Title: HARMONIE-AROME Radiation Studies 2011-2016

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HARMONIE-AROME radiation studies 2011-2016

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1 Introduction

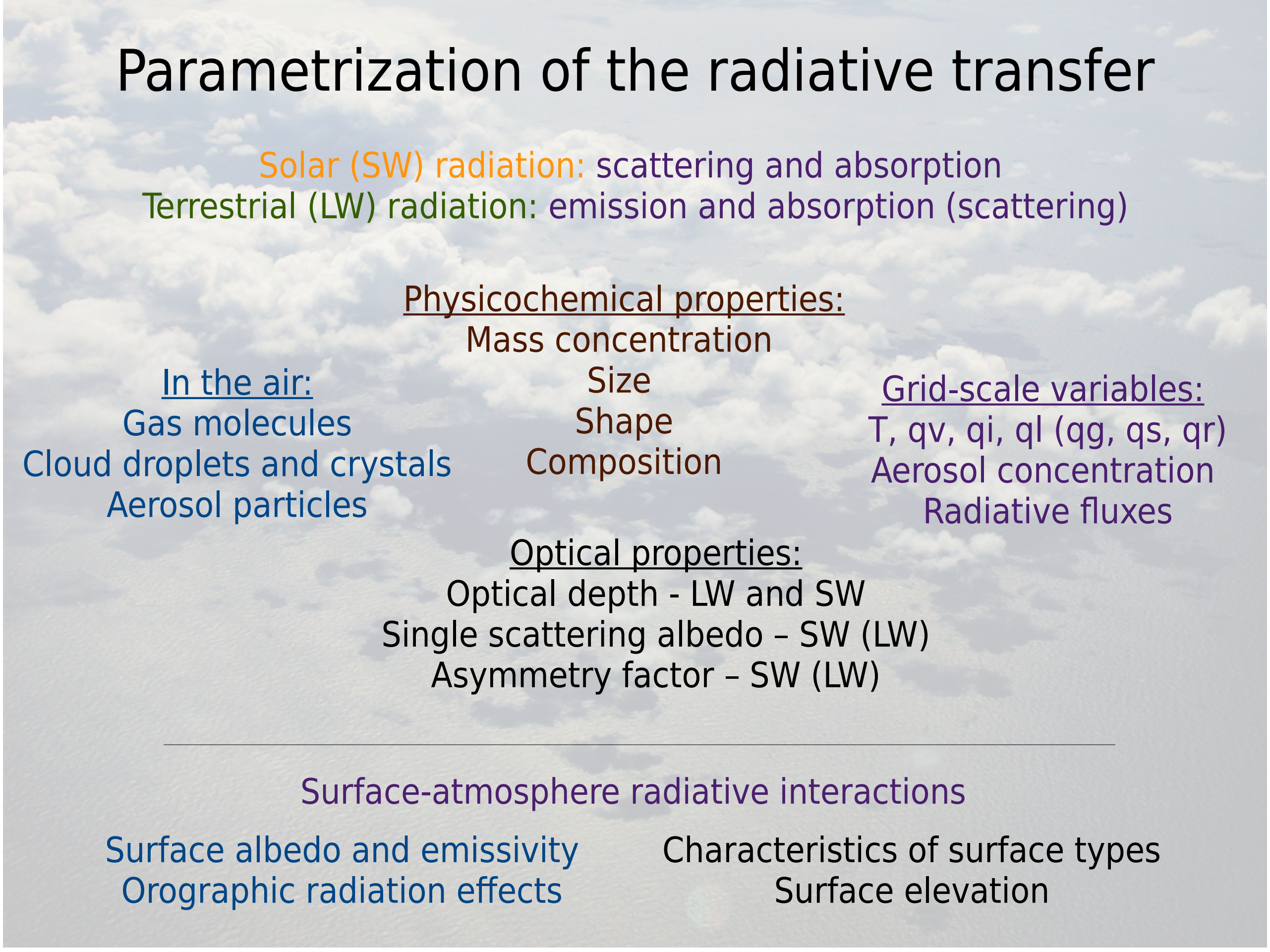
The idea for a HARMONIE-AROME radiation comparison was presented five years ago at the annual EWGLAM /SRNWP meeting (Rontu, 2011). It was suggested that the best radiation parametrizations for a meso-scale NWP model are those which can optimally and consistently use information about cloud microphysical properties, cloud extent, surface radiation properties and aerosol data available in the model; this information varies rapidly in both time and space. There was a need to create a platform for the comparison of radiation parametrizations of varying complexity in a unified environment. Consequently, such a platform has been built within the AROME physics subroutine (apl_arome), where the IFS (from here onwards: IFSRADIA; ECMWF, 2006), ALARO (ACRANEB2; Mašek et al., 2016) and HIRLAM (HLRADIA, Savijärvi, 1990; Wyser et al., 1999) radiation schemes can now be called using the same input fields. In addition, each scheme generates the same output parameters. To date, nine radiation working weeks have been arranged between 2012 and 2016 in order to make comparisons of and improvements to the schemes available in HARMONIE-AROME. A summary of some of this work and outcomes is presented in this article.

