Externalization of the effective radius from radiation

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1 Introduction

This stay was dedicated to externalization of the effective radii calculation from radiation. Main motivation is to have one common radius used both in microphysics and in radiation. On the microphysics side, externalization was already made by Daniel Martin.
During this stay, simple subroutine for externalizing effective radii from ACRANEB2 radiation was made. This radius was compared to the one obtained from microphysics.

2 Externalization subroutine

The effective radii of cloud liquid and ice particles are calculated in the subroutine AC_CLOUD_MODEL2. That routine is called from ACRANEB2 scheme for radiation. Having information about cloud liquid and cloud ice water content, a simple conversion between water content and effective particle size is used (eq. 46 and 47 from [2]). Liquid particles are of spherical shape, while ice particles can have different (non-spherical) shapes. Therefore, effective radius R_e in microns is calculated for cloud liquid, and effective dimension (diameter, D_e) for cloud ice.
Using Pade approximation of order (2,2):

$$R(x) = \frac{p_0 + p_1 x + p_2 x}{1 + q_1 x + q_2 x}, \tag{1}$$

where x is

$$x_l = \ln\left(\frac{R_e}{\mu\text{m}}\right), \tag{2}$$

$$x_i = \ln\left(\frac{D_e}{\mu\text{m}}\right); \tag{3}$$

cloud optical properties can be obtained with five fitting coefficients for each optical parameter (absorption coefficient, scattering coefficient and asymmetry factor) and cloud type (liquid and ice). Fitting formulas for the optical properties are:

$$\frac{k_i^{abs}}{\text{Pa}^{-1}} = \exp(R_i^{abs}(x_i)), \tag{4}$$

$$\frac{k_i^{scat'}}{\text{Pa}^{-1}} = \exp(R_i^{scat}(x_i)), \tag{5}$$

$$g' = \frac{1 + \tanh(R_i^{asym}(x_i))}{4}. \tag{6}$$

For more information about the calculation, see [2].

Starting point for the externalization procedure was cy46t1_bf.07 as the reference. Except for externalization, a few more changes have been made.
On the level of APLPAR and APL_AROME, we wanted to have effective radii in meters, both for cloud liquid and cloud ice. To achieve that, coefficients in 46 and 47 from [2], and five Pade coefficients from (1) had to be recalculated.
Externalization subroutine is called ACRANEB_RAD_EFF and effective radii are stored in the type structure defined in the module TYPE_RAD_EFF. Even though it is currently used in radiation only for cloud liquid and cloud ice, there are elements to have effective radii also for rain, snow and graupel. Calculated radii in meters are passed through ACRANEB2 radiation scheme and used in the subroutine AC_CLOUD_MODEL2.
All modified and new (in bold) subroutines are listed here:

`arpifs/phys_radi/acraneb2.F90`
`arpifs/module/type_rad_eff.F90`
`arpifs/module/yomphy3.F90`
`arpifs/module/yomphy.F90`
`arpifs/namelist/namphy.nam.h`
`arpifs/namelist/namphy3.F90`
`arpifs/setup/su0ohy.F90`
`arpifs/phys_dmn/suphy3.F90`
`arpifs/phys_dmn/ac_cloud_model2.F90`
`arpifs/phys_dmn/acraneb_rad_eff.F90`
`arpifs/phys_dmn/aplpar.F90`
`arpifs/phys_dmn/apl_arome/F90`

Externalization of effective radii from microphysics has been done by Daniel Martin. Externalizing subroutine is called micro_liquid_effective_radius.F90.

Calling tree for externalized calculation from ACRANEB2 is the following:

- APLPAR/APL_AROME - initialization of YLRAD_EFF structure
  - **ACRANEB_RAD_EFF - calculating effective radii and filling YDRAD_EFF**
  - ACRANEB2 - passing YDRAD_EFF to AC_CLOUD_MODEL2
    - AC_CLOUD_MODEL2 - using YDRAD_EFF

For the effective radii externalized from microphysics (in APL_AROME only), the calling tree is:

- APL_AROME - initialization of ZEFRA
  - ARO_ADJUST - passing calculated radii, PEFRA to APL_AROME
    - ICE_ADJUST - passing calculated radii, ZRE_LIQ_UM to ARO_ADJUST
      - **MICRO_LIQUID_EFFECTIVE_RADIUS - calculating cloud liquid effective radius, PRE_UM**

In bold are marked subroutines where effective radii are calculated.

