Working Area Dynamics & Coupling

Progress Report

Prepared by:	Area Leader Petra Smolíková
Period:	2017
Date:	7/3/2018

Progress summary

This report summarizes the work done in the Area of Dynamics and Coupling of RC LACE during 2017.

Scientific and technical main activities and achievements, major events

Let us mention the biggest achievements in the tasks planned for the year 2017.

Task 1. VFE NH

Subject: 1.1 Design of vertical finite elements scheme for NH version of the model

Description and objectives: The main objective of this task remains the same for years - to have a stable and robust vertical finite elements (VFE) discretization to be used in high resolution real simulations with orography with the expected benefit being the enhanced accuracy for the same vertical resolution when comparing with vertical finite difference (VFD) method. We want to stick as much as possible to the existing choices in the design of dynamical kernel (SI time scheme, mass based vertical coordinate) and to stay close to the design of VFE in hydrostatic model version (according to Untch and Hortal).

Status: Phasing to CY45T1 was finished in November 2017. The content of the branch covers the work done in 2014-2017 and may be summarized as follows:

1) **Two distinct definitions of finite element operators for vertical derivative and integral differing in the choice of boundary conditions** may be applied:

    a) **Explicit definition**: the data vector is enlarged by (possibly several) boundary conditions which are built directly into the projection matrix from the grid point space to the finite element space.

    b) **Implicit definition**: a special set of basis functions is chosen satisfying the given set of boundary conditions.

    The choice of definition of vertical operator for integration is controlled through the namelist parameter NVFE_INTBC, while the choice of definition for the vertical derivative operator is controlled through NVFE_DERBC parameter respectively. All previously used definitions are being kept as an alternative.

2) **Revised definition of knots and explicit values of hybrid vertical coordinate η on model half and full levels using minimization of a given cost function**: The position of knots is

based on the position of maxima of splines used for the definition of basis under the key LVFE_MAXIMAS=.T., or on a Greville abscissa under the key LVFE_MAXIMAS=.F. The result of the new procedure is that B-spline basis of order C-1 has maxima of splines on the full model levels, while the B-spline basis of order C has the maxima of splines on the model half levels, where C is the namelist parameter NVFE_ORDER representing the order of B-splines. The minimization uses the standard MINPACK routine LMDIM1.

3) **The clean implementation of the key LVFE_APPROX** for the non-oscillatory approximation of functions based on Schoenberg VDA algorithm which provides more stable and less noisy solution then previously implemented interpolating polynomial while keeping still high order of accuracy.

4) **Revised definition of m, A and B** used for model levels definition which satisfies natural relations, see report of Jozef Vivoda, 2017. The new definition enables the whole vertical discretization to profit from properties which may lead to better accuracy and less noise production.

5) **Revised formulation of pressure gradient term** in horizontal and vertical momentum equation in a way that the real pressure depth is treated consistently.

6) With the use of revised definition of knots and model half and full levels, the choice of invertible operators with fixed sequence of knots has been designed under the key LVFE_FIX_ORDER=.F. which enables **the usage of staggering of *gw* in the FE scheme**, similarly as it is done for FD. The modification appears under the switch LVFE_GW_HALF. Unfortunately, a noise appears in the solution of standard 2D vertical plane tests when this modification is switched on. The problem needs further investigation.

7) **Design of an interface routine** for the vertical integral and derivative (VERDISINT) with the aim to choose only parameters of the desired operation when applying vertical operators and to keep details of the operator´s definition as the internal procedure to the interface routine. The application of vertical derivative and integral operators should become easy and avoid long decision trees.

For finite differences used in vertical discretization, the implicit problem is solved through factorization of one single Helmholtz equation derived for vertical divergence variable d. For finite elements used in vertical discretization, this elimination is not possible because so called C1 constraint is not fulfilled. The implicit problem is solved here by elimination of all variables but two (vertical divergence d, horizontal divergence D) and by solution with a preconditioned iterative method. Recently, it has revealed that when eliminating all variables but horizontal divergence D, we may come to a discrete system of equations which are directly solvable without any constraint on vertical operators. Hence the iterative procedure used to solve the Helmholtz system with two variables (d,D) may be discarded and faster direct method may be used. This was found by Fabrice Voitus (Météo-France) during development of the quasi-elastic equation system and of Helmholtz solver for this system. Since cycle CY45T1, vertical finite element discretization may be tested with this direct Helmholtz inversion.

A draft of paper "Finite elements used in the vertical discretization of the fully compressible core of the ALADIN system" (Jozef Vivoda, Petra Smolíková, Juan Simarro) has been prepared and submitted to Monthly Weather Review.

THE WORK WILL CONTINUE IN 2018.

Executed efforts: 1 PM of research stay at CHMI (Jozef Vivoda), 5 PM of local work.

Documentation: Météo-France documentation to the cycle CY45T1; report from stay on web sites; draft of paper for MWR.

Task 2. Horizontal diffusion

Subject: 2.1 Tuning and redesign of the horizontal diffusion depending on the scale

Description and objectives: A numerical diffusion has a significant role among the other mixing parameterizations since it must be present from planetary to viscous scales, mimicking the continuation of the energy cascade at the end of model spectrum and simulating residual processes which are not well captured by other parameterizations, as well as acting to filter-out unwanted discretization noise. The SLHD (semi-Lagrangian horizontal diffusion) is a flexible tool to represent the numerical diffusion in the model which was proven to work well throughout a wide range of resolutions. Nevertheless, this tool has an enormous number of tuneable parameters and includes not only flow dependent grid-point diffusion, but a supporting spectral diffusion as well. The behaviour of the whole scheme in high resolutions appears to be not understood well. The topic covers the proposal of an experimental setup enabling to test schemes in multiscale environment, developing tools to diagnose energy and entropy in the model system and SLHD tuning to get a consistent and scale invariant parameterization of mixing processes. For the start of the work, the diffusion coefficient used in SLHD and being a monotonic function of the total flow deformation along the terrain following vertical levels will be redesigned.

