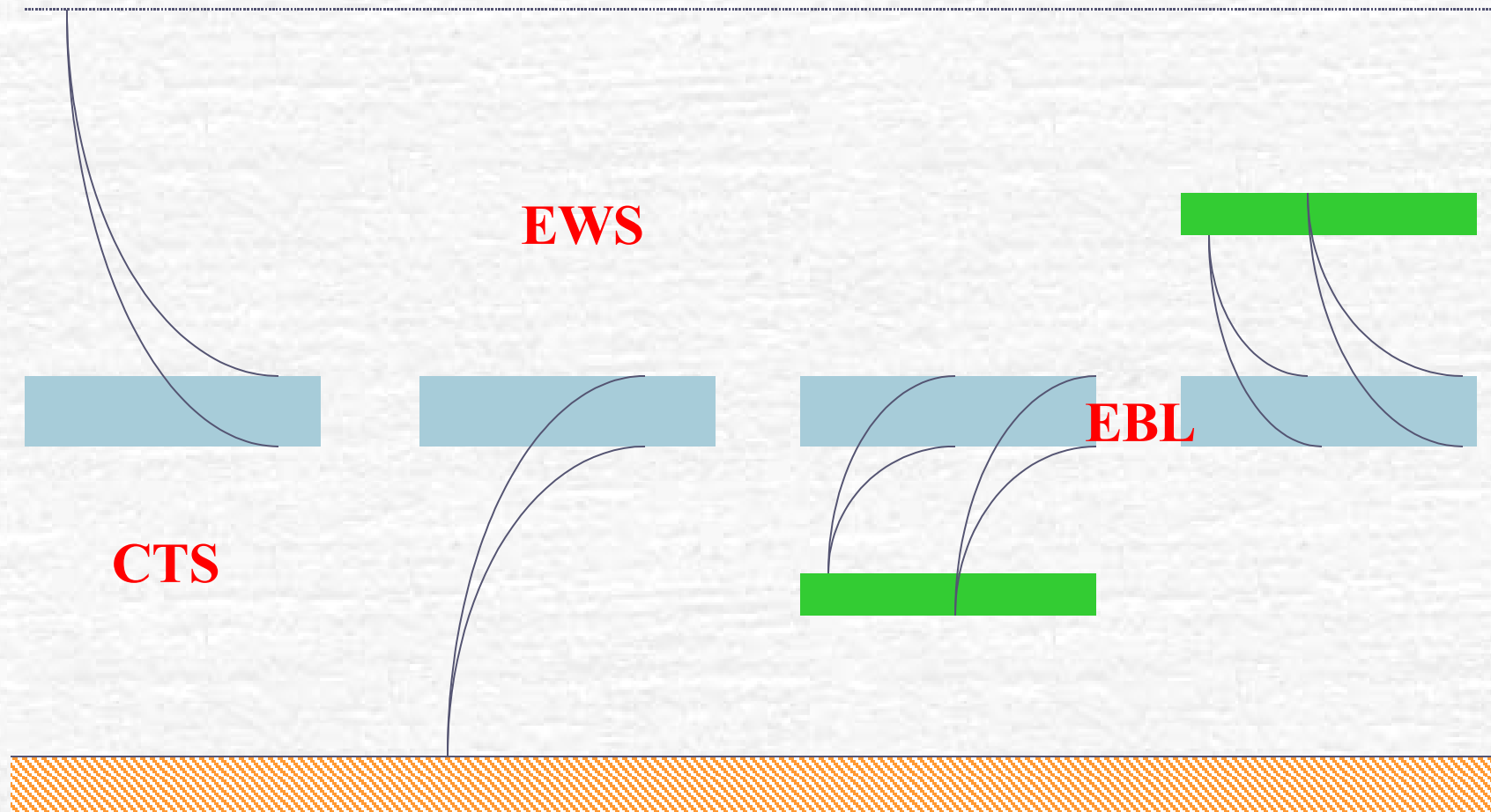
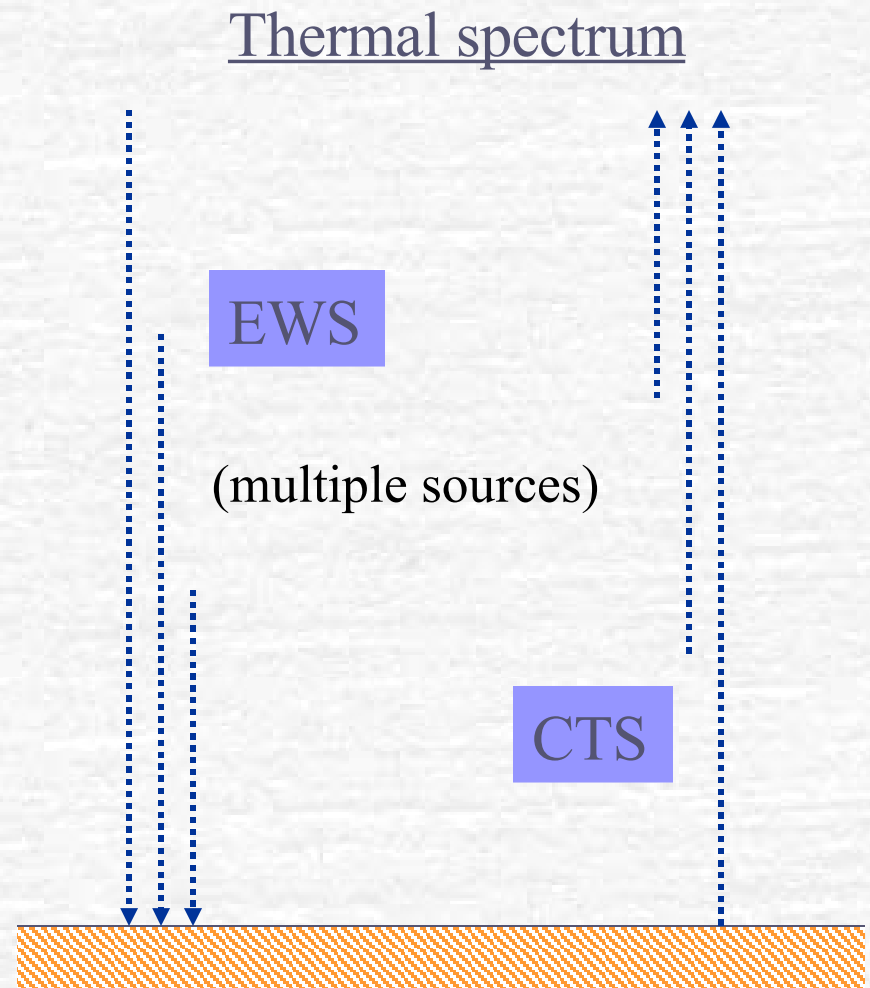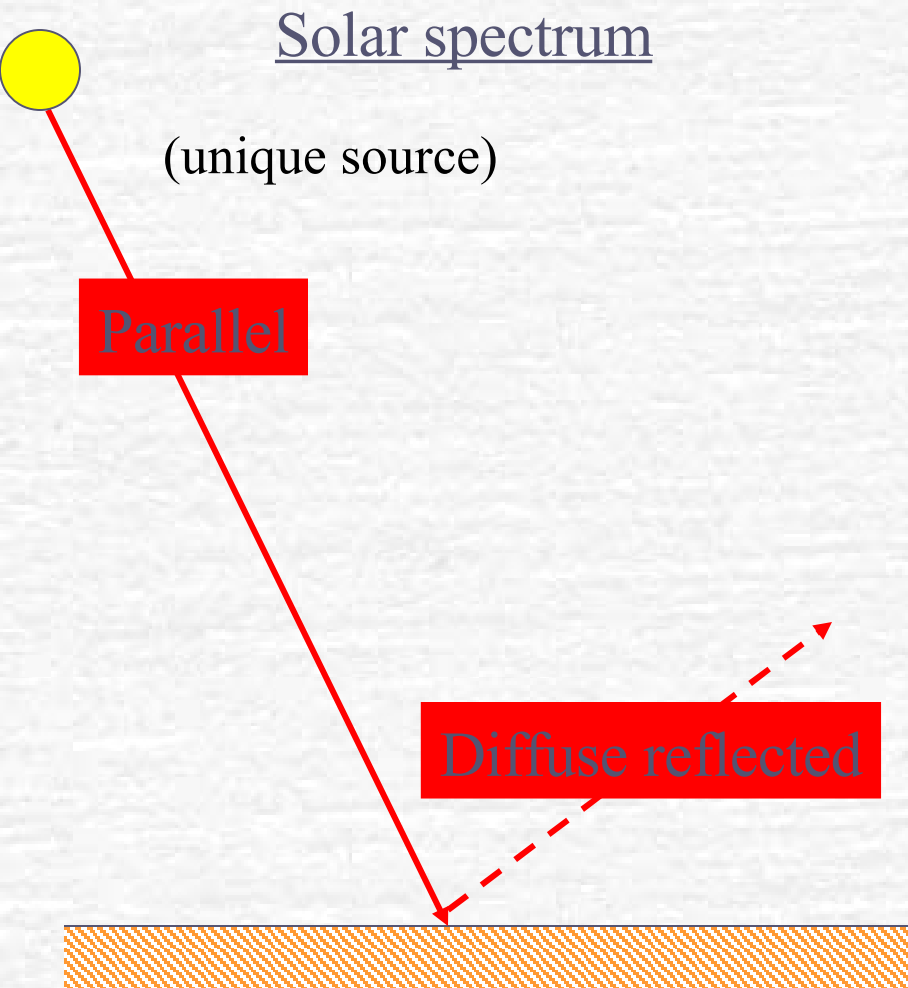# What about the interaction with scattering?

