Overview of ACRANEB2 baseline version

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Introduction

- ALARO-0 baseline uses old ACRANEB radiation transfer scheme
- radiation developments starting in March 2011 resulted in delivery of improved scheme, denoted as ACRANEB2
- in December 2013, ACRANEB2 baseline version was phased into official release cy40t1, where it is available both under APLPAR and APL_AROME via new flexible phys-dyn interface INTFLEX
- on APLPAR side old ACRANEB scheme was preserved for backward compatibility, but its development is now frozen
- ACRANEB2 scheme should become one of the key ingredients of ALARO-1 prototype

Basic ACRANEB2 assumptions

- ACRANEB2 inherited most of its basic choices from ACRANEB scheme, but it revised several important issues
- central idea is to have radiative scheme cheap enough to be called at every gridpoint and every timestep, which is vital for correct interaction with quickly evolving clouds
- at the same time, one tries to keep radiative transfer computations as realistic as possible $\Rightarrow$ compromises between cost and accuracy must be made

Radiatively active species

- radiatively active species treated in ACRANEB2 are gases, aerosols, cloud particles and earth's surface
- absorbing gases are H_2O, O_3 and CO_2+ (composite of CO_2, N_2O, CO, CH_4 and O_2, i.e. most important radiatively active gases with constant mixing ratios)

ACRANEB/ACRANEB2 CO_2+ composition		
gas	volume mixing ratio [ppmv]	
	IPCC 1990 (ACRANEB)	WDCGG 2010 (ACRANEB2)
CO_2	353.200	389.000
N_2O	0.310	0.323
CO	0.120	—
CH_4	1.725	1.808
O_2	209 480.600	209 460.000

- dry air contributes to Rayleigh scattering
- solar cloud absorption is subject to optical saturation, in thermal band clouds are grey
- aerosols and earth's surface are treated as grey bodies

Fitting references

- gaseous transmissions were fitted against SPLIDACO narrowband reference based on HITRAN 2008 line parameters, complemented by Serdyuchenko et al. 2013 dataset for shortwave ozone continuum absorption
- narrowband data for longwave H_2O e-type continuum were imported from model MT_CKD version 2.5.2 (Mlawer et al. 2012)
- aerosol optical properties are the same as in ACRANEB (retrieved from ECMWF radiation)
- cloud optical properties were fitted against Stephens 1978 liquid clouds and Edwards et al. 2007 ice clouds (optical saturation of ice clouds is still based on older Rockel et al. 1991 data)
- dependency of direct surface albedo on sun elevation was tuned against Yang et al. 2008 land albedo and Gardner and Sharp 2010 snow albedo

Spectral division

- for efficiency reasons, electromagnetic spectrum is divided into single shortwave (solar) and single longwave (thermal) interval $\Rightarrow$ broadband approach

spectral band	wavelength range [μm]
solar	0.245–4.642
thermal	4.642–104.5

- if one wants to keep sufficient degree of realism with such broad spectral intervals, he must address issues of **optical saturation** and **non-random spectral overlaps** between radiatively active species

- situation in solar band is much simplified by missing emission, but scattering is very important

- in thermal band scattering is much less important, but presence of emission requires efficient computation of atmospheric exchanges

