The ALADIN System and its Canonical Model Configurations AROME CY41T1 and ALARO CY40T1

Reply to the comments of reviewer 1

Indeed, this paper documents a NWP system that is the result of more than 25 years of R&D activities, and it is quite a challenge to document this. Reviewer 1 is right that this paper became the result of many contributions from many authors. All of his/her comments are relevant and to the point. We took the opportunity to implement them in a revised manuscript and we believe it improved a lot by doing so and thank him/her for this. We also made an effort the remove some sections that are not relevant for the presentation.

Replies to the General comments

1/ The text on pages 20-21 (especially lines 544-574) is quite cryptic and inconsistent with the rest of the paper. Here rather than documenting the particular physics package it looks like some ideas or guidelines are presented. They are however hardly justified by some published evidence or experience from other NWP centers. The ACRANEB2 radiation is used without a word of introduction there. The explanation is jumping from microphysics to convection. The presented text is not self-explanatory: What is meant for example "modularity at the level of processes"? I suppose every microphysics scheme is in a way modular by describing separately process by process. Some extensive revision and shortening of this text resulting ideally in description on what has been actually implemented would be highly desirable. (Without too much arguing WHY: This should have been published already elsewhere.)

Indeed, this part is now rewritten, (see lines 575-629).

2/ The text has the ambition to serve as an reference (for the ALADIN and also external community). To help this purpose it would greatly improve the navigation when the schemes described in section 2.2 are highlighted (in bold or italic) near the area they are described. When they are mentioned later on in the text a general reader would easily search for them even working with printed text. (For example by highlighting the SSDFI at L276 you will improve the readability of the text at L777.) This could be seen as a poor man's glossary.

Good suggestion, in the revised manuscript we introduce subsubsections with titles that include the name of the schemes.

We have moved the paragraph that identifies the differentiation of the LAM specific features w.r.t. to the global model features, to improve the structure of the section (now to be found in lines 221-226).

3/ Some part of the text looks like fillers. A reader may not see a clear reason for incorporating those into the paper. For example Figure 7 brings no specific extra information. It would make perhaps more sense if there is a comparison of the new and old Polish domains. But the same could be summarized easily without a figure. Especially when there is already Figure 6 illustrating roughly the same. Instead of complicated and sometimes very case specific results from newer model versions one would ex pect to find some highlight parameters of scores from global models (those used for boundary conditions), reference LAM version and new LAM version. This is clearly missing.

Indeed, and section 4 is mostly problematic for this.

We have restructured the text of this section in two clearly distinct subsections: **4.1 Current status of the implementations** and **4.2 Added value.** By doing so we removed the repetitions in the text. Added value is addressed in 4.2 in terms increased realism and by few scores targeting extreme precipitation (comparing the LAM to the global models ARPEGE and ECMWF). It is impossible to give an overview of all of the verifications of the applications in all of the 16 ALADIN countries. We select here a only few cases: Météo-France, ZAMG, RMI and Croatia. We also removed the example of Poland, it is indeed a filler. The other examples are now functional in our opinion.

There are also plenty of references having no relevance to the paper. As the data assimilation is out of the scope of this paper, a reader may ask why there are so many papers referred to this subject? Some other references are definitely not the most appropriate to the presented subject. Please be honest and provide only relevant references to the presented text.

The ALADIN System is the result of code developments since 1990. So it is rather normal that there is a lot of literature. Also, it describes three physics packages of ALADIN, AROME and ALARO, which increases the cited literature. Nevertheless, we have taken the opportunity to go through the citations and we removed the ones that we think are redundant, specifically the ones you question in your specific comments below.

4/ On page 5-6 you describe a procedure of a new model version assembling. It is not clear however how the evolution of the global model code is interfering with this. How the decision about what is implemented at the level of the LAM code is taken? Or does it mean everything developed for global model automatically propagates to the LAM? What about some specific global model issues which are not relevant for the LAM community (like specific treatment of poles)? Do you have some general guidelines or those are solved on case to case basis? Is there some experience with the opposite direction code propagation, like a code developed initially for the LAM model has been made available for the global model too? This perhaps rather particular question tries to reveal a bit more about this rather unique duality that the same code is used for LAM and global model communities.

First of all, this is not a new method, but this is the first time we describe the existing one in a publication. We have added a paragraph describing the general guidelines (called fundamental rules in the text), in lines 130-157.

Replies to the Specific comments & Technical corrections

1/ Purpose of the paper is given twice: p1/10 and once again p4/90-102. Could it be perhaps unified and reduced to just one list?

Indeed it is given once in the abstract and once in the introduction. We have reworded the scope in the abstract (lines 11-14) and have removed the scope description from the introduction. It is a filler as you mention above.

2/ Duplicated text describing the paper limitation: See p1/L15-6 and once again p4/L103-4. In this latter case the repetitive text brings just references to additional papers having no relevance to the described CMCs.

Here also, the introduction elaborates what is announced in the abstract. We have moved the climate application of the CMC to section 4.3 (lines 848 - 850). Data assimilation is an important part of

NWP so it should be mentioned at least. It comes now after the “This paper is organized as follows ...” part (lines 105-107). The references are removed removed from the introduction.

3/ p5/L132 text mentions a five-step process defining the scientific developments of the ALADIN System. Apparently there is no such description given in the paper (or it is well hidden). What this "five-step process" should be representing then? When it is given somewhere in the text please make it more explicit to be obvious without an extensive search.

Indeed. In fact this paragraph is very general and we moved it to the consortium description in the introduction (lines 27 - 37). If you read it carefully it contains 5 steps. But this is irrelevant here, so we do not mentioned the five steps anymore.

4/ p7/L182-5 Could you explain what is the driving force for you to insist on long time steps? Is it the computational efficiency? Or do you have some specific scientific reason for it? (The computational efficiency doesn’t need to be necessarily always justified by long time steps.) This claim feels bit like a dogma. But it is not clear for a reader why this is so important here.

The model has to be run on a large variety of computing platforms. This is now added in a footnote to the text on p. 7.

5/ p7/L195 Is the best reference for the SI scheme really the given papers from Caluwaerts et al?

The first one is not relevant. The second was meant as a review. We removed both of them.

6/ p8/L215 Could you bit develop on this claim relating the 3km threshold and "important" role for the non-hydrostatic dynamics? First, it is not clear how this threshold is defined in terms of model: Are you referring here the grid point distance of the computational mesh, the shortest wave represented by the model or even a size of the smallest fully resolved feature of the model? Second, please specify the "important role". Could you perhaps give some reference to clarify this claim? To the reviewer’s knowledge there is no clear agreement on it. One can perhaps find some effects not simulated with hydrostatic dynamics at those scales. But this still doesn’t justify the necessity to use non-hydrostatic dynamics there. One can argue that the non-hydrostatic schemes are only essential when it comes to the simulation of the convective effects. Here we are however referring scales bellow ~100m of grid resolution. Finally, the role of "details of the used numerical scheme" is also not very clear here. Do you mean the true resolution given by the particular numerical scheme? Or something else is meant? To conclude: this sentence sounds like referring some common truth. If there is such an evidence, please provide some reference. Alternatively please make this statement less controversial.

This is a fundamental discussion. It is not the goal of the paper to have that discussion here, but we describe the current practice with the consortium. We have reworded this, see lines 229 – 233.

We have also removed the reference to (1-5 km) in the introduction, it is not mentioned in line 90 of the new manuscript.

7/ p8/L220 For VFE there is more fundamental reference of Untch and Hortal to be used rather than the one given in the text.

Untch and Hortal 2004 are the implementations for the hydrostatic dynamical core. Vivoda and Smolikova developed a new VFE scheme for the NH dynamics. This is now reworded in lines 236 – 239.

8/ p9/L256 When you give the diffusion order, you should also specify the resolution (and/or) truncation. Does it mean all presented configurations from Table 4 are running with this 4th order horizontal diffusion (including 18 km Aladin-NORAF and 1.3 km Arome France)?

We actually have written that it is “usually” 4-th order.

This is indeed resolution dependent and may vary quite a lot among the various applications in table 5. Also some applications rely more on SLHD than on the Laplacian operator. A detailed description would lead us too far, so we remove this sentence about the 4th order from the text.

9/ p11/L291-3002 It is nowhere specified how wide the relaxation area is. From the text at p27 it is apparent the number of coupling zone points is varying. How the given values of parameters p (L301) are modified with respect to the changing z? It is quite evident the optimal value of p must be related to the number of points in the coupling zone and model resolution. Can it be precise here?

This is now explained (319 - 321). For the power p, ALADIN partners use the values from the standard namelists, i.e. the values mentioned in the paper.

10/ Several places like p12/L354 and p13/L363,364 are using term "dual parallelization". This is not at all very common term. Presumably it is meant mixed or hybrid MPI/OpenMPI parallelization? If so please change it to hybrid parallelization which is more commonly used name.

Yes. We now use the wording "hybrid (MPI/OpenMPI) parallelization” to clarify that, see line 194 and line 379.

11/ p16/L448 The sensitivity of the scheme to the time step length has been... changes. This sentence brings no information to a general reader. Please either provide some details or drop it.

We drop the line.

12/ p17/L487 This 15 minutes intermittency is used at every Arome configuration? Your example is given with Arome 1.3 km and 50s time-step. But there are some 2.5 km and 90s Arome configurations in the Table 4. Does it mean the 15 minutes remains fixed regardless the actual time-step length?

Yes, indeed, this 15 minutes choice does not depend of the horizontal resolution nor time step of the model. In Table 4, 90 should refer to vertical levels, not time step. We change “full radiation computations are performed once every 15 min” by “in all AROME configurations (2.5 or 1.3 horizontal resolution) full radiation computations are performed once every 15 min. For intermediate time steps, only solar azimuth angle varies.” (lines 515 -518).

13/ p14-p19 (Arome CMC) At scales of 1.3km is certainly not negligible a contribution of horizontal mixing/turbulence. Please give some details about your representation of those highly non-liner horizontal effects.

Yes, indeed, at 1.3km scales, there is probably a not negligible contribution of horizontal mixing/turbulence, but due to diffusive processes (Semi-Lagrangian advection for instance), the ‘effective’ resolution of the model is far from being 1.3km (Ricard et al.,2013) and we can still use a 1-D turbulence scheme (Honnert et al., 2016).

Honnert, R. : Representation of the grey zone of turbulence in the atmospheric boundary layer, Adv. Sci. Res., 13, 63-67, https://doi.org/10.5194/asr-13-63-2016, 2016.
Ricard, D., Lac, C., Riette, S., Legrand, R. and Mary, A. (2013), Kinetic energy spectra characteristics of two convection-permitting limited-area models AROME and Meso-NH. Q.J.R. Meteorol. Soc., 139: 1327–1341. doi:10.1002/qj.2025

This discussion would lead us too far so we prefer to not change the text.

14/ p20/L546-8 Separation of scales is not unnatural. I believe it is meant rather arbitrary. The separation of processes to dry and moist is equally unnatural/arbitrary, by the way. The text is not correct. There can't be such clear separation. This just says the microphysics is called twice in this case.

We agree. The separation issue has not been very well explained, thank you for pointing it out. We redrafted the relevant part of the text to make it clear we speak about diverging parameterization concepts. We also clarify there is a single (and not double) call to the microphysics, see lines 586 - 594.

15/ p22/23 Could you specify the closure used for the turbulence scheme? Is it closed by a mixing length? And if so, which one?

We now provide an explanation: lines 669 – 681.

16/ p23/L622-626 Rather strange text with a link to turbulence but then mentioning microphysics. What is the relevance of it? Does the microphysics influences the turbulence?

The paragraph is now rewritten: 690 – 694.

17/ p24/L654-5 This is rather strong claim. Could you perhaps give some reference or bring some more evidence supporting it?

This sentence is now rewritten in lines 723 – 726.

18/ p22/24 Can you give some description for the microphysics and gravity wave drag parameterization? A reader may wonder what makes those two schemes so unattractive that the only information about them can be found in the table 3.

It is the Catry et al. 2008 GWD. This is now introduced in a bit more detail in the new version of the text (it is the same as the one for the ALADIN CMC), see lines 727 – 732.

19/ The paper of Lopez(2002) being referred as the microphysics description is introducing only three prognostic variables: water vapour, cloud condensates and falling precipitation. Is this really the case for the presently used microphysics? If not could you explain the choice of prognostic variables related to the microphysics in ALARO CMC?

This has been addressed in the new text that was provided to respond to your general comment 1, see line 626.

20/ p25/L671: Missing "with" or "to"?

Indeed. This is now corrected, line 755.

21/ p26/Table 4. Please specify the date of validity. The actual state could be evolving.

Good point. A priori it is the date of submission, but it helps if it is added to the caption of the table. We also added it to the figure of the domains.

22/ p28/Fig 8 Are the curves based on annual verification of the two models? If so it is truly impressive, but better to say it more explicitly. In the other case please specify the verification period. It would be also useful to add the zero horizontal line (especially to the upper panel) in order to help the results interpretation.

This part of the text was removed in reply to your above comment on fillers.

23/ p32/Fig 11 The red dot is nearly invisible (especially when printed). Please use some better way to highlight it. This figure demonstrates the superiority of the newer version of ALARO over the operational one. Could you then add the operational results to illustrate it graphically?

The red dots are now replaced by black dots.

The difference in scores between the 1.3 km and our current 4 km resolution operational version is minor. This figure illustrates the increase in realism when increasing the resolution. It would lead too far to provide a case study.

24/ p33/Fig 12 Could you please zoom the figure to its lower third? It is really difficult to follow the presented the multiple lines of HR-alaro-88 and HR-alaro-HRDA.

Indeed. This is now done.

Reply to the comments of reviewer 2

We thank Per Unden for his comments and suggestions. We have implemented his suggestions in a revised manuscript.

Replies to his detailed comments

1. *typo: line 273 p 10: In operation . . .. should be operational*

This is corrected in the new version of the manuscript, see line 295.