(ACRANEB) method of idealised optical paths (A)

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↓ and F↑ 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

Solar spectrum

Thermal spectrum

(unique source)

Parallel

Diffuse reflected

EWS

(multiple sources)

CTS

(ACRANEB) method of idealised optical paths (B)

For this multiple sources' problem, the trick used here is 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 gets thus assigned, for the sole «EBL» calculation,

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 !!!

surface. One therefore simply does the approximation (rather «daring» but very economical):

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

(ACRANEB) method of idealised optical paths (C)

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.

Initial proposal

Complete comput. in clear sky

Comlete comput. in clear sky

To 'import' (large choice)

N δt

Exists !

Flux ↑&↓ LW & SW

Inversion

etc.

GMAP – ALADIN2

ACRANEB 2nd part

Fluxes of the time-step

δopt gaz (4 x)

Model of δopt Clouds + Aerosols

Méso-NH ?

δt model

For the AROME case; else, who wants …
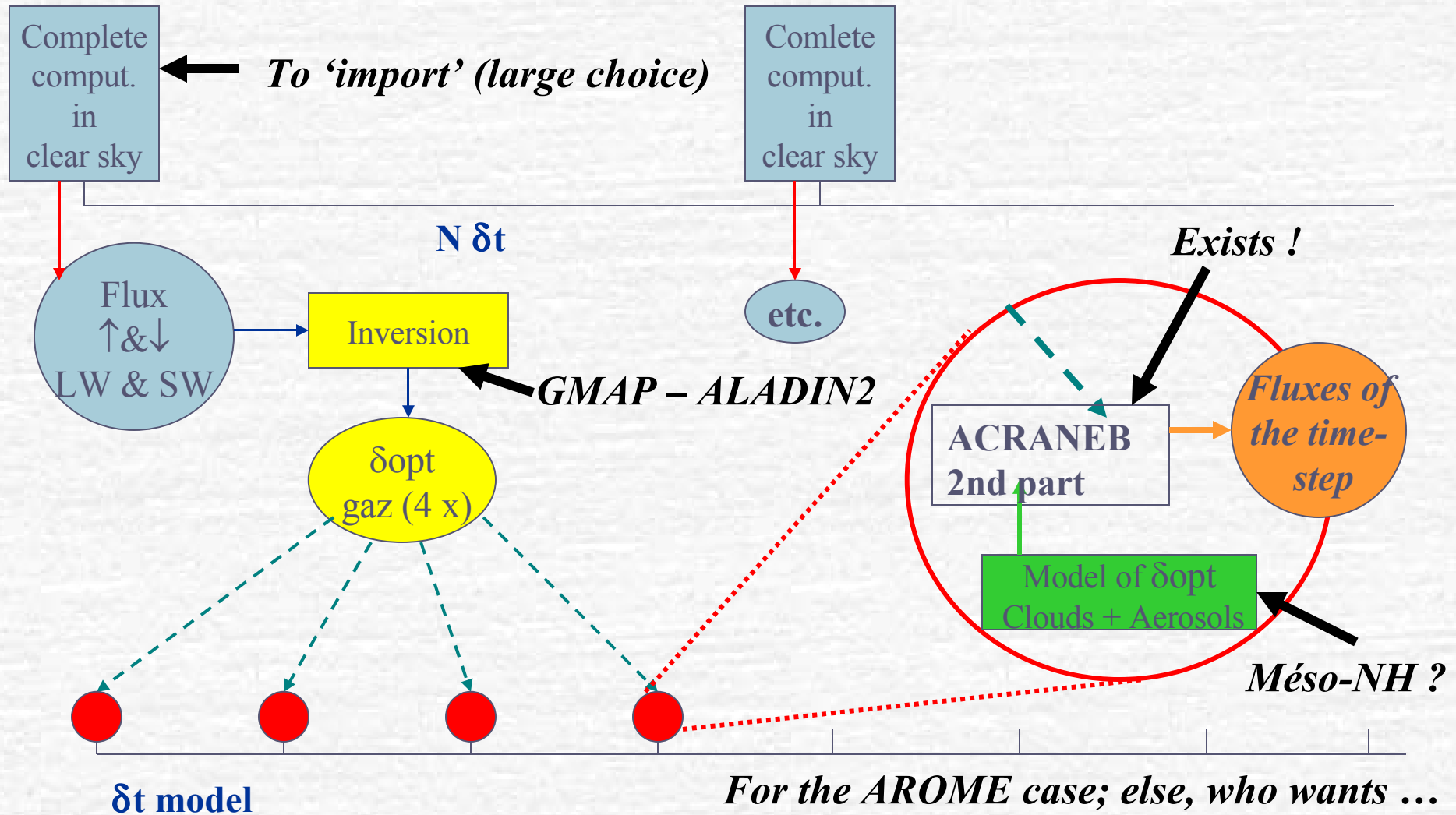
Modifications suggested by Richard Fournier

- 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_new*)

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] − α.([III]+[IV]-[V]) - (1-α).([VI]+[VII]-[VIII]) + [γ]

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 first 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).

Modified proposal (extreme case with 8 fields to store)

Complete comput. in clear sky

To 'import / reframe'

Complete comput. in clear sky

Exists !

N δt

Flux ↑&↓ LW & SW

'Interpolation'

Done (ALADIN2)

etc.

ACRANEB-8 2nd part

Fluxes of the time-step

δopt, α, γ gaz (8 x)

Model of δopt Clouds + Aerosols

????????

δt modèle

For the ALARO case ; else, who wants …
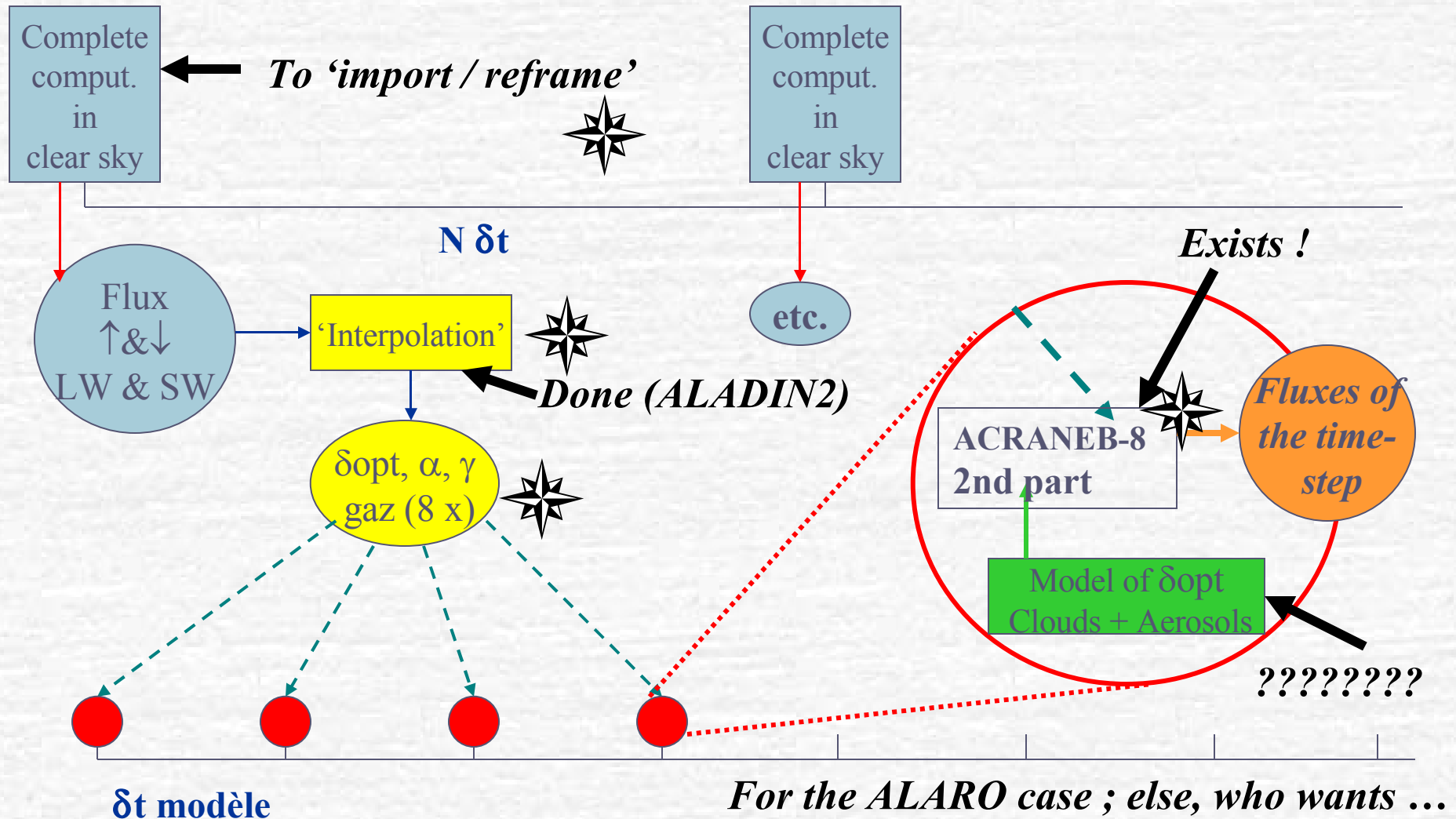
Advantages of the proposal

- It relies on well-proven approximations.