Gaseous absorption

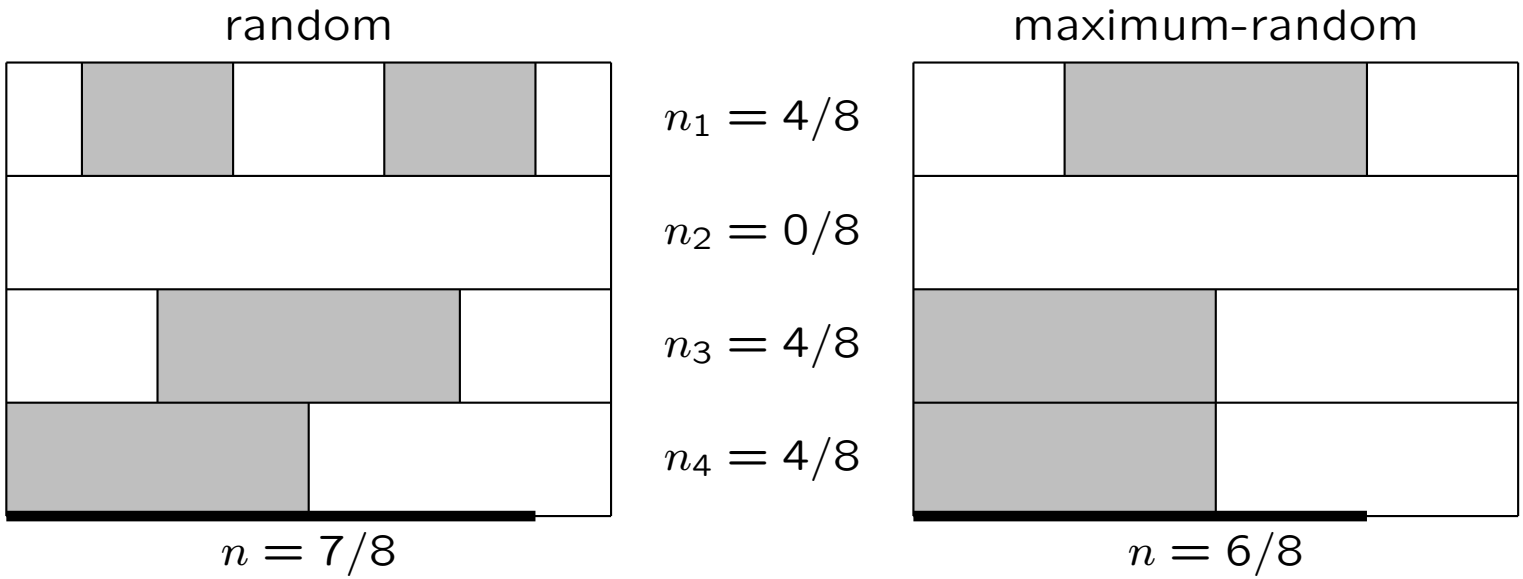
- gaseous optical depths are based on Malkmus band model with empirical broadband correction accounting for secondary saturation
- accuracy of gaseous optical depths is further improved by secondary corrective fits
- band model approach enables treatment of non-homogeneous optical paths by Curtis-Godson approximation
- Geleyn et al. 2005 extension of Malkmus band model to Voigt line shape is used
- in thermal band Planck weights linearized with respect to temperature of emitting body T_{e} are used (with linearization temperature $T_0 = 255.8\,\mathrm{K}$)

Cloud optical properties

- broadband cloud absorption/scattering coefficients and asymmetry factor are fitted directly as functions of liquid and ice water content
- their dependency on water droplet effective radius or ice crystal effective dimension is thus hidden
- since spectral variability in thermal band is weaker than for gases, Planck weigths with constant temperature $T_0 = 255.8\,\mathrm{K}$ are used
- solar cloud absorption is subject to saturation based on effective cloud optical depth between top of atmosphere and given layer (assuming diffuse transport inside clouds)

Cloud geometry

- each model layer is devided into clearsky part and cloudy part, with no lateral exchanges between them
- at layer interfaces, fluxes leaving clearsky and cloudy parts are redistributed according to assumed cloud geometry
- two supported options for overlaps between cloud layers are **random** (unphysical for higher vertical resolutions) and **maximum-random** (more realistic):



Spectral overlaps

- spectral correlation between transmissions of different species results in non-multiplicativity of their broadband values, respectively non-additivity of corresponding broadband optical depths:

$$\overline{\tau}_{12} = \overline{\tau_1 \cdot \tau_2} \neq \overline{\tau}_1 \cdot \overline{\tau}_2 \quad \Rightarrow \quad \overline{\delta}_{12} \neq \overline{\delta}_1 + \overline{\delta}_2 \qquad (\overline{\delta} \equiv -\ln \overline{\tau})$$

- ACRANEB2 parameterizes non-random pair overlaps between H_2O, O_3 and CO_2+, as it was shown that impact of their triple overlap is negligible
- non-random gaseous overlaps have only weak impact in solar band, where they are switched off for efficiency reasons
- apart from absorption of various gases in thermal band, ACRANEB2 assumes additivity of broadband optical depths of different species, which is important for getting δ-two stream coefficients of the mixture
- above assumption might need revision in case of gas-cloud spectral overlap, since in near-infrared region absorption of water vapor and clouds is strongly correlated