2. *line 240 p 9 : . . .. more conservative semi-Lagrangian . . ... : please make the link to the same but a bit longer explanation of this scheme around line 413. Perhaps also here refer to it as COMAD to make it consistent.*

The description more extensive description of COMA mentioned in the AROME CMC part is moved to section 2.2, and lines 439-440 then refer to section 2.2.1. This should improve readability.

3. line 420 p 11 : Please make the comparison with the TKE scheme in ALADIN/ARPEGE on line 391. From the text it appears to be the same scheme albeit with some different variables but it is relevant here to state what is shared and what the differences are between the TKE schemes, or indeed if they are or could be the same or share the same code.

The turbulence scheme used in Arome differs from the one used in Arpege/Aladin mainly on the vertical discretization of TKE defined on full levels versus half levels respectively. Both schemes have been compared in several 1D cases and the results are very similar. There is an ongoing work to share exactly the same code.

This is now explained in the text in lines 447 – 450.

4. line 439, p 16: In this way . . .. of a RH-scheme . . .. : I don't understand this at all. The earlier sentences all give the message that the scheme is everything but a RH scheme! Which of the "ways" just mentioned makes it a RH scheme? Please qualify and explain or change if it is an error.

We would say that in such particular conditions (no turbulence), with this extra term, the cloud schemes acts as a RH-Scheme. We explain this now in lines 465 – 469: "In order to represent ..."

5. line 450 p 16 2-moment scheme . . .. implemented . . .. : please add something like not activated since on 441 you describe the current one moment scheme, confusing for the non-initiated.

We added in the text "(used in research mode, not yet activated in operational)" in line 480-481.

6. Line 473 p 16: Again, please compare with ALADIN radiation on line 388. There are many common components in the basic scheme it seems.

ALADIN and AROME used radiation schemes are the same (RRTM for LW and Fouquar Morcrette for SW). There are only small differences in terms of cloud overlap assumptions and calling frequency (1h in ALADIN versus 15' in AROME).

The text has been modified to state this in line 501.

7. typo line 499 : Météo . . . - missing

This is now corrected.

8. Before Table 2. There should be a Table for the ALADIN baseline CMC as well – to be able to compare AROME and ALARO!

Indeed. The table is now added.

9. Figure 8. Please state if it is for the whole year of 2013 or which period.

This figure has been removed in reply to the general comment 3 of reviewer 1.

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The ALADIN System and its Canonical Model Configurations AROME CY41T1 and ALARO CY40T1

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It turned out that some accents were fo

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Abstract.

The ALADIN System is a numerical weather prediction (NWP) [illegible] tional ALADIN consortium for operational weather forecasting and research purposes. It is based on a code that is shared with the global model IFS of the ECMWF and the ARPEGE model of Météo-France. Today, this system can be used to provide a multitude of high-resolution limited-area model (LAM) configurations. A few configurations are thoroughly validated and prepared to be used for the operational weather forecasting in the 16 Partner Institutes of this consortium. These configurations are called the ALADIN Canonical Model Configurations (CMCs). There are currently three CMCs: the ALADIN baseline-CMC, the AROME CMC and the ALARO CMC. Other configurations are possible for research, such as process studies and climate simulations.

We put (NWP) before system.

The purpose of this paper is (i) to define the ALADIN System in relation to the global counterparts IFS and ARPEGE, (ii) to explain the notion of the CMCs, (iii) to document their most recent versions, and (iv) to illustrate the process of the validation and the [illegible] the operational forecast suites of the Partner Institutes of the ALA [illegible]

restructured in reply to RC1, specific comment 1/.Als

This paper is restricted to the forecast model only; data assimilation techniques and postprocessing techniques are part of the ALADIN System but they are not discussed here.

1 Introduction

The ALADIN System[1] is the set of pre-processing, data assimilation, forecast model and post-processing/verification software codes shared and developed by the Partners of the ALADIN consortium[2] to be used for running a high-resolution limited-area model (LAM) for producing the best possible operational Numerical Weather Prediction (NWP) applications based on a configuration compatible with their available computing resources. The ALADIN consortium is a collaboration between the National (Hydro)Meteorological Services (NHMSs) of 16 European and North-African countries[3], see ALADIN international team (1997). This consortium was created in 1990.

The ALADIN consortium carries out an ambitious research program and has delivered a state-of-the-art NWP system that is used by its Members states for their operational weather-forecasting applications. This is achieved by the following specific activities. The consortium performs research and development activities with the aim of maintaining the ALADIN System at scientific and technical state of the art level within the NWP community. It carries out the necessary scientific and technical studies to define and maintain the ALADIN System and its Canonical Model Configurations. The consortium organizes the general maintenance of the ALADIN System with the aim to create new Versions on a regular basis. It organizes coordination and networking activities in order to support the ALADIN Consortium members in their ability to run the ALADIN Canonical Model Configurations on the computing platforms of their national Institutes. The consortium provides a platform for sharing scientific results, numerical codes, operational environments, related expertise and know-how, as necessary for all ALADIN Consortium members to conduct operational and research activities with the same tools.

Reply to RC1, specific comment 3/.

The collaboration follows the initial objectives of the consortium, as they were introduced by its founder Jean-François Geleyn:

(a) to have or to gain with the help of other members the capability to define, build and run local versions of the ALADIN System, but also,

(b) to build the capability to conceive, develop, test and ultimately integrate scientific ideas locally and finally in the new versions of the ALADIN System.

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[1] The ALADIN acronym stands for Aire Limitée Adaptation Dynamique Développement International (International development for limited-area dynamical adaptation)

[2] See http://www.umr-cnrm.fr/aladin/.

[3] Currently the Partners of the ALADIN consortium are (1) Office National de la Météorologie, Algeria, (2) Zentralanstalt für Meteorologie und Geodynamik, Austria, (3) Royal Meteorological Institute of Belgium, Belgium, (4) Bulgarian National Institute of Meteorology and Hydrology, Bulgaria, (5) Meteorological and Hydrological Service, Croatia (6) Czech Hydrometeorological Institute, Czech Republic, (7) Météo-France, France, (8) Hungarian Meteorological Service, Hungary, (9) Direction de la Météorologie Nationale, Morocco, (10) Institute of Meteorology and Water Management - State Research Institute of Poland, Poland, (11) Instituto Português do Mar e da Atmosfera, Portugal, (12) National Meteorological Administration of Romania, Romania, (13) Slovak Hydrometeorological Institute, Slovakia, (14) Slovenian Environment Agency, Slovenia, (15) Institut National de la Météorologie de Tunisie, and (16) Turkish State Meteorological Service, Turkey.

Both objectives lead to the benefit of all through the exchange of expertise and the improvements of the ALADIN System, and contributes to the steady progress of the discipline of NWP (Bauer et al., 2015). One consequence is that the consortium as a whole is responsible for the code as a whole. Therefore, creating a new version of the source code and its maintenance is a transversal activity within the consortium.

While all Partner services have the capacity to implement their operational versions of the ALADIN System by themselves, some activities are organized into more formally structured cooperations to develop applications that go beyond the deliverables of the ALADIN consortium.

The ALADIN consortium hosts the geographically localized Regional Cooperation for Limited-Area Modelling in Central Europe consortium (RC LACE), with seven members: the national National (Hydro-)Meteorological Services of Austria, Croatia, Czech, Hungary, Romania, Slovakia and Slovenia. It contributes a lot on the development of the ALADIN System. It made key contributions to the ALADIN non-hydrostatic dynamical core and the development of the physics parameterizations, in particular the ALARO CMC that will be described in section 3.3. This consortium provides extra resources to exchange and to process meteorological data used for the operational data assimilation systems in the RC LACE Partner countries. RC LACE develops and operates a pan-European probabilistic system Limited Area Ensemble Forecasting LAEF based on the ALADIN System (Wang et al., 2011, 2014)

Since 2005, the ALADIN conso Irrelevant references have been removed. m[4] through a cooperation agreement (Bengtsson et al., 2017).

The codes of the ALADIN System are common with the codes of the global Integrated Forecast System (IFS) of the ECMWF[5] and the global ARPEGE model[6] of Météo-France (Courtier and Geleyn, 1988; Courtier et al., 1991). The common, shared codes of the ALADIN System are managed in a central repository maintained by Météo-France with the help of the Partners of the ALADIN consortium. From this repository versions of the ALADIN System are assembled on a regular basis following the updates of the IFS cycles and the scientific improvements developed within the LAM community. This includes an assembling of the latest developments of ECMWF and Météo-France. The code evolution of the ALADIN System is thereby triggered by (i) updates with respect to IFS/ARPEGE versions, (ii) the implementation of novel scientific developments and (iii) specific code modernization (e.g. towards object-oriented code design) or optimization (for High-Performance Computing, HPC).

The aim of this link between the LAM and global models is threefold. First we can consider the configurations of the ALADIN System as limited-area configurations of the global model. Secondly, by sharing parts of the codes, the maintenance efforts can be reduced and developments done in either global or limited-area models become mutually available. Lastly, as mentioned by Warner

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[4] HIgh-Resolution Limited-Area Model consortium

[5] European Centre for Medium-Range Weather Forecasts

[6] Action de Recherche Petite Echelle Grande Echelle

et al. (1997), keeping a maximum of consistency between the global model and the LAM model dynamics and physics can reduce the errors at the lateral boundaries (LBCs) and can be beneficial for the lateral-boundary coupling of the LAM.

A quasi infinite number of choices can be made in the scientific physics and dynamics options of the configurations of the ALADIN System. This offers a high degree of freedom for the participating Partners of the ALADIN consortium to configure their national NWP applications, and even to develop tailor-made applications to address specific requests from their end users. On the other hand, it should be stressed that not all combinations of the available dynamics and physics schemes lead to scientifically meaningful model configurations.

Historically the ALADIN model was created as the LAM version of ARPEGE (Radnóti et al., 1995). Since all of the ALADIN countries nowadays target their applications at resolutions within the so-called convection permitting scales, two physically-consistent model configurations called AROME[7] (Seity et al., 2011) and ALARO[8] have been developed to address the need for applications at these resolutions. The current efforts to assemble, validate, document and maintain new versions of the ALADIN System, are focused on these two 'canonical' model configurations. However, in order to keep the close link with the global model ARPEGE, a LAM configuration that uses the ARPEGE physics is maintained. This configuration is still called the ALADIN model configuration. The new versions of these ALADIN model configurations are not collectively exported to operational NWP applications of the ALADIN Partners anymore, but they undergo a minimal validation and can be used in scientific projects where a mesoscale model is needed.

We removed the reference to 1-5 km resolutions, see RC1, specific comment 6/

In reply to RC1, specific comment 2/: The "purpose of the paper" part is removed. We limit ourselves to "

This paper is organized as follows. In section 2 the ALADIN System will be described. The po [illegible] res [illegible] the newest version of the ALADIN System. In section 3 the notion of CMCs will be introduced in more detail. The scientific description of the recent CMCs will be presented. Section 4 will illustrate how the recent versions have been exported to the ALADIN Partner countries. The paper will be concluded with a discussion and a short outlook in section 5. The scope of this paper will be limited to the forecast model configurations. For instance, data assimilation is part of the ALADIN System codes but will not be described here nor any postprocessing methods.

2 Description of the ALADIN System

2.1 Generalities

A Version of the ALADIN System is a release of the ALADIN System. Some Versions are distributed at regular times to the ALADIN Partners for research and development, as well as for operational

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[7] AROME stands for Application of Research to Operations at Mesoscale.

[8] ALARO stands for ALadin-AROme.

purposes. These Versions are called export versions. A Configuration of the ALADIN System is a subset of ALADIN Codes used by a consortium member for its own implementation. Canonical Model Configurations (CMCs) are configurations of the ALADIN System for which the ALADIN consortium organizes collective efforts for the scientific and technical validation according to the state of the art of the latest research and development. The consortium also organizes the coordination and networking activities in order to install and run these canonical configurations in the operational NWP suites of the ALADIN Consortium Members.

Today there are two CMCs in the full sense: the AROME model configuration and the ALARO model configuration. While the ALADIN configuration is not exported to the Partners of the consortium anymore, it is considered as the baseline-CMC to ensure the link with the global model ARPEGE.

Code updates are done about every 6 months: one common with IFS/ARPEGE, one common only to the ALADIN Partners.

A new Version build is planned about one year in advance, and this original kick-off decision is followed by an “upstream coordination” process with the intention to anticipate as much as possible any potential conflict between expected code commitments. This effort is considered strategic for the NWP system, due to its highly integrated nature, and it is involving scientific experts along with system (programming) experts.

lines 130-157 added in reply to RC1 , general comment 4/.

The practical understanding of the link between the global IFS/ARPEGE and the limited area ALADIN code updates can be seen as a piece of genuine ARPEGE/ALADIN know-how. Scientific developments performed first in one system might be of potential interest to the other system, which raises the question of how to thoroughly analyse the implementation steps for such a transfer of science. A few fundamental rules are followed:

- for spectral space codes, adaptations from spherical harmonics to bi-Fourier sprectral decompositions (or vice versa) are routinely analysed. This adaptation usually will result in specific new codes mimicking the call trees and the general structure of the original development (e.g. horizontal diffusion).

- for the grid point computations involving geometry, adaptation from spherical definitions to plane projected settings, or vice versa, are done (e.g. horizontal interpolations). However, some general available data enable a common use of information in both codes, like the map factor of the projection or the direction of the geographical North.

- the handling of the poles is specific to the global code, and usually occurs as an optional code.

- the lateral boundaries are handled where necessary as optional code with respect to the global version. Alike, the treatment of lateral boundary coupling is an optional code within the general time stepping of the whole system.