- It follows the simplifying principle of constant gaseous optical depths for $N.\delta t$.

- 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.
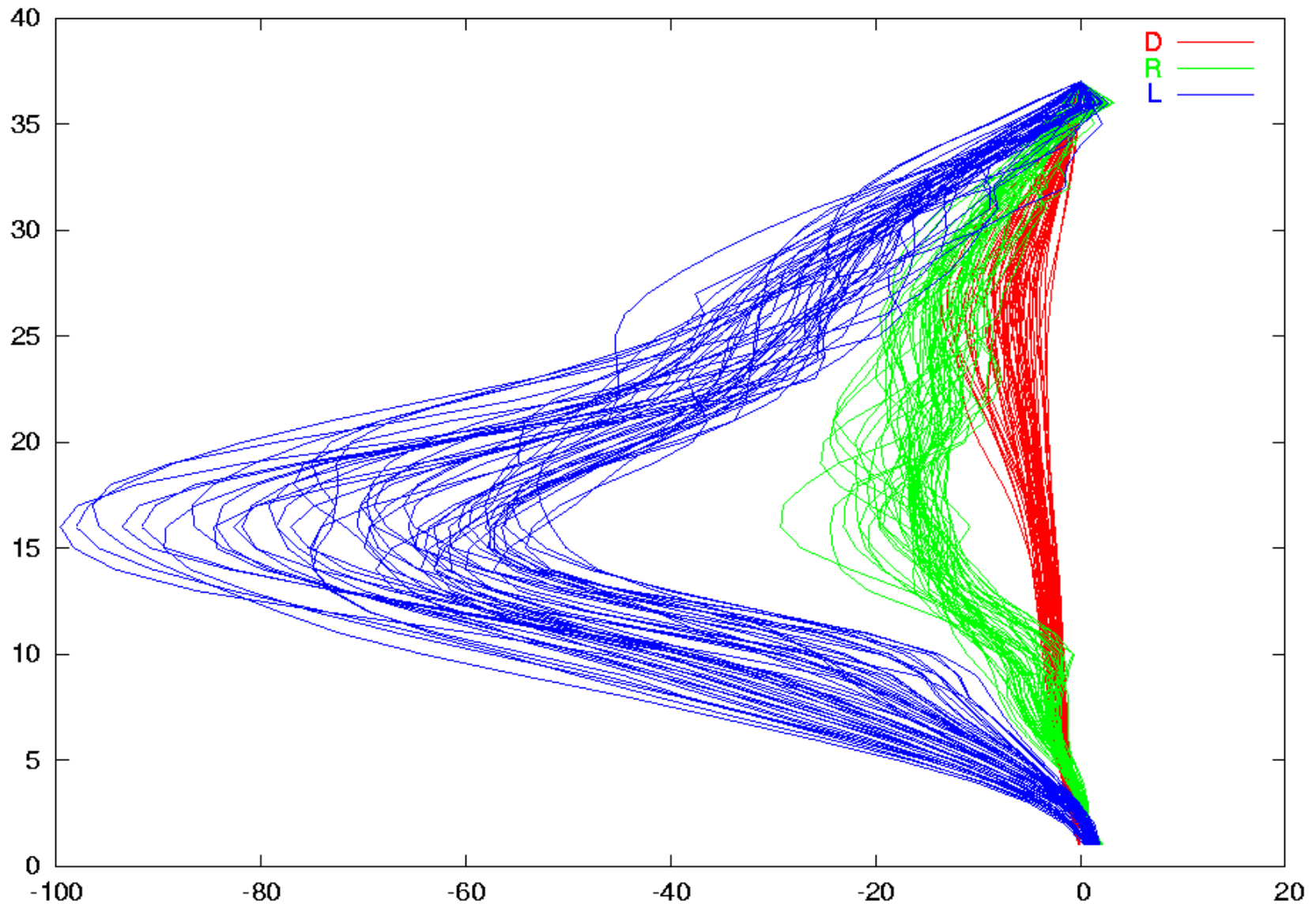
First results (parameterisation of α): fit to pressure/surf. pressure
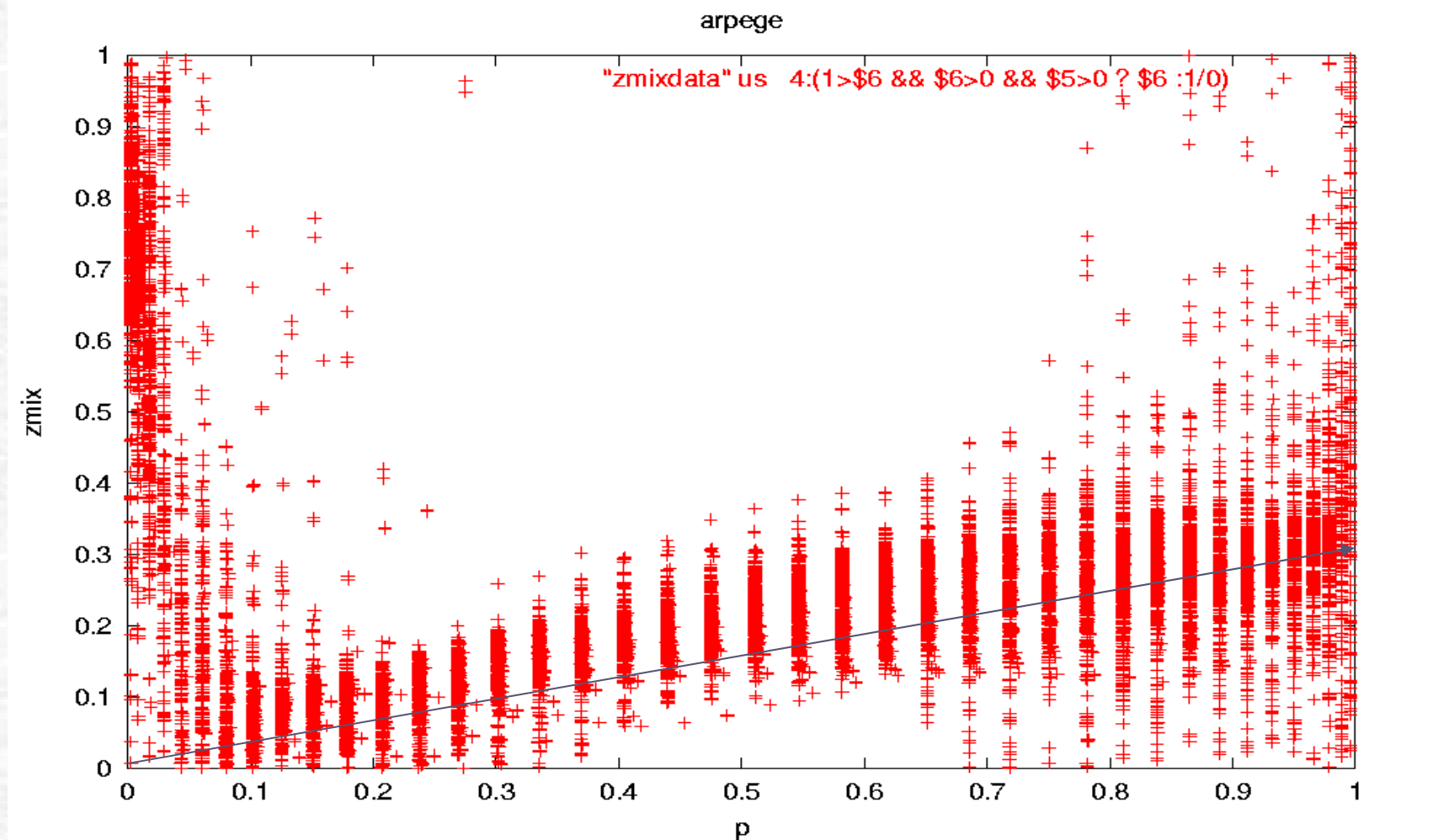
arpege