The aim of the radiation parametrizations in an NWP model is to estimate the radiative heating in the atmosphere due to the vertical divergence of the net longwave (LW) and net shortwave (SW) radiation fluxes. This is a source term in the thermodynamics equation in the model. The radiation parametrizations also provide the model with the surface-level downward (LWDN, SWDN) and upward (LWUP, SWUP) radiation fluxes, which are part of the surface energy balance and a lower boundary condition for the calculation of atmospheric radiation transfer.

The variables and processes inluded in the parametrization of the SW and LW radiative transfer in HARMONIE-AROME are illustrated schematically in Figure 1. Parametrizations of the optical properties (optical thickness, single-scattering albedo and asymmetry factor) of liquid clouds, ice clouds and six aerosol types are used in the SW part of the spectrum. These optical properties are also used in the LW calculations in the ACRANEB2 scheme. However, in IFSRADIA and HLRADIA LW scattering is neglected and therefore only the layer optical thicknesses are used for the corresponding LW calculations in these schemes. The optical properties are calculated as a function of the layer mass load, the effective sizes of the cloud particles and the aerosol type. The effective sizes of the cloud particles depend on the concentrations of cloud liquid, cloud ice and on temperature.

It is important to note that using (part of) the grid-scale mass of snow and graupel precipitating particles in the radiation parametrizations but assuming that these have the same inherent optical properties as cloud ice crystals, may lead to unexpected results. The entire chain of parametrizations needs to be considered in order to improve the atmospheric radiative transfer calculations.

The radiative properties of the surface (i.e. surface temperature, albedo and emissivity in addition to variables for orographic radiation parametrizations such as slope angles and local horizon) depend on surface properties (e.g. surface type, vegetation etc.) and elevation. These are provided by the physiography, climatology and analysis (e.g. snow cover) or are derived in other parametrizations (e.g. soil surface temperature).



Parametrization of the radiative transfer

Solar (SW) radiation: scattering and absorption
Terrestrial (LW) radiation: emission and absorption (scattering)

Physicochemical properties:
Mass concentration
Size
Shape
Composition

In the air:
Gas molecules
Cloud droplets and crystals
Aerosol particles

Grid-scale variables:
T, qv, qi, ql (qg, qs, qr)
Aerosol concentration
Radiative fluxes

Optical properties:
Optical depth - LW and SW
Single scattering albedo – SW (LW)
Asymmetry factor – SW (LW)

Surface-atmosphere radiative interactions

Surface albedo and emissivity
Orographic radiation effects

Characteristics of surface types
Surface elevation

Figure 1: *Variables and processes inluded in the parametrization of the SW and LW radiative transfer in HARMONIE-AROME. Notation of the grid-scale variables: T = temperature, qv = specific humidity, qi = specific cloud ice water content (cloud crystals), ql = specific cloud liquid water content (cloud droplets), qg = specific precipitating graupel content, qs = specific precipitating snow content, qr = specific rain content (rain drops). qg, qs and qr as well as LW scattering are in brackets because their inclusion in the radiative transfer calculations is optional.*