Section 2.2 provides more details about the code architecture of the ALADIN System within the IFS/ARPEGE framework. This rather unique duality between two geophysical numerical simulation codes has offered opportunities of cross-fertilization, like for instance the implementation of a nonhydrostatic dynamical kernel. The first code of nonhydrostatic dynamics appeared in the limited area system, and was a few years later adapted to the global version. Note that adapting to the global code was not a mandatory decision for the full IFS/ARPEGE and ALADIN Systems to be maintained in regular conditions. The decision eventually was taken when the scientific opportunity for this transfer became obvious. In the other way round, the first versions of the Semi-Lagrangian advection code were developed in IFS/ARPEGE and then converted into the limited area version. This conversion actually happened quickly, as it opened the floor for significantly longer time steps in the hydrostatic LAM configurations that were operated in the 1990ies.

The practical steps of the initial build of a new ALADIN Version release are mostly taking place at Météo-France: merge of code contributions, early validation process. Progressively, as the early versions become technically stable, some remote installation and further validation can take place, until the new release is declared. This process does not comprise pre-operational local implementations in which then the meteorological quality of a new release is evaluated, beyond the technical tests.

The technical validation is done in several steps, some of which being ignored if found unnecessary:

1. a benchmark of base tests: adiabatic model versions, change of model grid geometry versions, tangent-linear/adjoint model run tests, and specific forecast tests including physics packages among which those used for defining the CMCs;

2. comparison with the previous reference version, aiming to trace back changes that disrupt bit reproducibility, or to put it differently, verifying that bit reproducibility is broken for understood reasons;

3. computation of statistical scores such as bias and root-mean-square errors (RMSE) with respect to observations or reference analyses;

4. specific model output diagnostics used in research mode like averages of model tendencies;

5. one-dimensional model tests to assess profiles of fields and their tendencies;

6. specific data assimilation test periods are run (the time period is chosen in order to match with a recent context for the throughput of observations).

This process is meant to bring the embedded implementations of the LAM configurations of the ALADIN System in phase with the cycles of the global IFS and the ARPEGE models and is called "phasing". The cycle numbers of the ALADIN Versions are the same as the corresponding cycles of IFS and ARPEGE. The outcome of the build and validation process is a new Version of the ALADIN System labelled in the Météo-France central source code repository. Mature Versions of the ALADIN System are packages in so-called “export versions” for installation in the ALADIN Partner centers.

2.2 The scientific and technical specificities of the code architecture of the ALADIN System

The definition of the ALADIN System is rooted in the options of the shared code to configure the LAM model configurations. This section describes the architecture of the code to outline what is common with the global model and what differentiates the LAM configurations from the global model.

One of the main concerns in the developments of these codes[9] is the special care taken to be able to run the model configurations with long time steps or, to put it non-dimensionally, with large Courant numbers. Most of the choices in the development of the numerical treatments of the dynamics and the physics parameterizations are made from that point of view. As far as is known today, from recent intercomparisons (see e.g. Michalakes et al., 2015) this key feature, combined with hybrid (MPI/OpenMP) parallelization capabilities makes IFS/ARPEGE/ALADIN models the most efficient or cheapest ones to run, each in their categories, in terms of "time to solution".

reply to RC1, specific comment 10/

The code of the ALADIN System is shared with the code of the IFS of ECMWF and the ARPEGE model of Météo-France. The current operational versions use a spectral dynamical core with a two-time level semi-Lagrangian semi-implicit scheme (Ritchie et al., 1995; Robert et al., 1972; Simmons et al., 1978; Temperton et al., 2001). The use of a spectral transform method naturally implies that there is no horizontal staggering of the variables in the gridpoint calculations part. To solve the semi-implicit problem, the dynamic equations are reduced to a single Helmholz equation in the horizontal divergence. In the equations of the dynamics the u and v components of the wind fields are recast in terms of absolute momentum. As such the Coriolis term, as well as the curvature terms, do not appear on the right-hand side and, as a result, do not enter the linearized semi-implicit (SI) formulation. Indeed, the approach taken to solve the SI problem is remarkably efficient insofar as the problem is horizontally separable: then, the spectral method enables an elegant, direct purely algebraic solution. This efficiency is lost whenever parameters depending on the horizontal coordinates are kept in the linear problem. Actually, one such parameter, the map factor, does enter the SI problem, but its horizontal dependency is handled in a semi-analytical way, leading to a weakly non-diagonal problem in spectral space, therefore enabling to keep most of the advantages of the spectral solving method.

References removed, s

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[9] Historically the code had to run in time critical applications on a large variety of available computing platforms across the different Partners of the ALADIN consortium. Hence the specific care for numerical efficiency through the use of large time steps.

Reply to RC1, specific comment nr. 4/

Table 1. Schematic overview of the time-step algorithm of the configurations of the ALADIN System and the choices that differentiate them with respect to the global ARPEGE model.

	step	options (LAM vs. global)
1.	horizontal derivatives (vorticity, divergence and pressure/temperature gradients)	
2.	inverse spectral transform: spectral to gridpoint	{ bi-FFT^{-1} Legendre, FFT
3.	computation of the physics contributions	{ AROME physics ALADIN/ALARO physics
4.	calculation of the tendencies of the prognostic variables of the model state	INTFLEX
5.	computation of the explicit gridpoint dynamics and adding it to the total tendencies of the prognostic variables	{ IFS/ARPEGE/ALADIN hydrostatic ALADIN-NH
6.	computation of the semi-Lagrangian departure points and interpolation of the tendencies to these points	SLHD
7.	addition of the interpolated tendencies to the model state	
8.	lateral boundary coupling	bi-periodic LBC conditions
9.	direct spectral transforms	{ bi-FFT Legendre, FFT
10.	solving the semi-implicit Helmholtz equation	{ IFS/ARPEGE/ALADIN hydrostatic ALADIN NH

The time-step computations are organized in such a way that the same dynamics formulations can be used for both limited-area and global geometries. The time-step algorithm is schematically outlined in table 1 in a simplified manner. Mind that this algorithm is not the same for IFS as far as the physical parameterizations calculations are concerned. In the IFS, the physics is performed on variables at different times depending on the physical process, whereas in the ARPEGE model and the ALADIN System it is performed entirely on the $t - \delta t$ state variable before calling the explicit part of the dynamics, see Termonia and Hamdi (2007).

Three features differentiate the ALADIN System configurations from its global counter part:

This paragraph was moved here to be able to restucture the text with the subsubsection 2.2.1 - 2.2.

1. [illegible] transforms (steps 1, 2, 9 in table 1) and a formulation of the Helmholtz equation in term of the proper operators and map factors (step 10),
2. the lateral-boundary conditions (LBCs) (step 8 in table 1) and
3. the physics packages which are adapted in step 3 in table 1, for an application at the high-resolutions targeting the convection-permitting scales, as shown in Fig. 2.

2.2.1 The ALADIN-NH non-hydrostatic dynamical core

RC1 2/: we restructure the text with subsubsections

The code can be run with a non-hydrostatic dynamical core that solves the fully compressible Euler equations (Bubnová et al., 1995). This dynamical core is referred to as ALADIN-NH and may be used in both AROME CMC and ALARO CMC typically for horizontal grid point distance shorter than approximately 3 km. Reply to RC1, specific comment 6/. allest circulation structures resolved in horizontal becomes comparable to their largest vertical size and so the non-hydrostatic effects become progressively important starting from there.

The vertical coordinate system uses a mass-based hybrid pressure terrain-following coordinate η (Simmons and Burridge, 1981; Laprise, 1992). The vertical discretization is based on finite differences (Simmons and Burridge, 1981) or finite elements. For the latter the implementation of B-splines of either linear or cubic order (Untch and Hortal, 2004) can be used in the hydrostatic case only, while in the non-hydrostatic case B-splines of general order are introduced according to Vivoda and Smolíková (2013). Reply to RC1, specific comment 7/. -NH dynamical core not only the integral operators but also the vertical derivatives need to be discretized since they appear in the set of basic equations. Moreover, the basic constraints being satisfied in the continuous case with the finite-differences vertical discretization are not fulfilled by the finite-element vertical discretization. It follows that the elimination of all prognostic variables but one is not possible when solving Helmholtz equation and an iterative procedure is being applied in this case.

There are two additional prognostic variables compared to the hydrostatic model core: the non-hydrostatic pressure departure from the hydrostatic pressure and a specific expression of the vertical-divergence variable, denoted as d.

This choice ensures satisfactory stability properties of the semi-implicit scheme (Bénard et al., 2004, 2005). However, in the semi-Lagrangian advection scheme, in the case of a flow over steep slopes, the accuracy of the calculation may be reduced depending on the choice of the bottom boundary condition for d. The solution proposed by Smith (2002) is to use the vertical wind w instead of vertical divergence in the explicit part of the semi-implicit calculations. This allows the free-slip lower boundary condition to be introduced in its most natural form, without the need for any extra assumptions. These simpler calculations then lead to an enhanced accuracy in the vicinity of steep slopes. Vertical staggering of prognostic variables is a necessary consequence of this approach resulting in the calculation of two sets of semi-Lagrangian trajectories, one at full model levels for most of the prognostic variables and a second one at the intermediate levels for the vertical velocities. Furthermore, a transformation from w to d and vice versa needs to be performed at the beginning and at the end of the explicit computations. Recently, more conservative semi-Lagrangian horizontal weights were proposed which take into account the deformation of air parcels along each direction in the COMAD scheme (Malardel and Ricard, 2015). This scheme allows to use more conservative horizontal interpolation weights for the variables temperature, wind, specific moisture, surface pressure, pressure departure and vertical divergence. Reply to RC2, comment 2.

The non-hydrostatic equation set can be solved using a separable, linear non-iterative semi-implicit problem. However, the parameter domain of stability is reduced with respect to the hydrostatic case. One way of improving it is to use two distinct temperatures in the scheme, instead of a single one.

Roughly, one characterizes gravity waves, the other acoustic waves. To go further, Bénard (2003) proposes to see the semi-implicit scheme as a highly linearized single iteration approximation to the tangent-linear iterative fix-point search of the more exact solution. From this analysis, he derives a more stable but iterative scheme called the Iterative Centered Implicit scheme. A number of dynamical non-linear terms are recomputed at each iteration, with optional precision (and cost) levels, and the SI solved again with recomputed right-hand terms. This scheme can alternatively be viewed as belonging to the predictor-corrector family.

The dynamical core (both hydrostatic and non-hydrostatic) includes a linear numerical horizontal diffusion based on a power of the Laplace operator as proposed by Jakimow et al. (1992). The operator is included in the solver of the Helmholtz equation in the spectral part of the computations in step 10 in table 1 and is thus solved implicitly. For the iterative centered implicit time scheme, the spectral horizontal diffusion is applied at each iteration step, whilst physical tendencies and semi-Lagrangian trajectories may not be recomputed and could be kept from the predictor step.

Reply to RC1, specific comment 8/. We do not specify the fourth order anymore.

2.2.2 SLHD: a semi-Lagrangian horizontal diffusion scheme

The code also allows to use a non-linear Semi-Lagrangian Horizontal Diffusion (SLHD) scheme, computed under step 6 of the time-step algorithm in table 1. The original version of the scheme was developed and implemented by Váňa et al. (2008). Later its conservative properties were improved by using a carefully constructed class of semi-Lagrangian interpolators, exploiting the fact that accuracy and damping properties of an interpolator are not strictly tied. On a 4-point stencil in one dimension it is possible to construct a class of second order accurate interpolators with broadly varying damping, and with spectral selectivity equivalent to the fourth order diffusion. An additional control of spectral response is obtained by using an optional Laplacian smoother. Non-linearity of the SLHD scheme is achieved via a modulation of the diffusion strength by the horizontal deformation rate of the flow. Due to its grid-point character, the scheme enables to apply diffusion also on quantities that are not transformed to spectral space, such as specific humidity, cloud condensates, or the turbulent kinetic energy (TKE).

2.2.3 Digital-Filtering Initialization (DFI) and scale selective DFI (SSDFI)

The shared code also allows to perform a Digital-Filtering Initialization (DFI) on a model state (Lynch, 1990). In operational applications an optional version is used (Lynch et al., 1997) based on a Dolph-Chebyshev filter (Lynch, 1997). Termonia (2008) observed that such temporal filters may filter out fast moving signals in the small scales and implemented a Scale-Selective Digital-Filtering Initialization (SSDFI) in the shared ARPEGE/ALADIN code.

Sentence corrected see, RC2, comment 1/:

Most of the above-described features are embedded in the common code with the global ARPEGE model.

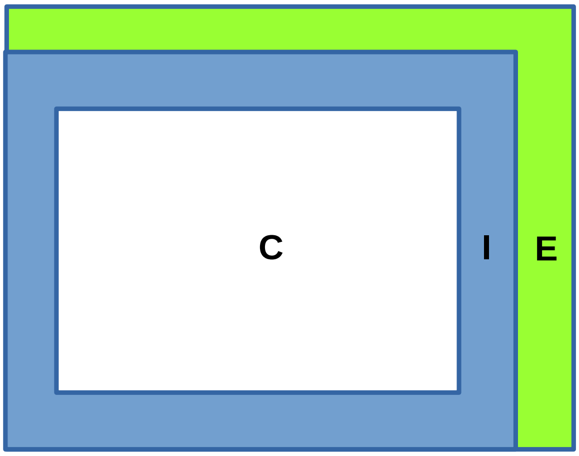

Figure 1. The domain of the LAM model is composed of three zones: a physical central zone (C), an intermediate zone (I) where the lateral-boundary conditions are imposed by a relaxation, and the extension zone (E) where artificial periodic extensions of the fields are inserted.

2.2.4 Implementation of the Davies lateral-boundary coupling

The structure of the geographical domain of the LAM configurations is based on the idea of Haugen and Machenhauer (1993). It has three zones as shown in Fig. 1 consisting of a physical central zone (C), an intermediate zone (I) where the lateral-boundary conditions are imposed by a relaxation, and a so-called extension zone (E) where artificial periodic extensions of the fields are inserted before performing the direct fast Fourier transforms. The double periodicity implies that the geometry of the spectral LAM is essentially a torus as opposed to a sphere for the global model configurations. In operational applications the C+I domain is most commonly mapped onto the sphere by means of a conformal-Lambert projection. The other two conformal projections are also possible, namely the polar stereographic and the Mercator projections.