Saturation of Rayleigh scattering

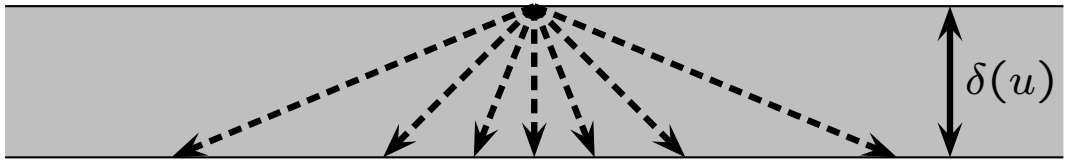
- Rayleigh scattering is strongly wavelength dependent (it varies roughly as λ^{-4})
- broadband Rayleigh scattering coefficient should thus be subject to optical saturation
- saturation effect was parameterized in similar manner as for solar cloud absorption, relying on dominant role of primary scattering in clearsky case (saturation is evaluated along direct solar ray)
- even if parameterization was not yet fully validated against narrow-band reference including gaseous absorption, it should be superior to traditional treatment, improving clearsky planetary albedo and vertical distribution of solar heating rates

Multiple scattering

- multiple scattering is accounted for via δ-two stream approximation applied on plane-parallel homogeneous layers, combined with adding method $\Rightarrow$ results in linear system for fluxes at layer interfaces
- δ-two stream formulation of Ritter and Geleyn 1992 is used, assuming hemispherically constant intensities and scaled phase function linear in cosine of scattering angle
- amount of energy scattered via forward δ-peak equals to g^2, where g is asymmetry factor
- it means that Rayleigh scattering phase function is approximated by isotropic one, while for strongly asymmetric aerosol and cloud scattering big portion of energy is scattered in forward direction alias not scattered at all
- accuracy of above δ-two stream formulation is comparable to PIFM or δ-Eddington methods

Diffusivity factor

- diffuse radiation crosses absorbing layer with vertical absorber amount u and optical depth $\delta(u)$ at various angles:



- layer diffuse transmission is given by angular average of ray transmissions and can be written in conventional form when absorber amount u is multiplied by diffusivity factor $1/\bar{\mu}$, where μ is cosine of zenithal angle:

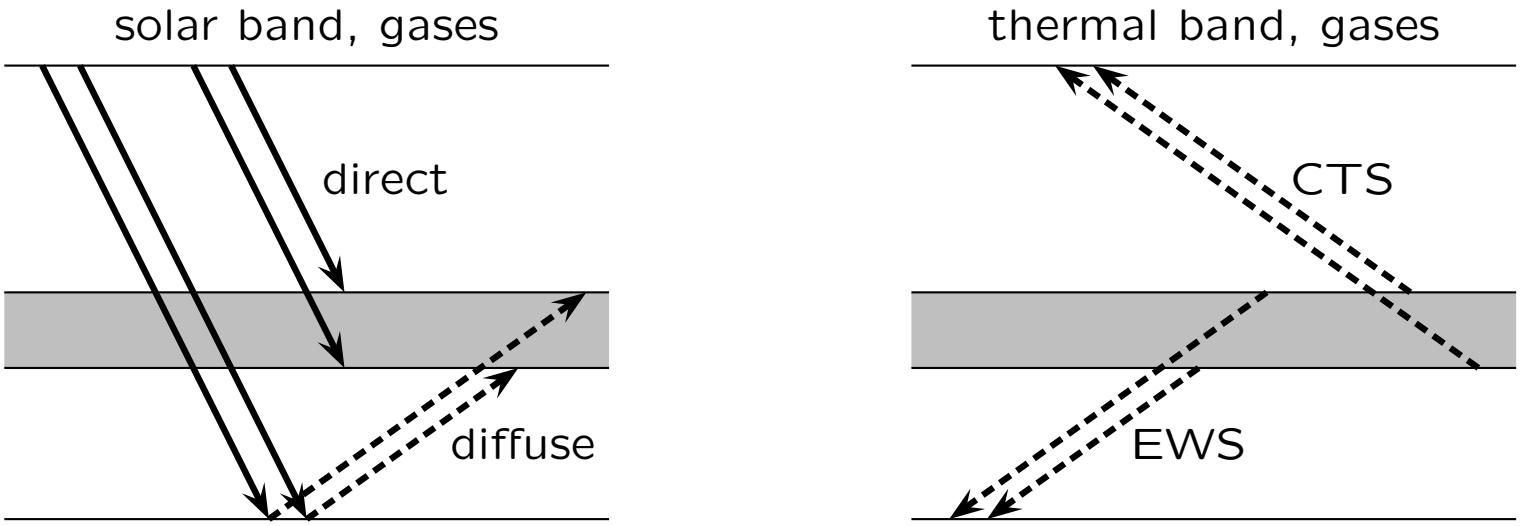
$$\tau = 2\int_0^1 \exp[-\delta(u/\mu)]\mu \,\mathrm{d}\mu = \exp[-\delta(u/\bar{\mu})]$$