"zmixdata" us 4:(1>$6 && $6>0 && $5>0 ? $6 :1/0)
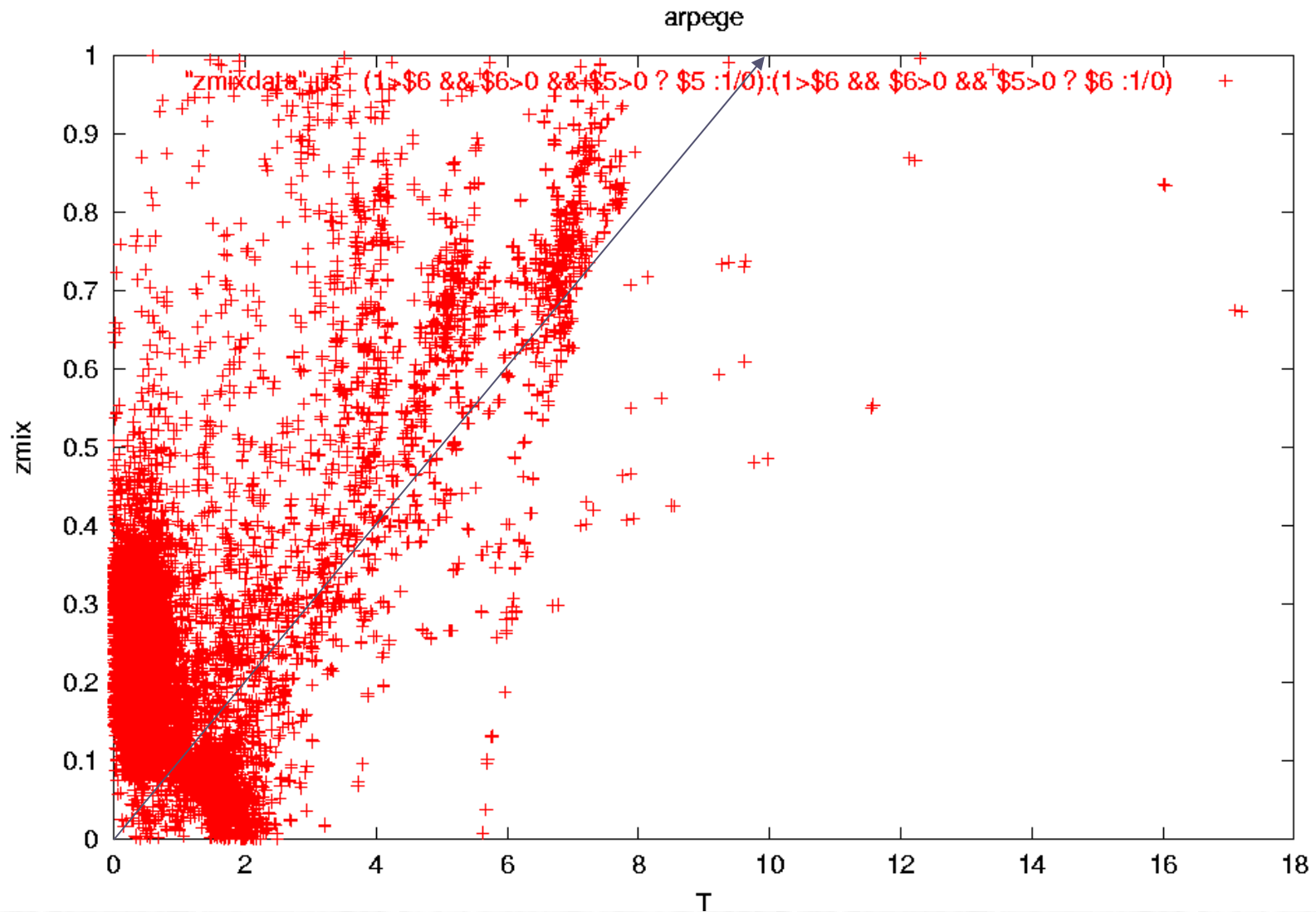
First results (parameterisation of α): two parameters fit
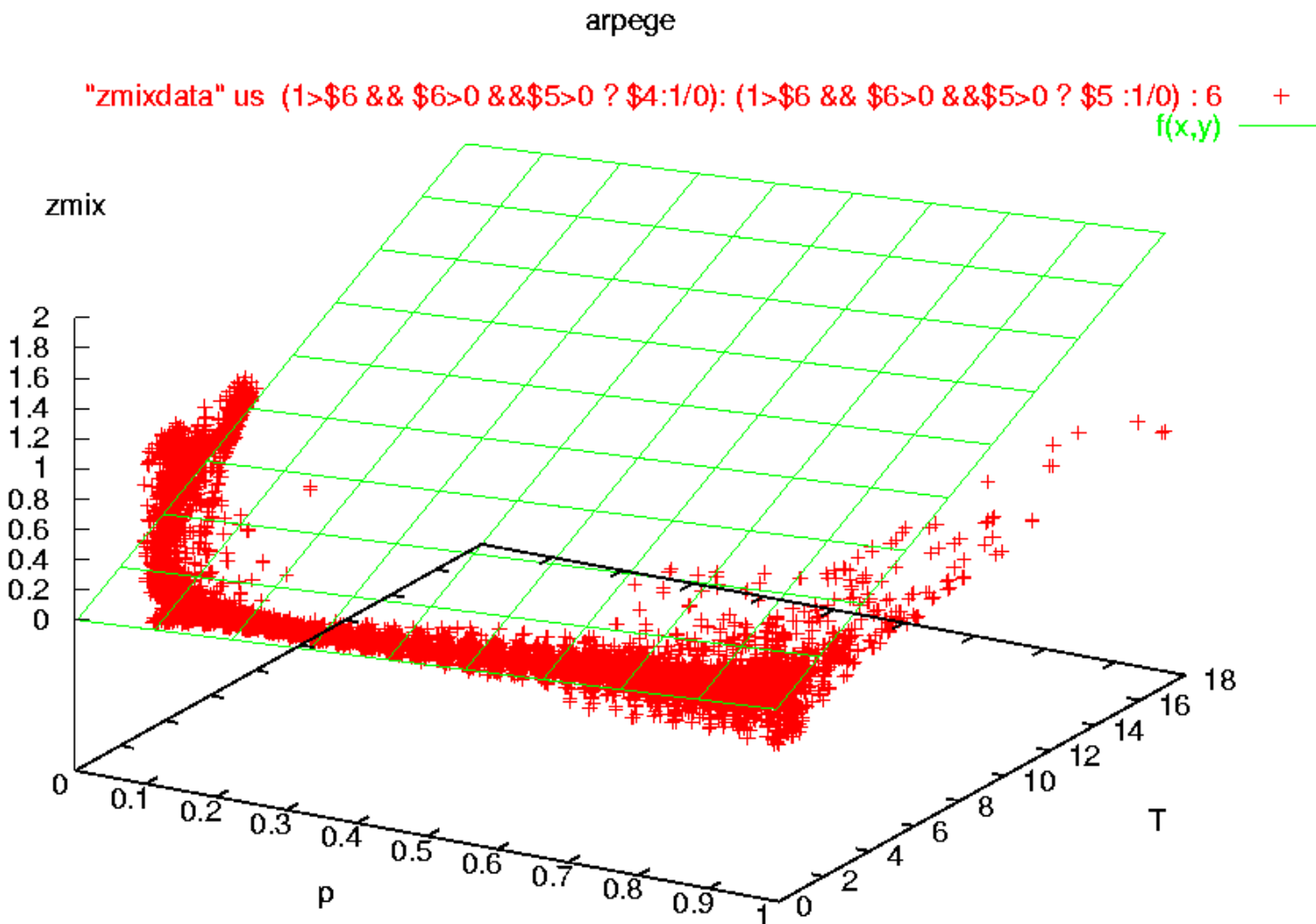
First results (parameterisation of α): dispersion diagram for total fluxes
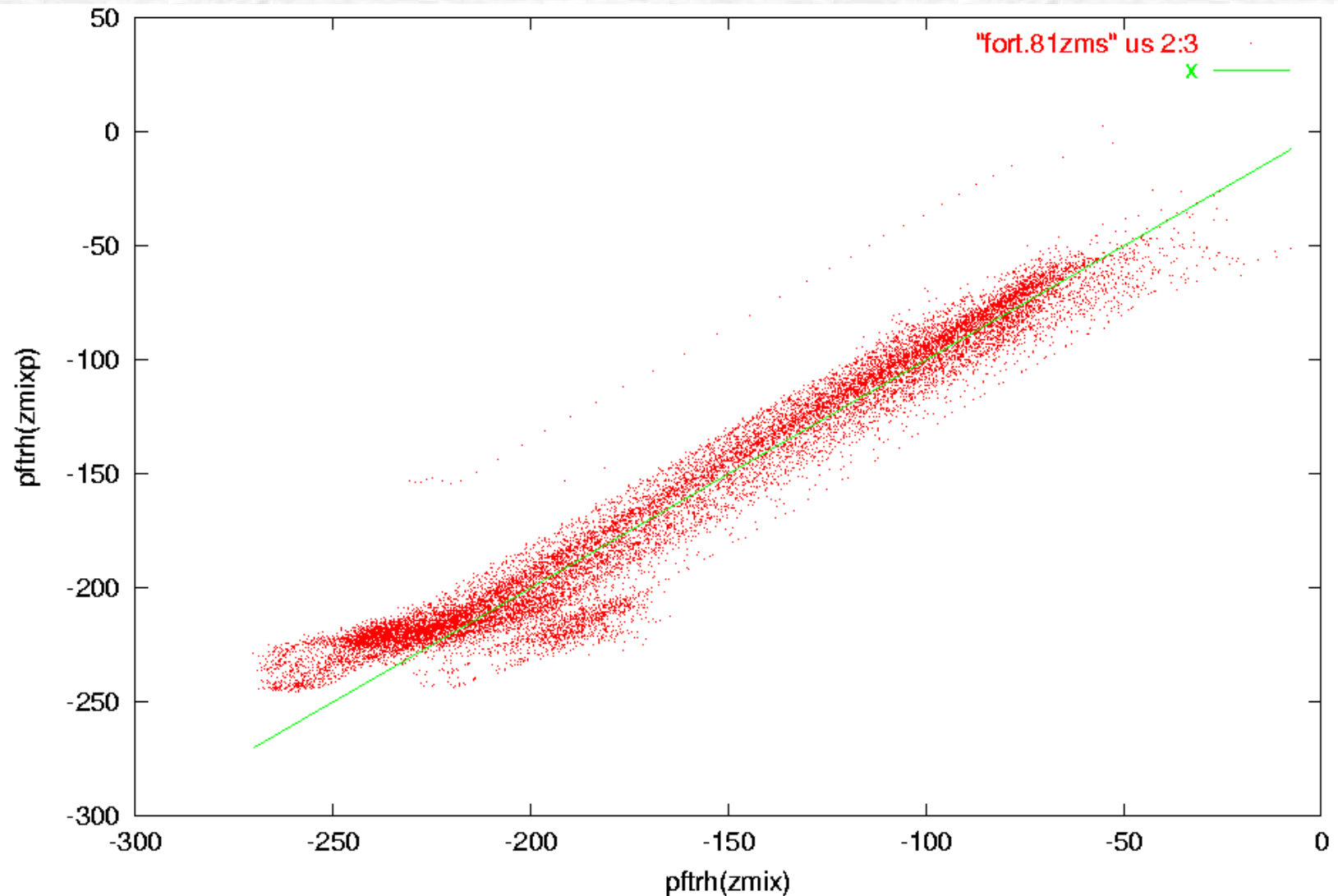
Temperature biases in zonal mean