The LAM configurations of the ALADIN System use the Davies (1976) relaxation scheme in the I zone in Fig. 1, which nudges the fields from the fields of the host model to the guest model. Instead of using the proposed nudging coefficients by Davies (1983), in the ALADIN System this is done by a parameterized function:

$$\alpha(z) = 1 - (p+1)\, z^p + p z^{p+1}\,, \qquad (1)$$

where z is the normalized distance form the boundary of the C zone to the border of the I zone. The shape of the relaxation curve α is fixed by tuning the variable p (the current configurations use a value of $p = 2.16$ for wind and temperature, and $p = 5.52$ for water vapor and hydrometeors). The width of the I zone is typically 8 grid points, but this number is increased in the implementations with high resolutions (e.g. for the 1.3 km resolution setup of Météo-France 16 grid points are used). For the size of the E zone 12 grid points are taken.

Reply to RC1, specific comment 9/.

In the ALADIN System the lateral-boundary conditions are imposed in step 8 in table 1 just before the spectral transforms. This is done by relaxing the result of the explicit part of the dynamics (computed in step 5 in table 1) to the fields of the host model after they have been subjected to the operator of the semi-implicit scheme as proposed by Radnóti (1995). Symbolically this looks like,

$$\mathbf{X}^{cpl} = \alpha \mathbf{X}_G + (1-\alpha)\left(1 - \frac{\Delta t}{2}\mathcal{L}\right)\mathbf{X}_H\,, \tag{2}$$

where $\mathbf{X_G}$ is the updated tendency of the LAM model state after step 7, $\mathbf{X}_H$ is the field of the host model, $\mathcal{L}$ is the linear operator of the semi-implicit scheme and α is taken as in Eq. 1. The result of Eq. 2, $\mathbf{X}^{cpl}$ is then transformed to spectral space and becomes the input to the Helmholtz solver in step 10. The fields are made periodic in the extension zone by spline functions.

2.2.5 Implementation Boyd's scheme and extensions thereof

The new biperiodization and LBC scheme proposed by Boyd (2005) has been implemented in the ALADIN System by Termonia et al. (2012). They introduced some other options to adapt it to the semi-Lagrangian scheme and to make the scheme more flexible. For instance, the code can be run with a disjoint split between the relaxation in the I zone and the biperiodic windowing in the E zone of Fig. 1, which improves upon the original proposal of Boyd (2005) where the relaxation and the biperiodic windowing overlap. It has been shown that such a configuration with a truncation of the semi-Lagrangian trajectories at the edge of the C+I zone, gives better results than the Davies scheme (Degrauwe et al., 2012).

2.2.6 Interpolations of initial and coupling data in space and time

In practice the configurations of the ALADIN System are coupled to the IFS or to the ARPEGE model. To this end the dynamical fields are spatially interpolated to the LAM domain. The periodic extensions are inserted in the E zone at this stage. To run the system with Boyd's scheme, one needs the information of the fields of the host model outside the C and the I zone, see Termonia et al. (2012). The results are stored in files. These files usually contain the spectral coefficients of the dynamical fields. Such files are created at Météo-France or ECMWF and transferred to the ALADIN Partners in a timely manner. They are computed with the resolution corresponding to the average horizontal resolution of the driving model, not the target one, to save bandwidth and transfer time. These files are short-handedly called the telecom files.

The interpolation software also allows to interpolate the fields of a LAM configuration to a LAM subdomain with possibly a new resolution. The telecom files are created at regular times with one-hour, three-hour or six-hour time intervals. These files are read during a forecast run of the guest model and interpolated in time to get the fields at each time step. Mind that time interpolations of the bi-periodic fields yields bi-periodic fields. In practice the time interpolation is carried out by a linear interpolation or a quadratic interpolation (Tudor and Termonia, 2010). Termonia (2004) found that a temporal interpolation of 3-h coupling updates may, in rare cases of a fast moving storm entering the domain through the boundaries, result in errors of up to about 10 hPa in the mean-sea level pressure fields (Termonia et al., 2009). Termonia et al. (2011) proposed to use an error-detection procedure based on a recursive digital filtering procedure within the global model and to apply a restart in such cases. This procedure is used operationally in the forecast suite of the Royal Meteorological Institute (RMI). Alternative ways for detecting the errors from the fields available in the telecom files from IFS have been explored (Tudor, 2015).

2.2.7 The coupling of the physics schemes to the dynamical core by the flexible physics-dynamics interface INTFLEX

The scientific content of the physics schemes that are called under step 3 in table 1 for ALADIN, ALARO and AROME will be described in section 3.

The coupling of the physics to the dynamics (step 4 in table 1) is based on a flux-conservative formulation developed by Catry et al. (2007). A flexible version of this physics-dynamics interface, called INTFLEX, has been recently implemented and validated in the common code by Degrauwe et al. (2016) that facilitates the implementation of new species and processes. The use of INTFLEX for the AROME configuration has improved the life-cycle dynamics of the cold pool mechanism in deep convective systems. The INTFLEX code functions as an interface routine to plug in the different physics packages in the time-step algorithm. It is common to the ARPEGE model and to the configurations of the ALADIN System.

2.2.8 Parallellism

For the efficiency of the LAM configurations on modern parallel computing architectures, the same strategies as for the global IFS/ARPEGE models are employed, with limited needs of adaptation. Mostly thanks to ECMWF and the integration concept, this code is characterized by a rather rare fully parameterized hybrid parallelization (MPI/OpenMP) capability. This means that the code can use various mix of distributed memory parallel tasks and shared memory parallel threads. On the current dominant interconnected multi-CPU boards, the LAM configurations primarily use the same cache-blocking mechanism for cache-based computers[10] (Zwieflhofer et al., 2003; Hamrud et al., 2012). This comes along with two-dimensional Message Passing distributions (MPI), both in spectral

reply to RC1, specific comment 10/

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[10] These are the so-called NPROMA blocks, named after the dimensioning NPROMA variable. This variable was initially designed to optimize the vectorization length on vector machines. The NPROMA blocking was developed first for vector shared memory machines. Then the code was adapted for vector distributed memory machines by introducing MPI. Then OpenMP has been progressively implemented.

space, and in gridpoint space. On top of this cache-blocking slicing the LAM configurations can further use a parallelism by OPEN-MP threads.

Recently, the performances on large computing domains has been significantly improved by introducing an input/output server developed by Météo-France. It enables to resume the time integration itself, while the writing to disk is performed in parallel. Reading may also be distributed. Dual parallelization makes it possible to use multicore boards. Dual parallelization combined with parallel I/O together with a much reduced number of time-steps to reach a given forecast range makes these codes extremely efficient, even though the transpositions required by the use of spectral transforms are not ideal from a scalability viewpoint.

The main three particularities of the LAM parallelism with respect to the global model configurations concern:

1. the handling of the coupling data in gridpoint space, for which a specific Message Passing distribution and parallelism has been developed;
2. the handling of the limited area aspects in gridpoint space. Unlike in the global model, the semi-Lagrangian trajectories have to be constrained to the physical area C+I and possibly a margin of the extension zone in the case of the Boyd solution mentioned above. Also, the semi-Lagrangian trajectories are computed on a plane, which requires, among other things, to construct the so-called halo for the MPI implementation in a different way.
3. In spectral space, the distributed Fourier-transform code is shared with the global model in the zonal direction; while in the other direction a second distributed Fourier transform code replaces the distributed Legendre transforms.

3 The Canonical Model Configurations

The three physics packages ALADIN, AROME and ALARO can be called under step 3 of the time-step organization in table 1. Their target resolutions are illustrated in Fig. 2. The AROME CMC and the ALARO CMC are respectively based on the cycles CY41T1 and CY40T1 and both are described in sections 3.2 and 3.3.

3.1 The ALADIN baseline-CMC

The current ALADIN baseline CMC calls the ARPEGE physics that is used at Météo-France between summer 2013 and spring 2017. Here we limit ourselves to a brief description of this version.

Its radiation scheme is based for the long-wave on the so-called RRTM scheme (Mlawer et al., 1997; Iacono et al., 2008) and for the short wave the six-band Fouquart-Morcrette scheme (Fouquart and Bonnel, 1980; Morcrette, 1993). The boundary layer parameterization is based on the prognostic equation of the Turbulent Kinetic Energy (Cuxart et al., 2000) that is also used in the AROME CMC

Figure 2. The different LAM configurations of the ALADIN System and their target resolutions.

Table 2. The ALADIN CMC

table added, RC2, comment 8.

parameterization/dynamics	schen	
dynamics	hydrostatic ARPEGE/ALADIN	Temperton et al. (2001); Radnóti et al. (1995)
radiation	RRTMG_LW, SW6	Mlawer et al. (1997); Iacono et al. (2008); Fouquart and Bonnel (1980)
turbulence	CBR	Cuxart et al. (2000); Bougeault and Lacarrere (1989)
microphysics		Lopez (2002); Bouteloup et al. (2005)
shallow convection	KFB	Bechtold et al. (2001); Bazile et al. (2011)
deep convection		Bougeault (1985)
clouds		Smith (1990)
sedimentation scheme		Bouteloup et al. (2011)
orographic gravity wave drag		Catry et al. (2008)
surface scheme	SURFEX	Masson et al. (2013)
LBC scheme	Davies scheme	Davies (1976),Radnóti (1995), Termonia et al. (2012)

but associated with the shallow convection scheme (KFB) based on a CAPE closure (Bechtold et al., 2001), both schemes are linked to the thermal production of TKE computed by the KFB scheme and by a modification of the original mixing length from Bougeault and Lacarrere (1989) by the shallow cloud from KFB (Bazile et al., 2011). The deep convection is represented by an updated version of the mass-flux scheme based on a moisture convergence closure (Bougeault, 1985). Alternatively, deep convection can now be represented using the PCMT scheme (Prognostic Condensates Microphysics and Transport) (Piriou et al., 2007; Guérémy, 2011). This scheme is already operational in the ARPEGE ensemble prediction system, and will soon be in ARPEGE. The cloud microphysics has four prognostic variables (cloud water and ice and liquid and solid precipitation) for the resolved precipitation (Lopez, 2002; Bouteloup et al., 2005) and the probability distribution function for the statistical cloud scheme comes from (Smith, 1990). A parameterization of subgrid orographic effects (Catry et al., 2008) represents gravity wave drag, wave deposition, wave trapping, form drag and lift effects. For the continental surface the SURFEX software (Masson et al., 2003) is used with the

Table 3. The AROME CMC

parameterization/dynamics	scheme	references
dynamics	non-hydrostatic ALADIN	Bénard et al. (2010)
radiation	RRTMG_LW, SW6	Iacono et al. (2008), Mlawer et al. (1997), Fouquart and Bonnel (1980) Morcrette (2001)
turbulence	CBR	Cuxart et al. (2000), Bougeault and Lacarrere (1989)
microphysics	ICE3	Pinty and Jabouille (1998)
shallow convection	PMMC09	Pergaud et al. (2009)
deep convection	–	
clouds		Bechtold et al. (1995); Pergaud et al. (2009)
sedimentation scheme		Bouteloup et al. (2011)
surface scheme	SURFEX	Masson et al. (2013)
LBC scheme	Davies scheme	Davies (1976),Radnóti (1995), Termonia et al. (2012)

options used in the AROME model configuration, as will be described below and in section 3.2. The chosen physics schemes of the ALADIN CMC are summarized in table 2.

3.2 The AROME CMC

The AROME canonical model configuration has been developed to run in the convection-permitting resolutions starting from 2.5-km resolution. It is a non-hydrostatic convective-scale limited-area model setup described by Seity et al. (2011) and Brousseau et al. (2016). Its physical parameterizations come mostly from the Méso-NH research model (Lafore et al., 1998) whereas the dynamical core is the Non-Hydrostatic ALADIN one described in section 2.2.1. It is run with a light, single-iteration predictor-corrector step which allows to use long time steps (50s at 1.3km horizontal resolution for instance). The recent versions of the AROME configurations[11] use the COMAD scheme for the semi-Lagrangian advection as is also described in section 2.2.1.

Reply to RC2, cor

The AROME configuration uses a turbulence scheme based on a prognostic equation of turbulent kinetic energy (TKE), a mass flux shallow convection scheme, a one-moment microphysics prognostic scheme, a detailed surface scheme, and a radiation scheme described below.

The representation of the turbulence is based on a prognostic TKE equation (Cuxart et al., 2000) combined with a diagnostic mixing length (Bougeault and Lacarrere, 1989). The conservative variables defined for this TKE scheme are liquid potential temperature, and the total water vapor (addition of water vapor and cloud water specific contents). The turbulence scheme used in AROME differs from the one used in ALADIN mainly on the vertical discretization of TKE defined on full levels versus half levels respectively. Both schemes have been compared in several 1D cases and the results are very similar. There is an an ongoing work to share exactly the same code.

Reply to RC2, comment 3

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[11] COMAD is active in the ALADIN System code since CY40T1 and in particular in the current cycle CY41T1 described here.

A mass flux scheme (Pergaud et al., 2009) based on the eddy diffusivity mass flux (EDMF) approach (Soares et al., 2004) is used as parameterization of dry thermals and shallow cumuli. This scheme uses the same conservative variables as the turbulence scheme. In the boundary layer, the formulations depend on the buoyancy and on the vertical speed of the updraft, whereas in clouds, they are computed using a Kain-Fritsch buoyancy sorting (Kain and Fritsch, 1990). Some improvements have been introduced in the latest version of the scheme (more consistent treatment of solid phase in the updraft, algorithmic corrections).