3 Validation

The code changes were tested both with APLPAR and APL_AROME on a horizontal resolution of 2.325 km and 87 vertical levels. The radiation scheme used was ACRANEB2. Timestep for ALARO was 90 s and for AROME 60 s. Domain size is shown in Figure 1.

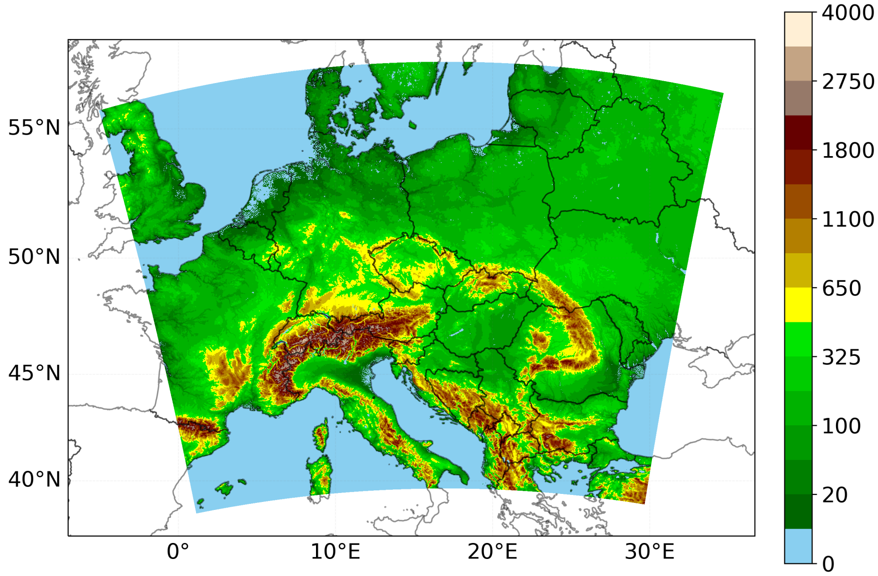


Figure 1: Orography of the domain area in [m]

The model was run for the case of 20^{th} of February, 2021. Forecast length was 24 hours.
Validation of the externalization process has been made on the following experiments:

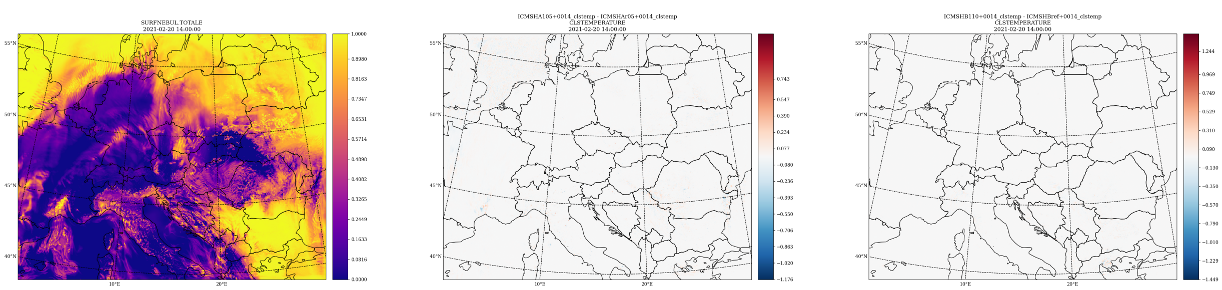
- **EXP1** externalized calculation with changed units
- **EXP2** externalized calculation without changed units
- **EXP3** externalized calculation with changed units, but all coefficients in Pade approximation set to 0.