OPER   **TEST**
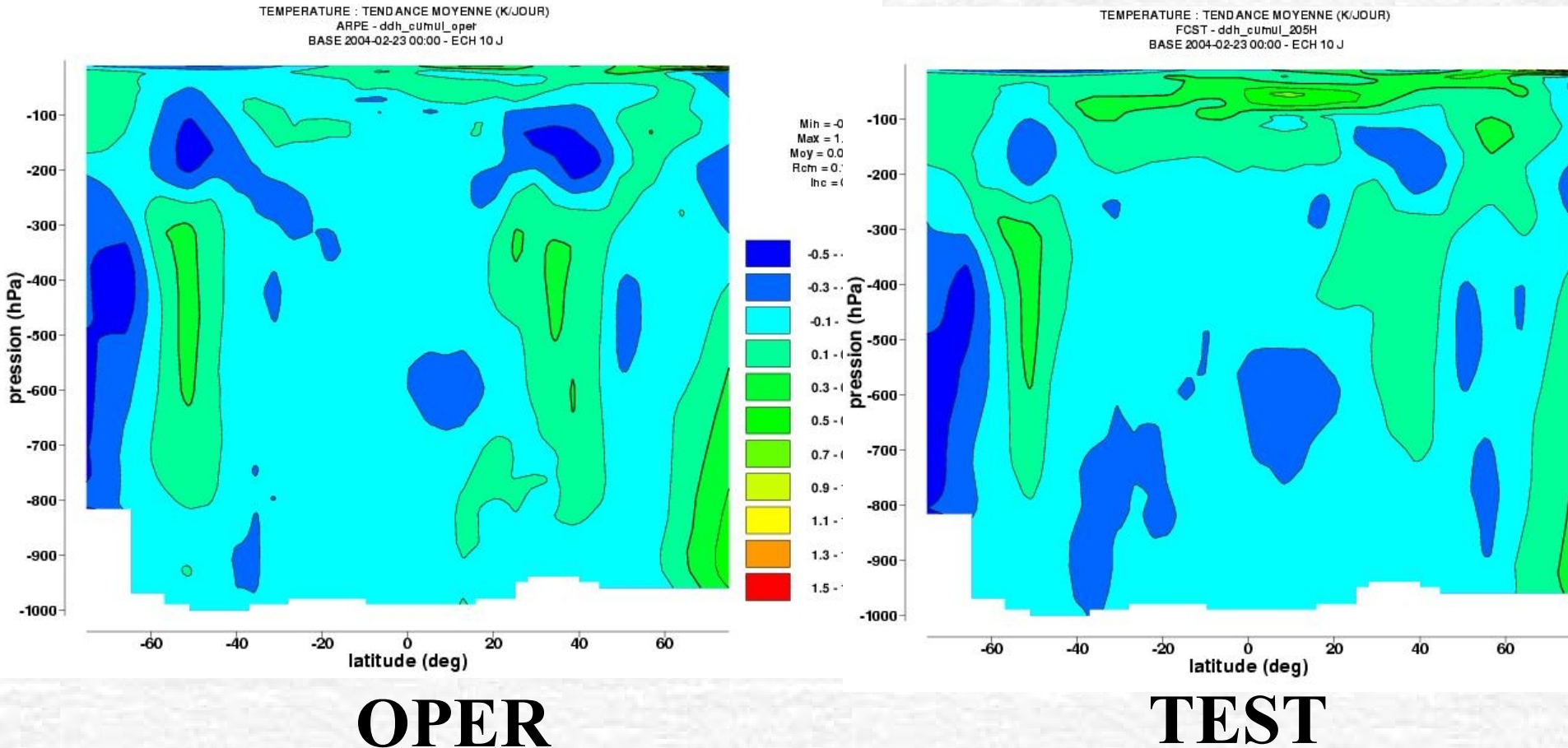
Specific humidity biases in zonal mean