A statistical cloud scheme is used in AROME (Bechtold et al., 1995; Bougeault, 1982) based on the computation of the variance of the departure to a local saturation inside the grid box diagnosed by the turbulence scheme. The cloud fraction and the cloud condensate content are given by a combination between a Gaussian and a skewed exponential PDF. The cloud profiles of the shallow convection are combined with the cloud parameters resulting from the statistical adjustment. Apart from turbulence and convection, there can be other sources of variance like gravity waves, in particular with stable conditions when turbulent and convective contributions are too weak to produce clouds. In order to represent these extra sources of variance, a variance term proportional to the saturation total water specific humidity is added to the one computed by the turbulence scheme (de Rooy et al., 2010). In this way, in particular conditions (weak turbulence), the cloud scheme's gets the characteristics are those of a RH-scheme, where cloud cover is simply a function of the relative humidity.

In reply to RC2,

AROME uses a one-moment microphysics scheme (Pinty and Jabouille, 1998; Lascaux et al., 2006), named ICE3, with five prognostic variables of water condensates (cloud droplets, rain, ice crystals, snow and graupel). ICE3 is a three-class ice parameterization coupled to a Kessler's scheme for the warm processes. Hail is also implemented but not activated in the current version of AROME. The diameter spectrum of each water species is assumed to follow a generalized Gamma distribution. Power-law relationships are used to link the mass and the terminal fall speed velocity to the particle diameters. More than 25 processes are parameterized in a sequential way inside this scheme. A PDF-based sedimentation scheme is used for the numerical efficiency of the microphysics comp [illegible] with relatively long time steps, as described in Bouteloup et al. (2011). In order to investig [illegible] aerosol-cloud interactions, a 2-moment mixed microphysical scheme (Vié et al., 2016) ha [illegible] developed in Meso-NH and implemented in AROME (used in research mode, not yet activ [illegible] the operational suite).

Reply to RC1, specific commen

Reply to RC2, comment 5.

AROME uses the surface modelling platform SURFEX (Masson et al., 2013). Each mod [illegible] box is split into four tiles: land, towns, sea, and inland waters (lakes and rivers). The Interactions between Soil, Biosphere, and Atmosphere (ISBA) parameterization (Noilhan and Planton, 1989) with three vertical layers inside the ground is activated over land tiles. The Town Energy Budget (TEB) scheme used for urban tiles (Masson, 2000) simulates urban microclimate features, such as urban heat islands. Sea tiles use a bulk iterative parameterization, named ECUME (Exchange Coefficients from Unified Multicampaigns Estimates) (Belamari and Pirani, 2007). It is a bulk iterative parameterization developed in order to obtain an optimized parameterization covering a wide range of atmospheric and oceanic conditions. Concerning inland waters, the classic Charnock (Charnock, 1955) formulation is used. Physiographic data are initialized with the ECOCLIMAP database (Masson et al., 2003) at 1-km resolution. The orography is computed from the GMTED2010 database at 250 m resolution (Carabajal et al., 2011). The FAO HWSD database at 1-km resolution is used for the fraction of clay and sand in the soil. The HIRLAM parameterization of orography/radiation interactions (Senkova et al., 2007) has been adapted and implemented in the SURFEX version. Orographic shadowing and slopes parameterizations are used operationally to modify solar direct radiative fluxes. One main effect of including shadowing and slopes effects is that the clear-sky sunshine duration is drastically modified in mountainous areas, with values changed from almost constant to highly varying (sunshine duration can for instance locally reach about zero on grid points with all-day shadow conditions in the French Alps).

AROME uses the same radiation scheme as the ALADIN-baseline CMC. It is a simplified version of the European Centre for Medium-Range Weather Forecasts (ECMWF) radiation parameterizations. The shortwave radiation scheme (Fouquart and Bonnel, 1980) uses six spectral bands. Cloud optical properties are derived from Morcrette and Fouquart (1986) for liquid clouds and Ebert and Curry (1992) for ice clouds. Cloud cover is computed using a maximum-random overlap assumption. The effective radius of liquid cloud particles is diagnosed from cloud liquid water using the Martin et al. (1994) formulation. Cloud nuclei concentrations are assumed to be constant, with one value over land and another over the ocean. The effective radius of ice clouds particles is diagnosed from temperature using a revision of the Ou and Liou (1995) formulation. Long-wave radiation is computed by the Rapid Radiative Transfer Model (RRTM) code (Mlawer et al., 1997) using climatological distributions of ozone and aerosols. Ozone monthly profiles are given by analytical functions that have been fitted to the U.K. Universities Global Atmospheric Modelling Programme (UGAMP) climatology (Li and Shine, 1995) with three coefficients (Bouteloup and Toth, 2003). The distributions of organic, sulfate, dust like and black carbon, plus uniformly distributed stratospheric background aerosols, are extracted from the Tegen climatology (Tegen et al., 1997). Because of computational constraints, in all AROME configurations (2.5 or 1.3 horizontal resolution) full radiation computations are performed once every 15 min. For intermediate time steps, only solar azimuth angle varies.

RC2, comment 6.

Reply to RC1, specific comment 12/.

The choices of the physics parameterizations of the AROME CMC are summarized in table 3. With these settings of the AROME model dynamics and physics parameterizations, the AROME CMC is capable of capturing in occasionally impressive manner the location, timing and strength of intense small scale weather patterns. Fig. 3 is an illustration of a case of onset of severe convective precipitation over the French Riviera and the city of Cannes (3 October 2015). For this case, where large scale and local effects most likely both are important for triggering the onset of the heavy

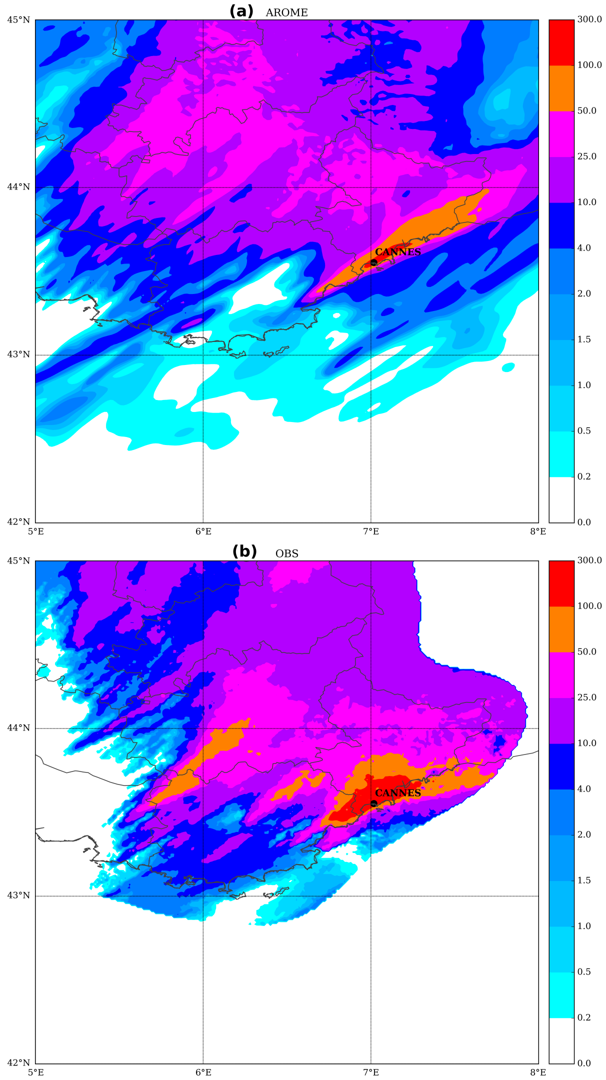

Figure 3. Maps of 3h cumulated precipitations between 18 UTC and 21 UTC over the South-East of France, for the case of 3 October 2015. (a) AROME-France forecast starting at 03 UTC, (b) Antilope 3h precipitation analysis taken as proxy to the observation (Laurentin, 2008).

precipitation (more than 100mm in 3h), the model forecast started 15h before the validation time already provided a very realistic description of the event.

Météo-France is the main center for the developments of the AROME CMC. The French operational implementation, called AROME-France, is the flagship regional forecast system covering mainland France and the neighboring regions. The AROME configuration has been first implemented in operations on 18 December 2008 in Météo-France. The current version has a resolution of 1.3km and 90 vertical levels. The ensemble version and a [illegible] nd commercial

RC2, comment 7.

applications are based on a 2.5km resolution, using the same 90 levels, reaching very close to the surface.

The AROME configuration is also, by design, a vehicle for the developments of data assimilation of high-resolution observational data (Fischer et al., 2005; Wattrelot et al., 2014; Brousseau et al., 2016). Thus the AROME-France initial conditions at model resolution are provided by an hourly 3D-var cycle for the atmospheric fields and a 3-h Optimal Interpolation for the surface fields.

The performance of the AROME CMC at Météo-France is regularly statistically assessed with respect to observations or specific analysis products. The verification encompasses WMO types of scores and more focused statistical evaluations as illustrated in Fig. 4. Figs. 4 (a) and (b) show the frequency bias and the Brier Skill Score for a range of precipitation thresholds for the whole year of 2016, respectively. In these two evaluations, the ability of AROME to outperform a rule of persistence of the forecast is assessed. The reference values, considered as the “truth”, are specific analyses of accumulated precipitation obtained from the French ANTILOPE analysis product, which combines radar and rain gauge data (Laurantin, 2008). Ideally, both the frequency bias and the Brier Skill Score should be one for any threshold (for any event). While obviously the operational AROME system would not exactly reach the theoretical “perfect model” values, the departure from the perfect model results is better appreciated when compared to the results of another modeling system. At Météo-France, AROME results can readily be compared to those of the global ARPEGE system, which are also depicted in Fig. 4. The comparison illustrates that the AROME system significantly improves the bias of forecast precipitation amounts as well as the Brier Skill Score for almost all thresholds, with respect to ARPEGE.

3.3 The ALARO CMC

The ALARO physics is implemented in the ALADIN System under the same calling routines as the ones for the ALADIN configurations in step 3 of table 1.

The aim of the ALARO configurations of the ALADIN System is to provide a setup that can also be used in intermediate resolutions between the meso-scale and the convection-permitting scales, see Fig. 2. The partners of the ALADIN consortium are running their applications on a variety of computing platforms with different available computing resources. This approach allowed those who can not afford to run the model at kilometric resolutions to increase the resolutions in a progressive way. De Troch et al. (2013) demonstrated the multiscale behavior of ALARO in the statistics of extreme precipitation in long climate runs.

The basis for this is the application of a multiscale parameterization concept. For moist deep convection, the Modular Multiscale Microphysics and Transport scheme (3MT) has been developed to overcome problems when convection gets partly resolved at the so-called grey zone model resolutions. The ALARO configuration is built upon this physics parameterizations concept relying on the

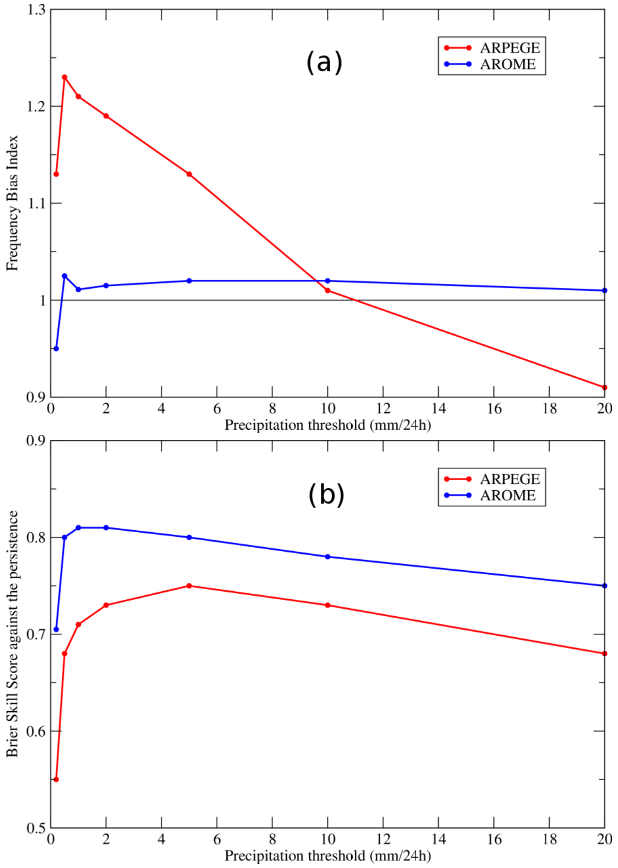

Figure 4. Frequency Bias Index (a) and Brier Skill Score (b) against the persistence for a fixed neighborhood of about 50 km (Amodei et al., 2015) computed for 24h accumulated precipitation over France as a function of classes of precipitation (0.2, 0.5, 1, 2, 5, 10, 20 mm/24h). Forecasts are provided by the AROME-France and ARPEGE operational NWP systems at Météo-France, the start time is 00 UTC, the forecast lead time is 30h and the scores are computed for the year 2016. The ANTILOPE precipitation analysis (Laurantin, 2008), combining radar and gauge data, is taken as reference. All data were interpolated on a regular grid of 2.5km.

governing equations for the moist physics, cast in a flux-form (Catry et al., 2007), a corner stone for the clean interface between the model physics and dynamics.

From the code point of view, new versions of the schemes are developed by taking utmost care of the ascending compatibility with the former versions. This allows easier validations, progressive upgrades and tailoring of the scientific complexity of the local applications. The coding and the numerical solutions strive for economical use of computing resources and are developed to allow for the long time steps allowed by the dynamical core. New schemes are also designed to be modular rather at the level of processes than at the level of full schemes.

"the" added in the text.

The 3MT scheme is based on a mass-flux formulation and is designed to be used at the so-called co ometers

575-629: rewritten in response the general comment 1/ of Reviewer 1.