As the reference was used unmodified code with equivalent settings.
First experiment, including all changes showed weak irreproducibility for the checked variable, screen level temperature. Over the whole domain, bias of the difference between the experiment and the reference was of the order of magnitude up to 10^{-4} K.
Second experiment showed that irreproducibility, although weaker, is present even without changing units, just due to externalizing calculation of the effective radius.
In third experiment, we ensure that $R(x)$ in (1) is equal to zero, $k^{abs} = k^{scat'} = 1$ and $g' = \frac{1}{4}$. Like that, code changes should not have any impact on the results. However, small differences are still present after the sunrise. This shows that there is unexplained irreproducibility in the shortwave calculations, which has been seen also during ALARO refactoring.
In Table 1 are shown biases of the experiments with respect to the reference over the whole domain for screen level temperature.

Table 1: Biases of the difference between the experiments and the reference over the whole domain for screen level temperature

	ALARO			AROME		
h	**EXP1 [K]**	**EXP2 [K]**	**EXP3 [K]**	**EXP1 [K]**	**EXP2 [K]**	**EXP3 [K]**
00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
04	2.5837E-05	4.2914E-06	0.0000E+00	6.0605E-05	7.9109E-07	0.0000E+00
08	1.9828E-04	1.3464E-04	2.1243E-05	2.2127E-05	-6.0963E-06	1.3855E-06
12	2.3257E-04	2.3029E-04	-1.0507E-05	1.1806E-05	-1.0190E-05	-2.8759E-06
16	3.3321E-06	9.2965E-06	5.1721E-05	3.1529E-05	-6.9878E-06	-9.4536E-07
20	-3.0548E-04	-3.1449E-05	-3.4292E-05	1.3958E-04	-1.1891E-05	3.8876E-05
24	-3.5630E-04	-7.3284E-05	-1.2089E-04	9.5036E-05	2.0082E-05	2.6659E-05

In Figure 2 are shown fields of cloudiness from the reference ALARO experiment, differences between final and reference experiment for ALARO and AROME.
It is visible that there are only small changes. Locally, differences reach maximal values of 1.2 K at the south of France for ALARO and 1.5 K over Greece for AROME. Such small local changes can be assumed as a meteorological reproducibility.



(a) total cloudiness, ALARO reference

(b) ALARO

(c) AROME

Figure 2: Total cloudiness of the ALARO reference experiment (left), difference between experiment with externalized effective radii calculation and reference for ALARO (middle) and AROME (right)

4 Comparison with the effective radius from microphysics

Calculation of the effective radius has different approaches in radiation and in microphysics. First, it has to be mentioned that in calculation externalized from microphysics only effective radius of cloud liquid is being calculated, while in radiation also for cloud ice. Apart from that, different formulations are used.
In radiation, effective radii are approximated by a power function (see 46 in [2]):

$$R_e^{rad} = A + B(\frac{\rho_l}{\rho_1})^C, \tag{7}$$

which is dependent only on the cloud liquid water content (ρ_l), ρ_1 is 1 kg/m^3. To have effective radii in meters, A, B and C have values shown in Table 2:

Table 2: Values of the coefficients in the approximation formula for calculation of cloud liquid and cloud ice effective radii in ACRANEB2 radiation

	cloud liquid	**cloud ice**
A [m]	5.200E-06	0
B [m]	4.655E-05	1.620E-04
C [1]	3.000E-01	9.800E-02

In microphysics, Martin et al [1] parameterization for cloud liquid effective radius is used:

$$R_e^{micro} = \left(\frac{3\rho_l}{4\pi\rho_w N_{TOT} k}\right)^{1/3}, \tag{8}$$

where ρ_l is liquid water content, ρ_w density of water, N_{TOT} number concentration of liquid particles in the unit volume of air and k is a coefficient representing spectral distribution of the particle size. Its value can differ but in the code it is 0.77 over sea and 0.69 over land.
Combining equations (7) and (8), we can get the relation between the two effective radii for the cloud liquid particles, one from radiation and the other from microphysics:

$$R_e^{micro} = \left(\frac{3\rho_1}{4\pi\rho_w N_{TOT} k}\right)^{\frac{1}{3}} \left(\frac{R_e^{rad} - A}{B}\right)^{\frac{1}{3\cdot C}} \tag{9}$$