Within the HARMONIE-AROME framework, it is possible to address the questions posed in the 2011 EWGLAM / SRNWP presentation (quotation rephrased):

“The aim of the model comparison experiment is to compare and validate HIRLAM-ALARO-AROME radiation parametrizations over complex terrain. The experiment should provide the information needed to understand the relative importance of the following in mesoscale models:

1. Advanced multi-band clear-sky radiative transfer parametrizations (provided by the ECMWF radiation scheme within AROME)
2. Accurate handling of cloud-radiation interactions, necessary due to the improved time resolution of radiation calculations
3. Improved treatment of radiation-surface-interactions, including sloping surface parametrizations.”

The hypothesis was that in the mesoscale models the fast interactions between clouds and radiation and the surface and radiation could be of greater importance than accounting for the spectral details of the clear-sky radiation. Thus, computationally affordable single-band schemes like HLRADIA and ACRANEB2, which can be run at high temporal and spatial resolution at the expense of high spectral resolution, could be more suitable for this type of model than schemes like IFSRADIA which are developed for large-scale models.

2 Atmospheric comparisons

SW radiation fluxes from the IFSRADIA and HLRADIA schemes were tested by Nielsen et al. (2014) and compared to DISORT (Stamnes et al., 1988, 2000) benchmark results in single-column MUSC experiments, based on code from the harmonie-37h1.radiation branch. In this study, a diagnostic MUSC framework without integrations in time, was applied in clear and cloudy sky aerosol-free test cases. The cloud condensate content (liquid and ice) and the effective particle sizes were prescribed; no observations were used in the comparisons. It was found that the results of the experiments using the simple broadband HLRADIA scheme are as good as those from the spectral IFSRADIA scheme, especially in cases involving liquid clouds. A new parametrization of cloud liquid optical properties for IFSRADIA (the Nielsen cloud liquid optical property scheme) was suggested and found to perform better than the default Fouquart scheme (Fouquart, 1987) for a range of sensitivity tests.

The current status of the actions related to SW radiation, suggested by Nielsen et al. (2014), is summarized below:

- The current choice of six SW spectral bands in HARMONIE-AROME/IFS should be re-assessed, as the first spectral band is irrelevant for NWP modelling. *Status: task found to be of low priority, not done.*
- The effect of changing the SW cloud inhomogeneity factor from 0.7 in IFSRADIA (0.8 in HLRADIA) to 1.0 should be tested against observations of global radiation in the framework of 3D HARMONIE-AROME experiments. *Status: tested using IFSRADIA, update accepted in HARMONIE cycle 40h1 (Gleeson et al., 2015).*
- The effects of using the Nielsen cloud liquid optical property parametrization within the IFS scheme on the general 3D NWP results should be tested against observations of global radiation. *Status: tested over the Irish operational domain, update accepted in HARMONIE cycle 40h1 (Gleeson et al., 2015).*
- In order to improve the delta-Eddington radiative transfer calculations, the possibility of using a variable average zenith angle for diffuse irradiances (as outlined in Räisänen, 2002) should be investigated. *Status: not done.*
- The HLRADIA gaseous transmission coefficients should be tuned to the Kato-DISORT clear sky results presented in Nielsen et al. (2014) and repeated for the other AFGL atmospheric profiles. *Status: done, coefficients updated (Gleeson et al., 2015).*
- The impact of aerosols needs to be investigated. *Status: done, results published in Gleeson et al. (2016); Toll et al. (2016, 2015)*

The direct radiative effect of aerosols on SW radiation fluxes under clear-sky conditions in HARMONIE-AROME was studied by Gleeson et al. (2016). Diagnostic single-column MUSC experiments were performed in this case also, but observational data from the Tõravere observatory in Estonia were used to define the aerosol load and to estimate the inherent optical properties of the aerosols. A case study involving Russian forest fires during the summer of 2010 was selected for the experiments. In this case the aerosol was assigned to the land aerosol category in MUSC. The simulated SWDN fluxes were compared to observations of global radiation. The initial atmospheric state (temperature, humidity etc.) was extracted from 3D HARMONIE-AROME experiments at each hour for which a diagnostic MUSC experiment was run.