Table 4. The ALARO CMC

parameterization/dynamics	scheme	references
dynamics for dx > 4km	hydrostatic ARPEGE/ALADIN	Temperton et al. (2001), Radnóti et al. (1995)
dynamics for dx < 4km	non-hydrostatic ALADIN	Bénard et al. (2010)
radiation	ACRANEB2	Mašek et al. (2016), Geleyn et al. (2017)
turbulence	TOUCANS	Ďurán et al. (2014), Marquet and Geleyn (2013)
microphysics	Lopez	Lopez (2002)
shallow convection	TOUCANS	Ďurán et al. (2014), Marquet and Geleyn (2013)
deep convection	3MT	Gerard et al. (2009)
sedimentation scheme		Geleyn et al. (2008)
orographic gravity wave drag		Catry et al. (2008)
surface scheme	ISBA	Noilhan and Planton (1989)
LBC scheme	Davies scheme	Davies (1976),Radnóti (1995), Termonia et al. (2012)

down to a few hundred meter. It is described in detail in Gerard et al. (2009). Here we recall the main assumptions that were used for the development of this scheme.

The 3MT scheme does not rely on any assumption that convective cells cover a negligible fraction of the grid-box area, since this is not valid when increasing the resolution. Diagnostic relationships are therefore replaced by a time integration of the deep convection equations. In particular, the prognostic equations are solved for the updraft velocity, the downdraft velocity and also for the mesh area fractions occupied by the updraft and the downdraft respectively. The quasi-equilibrium hypothesis commonly used in deep convection parameterizations, is abandoned. Instead 3MT uses a prognostic closure, relying on the cloud-base updraft area evolution.

[illegible] separation, common to coarser resolution models, is [illegible] et al. (2007) to separate convective transport and microphysics terms was further elaborated in 3MT. The net condensation in the updrafts is directly estimated and passed to the microphysics scheme for a joint treatment with the cloud scheme condensation input. This together with the above mentioned prognostic formulation of the convective transport allows escaping otherwise quite a delicate parameterization of the detrainment and the pseudo-subsidence terms. It can be seen from a detailed analysis of the equations (not done here) that the 3MT scheme formulation mimics the behaviour of Cloud-System-Resolving Models (CSRMs) in the cloud-resolving limit.

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In coarser resolution models, the condensation is usually treated by two separate parameterization schemes, the so-called cloud scheme for non-convective (stratiform) clouds and the moist deep convection scheme. In contrast CSRMs rely on convective drafts that are fully resolved by the model dynamics and all the condensation is computed by the cloud scheme. To avoid these two limits inapplicable within the convection-permitting scales and also to allow for a smooth transition to the

CSRM limit, the scheme steps are organised in a cascade. The cloud scheme condensation, derived from Xu and Randall (1996) and alternatively from Smith (1990) is computed first. It provides a modified thermodynamic state as input for the convective updraft computations to prevent a double condensation counting. The cloud-scheme and updraft condensation fluxes are then joined later and treated by a single call to the microphysics. This sequence is made possible by the above mentioned microphysics-transport separation. The resulting precipitation flux gives an input to the downdraft computation, treating transport and complementary evaporation of precipitation.

In the convection-permitting scales it is still necessary to account for the sub-grid scale features of the unresolved updrafts condensation and the resulting precipitation. In the 3MT scheme this is done at the thermodynamic adjustment step of the cloud scheme and in the microphysics. Suspended water droplets and ice crystals of the convective cloud portion of the grid box are protected against their re-evaporation during the adjustment in the next time-step. The microphysics computations take into account the geometry of clouds and precipitation vertical overlaps to get a more realistic cloud and precipitation scene within the grid box. The geometry scheme is the exponential-random one Hogan and Illingworth (2000) with a seasonal variation inspired by Oreopoulos et al. (2012). Seeking parameterizations consistency, the same vertical overlap scheme is used in the radiation scheme, described below. It should be noted that the overlap computations are general and fully valid even if there is no contribution from the sub-grid updraft condensation. It also should be noted that precipitation could activate downdrafts without an a priori existence of updrafts.

Microphysics is therefore at the central position of the 3MT scheme in the organization of the ALARO CMC physics time-step, which single call ensures a smooth and implicit transition between grid-scale and unresolved origin of precipitation. It works with six species – dry air, water vapour, suspended liquid and ice cloud water, rain and snow. The thermodynamics obeys the governing equations of Catry et al. (2007) and it is equally applicable if eventual subtypes of solid precipitations like graupel and/or hail are introduced. By construction modularity is kept at the level of processes allowing for their progressive sophistication within the same frame, e.g. vertical overlap geometry and sedimentation. At their current version the parameterizations of auto-conversion, collection, evaporation and freezing/melting are inspired by the work of Lopez (2002). Wegener-Bergeron-Findeisen effect is treated as an auto-conversion following Hage (1995). The sedimentation of precipitations is computed statistically (Geleyn et al., 2008) with a variable fall speed of species.

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In order to enhance consistency and unification of parameterizations, the strategy employed in ALARO is to go to prognostic, memory keeping schemes (Yano et al., 2016). As an example, in 3MT the convective mesh updraft and downdraft fractions have a prognostic formulation. Similarly, prognostic equations for updraft and downdraft vertical velocities based on the proposal by Gerard and Geleyn (2005) are introduced. The result is a CSRM-type set of equations without any explicit presence of detrainment terms. In other words, it interacts with the dynamics in the same manner as a CSRM-type of model does.

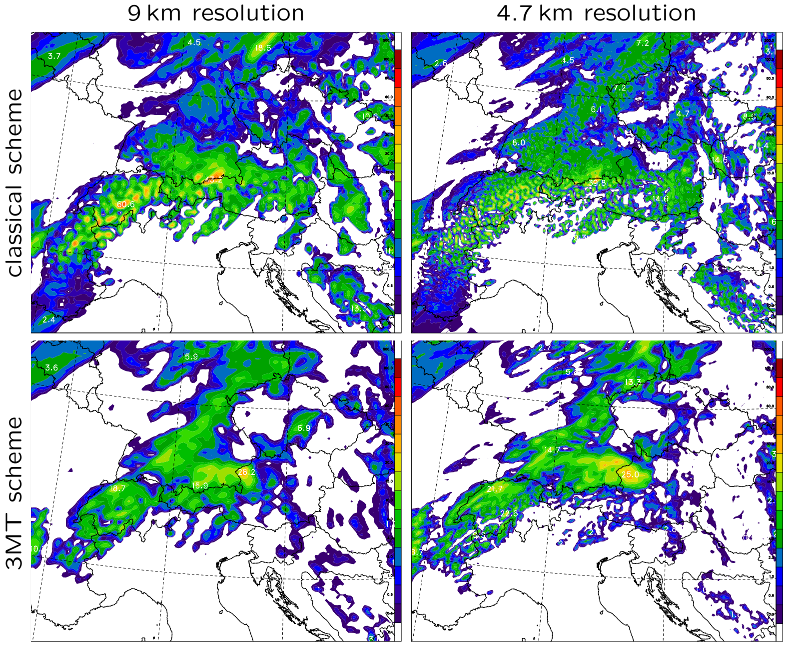

Figure 5. Precipitation accumulated between the +12 and +18 hour forecast times starting on 21 June 2006 at 00 UTC given by the ALARO application in CHMI (Prague). The chosen case is a summer convection in Central Europe. The contour levels are 0.1, 0.3, 0.6, 1, 2, 4, 6, 10, 15, 20, 30, 40, 60, 80 and 100 mm/6h.

One can argue that bulk parameterizations should converge in their behavior to the behavior of CSRMs in the cloud-resolving limiting resolutions. If the prognostic equations of the mesh fraction and the updraft-vertical velocity scale properly, then the equations should converge to the equations of a CSRM. This yields a mechanism to control this convergence and to formulate a scale-aware parameterization of deep convection.

The 3MT scheme was introduced mid 2008 in a predecessor of the ALARO configuration operations in the application in CHMI (Prague), allowing to increase the resolution to 4.7 km, i.e. to enter the grey zone of moist deep convection. It was the world first application of the prognostic microphysics-transport separation concept in NWP. The multi-scale properties of 3MT are demonstrated in Figure 5, comparing precipitation patterns obtained with a classical steady plume type of moist deep convection scheme (Gerard and Geleyn, 2005) and 3MT at resolutions of 9km and 4.7km.

dot instead of comma.

Recently, good results were found up to a resolution of 1km, when running the so called Grey zone experiment Cold Air Outbreak case (Field et al., 2016). Further enhancements are currently entering the common library: unsaturated downdraft and complementary sub-grid-scale updraft formulations, which are expected to still improve the convergence of the parameterized moist deep convection to the resolved case (Gerard, 2015; De Meutter et al., 2015).

In the same spirit of separating the precipitating and non-precipitating processes, shallow convection is part of the turbulence scheme TOUCANS (Third Order moments Unified Condensation And N-dependent Solver). This parameterization of turbulence takes the advantage of recent theoretical proposals, such as the revisited Mellor-Yamada system (Mellor, 1973; Mellor and Yamada, 1974, 1982; Cheng et al., 2002; Canuto et al., 2008) , quasi-normal scale elimination (QNSE) theory (Sukoriansky et al., 2005), and energy and flux budget (EFB) theory (Zilitinkevich et al., 2013), following Ďurán et al. (2014). All of these theories abandon the concept of the critical Richardson number, beyond which turbulence would cease.

capital N.

Since TOUCANS can emulate Mellor-Yamada type of stability dependency functions, valid for all stability conditions, as well as the QNSE and EFB systems; all these models of turbulence are coded. The ALARO CMC retains the so-called model II of Ďurán et al. (2014). In addition, the scheme has been extended to a non-local Third Order Moments (TOMs) terms (based on Canuto et al. (2007)) and to a prognostic equation for moist Total Turbulent Energy (TTE). This concept makes it possible to better treat the anisotropy of the flow and to account for counter-gradient heat fluxes.

The closure-discretization method is a “stability dependent adjustment for turbulent energy modeling” (Ďurán et al., 2014), meaning that prognostic equations for turbulent energies are used, but the turbulent fluxes in the source terms are computed by assuming equilibrium of turbulent energies. This assumption ensures realizibility of the scheme for all conditions (Ďurán et al., 2014, 8.b in). Because ot the specific computation of source terms, the scheme could be classified to be between level 2.0 and level 2.5 level of Mellor-Yamada turbulence closure model if only TKE is used as turbulence prognostic variable. By adding a second prognostic energy, the scheme effectively has a prognostic equation for heat variance, and could be classified between level 2.0 and level 3.0 in Mellor-Yamada system. There are four closure values of the so-called free parameters, which are set accordingly to the model of turbulence, and the turbulence (exchange coefficient) length scale. A conversion between the length scale and a concrete choice of the mixing length is applied. Prandtl type mixing length (Geleyn et al., 2006) or TKE-based mixing length (Bougeault and Lacarrere, 1989) formulations can be used.

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The introduction of moisture in the turbulence scheme, i.e. accounting for phase changes, leading to density changes and latent heat release, is based on the recent formulation of moist Brunt-Väisälä Frequency (BVF) (Marquet and Geleyn, 2013). The non-precipitating (shallow) convection scheme of TOUCANS also makes use of this moist BVF, abandoning the older concept of the modified

Richardson number in presence of condensed water. As for the other ALARO schemes, TOUCANS obeys the governing equations, principles of modularity, memory through prognostic schemes, and ascending compatibility. Indeed, the older turbulence scheme (Louis, 1979) can be emulated by the TOUCANS Framework.

As an enhancement of the Louis scheme a pseudo-prognostic TKE treatment (Geleyn et al., 2006) was introduced in a predecessor of the ALARO configuration and was put in operations in early 2007. The ALARO CMC with the so-called turbulence model II choice in TOUCANS has been operationally implemented in early 2015 together with the new radiation scheme ACRANEB2 described below.

Reply to RC1, specific

Parameterization of radiative transfer is one of the most expensive computations in NWP models, therefore a compromise between the cost and accuracy is required. In the case of ALARO the choice is to keep the cloud-radiation interaction at full spatial and temporal model resolutions, to account for the fast development and the increased variability of cloudiness that manifest themselves with the increasing resolutions of the model applications. To achieve this, the ALARO CMC builds on a broadband approach with single shortwave and single long-wave spectral intervals, where almost linear scalability of long-wave computations (including scattering) with respect to the number of vertical levels is obtained via the so-called Net Exchanged Rate (NER) decomposition with bracketing.

Currently, the ALARO CMC offers two radiative transfer schemes. The original one denoted ACRANEB is best described in chapter 9.3 of Coiffier (2011), with some components originating from Ritter and Geleyn (1992). Thanks to cheap gaseous transmission calculations based on Padé corrected Malkmus band model, and to statistically fitted bracketing weights, full radiative transfer computations at every model grid-point and time-step are affordable. Somewhat less accurate gaseous transmissions are counterweighted by the full cloud/gas-radiation interaction, ensuring realistic model feedbacks.

The second version called ACRANEB2 (Mašek et al., 2016; Geleyn et al., 2017) was developed with the goal to increase the accuracy of gaseous transmissions, cloud optical properties and the NER technique, while still keeping the full cloud-radiation interaction. Several spectrally unresolved effects had to be parameterized. Cloud optical properties were refitted against modern datasets and the shortwave cloud optical saturation was revised. The computational efficiency of the scheme is ensured by selective intermittency, where rapidly varying cloud optical properties are updated at every model time-step, while slowly varying gaseous transmissions only once per hour. In a shortwave band, gaseous transmissions at every model time-step are updated to the actual sun elevation. In a long-wave band, a two-level intermittency is applied, where the full set of gaseous transmissions needed for the self-calibration of the bracketing weights is calculated only every 3 hours. From the cost versus accuracy point of view, ACRANEB2 is one of the best balanced radiation schemes used in NWP, which makes it fully competitive to the mainstream strategy based on infrequent calls of very accurate but expensive correlated k-distribution method. The key point making the selective intermittency affordable in terms of memory requirements is the use of broadband approach. This is because the storage needed for gaseous transmissions is linearly increasing with the number of spectral bands.