EAU VAPEUR : TENDANCE MOYENNE (/JOUR)
ARPE - ddh_cumul_oper
BASE 2004-02-23 00:00 - ECH 10 J
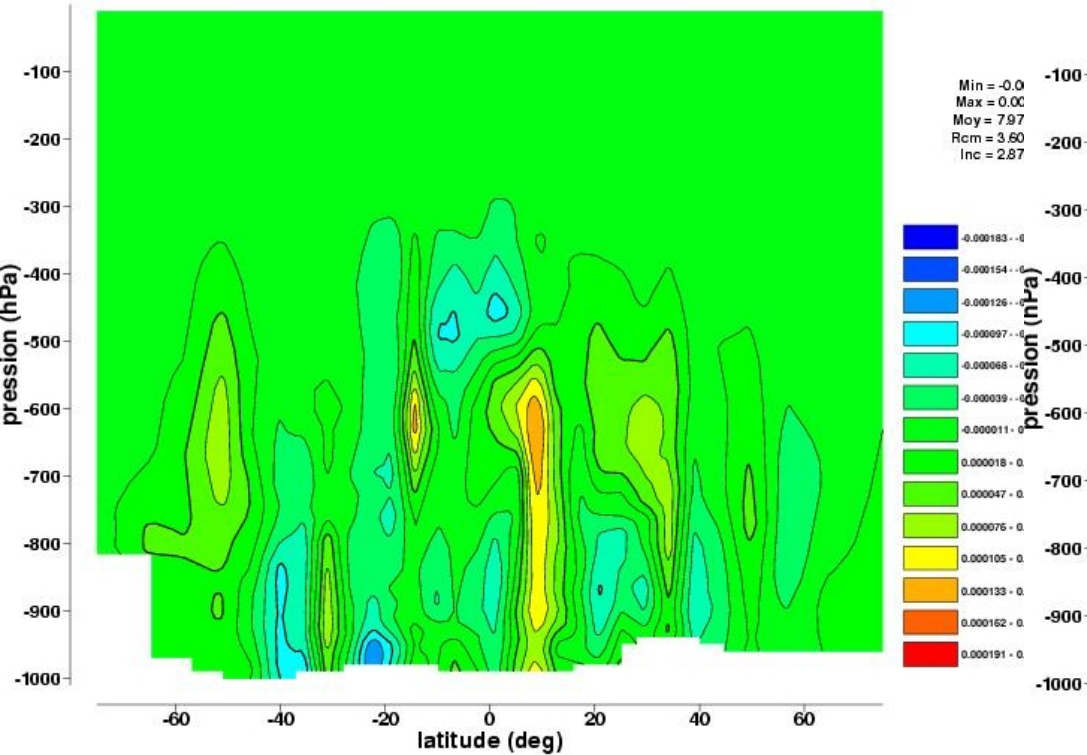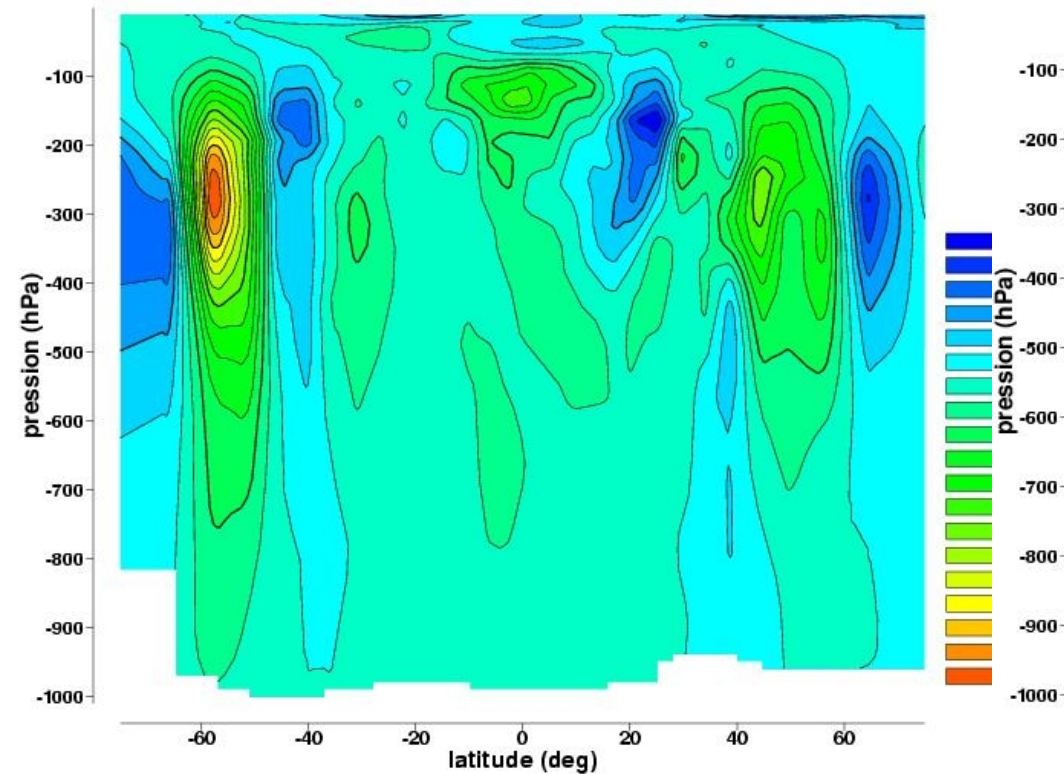
EAU VAPEUR : TENDANCE MOYENNE (/JOUR)
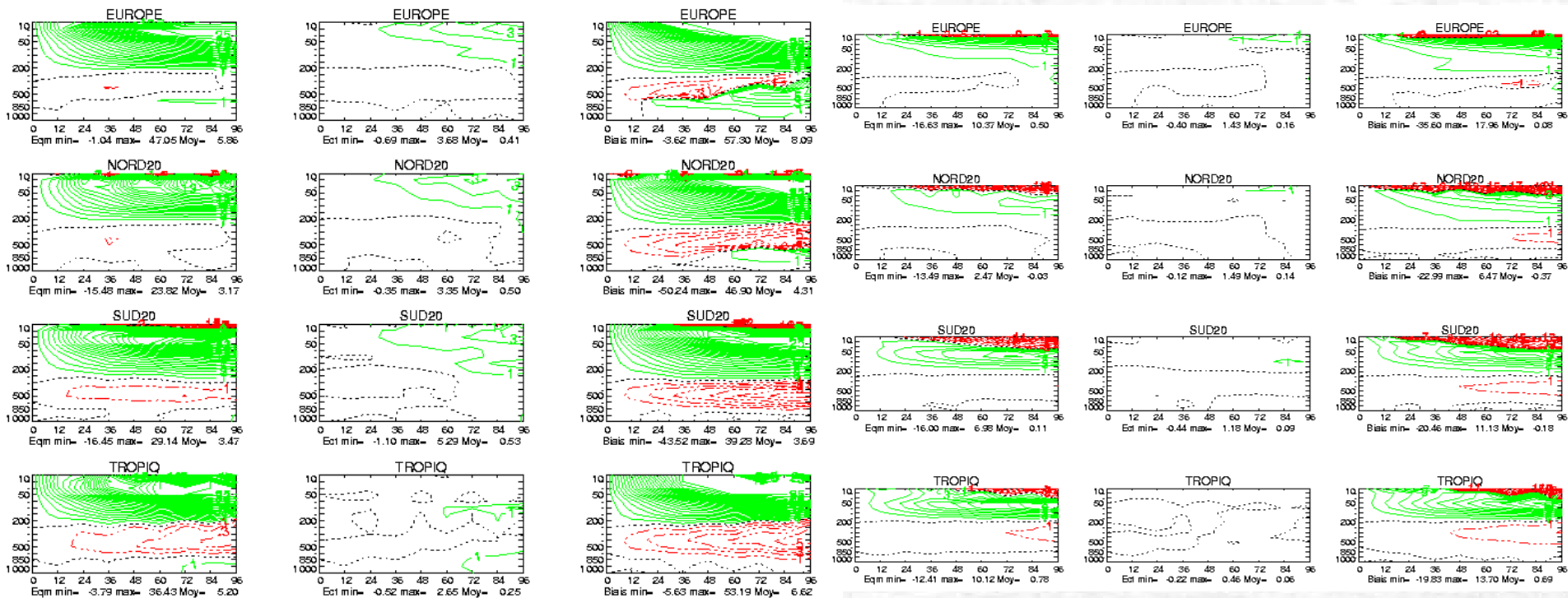FCST - ddh_cumul_205H
BASE 2004-02-23 00:00 - ECH 10 J
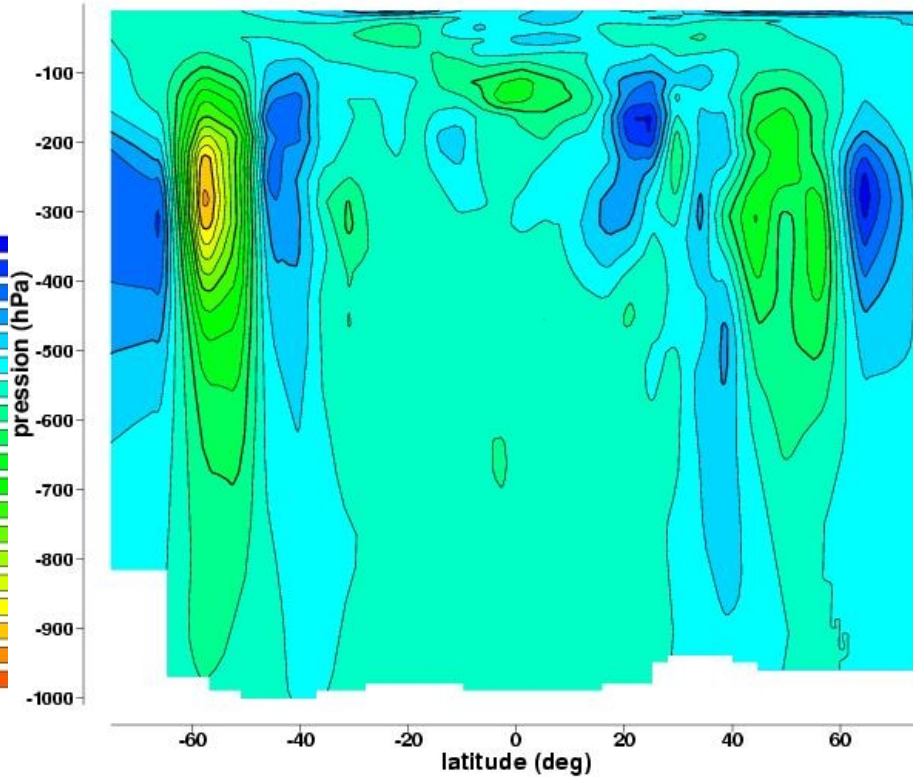
OPER   **TEST**

Kinetic energy biases in zonal mean

OPER

TEST

Part 1: 'V => VIII'   **Part 2: details**

Part 1: 'V => VIII'   **Part 2: details**

Scores with respect to FMR (new ARPEGE / ALADIN-France oper) : synthesis

- Better in terms of geopotential
- Worse in terms of temperature (?!?!)
- Equal in terms of wind for Euratl., N20
- Worse in terms of wind for Tropics, S20 (too Euro-like tuning of the statistical coefficients?)

Going back to the gaseous transmission functions

- In order to be a full 'minimum-cost reference', the ACRANEB computations (old and new) are currently extended to the Voigt line-profile (from the Lorenzian one) in order to cope with high model tops.