- diffusivity factor depends on shape of $\delta(u)$, for hemispherically constant incident radiation it is from interval $[1, 2]$

- ACRANEB2 uses constant diffusivity factor 2 for aerosols and clouds, while for gases it varies from 2 in weak line limit to $\sqrt{\mathrm{e}}$ in strong line limit

Idealized optical paths

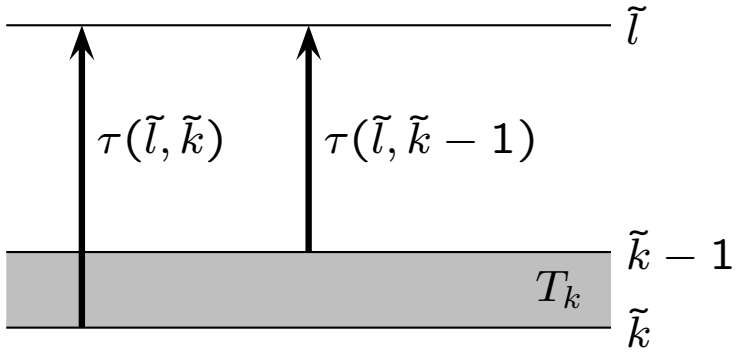
- optical saturation depends on initial spectral composition of radiation and its path across absorbing/scattering medium
- presence of multiple scattering prolongates undertaken path in a complicated way, difficult to be handled exactly
- this is why concept of idealized optical paths was introduced, starting either at top of atmosphere or at emitting layer and taking into account dominant processes in given circumstances:



Emissivity type computation

- emission present in thermal band is seen as source term in δ-two stream plus adding system for fluxes
- in the absence of scattering, contribution of layer k to thermal flux at level $\tilde{l}$ is given by:

$$F^{\uparrow}_{\tilde{l}k} = \sigma {T_k}^4 \left[\tau(\tilde{l}, \tilde{k}-1) - \tau(\tilde{l}, \tilde{k})\right]$$



- above formula is a core of so called emissivity type computation
- evaluation of upward/downward flux at given level requires summation over layers below/above, so the cost of full computation is quadratic in number of levels
- inclusion of scattering would require to solve δ-two stream plus adding system for each emitting layer separately, using proper optical depths and summing up resulting fluxes on each level

Net exchanged rate scheme (NER)

- main limitation of emissivity type computation is the fact that broadband optical depth of emitting layer depends on position of the observer, while δ-two stream plus adding system requires unique optical depth for each layer
- heart of NER scheme is decomposition of **net flux difference** across given layer into three contributions – cooling to space (CTS), exchange with surface (EWS) and exchange between layers (EBL)
- above decomposition enables to compute dominant CTS and EWS fluxes accurately, while the most costly but least significant EBL flux can be approximated
- CTS and EWS fluxes can be obtained by two δ-two stream plus adding solvings, each using optical depths relevant for given exchange and suitably scaled source term
- estimation of EBL flux is more elaborated and requires 6 extra δ-two stream plus adding solvings
- at the end all three fluxes are summed, giving net thermal flux

Bracketing technique

- in the absence of scattering (no clouds and aerosols, blackbody surface), EBL flux can be determined by emissivity type computation
- it can be done using three sets of layer optical depths – true (observer at level where the flux is evaluated), minimum (observer at most distant level, i.e. either top of atmosphere or surface) and maximum (observer at layer boundary)
- unlike the true case, min/max computations are cheap thanks to the fact that min/max optical depths are additive by construction
- they provide estimates of min/max EBL flux, because thick layer exchanges more with other layers than thin layer
- clearsky EBL flux can then be placed between its min/max estimates, defining bracketing weight α:

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

- clearsky value of bracketing weight α is finally used to get cloudy EBL flux from its cloudy min/max estimates