Reply to RC1, specific

The ALARO CMC, in contrast to the AROME one, contains the gravity wave drag parameterization (Catry et al., 2008) needed when running at coarser resolutions. The resolution limit from which this parameterization can be dropped is considered to be roughly 5 km, yet the operational experience with ALARO run at 4.7 km still shows its benefit. This scheme is shared with the global model ARPEGE although it uses a different tuning in ALARO; in other words it is shared with the ALADIN baseline-CMC.

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The choices of the physics parameterizations of the ALARO CMC are summarized in table 4.

The reference versions of the ALARO are maintained in CHMI. Scientifically sound versions are committed during the phasings to the central repository in Météo-France. The ALARO CMCs are created once their model configurations have successfully passed the technical validations mentioned in section 2.1.

Some physics parameterizations can be shared between the two configurations. For instance, the ALARO CMC calls the ISBA surface scheme directly, but it is possible to call the SURFEX scheme from the ALARO configurations. The performance of such an inclusion has been tested by Hamdi et al. (2014) in cycle CY36 of the ALADIN System. Additionally the interfaces to the radiation scheme have been cleaned and the ACRANEB2 radiation scheme (Mašek et al., 2016; Geleyn et al., 2017) of the ALARO configurations can be called from the AROME physics package relying on the common physics-dynamics interface INTFLEX.

4 Operational implementation of the ALADIN CMCs in the Partner countries

This section has been restructured following RC1 general comment 3/ into the three subsections 4.1, 4.2

during the past course of the ALADIN project. Dedicated and coordinated efforts are made to support the installations of the newest cycle at Partners' NHMS in order bring to them at a state-of-the-art level, allowing to implement the newest research and development achievements. The support also comprises the collection and redistribution of information about known problems and their fixes.

4.1 Current status of the implementations

The ALADIN System is run operationally at all 16 Partners' NHMSs on the domains depicted in Fig. 6. The model configurations are coupled to the global models ARPEGE or IFS. The lateral boundary coupling data is transferred in a timely manner from Météo-France for the ARPEGE model

typo corrected in reply to RC1, specific comment 20/

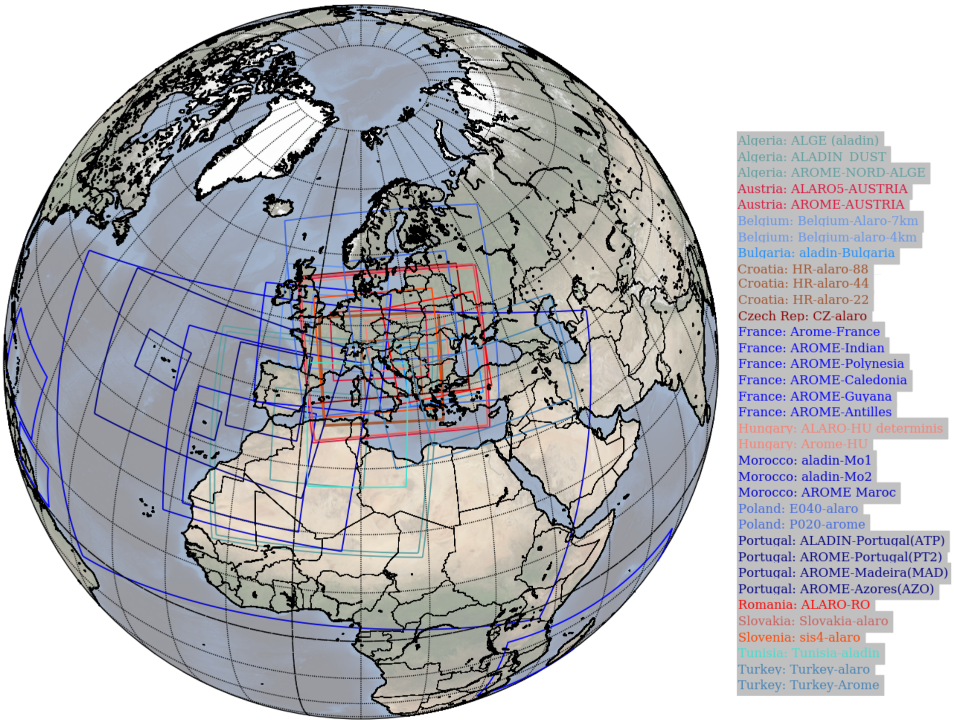

Figure 6. The operational domains of ALADIN System within the ALADIN consortium (situation in April 2017).

RC1, specific comment 21/

and from ECMWF for the IFS data. Every Partner adapts the ALADIN System parameters (domain size, horizontal and vertical resolution, integration length, driving model) according to his needs and according to his telecommunications and computing capacities. The different operational versions are named by the partners, referring to the three configurations ALADIN, AROME or ALARO. Table 5 summarizes the ALADIN System applications in the Partners countries with their main characteristics.

Typical configurations are run with horizontal resolutions of 1.3 km and 2.5 km for AROME and about 4-5 km for ALARO. Some Partners run both configurations in a double-nesting setup: for instance, ALARO (or ALADIN) on a larger domain with a coarser resolution of 4-10 km, driven either by IFS or ARPEGE global model, and a convection-permitting AROME or ALARO configuration on a smaller domain focusing on the Partner's country and close neighborhoods, that is usually coupled to the intermediate ALARO (or the ALADIN) model configuration.

Currently the ALADIN consortium is installing cycles CY40T1 and CY41T1 that are described in section 3 in its operational applications. As can be seen from table 5, not all Partners have made the switch to the latest CMC at the time of writing. Although it is strongly encouraged to follow the new cycles, some Partners may still use older Versions in some cases. For instance some Partners

Table 5. The configurations of the ALADIN System running in the ALADIN partner countries (as in April 2017), with their nationally-used name, horizontal resolution (HRES), domain size, number of vertical levels (NLEV), version of the ALADIN System, coupling model and the used configuration (ALADIN, ALARO, AROME).

RC1, specific comment 21/.

Partner	Oper. Model	HRES	Domain size	NLEV	Model version	Coupled with	Configuration
Algeria	ALADIN-ALGE	8.00	450x450	70	CY40T1	ARPEGE	ALADIN
Algeria	ALADIN-DUST	14.00	250x250	70	CY38T1	ARPEGE	ALADIN
Algeria	AROME-NORD-ALGE	3.00	500x500	41	CY40T1	ALADIN-ALGE	AROME
Austria	ALARO5-AUSTRIA	4.82	540x600	60	CY36T1	IFS	ALARO
Austria	AROME-AUSTRIA	2.50	432x600	90	CY40T1	IFS	AROME
Belgium	Belgium-Alaro-7km	6.97	240x240	46	CY38T1	ARPEGE	ALARO
Belgium	Belgium-alaro-4km	4.01	181x181	46	CY38T1	ARPEGE	ALARO
Bulgaria	aladin-Bulgaria	7.00	144x180	70	CY38T1	ARPEGE	ALADIN
Croatia	HR-alaro-88	8.00	216x240	37	CY38T1	IFS	ALARO
Croatia	HR-alaro-44	4.00	432x480	73	CY38T1	IFS	ALARO
Croatia	HR-alaro-22	2.00	450x450	37	CY36T1	HR-alaro-88	ALARO
Croatia	HR-alaro-HRDA	2.00	450x450	15	CY38T1	HR-alaro-88	ALARO
Czech Rep	CZ-alaro	4.71	432x540	87	CY38T1	ARPEGE	ALARO
France	Arome-France	1.30	1440x1536	90	CY41T1	ARPEGE	AROME
France	AROME-Indean Ocean	2.50	900x1600	90	CY41T1	IFS	AROME
France	AROME-Polynesia	2.50	600x600	90	CY41T1	IFS	AROME
France	AROME-Caledonia	2.50	600x600	90	CY41T1	IFS	AROME
France	AROME-Guyana	2.50	384x500	90	CY41T1	IFS	AROME
France	AROME-Caribbean	2.50	576x720	90	CY41T1	IFS	AROME
Hungary	ALARO-HU determinis	7.96	320x360	49	CY38T1	IFS	ALARO
Hungary	Arome-HU	2.50	320x500	60	CY38T1	IFS	AROME
Morocco	Aladin-NORAF	18.00	324x540	70	CY41T1	ARPEGE	ALADIN
Morocco	ALADIN Maroc	7.50	400x400	70	CY41T1	ARPEGE	ALADIN
Morocco	ALADIN Ma 3DVar	10.00	320X320	60	CY36T1	ARPEGE	AROME
Morocco	AROME Maroc	2.50	800x800	60	CY41T1	ALADIN Ma 3DVar	AROME
Poland	E040-alaro	4.00	800x800	60	CY40T1	ARPEGE	ALARO
Poland	P020-arome	2.04	810x810	60	CY40T1	E040-alaro	AROME
Portugal	ALADIN-Portugal(ATP)	9.00	288x450	46	CY38T1	ARPEGE	ALADIN
Portugal	AROME-Portugal(PT2)	2.50	540x480	46	CY38T1	ARPEGE	AROME
Portugal	AROME-Madeira(MAD)	2.50	200x192	46	CY38T1	ARPEGE	AROME
Portugal	AROME-Azores(AZO)	2.50	270x360	46	CY38T1	ARPEGE	AROME
Romania	ALARO-RO	6.50	240x240	60	CY40T1	ARPEGE	ALARO
Slovakia	Slovakia-alaro	4.50	576x625	63	CY36T1	ARPEGE	ALARO
Slovenia	sis4-alaro	4.40	432x432	87	CY38T1	IFS	ALARO
Tunisia	Tunisia-ALADIN	7.50	216x270	70	CY38T1	ARPEGE	ALADIN
Turkey	Turkey-alaro	4.50	450x720	60	CY38T1	ARPEGE	ALARO
Turkey	Turkey-Arome	2.50	512x1000	60	CY38T1	ARPEGE	AROME

may be in an acquisition phase for a new HPC machine in their Institue and postpone an upgrade to the next cycle.

It should be mentioned also that CMCs of the ALADIN System are being used with data assimilation, with ensemble prediction systems (EPS) and with rapid update cycles for nowcasting purposes. For instance, the AROME CMC is operationally implemented in Météo-France's nowcasting system (Auger et al., 2015) and in five Overseas 2.5km versions (Soutwestern Indian Ocean, Caribbean, French Guyana, Polynesia and New Caledonia). A 12-member ensemble prediction system using AROME at 2.5km resolution, named PEARO (Bouttier et al., 2016; Raynaud and Bouttier, 2016), is also daily running on Météo-France's computing system. ZAMG also develops a comparable system based on the AROME CMC, see Schellander-Gorgas et al. (2017). A detailed description of the activities regarding data assimilation, EPS and nowcasting within the ALADIN consortium is outside the scope of this paper.

4.2 Added value

In terms of local implementation, the operational ALADIN System configurations mostly focus on the need to provide a state-of-the-art forecasting system with convective scale resolution. The goal is to provide forecasters, other production departments in ALADIN national weather services, and eventually stakeholders and users of various type, an added value forecast of severe weather outbreaks, very local weather patterns and a variety of meteorological output fields and products. A typical example of severe weather of concern is heavy precipitation and strong convection, with their possible associated features like severe wind gusts, heavy hail or flooding.

The progressive increase of resolution led to more realistic forecasts of convective systems. As an example, Fig. 7 displays the number of convective cells as a function of their size, represented by the cloud-covered area, derived respectively from the observations of the French radar network, the 2.5-km version of AROME-France, and the newer 1.3-km version (Fig. 7 is adapted from Brousseau et al. (2016)). The new version of AROME provides a more realistic distribution of cell size, with both a larger amount of small cells, as suggested by the radar data, and a slight decrease of the number of large ones. Brousseau et al. (2016) also reported an improved timing of the diurnal cycle of convective activity, improved scores of accumulated rainfall thresholds or wind gusts.

The new Versions of the ALADIN System are also verified for specific past cases that are of primary interest, demonstrating added value of the high-resolution forecasts with respect to the global model or with respect to the previous versions. Fig. 8 shows an example of a warning of the AROME configuration AROME-Aut[12] running in Zentralanstalt für Meteorologie und Geodynamik (ZAMG) (see table 5). It is the June 1st 2016 forecast of a flash flood event that took place at the border region between Austria and Germany. Fig. 8a shows the 24 hour accumulated INCA precipitation analysis (combination of rain gauge and radar data, see Haiden et al. (2011)) for Austria and the surrounding

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[12] This version uses a combined 3DVAR for the atmosphere and an optimal-interpolation (OI) for the surface to create the initial conditions. The lateral boundary conditions with hourly resolution are created from the IFS high-resolution (HRES) model.

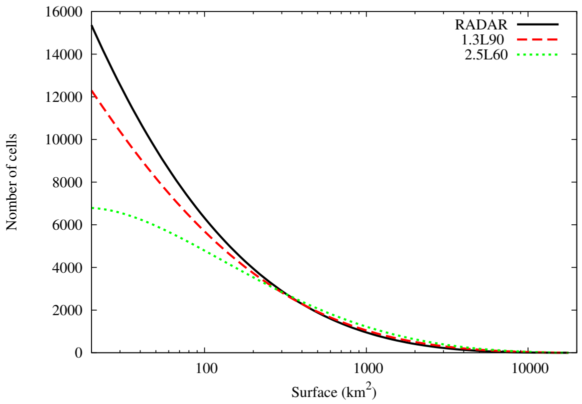


Figure 7. Distribution of the number of convective cells against their size represented by an estimate of the cloudy area, as derived from the data of the French radar network (40 dBz reflectivity detection level, solid black curve), from the 1.3km/90 level AROME version (dashed red curve) and from the 2.5km/60level AROME (dotted green curve). The statistics have been aggregated over 48 convective days of 2012. Adapted from Brousseau et al. (2016).