We found that the optical properties of the aerosols and their spectral distribution, and not only the mass concentration, are important. Compared to observations, the broadband radiation schemes (HLRADIA, ACRANEB2) were found to provide similar global radiation fluxes to the six-band IFSRADIA scheme. We also found that the simulated global radiation shows better agreement with the measurements when the broadband aerosol optical depth (AOD) and the corresponding single-scattering albedo and asymmetry factor, derived from observations, were used instead of the climatological or parameterized aerosol optical properties (Tegen et al., 1997; Hess et al., 1998).

Aerosol-radiation interactions were also discussed in the synoptic-scale studies by Toll et al. (2016) and Toll et al. (2015). In these studies, 3D model experiments using ALARO physics, as opposed to AROME physics, and the IFSRADIA radiation scheme were performed over Europe for a time period where the aerosol distribution was close to the climatological average and separately for the summer 2010 Russian wildfire case study. For the period where the aerosol distribution was close to the climatological average, accounting for the direct radiative effect of aerosols using the more realistic time-varying aerosol data from the Monitoring Atmospheric Composition and Climate (MACC) reanalysis (Inness et al., 2013) rather than the default climatology of (Tegen et al., 1997) improved the accuracy of the simulated radiative fluxes. Improvements in the temperature and humidity forecasts in the lower troposphere were also found compared to the case where the direct radiative effect of aerosols was not included. Although the dependency of forecast synoptic conditions on the aerosol dataset was found to be weak, it is important to at least account for the climatological average of the direct radiative effect of aerosols over Europe. On the other hand, for the wildfire period in Russia and Eastern Europe during the summer of 2010 where aerosol concentrations were very high, near-real-time aerosol distributions rather than climatological averages, were needed to account for the direct radiative effect of the aerosols. Including aerosols from the MACC reanalysis rather than the default Tegen climatology considerably improved the forecast of near surface temperatures, global radiation and the vertical profile of temperature.

3 Surface interactions

Surface albedo is needed by the atmospheric SW radiation parametrizations and possibly as output from the forecast model. It is an important parameter which affects radiation-surface interactions. The derivation of the grid-scale albedo for the radiation parametrizatons in HARMONIE-AROME is complicated and may still contain inconsistencies. In the future, it may be possible to use albedo climatologies, e.g. Blanc et al. (2014) or analysed albedos based on near-real-time satellite observations.

There are three aspects to surface albedo: spectral, surface and time dependance. The albedo of bare land and vegetation for the UV, visible and near-IR wavelength bands is provided by SURFEX (PGD). From these, the value for each of the six spectral bands of IFSRADIA, and a broadband value for ACRANEB2 and HLRADIA, is derived using the assumed spectral distribution of SW radiation in the lower troposphere. Currently, the albedo of snow is a prognostic variable in the default snow parametrization scheme in HARMONIE-AROME (applied for seasonal snow, but not for glaciers!). Sea and lake surface albedos are modified by corresponding parametrizations. Separate albedos are defined for the direct solar beam and for diffuse radiation. A simple formula, dependent on the solar zenith angle (SZA), $albedo_{dir} = albedo_{dif} + 0.2/(1 + cos(SZA)) - 0.12$, is suggested for the calculation of the direct beam albedo.

Another example of radiation-surface interactions are the effects of orography on radiation. Recently, parametrizations developed for the HIRLAM model (Senkova et al., 2007) have been imported to SURFEX (Wastl et al., 2015; Rontu et al., 2016) and are available via the apl_arome and aplpar interfaces in HARMONIE-AROME. In these parametrizations the surface slope, sky view and shadow factors are used to modify the surface SWDN and LWDN radiation fluxes calculated by any of the available atmospheric radiation parametrization schemes. The factors are derived from the high-resolution source orography data for each gridpoint in the model domain. Detailed sensitivity studies, over the Sochi Olympics area, using 3D and single-column experiments, showed that substantial, and physically realistic, changes in SWDN and LWDN radiation fluxes take place locally.