Intermittency

- computation of gaseous transmissions is costly, but their temporal evolution is relatively slow
- real case experiments showed that it is sufficient to update thermal gaseous transmissions only once per hour
- radiative transfer equation must still be solved at every timestep, since temperature and especially cloudiness evolve rapidly
- temperature enters not only broadband gaseous transmissions (via line strenghts, line halfwidths and Planck weights), but also emission source terms (via σT^4 factors)
- in case of very costly exact computation of clearsky bracketing weights (it requires gaseous transmissions between each pair of levels), 3 hourly update frequency is sufficient
- two level 1 h/3 h intermittency makes cost of ACRANEB2 thermal computations acceptable

CPU cost

- CPU cost of 24 hour ALARO-0 integrations with different radiation schemes and intermittent strategies was evaluated on CHMI operational domain ($\Delta x = 4.7\,\mathrm{km}$, 87 levels, $\Delta t = 180\,\mathrm{s}$):

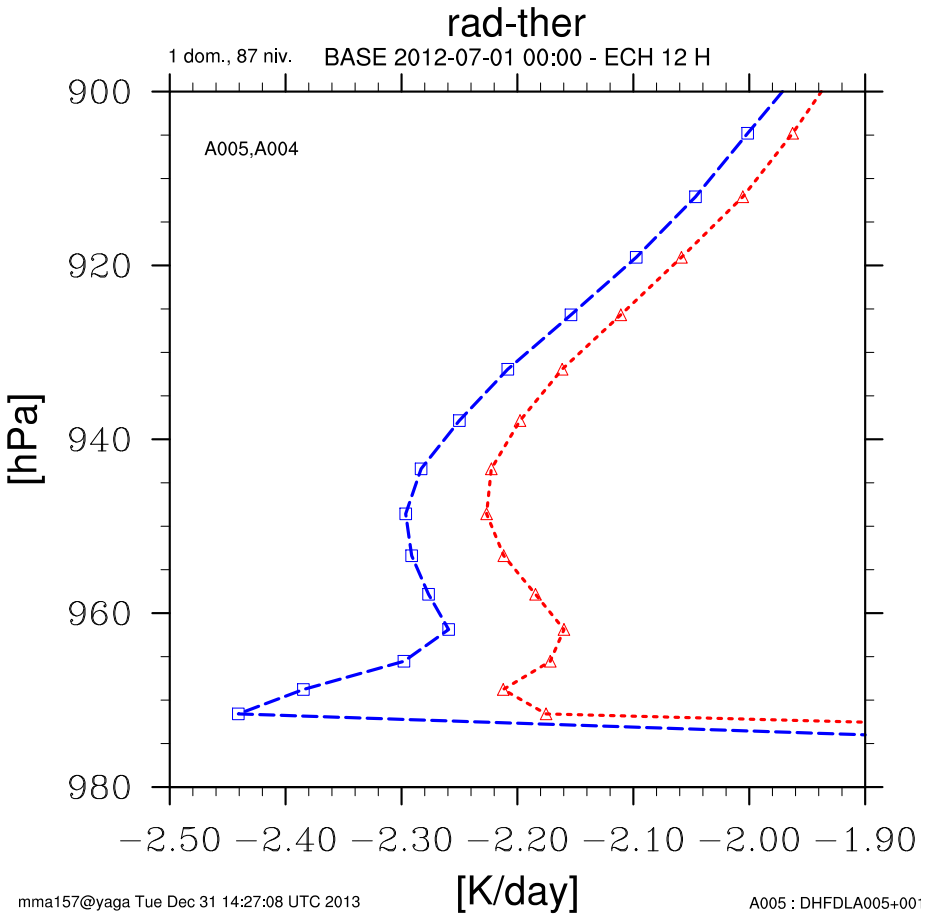
radiative scheme	update frequency			relative CPU cost
	clouds	gases	bracketing weights	
ACRANEB	3 min	3 min	3 min, statistical fit	1.00 (reference)
ACRANEB	3 min	3 min	3 min	1.49
ACRANEB2	3 min	3 min	3 min	5.42
ACRANEB2	3 min	1 h	3 h	1.07
RRTM/FMR	3 min	3 min	–	2.40
RRTM/FMR	1 h	1 h	–	1.03

- ACRANEB with statistical model and no intermittency has cost comparable to RRTM with 1 h intermittency, but it is less accurate
- ACRANEB2 with no intermittency is awfully expensive, but use of two level 1 h/3 h intermittency makes the integration only about 7% more expensive than that using ACRANEB with statistical model
- cost of ACRANEB2 and RRTM intermittent strategies is similar, advantage of ACRANEB2 over RRTM is update of cloudiness at every timestep, which has visible impact