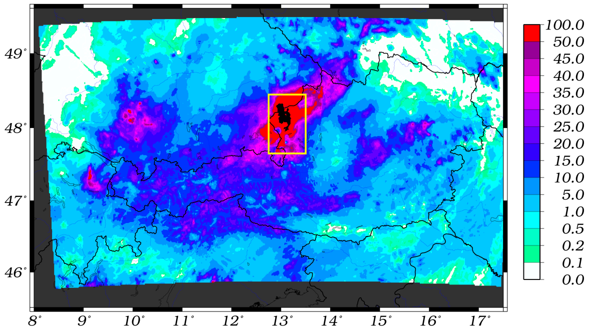
Table 6. 24 hour accumulated area mean and area max values for the region (longitude /latitude: 12.75 - 13.5 / 47.65 - 48.45) for INCA, AROME-aut and IFS-HRES.

	Area mean [mm/24h]	Area max [mm/24h]
INCA analysis	58.0	141.6
AROME-Aut	41.5	137.5
IFS HRES	26.6	41.3

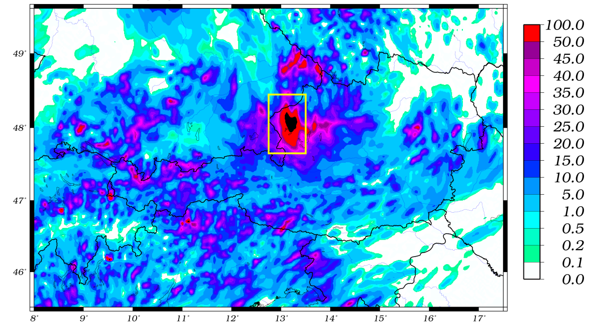
regions. It can be seen that the observed values exceeded 100mm in 24 hours. However, the intensity of the flooding observed in this region and the river gauge measurements indicate that local maxima of precipitation must have been significantly higher than 100mm/24h up to even 200mm/24hours. Figs, 8b and 8c represent the corresponding precipitation forecast for AROME-Aut and IFS HRES. One can see that the localization of the strongest activity is captured well in both models, AROME and IFS, but the overall amplitude is much better simulated by AROME-Aut. This is confirmed when considering the area mean and area max values of INCA, AROME-Aut and IFS HRES in table 6. The area values shown are computed for a rectangular region indicated by a yellow square in Fig. 8.

Efforts are made to steadily increase the resolutions of the applications. For instance, the operational viability of the CY40T1 ALARO CMC is tested at km-scale resolution over Belgium by the Royal Meteorological Institute of Belgium (RMI), as represented the lower part of the diagram in Fig. 2. It is a regular 1.3 km grid on a Lambert projection, with its center at (50.57 N, 4.55 E), with 588 physical gridpoints in the East-West and North-South directions, and with 87 vertical layers. This ALARO CMC run at km-scale was evaluated for a severe convective storm of 18 August

(a) INCA ANALYSIS



(b) AROME FORECAST



(c) ECMWF/IFS FORECAST

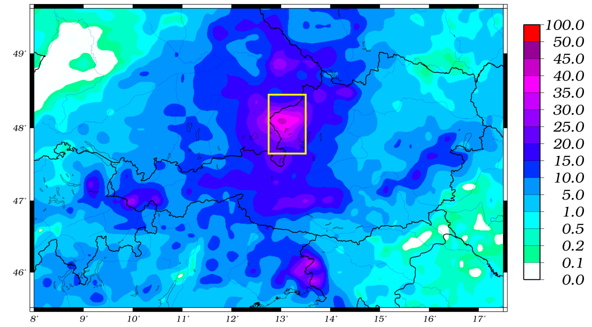


Figure 8. (a) INCA precipitation analysis for the 24 hour period of 20160531 12 UTC - 20160601 12 UTC, (b) AROME-Aut 24 hour accumulated precipitation forecast for the period of 20160531 12 UTC - 20160601 12 UTC (Initialization time: 20160531 12 UTC), and (c) IFS-HRES 24 hour accumulated precipitation forecast for the period of 20160531 12 UTC - 20160601 12 UTC (Initialization time: 20160531 12 UTC).

2011 causing casualties at the Pukkelpop music festival in Belgium, see De Meutter et al. (2015). Fig. 9 presents the accumulated precipitation between +06h and +30h forecast ranges simulated by ALARO and observed with the Radar of Wideumont of the Royal Meteorological Institute, Belgium

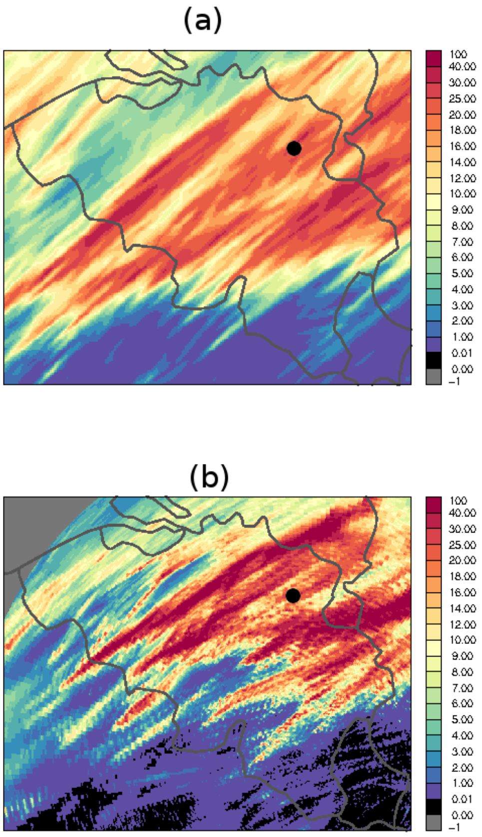


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Figure 9. The accumulated precipitation between +06h and +30h forecast range (a) simulated by ALARO and (b) observed with the Radar of Wideumont, Belgium.

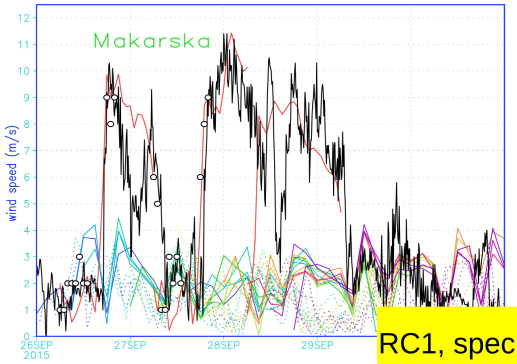
(Delobbe and Holleman, 2006). The red dot presents the location of the Pukkelpop music festival. The newer version of ALARO reproduces the location and the amount of precipitation for this storm better than the current operational version that is run at 4-km resolution.

4.3 Tailor-made configurations

Configurations of ALADIN System are used by the partners of the consortium for scientific studies. In many cases, the partners rely on their own expertise to adapt the Versions of the ALADIN System to develop tailor-made tools for their national needs.

As an illustration, the configurations of the ALADIN System of Croatia (shown in table 5) have been used for dynamical adaptation of the wind field to 2-km resolution since 2000, see Ivatek-Šahdan and Tudor (2004).

ALARO-HRDA has had a large success in forecasting spatial and temporal variability of local windstorm Bura (Grisogono and Belušić (2009)). The high resolution wind field forecast has been an



RC1, specific comment 24/: scale of the figure is c

Figure 10. Wind speed in Makarska (lon 17.02, lat 43.28) from 00 UTC 26 September 2015 until 00 UTC 1 October 2015, measured by the local automatic station with 10-minute intervals (black), the local synoptic station (black circles), and forecasts: HR-alaro-22 (red), HR-alaro-88 (full lines) and HR-alaro-HRDA (dashed) are plotted in rainbow sequence depending on the analysis time (blue for the run starting at 00 UTC 26 Sep 2015, light blue for 06 UTC the same day etc.).

essential ingredient issuing warnings for hazardous weather and safety of traffic at sea and on land. ALARO-HRDA was used to create a wind atlas of Croatia by downscaling the ECMWF ERA40 reanalysis data (Uppala et al., 2005) through ALARO-88 as an intermediate step, using an older version of ALARO configuration.

added to the sentence.

There are episodes of severe Bura associated to local dynamical phenomena that require high resolution forecasts using non-hydrostatic dynamics and complete ALARO physics package (Tudor and Ivatek-Šahdan, 2010). The ALARO configuration has been adapted by the Meteorological and Hydrological Service to run at a resolution of 2 km, the so-called HR-alaro-22 (indicated in table 5). It is in the operational suite since July 2011. The wind field forecast is improved (Figure 10) for local short burst events. This ALARO configuration of the ALADIN System uses the ALADIN NH dynamics, the ALARO physics package, the SSDFI for initialization and is coupled to the global model with a 1-h coupling-update frequency.

Configurations of the ALADIN System are still used for applications where meso-scale applications are required, for instance,

(Déqué and Somot, 2008; Colin et a

Climate applications are briefly mentioned now here and not anymore in the

ration is used by the UERRA project (FP7 p

M. Deque (after discussion within Meteo France) proposed to cite the

(3Dvar) at 11km over Europe for the period

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[13] see its project web site www.uerra.eu

5 Discussion and outlook

The aim of this paper was to describe the current state of the forecast model configurations of the ALADIN System and review the rationale behind the scientific options made in the past developments of the ALADIN System. Given the increase of choices in the model configurations, the ALADIN consortium introduced the notion of Canonical Model Configurations. These are privileged, physically-consistent configurations that are intensively validated and for which support from the consortium is provided to implement them as operational applications in the ALADIN Partner countries. The status of the current two CMCs AROME and ALARO was described and a status report on their validation and implementation in the ALADIN Partner's NWP applications was given. While doing so this paper clarified the meaning of the acronyms used within the ALADIN consortium.

The scope of the present paper was limited to the forecast model configurations, excluding data assimilation, EPS perturbation methods, post-processing software, scripting systems and so forth, but relevant references to these systems were given throughout the paper without aiming to be exhaustive.

The ALADIN consortium provides a platform for the ALADIN members for organizing optional[14] activities related to numerical weather prediction. This can be done by individual members or in more intense optional multilateral collaborations. The applications range from nowcasting tools, specific academic case studies, to past and future climate simulations. Long model runs are used for creating high-resolution wind-climate atlases.

Codes developed within the context of the cooperation agreement with the HIRLAM consortium, have been colloquially called HARMONIE[15] in the past. Recently Bengtsson et al. (2017) clarified the meaning of the acronym HARMONIE. HIRLAM adapted the AROME CMC to create its HIRLAM reference configuration and this is called the HARMONIE-AROME configuration. It has been decided to limit the meaning of the acronym HARMONIE to this configuration only. In other words, the acronym HARMONIE does not cover to the configurations of the ALADIN System. The model configurations used in Termonia et al. (2012) were configurations of the ALADIN System. Of course, the schemes presented in that paper can also be applied in the HARMONIE-AROME configuration but they should not be understood as being restricted solely to the HARMONIE-AROME configuration.

typo corrected: one I removed.

The shared codes are undergoing a number of code modernizations driven by the strong will to keep them fit both for optimal use of upcoming high-performance computing architectures and for further scientific and meteorological evolutions. This is a significant investment, performed together with ECMWF. It involves the use of object-oriented software layers to provide a further abstraction level in data assi[illegible] hand, and in compute grids on the other hand, accompanied

"s" is removed.

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[14] Optional activities mean that the ALADIN consortium does not per se, today, provides coordination for these activities among its members, but facilitates them through the management and the delivery of the codes of the ALADIN System.

[15] HARMONIE stands for HIRLAM ALADIN Research on Meso-scale Operational NWP in Euromed

by disentangling and modularization, optimization and portability issues (including reliability on massively parallel HPC). Extra work on the development of scripts for data assimilation is planned. There are no short-term reasons to abandon the spectral numerical techniques of the dynamical core of the ALADIN System as long as the inherent scalability weakness is more than balanced by the advantage of being able to run with large Courant numbers. Nonetheless, the ALADIN consortium carries out research on scalability and efficiency issues including the study of local discretization methods with research studies ranging from adapting the semi-implicit problem formulation and solution to try and keep the large Courant number time-stepping, to being able to solve the same equations using a HEVI (horizontally explicit, vertically implicit) scheme, the latter being a kind of fall-back solution.

Code Availability. The ALADIN Codes, along with all their related intellectual property rights, are owned by the Members of the ALADIN consortium and are shared with the Members of the HIRLAM consortium in the frame of a cooperation agreement. This agreement allows each Member of either consortium to license the shared ALADIN-HIRLAM codes to academic institutions of their home country for non-commercial research.

Obtaining the ALADIN System codes. Access to the codes of the ALADIN System can be obtained by contacting one of the Member institutes mentioned in the introduction of this paper or by submitting a request in the Contact link below the page of the ALADIN website (http://www.umr-cnrm.fr/aladin/) and the access will be subject to signing a standardized ALADIN-HIRLAM License agreement.

We provide the Contact link or

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The reviewers are acknowledged.

The activities of the ALADIN consortium started in 1991 after an initiative taken by Meteo-France. The current system is the result of the contributions of many experts from the ALADIN, the ARPEGE and the IFS communities. The merits of the authors in the developments of the ALADIN System are small compared to this. The present paper is meant to give a status review of the current system according to our best efforts. While the list of contributors is too long to be acknowledged here, we point out the unique contributions of the late Jean-François Geleyn. He was the driving force behind the creation of the ALADIN consortium and he was the leading scientist of the developments of the ALADIN System. His vision further enabled the training of many young scientists throughout Europe and North-Africa to state-of-art numerical weather prediction. When he passed away in 2015 the consortium lost an exceptional mind. We dedicate this paper to his memory.

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