However, their influence on the simulated screen-level temperatures was small (Rontu et al., 2016). A conclusion from the Sochi study was that a comparison of the simulated and observed radiation fluxes would offer a more reliable alternative to screen-level temperatures for model validation. This is dicsussed in more detail in Section 4.

It is recommended that the output albedo, possibly requested by users of HARMONIE forecasts, is derived from the accumulated surface SWDN and SWUP radiation fluxes. Using this method, additional effects due to urban or orographic radiation parametrizations, which can be implicitly included in the atmospheric radiative transfer calculations as described in the previous paragraph, can be taken into account.

4 Validation by radiation

Observed radiation fluxes provided by surface stations and satellites offer an interesting possibility for validating NWP models:

- Observed and predicted fluxes have a greater correspondence to each other than observed and predicted cloud cover or screen-level temperatures for example.
- More ground-based and satellite SW observations are becoming available – how should we use these for systematic monitoring and validation of NWP models?
- Reliable SW radiation fluxes are increasingly required for the solar energy industry.

An example of using surface-based downwelling and upwelling SW and LW fluxes for intercomparison of the IFSRADIA, ACRANEB2 and HLRADIA radiation schemes within HARMONIE-AROME was shown by Kangas et al. (2016), who described the mast verification system maintained by FMI *http://fminwp.fmi.fi/mastverif*. It was found that the three radiation schemes produced somewhat different LWDN radiation fluxes under cloudy conditions. However, this did not change the overall cold bias in the predicted screen-level temperature compared to observations recorded at the FMI-ARC Sodankylä observatory.

SWUP (reflected SW radiation at the surface) is related to the surface albedo. Observations of this parameter represent local conditions, especially over snow covered areas. LWUP is related to surface temperature and again represents local conditions over open and, possibly snow-covered, land for example. The grid-average values of SWUP and LWUP in an NWP model, even a very fine resolution model, represent a bird's-eye view of the parameter. In Sodankylä during spring this is analagous to flying high over the tree tops and seeing dark trees in addition to the white snow-covered surface. For this reason, modelled and observed SWUP is generally not comparable. More studies are needed in order to understand the statistical dependency between surface temperature and LWUP.

Simulated and observed LWDN fluxes are related to the cloud condensate content (liquid and ice), cloud cover, cloud bottom temperature and, in clear-sky cases, to the near-surface air temperature and humidity. SWDN is related to cloud condensate content, cloud particle size and cloud cover. Under clear sky conditions aerosol content and specific humidity play the most significant roles. Real-time SWDN flux measurements are available at SYNOP stations in many countries and thus offer the potential of including such observations in the standard verification of HARMONIE-AROME.

Gleeson et al. (2015) introduced validation of SWDN radiation using the clear sky index (CSI). This is a useful parameter for comparing SW radiation because it also acts as a proxy for cloud cover and cloud condensate amounts. The index is the ratio of global SWDN divided by the maximum possible global SWDN for a given location, date and time. A reliable estimate of the maximum clear-sky SW radiation flux can be obtained from the model. However, in this study, it was calculated by applying the HLRADIA clear-sky formulation off-line.

Using CSI as a proxy for cloudiness highlights the binary (on/off) nature of cloud cover in HARMONIE-AROME. This is indicated by the U-shape of the model curves in Figure 2 which shows the CSI calculated for