Accuracy of RRTM and ACRANEB2 intermittent strategies

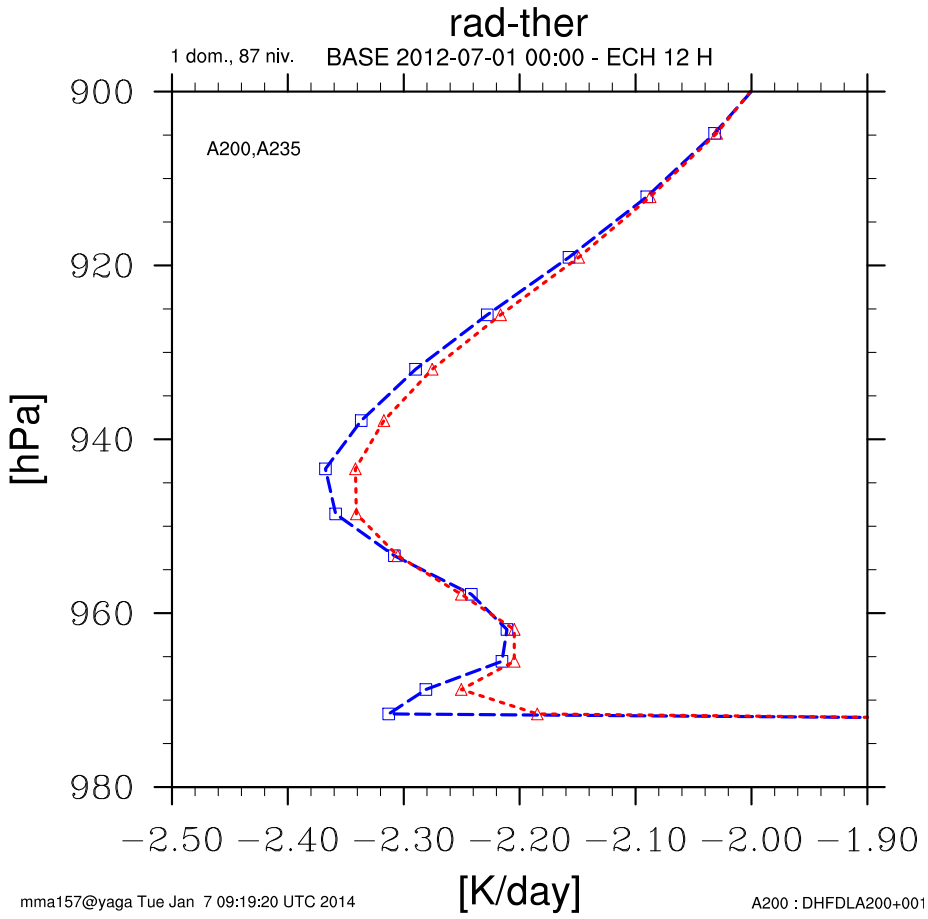
DDH thermal heating rates, 12 h integration, summer case with front passage

RRTM



no intermittency
1 h intermittency **including** clouds

ACRANEB2



no intermittency
1 h/3 h intermittency **excluding** clouds

Assembling of thermal computations

- computation of net thermal flux F involves 8 δ-two stream solvings:

$$F = F^{\mathrm{CTS}} + F^{\mathrm{EWS}} + (1-\alpha)\underbrace{[F_{\mathrm{min}} - F^{\mathrm{CTS}}_{\mathrm{min}} - F^{\mathrm{EWS}}_{\mathrm{min}}]}_{\text{min EBL flux}} + \alpha\underbrace{[F_{\mathrm{max}} - F^{\mathrm{CTS}}_{\mathrm{max}} - F^{\mathrm{EWS}}_{\mathrm{max}}]}_{\text{max EBL flux}}$$

$$\alpha = \left(\frac{F^{\mathrm{EBL}} - F^{\mathrm{EBL}}_{\mathrm{min}}}{F^{\mathrm{EBL}}_{\mathrm{max}} - F^{\mathrm{EBL}}_{\mathrm{min}}}\right)_{\mathrm{clearsky}}$$

- fluxes in red color are computed with linear T_{e} correction, the rest is obtained using static thermal weights
- costly computation of clearsky EBL flux is done intermittently, with update frequency 3 hours
- emissivity type computation with inclusion of scattering would require **one** δ-two stream plus adding **solving per layer** $\Rightarrow$ not feasible with high vertical resolutions
- NER scheme with bracketting includes scattering by using just **8 solvings**, indepentently on number of layers
- it remains accurate thanks to making approximations on the least sensitive place, i.e. in computation of EBL flux