- The work on more accurate transmission functions has 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_NEW using the gazeous RRTM transmission functions

Purpose: To use new kind of basic input for ACRANEB_NEW 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_NEW
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**:

$$\tau_r(u, p, T) = \sum_{i=1}^{N} w_i e^{-k_i u \left(P/P^*\right)^{ai} \left(T/T^*\right)^{bi}}$$

- For each layer and spectral sub-interval:

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

- 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: H_2O, CO_2, O_3, CH_4, N_2O, CFC11, CFC12

- Ref: Mlawer et al. 1997

- Acraneb : 1 spectral interval, 3 absorbers (H_2O, CO_2^+, O_3)

RRTM database for LW computations

(P,T)
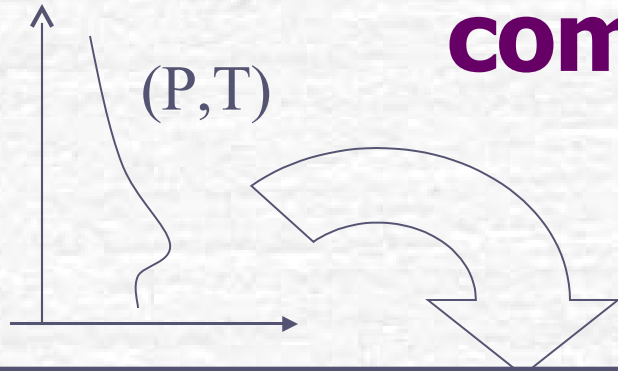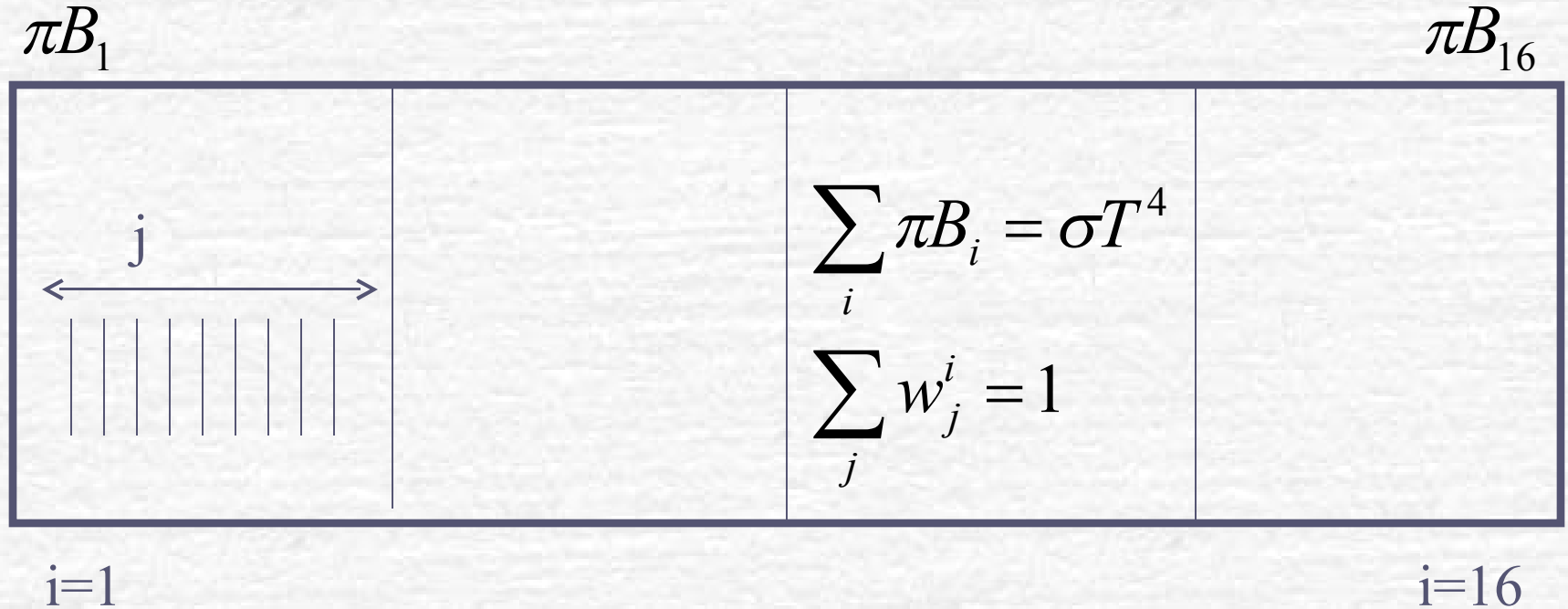
Tabulations of

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

4 points interpolations

140 ki & 140 weights of Planck function :

$$w_j^i \qquad k_j^i$$

πB_1 πB_{16}

$$\sum_i \pi B_i = \sigma T^4$$

$$\sum_j w_j^i = 1$$

j

i=1 i=16

$$\Phi_{i,j} = \frac{\pi B_i * w_j^i}{\sigma T^4}$$

$$\tau_{i,j} = \exp\left(- k_j^i\right)$$

With these 2 arrays we can compute everything needed in acraneb_new

Evaluation of optical depths
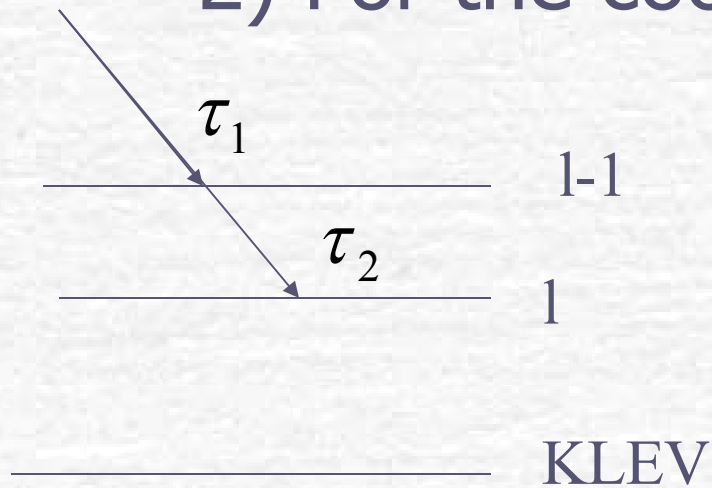
- 1) For the local effect (EBL term)

$$e^{-\delta_l} = \sum_i \Phi_i^l \tau_i^l \longrightarrow \delta_l$$
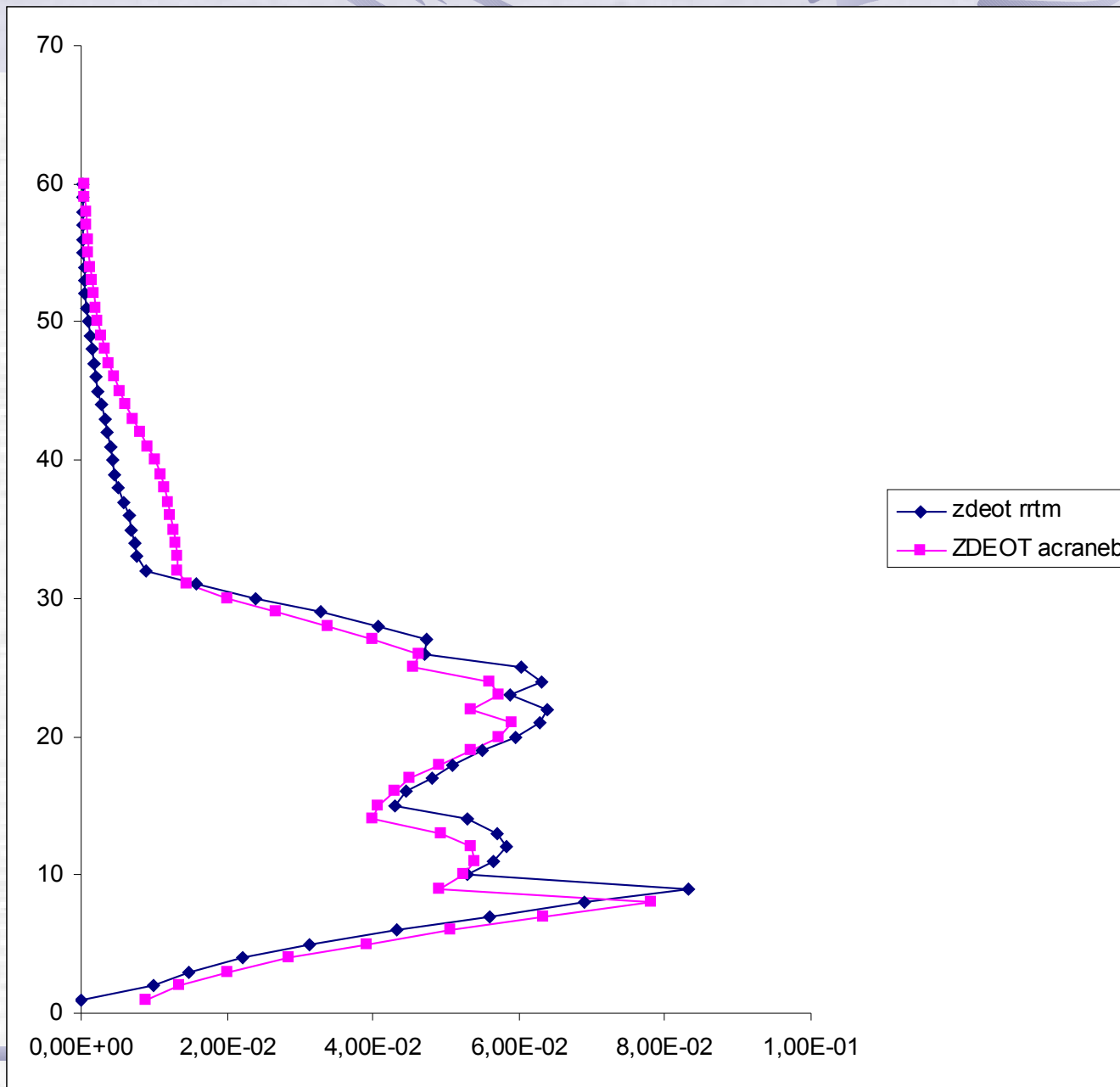
l: vertical level
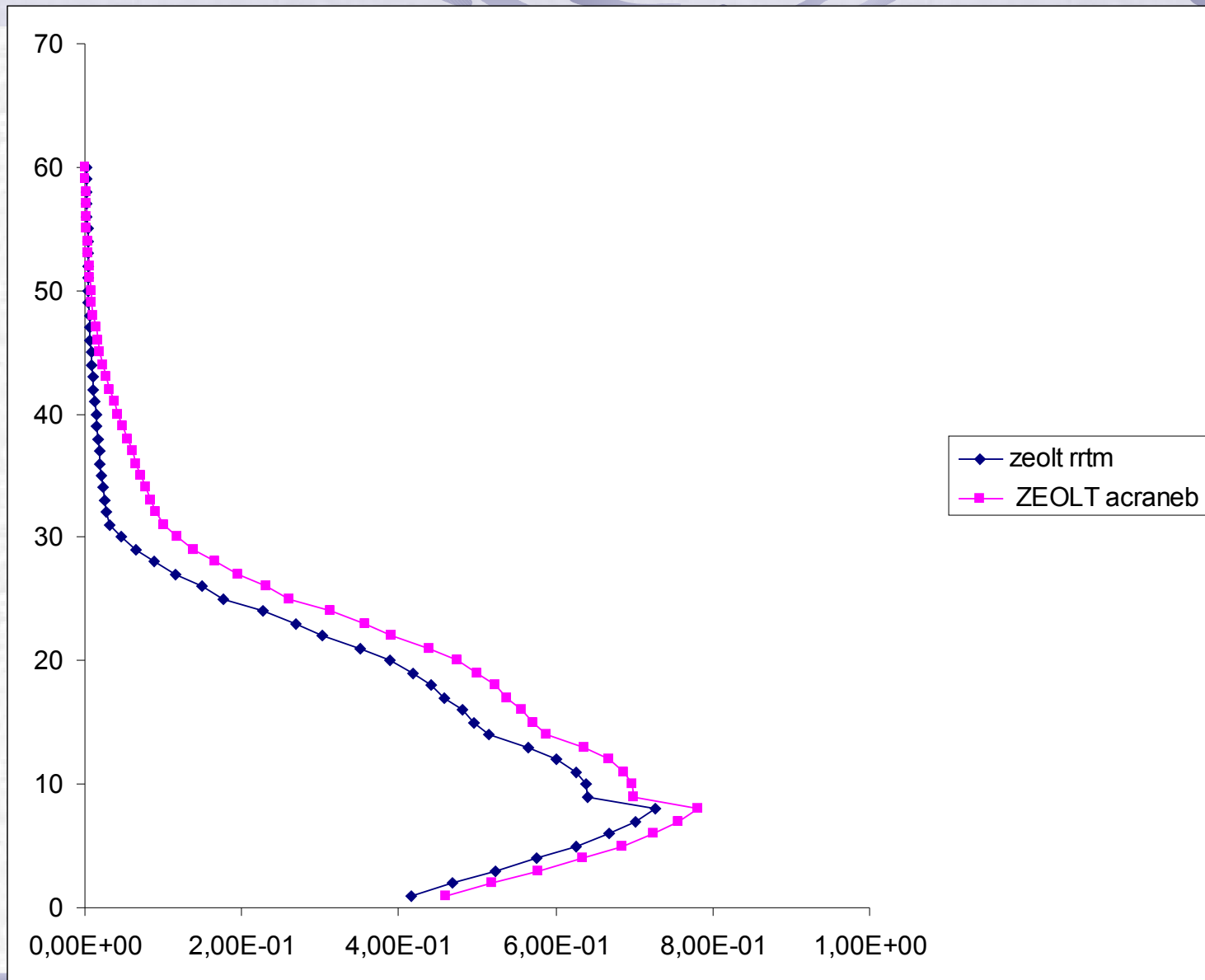
Evaluation of optical depths