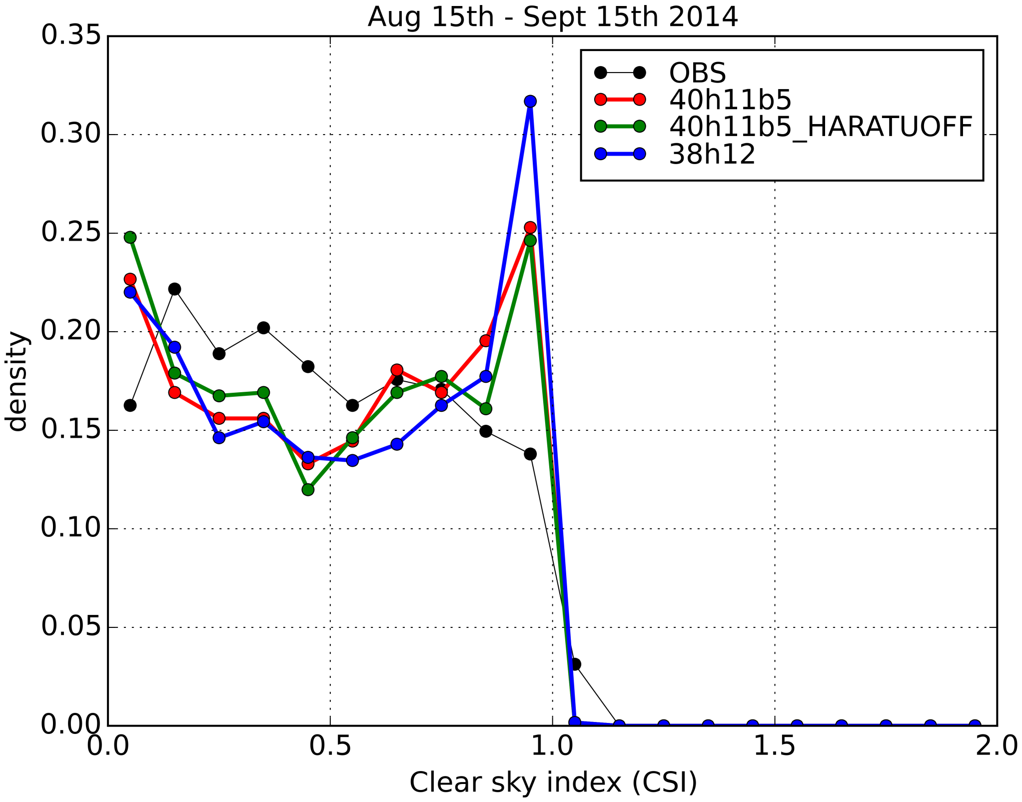


Figure 2: *Probability distribution function of the Clear Sky Index (CSI) based on observations (at 6 synoptic stations in Ireland; black dotted continuous line) and HARMONIE-AROME 6-hour forecasts (for 3 configurations of the model (red, green, blue dotted continuous lines) - see inserted legend for details) for the period August 15th to September 15th 2014. In general the CSI is close to 1 under clear sky conditions. However, the CSI may also be high for cases with total cover when the clouds are thin.*

Irish stations in August/September 2014 using observations and 3 configurations of HARMONIE-AROME: 1) cycle 38h1.2, 2) cycle 40h1.1.beta.2 (using the Nielsen SW cloud liquid optical property scheme, a cloud inhomogeneity of 1.0 and updated atmospheric turbulence scheme HARATU (HARMONIE-RACMO TUrbulence), 3) same as 2) but without HARATU.

5 System aspects

Three radiation schemes (IFSRADIA, ACRANEB2 and HLRADIA) have been configured in the HARMONIE-AROME radiation development branch and in several MUSC experiments using the HARMONIE-AROME framework up to cycle 40. It is planned to make these available and to carry out further testing using the harmonie-43h1 cycle. In cycle 43, SURFEX v.8 will be available. Within this framework it will also be possible to implement the orographic radiation parametrizations for further testing and possible operational use.

It is planned to introduce more up-to-date aerosol data into the forecast system. The work will start with a renewal of the climatological aerosol data, with the eventual goal of using the near-real-time aerosol data available at ECMWF. The radiation schemes in HARMONIE-AROME have already been shown to be capable of using this aerosol data. However, work needs to be done on the indirect (cloud-related) effects of aerosols.

We have suggested introducing surface-based global radiation observations into the standard validation of the operational HARMONIE-AROME system. An inventory of available observations and an implementation plan are needed for this.

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