Finally, something for practical life: ACRANEB2 usage

Activation of ACRANEB2

- ACRANEB/ACRANEB2 radiation is activated via namelist &NAMPHY logical key LRAY (it is exclusive with other radiation schemes, activated by keys LRAYFM, LRAYFM15, LRRTM or LSRTM)
- selection between the two schemes is then done via namelist &NAMPHY variable NRAY (1 – ACRANEB, 2 – ACRANEB2)
- namelist &NAMPHY contains ACRANEB/ACRANEB2 **basic choices** (Lorentz/Voigt line shape, old/new aerosols, old/new cloud optical properties, random/maximum-random overlaps between cloud layers, NER configuration, intermittency)
- namelist &NAMPHY3 contains exclusively ACRANEB/ACRANEB2 **low level settings** (gaseous transmissions, CO2 mass mixing ratio, statistical model, Rayleigh scattering, aerosol and cloud optical properties, ...), most of them are not supposed to be changed by common user
- some namelist variables are not shared between ACRANEB and ACRANEB2, their values are printed to output listing only when relevant (i.e. depending on NRAY value)

Recommended ACRANEB2 baseline configuration

variable	value	meaning
		&NAMPHY
LRAY	.T.	activates ACRANEB/ACRANEB2 radiation
NRAY	2	selects ACRANEB2
LCLSATUR	.T.	new cloud optical properties
LRNUMX	.T.	maximum-random overlaps between cloud layers
LVOIGT	.T.	Malkmus formula corrected to Voigt line shape
LVFULL	.F.	cheap variant of Voigt line shape correction
LRPROX	.F.	adjacent exchanges not computed exactly, but included in EBL flux estimate
LRTPP	.T.	non-isothermal layer correction of adjacent exchanges (for LRPROX=.F. applies only to lowest layer EWS)
NTHRAYFR	-1	1 hour intermittency interval for thermal gaseous transmissions (negative – hours; positive – timesteps)
NRAUTOEV(*)	3	3 times longer intermittency interval for bracketing weights, i.e. 3 hours (0 – statistical model)
		&NAMPHY3
RLAMB_SOLID	0.6	proportion of Lambertian reflection for solid surfaces (default 0. reproduces old ACRANEB behaviour)

(*) variable NRAUTOEV replaces former ACRANEB logical key LRAUTOEV, where old setting LRAUTOEV=.F./.T. corresponds to new setting NRAUTOEV=0/1 (NRAUTOEV $>$ 1 has no meaning for ACRANEB)

NER switches without meaning for ACRANEB2

variable	why ignored in ACRANEB2
&NAMPHY	
LREWS	EWS computation is always on
LRMIX	bracketing in EBL estimation is always on
LRTDL	transmissions of double layers are never approximated by product of individual transmissions
LRSTAB	long timestep stabilization of main NER terms is always on
LNEWSTAT	selects between two versions of old statistical model

NER extensions available in ACRANEB2

- LRTPP=.T. can be used also with LRPROX=.F., in such case it applies non-isothermal layer correction to exchange of lowest model layer with surface (in ACRANEB this combination has no effect)

- intermittent computation of bracketing weights is available via setting NRAUTOEV $>$ 1 (ACRANEB2 baseline version uses it as a replacement of statistical model which does not work well with LRPROX=.F.)

Changing CO_2 concentration

- CO_2 mass mixing ratio used in ACRANEB2 computations can be changed via &NAMPHY3 namelist variable QCO2
- default value is QCO2=0.5911E-03 alias 591.1 ppmw, corresponding to volume mixing ratio 389.0 ppmv
- changing QCO2 alone is **not recommended**, since it rescales concentrations of other gases present in CO_2+ composite accordingly, but change of O_2 concentration is undesirable
- in climate simulations two things can be done:
  1. transmissions fits for pure CO_2 are available for ACRANEB2, they can be set via namelist &NAMPHY3 and then QCO2 can be filled with equivalent CO_2 concentrations
  2. upon request, CO_2+ transmissions can be refitted for desired atmospheric composition and set via namelist &NAMPHY3 together with corresponding QCO2 value
- first option is easier to use, but it treats impact of other well-mixed gases via simplistic concept of equivalent CO_2

Enjoy!