2) For the cooling to space (CTS term)

τ_1

τ_2

l-1

l

KLEV

$$\tau_1 = \sum_i \Phi_i^{l-1} \prod_{k=0,l-1} \tau_i^k$$
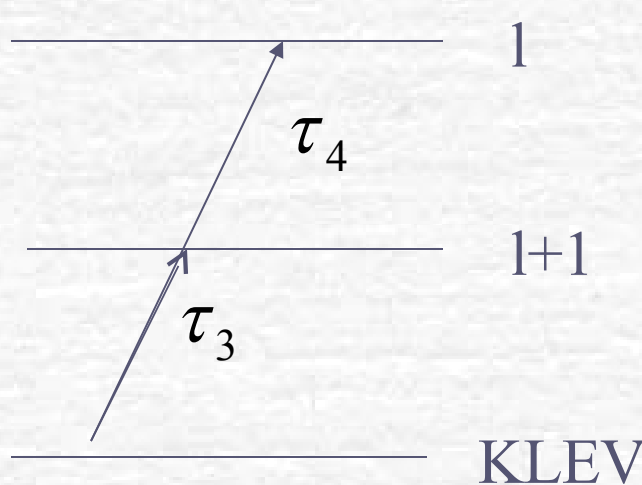
$$\tau_2 = \sum_i \Phi_i^l \prod_{k=0,l} \tau_i^k$$

$$\delta_{CTS} = \ln \frac{[\ ]}{[\ ]}$$

Evaluation of optical depths

3) For the exchange with surface (EWS term)

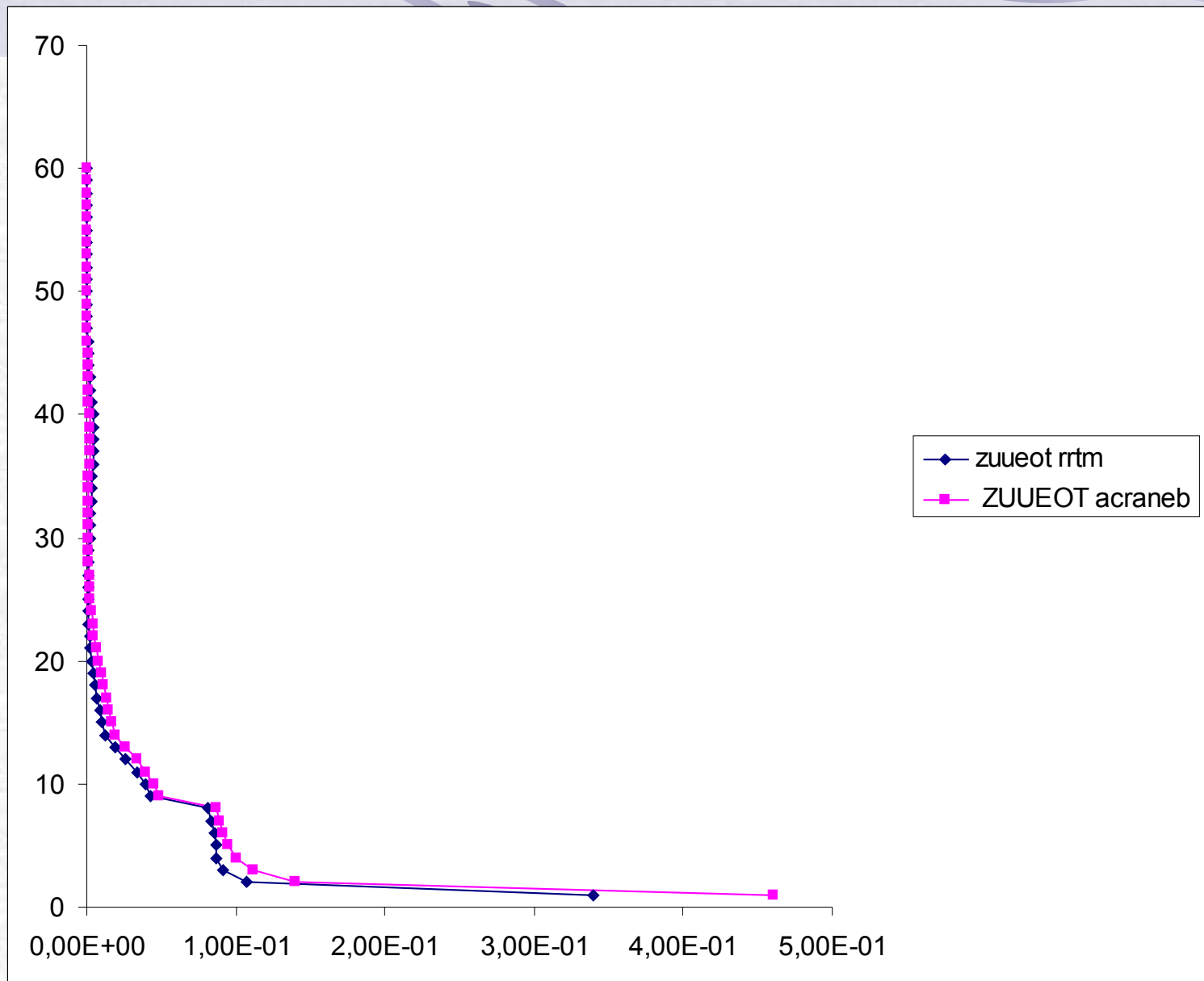1

τ_4

l+1

τ_3

KLEV

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

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

$$\delta_{EWS} = \ln \frac{[\ ]}{[\ ]}$$

Conclusions

- The NER method is particularly fruitful and well suited to the flexibility-modularity character sought for the ALARO radiative computations.

- Combined to the current 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 $\Leftrightarrow$ 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.

A lot of work still to be done

Volunteers welcome !!!