If we insert values for $\rho_w = 1000$ kg/m^3, $N_{TOT} = 10^8$ m^{-3} and $\rho_1 = 1$ kg/m^3, we get:

$$R_e^{micro} = 10^{-\frac{11}{3}} \left(\frac{3}{4\pi k}\right)^{\frac{1}{3}} \left(\frac{R_e^{rad} - A}{B}\right)^{\frac{1}{3\cdot C}} \tag{10}$$

In case of $C = 0.3$, their relation is almost linear.
In Figure 3, scatter plot of R_e^{micro} and R_e^{rad} from the model output is shown. Values are taken from the test case for the whole domain, every 10 minutes. Red line is representing relation (9).
It can be concluded that for big radii ($R_e^{micro} > 6$ μm), values are following the red line. For smaller values, there is significant deviation from the relation (9).
That deviation can be explained by the fact that in-cloud liquid water content ρ_l in equations (7) and (8) is not the same. It is calculated from specific water content and air density and then divided by the cloud fraction. Cloud fraction in microphysics and in radiation is not calculated in the same way. They are matching for high specific water contents, when they are equal to 1 (overcast). For smaller specific water contents, however, AROME cloud fraction entering radiation is evidently not the same as the one used in microphysics. Origin of this difference has to be understood.

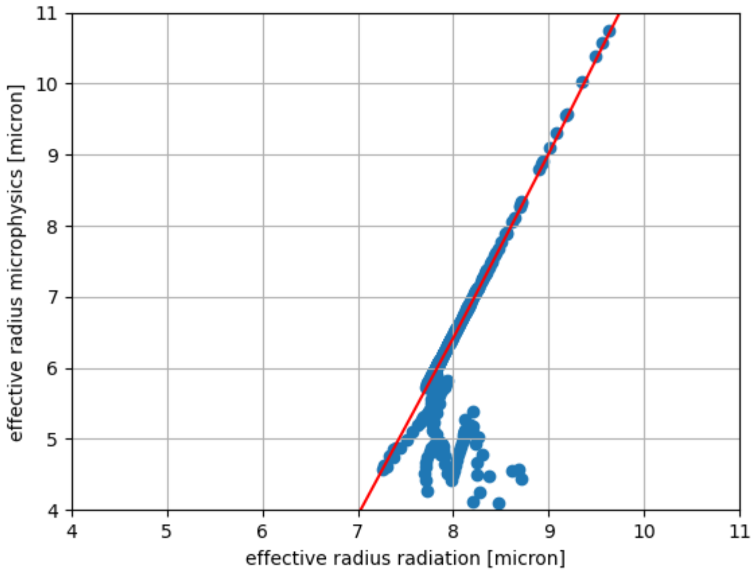


Figure 3: Scatter plot of effective radii from microphysics and radiation from the model and red line is representing their theoretical relation.

5 Conclusion

For the purpose of interoperability across ACCORD consortium and inside of the code, there was idea to have externalized calculation of cloud water particles effective radii. Calculation of effective radii in meters for cloud liquid and cloud ice has been externalized from ACRANEB2 radiation scheme. Results are not reproducible with the old way, but we concluded that differences are minor and can be neglected. Between the effective radii calculated in radiation and in microphysics, there is power relation which would allow transformation from one to the other using simple conversion formula. However, it should be further investigated for the case of small droplet sizes where difference in the cloud fraction between radiation and microphysics causes deviation from the conversion formula. Treatment of cloud fraction in AROME must be understood, so that we can use microphysical effective radii in radiation properly.

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References

[1] G. M. Martin, D. W. Johnson, and A. Spice. “The Measurement and Parameterization of Effective Radius of Droplets in Warm Stratocumulus Clouds”. In: *J. Atmos. Sci.* 51 (1994), pp. 1823–1842. DOI: `https://doi.org/10.1175/1520-0469(1994)051%3C1823:TMAPOE%3E2.0.CO;2`.

[2] J. Mašek et al. “Single interval shortwave radiation scheme with parameterized optical saturation and spectral overlaps”. In: *Q. J. R. Meteorol. Soc.* 142 (2016), pp. 304–326. DOI: `10.1002/qj.2653`.