Status: The environment for assessing the strength of applied grid-point diffusion (SLHD) was prepared. The grid-point diffusion is controlled through the flow deformation along terrain following model levels. From this 2D deformation a parameter kappa is calculated which indicates how SLHD is applied in the given point. We found in experiments in high (1km) resolution that kappa has dichotomic character; having values close to 0 in some points and close to 1 in other points and very little intermediate values. This character may be seen in most of the domain except the top boundary where reduced spectral diffusion is applied. This behavior is undesirable and some modification in the kappa definition could be envisaged. The idea of introducing 3D formulation of flow deformation based on the Smagorinsky 3D scheme was implemented in the model. In experiments done so far the influence of the new definition was modest. We observed that orography influenced the values of kappa even in higher model levels.

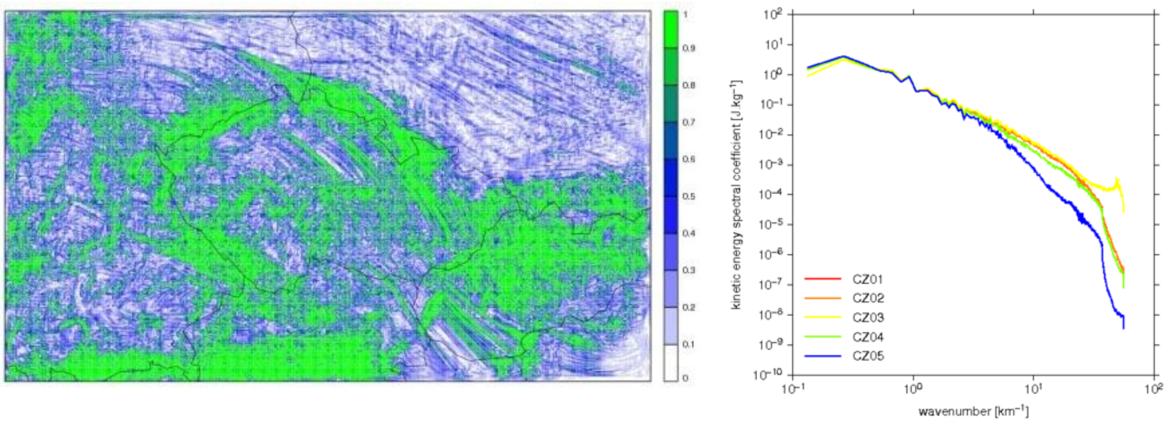

Figure 1: Some experiments with SLHD: Left: kappa for experiment CZ01 from 27 January 2008 00UTC, forecast for 12 hours. Right: kinetic energy spectrum for several experiments. CZ03 shows energy accumulation when non-hydrostatic variables are not diffused enough.

Several experiments in distinct resolution were run. The total kinetic energy spectra, and vertical kinetic energy spectra have been compared with turbulent kinetic energy, being calculated in TOUCANS (vertical turbulence parametrization of ALARO CMC). The aim is to see their change throughout different resolutions. However for such kind of diagnostics very clean experiments are needed with the same model domain for all resolutions. Such experiments were prepared for the future work.

The topic is ONGOING.

Contributors: Viktória Homonnai (OMSZ), Petra Smolíková (CHMI)

Executed efforts: 1 PM – research stay at CHMI, Prague, 2 PM of local work

Documentation: report on the LACE web pages

Task 3. Time scheme

Subject: 3.1 Generalization of the semi-implicit reference state to include vertical profile of background variables and horizontal features as orography

Description and objectives: One of the possible ways to attack this subject is a direct inclusion of the tangent-linear approximated model in the semi-implicit time scheme. The stabilising effect of such method was identified at ECMWF for the hydrostatic IFS by Filip Váňa, and the potential of the new design of SI scheme has been exploited in low spatial resolution (corresponding to usual values in global applications). The most interesting point is the incorporation of orography and real vertical profiles into the linear model, while in the existing reference state for linearization no orography and only constant vertical profiles are present. The consequence of this new design of SI scheme would be no need of the spectral space representation of model variables and of transformations between spectral and grid-point spaces once the horizontal derivatives are calculated in a local way (for example through finite differences). The crucial point is here the iterative method used to solve the Helmholtz problem and its convergence behaviour in higher spatial resolutions (with steeper slopes). There are other less ambitious ways how the vertical profile of the reference state could be incorporated in the semi-implicit scheme which may be also investigated.

Status: **The topic is POSTPONED.**

Executed efforts: none

Documentation: none

Subject: 3.2 The trajectory search in the SL advection scheme

Description and objectives: It was reported that LPC_FULL scheme with reiteration of SL trajectories produce noisy solution. We have confirmed these results. We tried to understand this phenomenon. As we increase the model horizontal resolution, the local divergence can increase significantly and the Lipschwitz criteria may be broken locally. Then the trajectory search may become divergent. Then the increase in the number of iterations in the process to search for a SL trajectory may lead to even less accurate solutions. Similar problems have been identified at ECMWF in IFS and fixed by local change of the computation of the half level wind. These considerations should be confirmed in more detailed study.

Status: The first step in order to implement this idea was to verify the distances between two points representing estimations of the origin point from two successive iterations. This

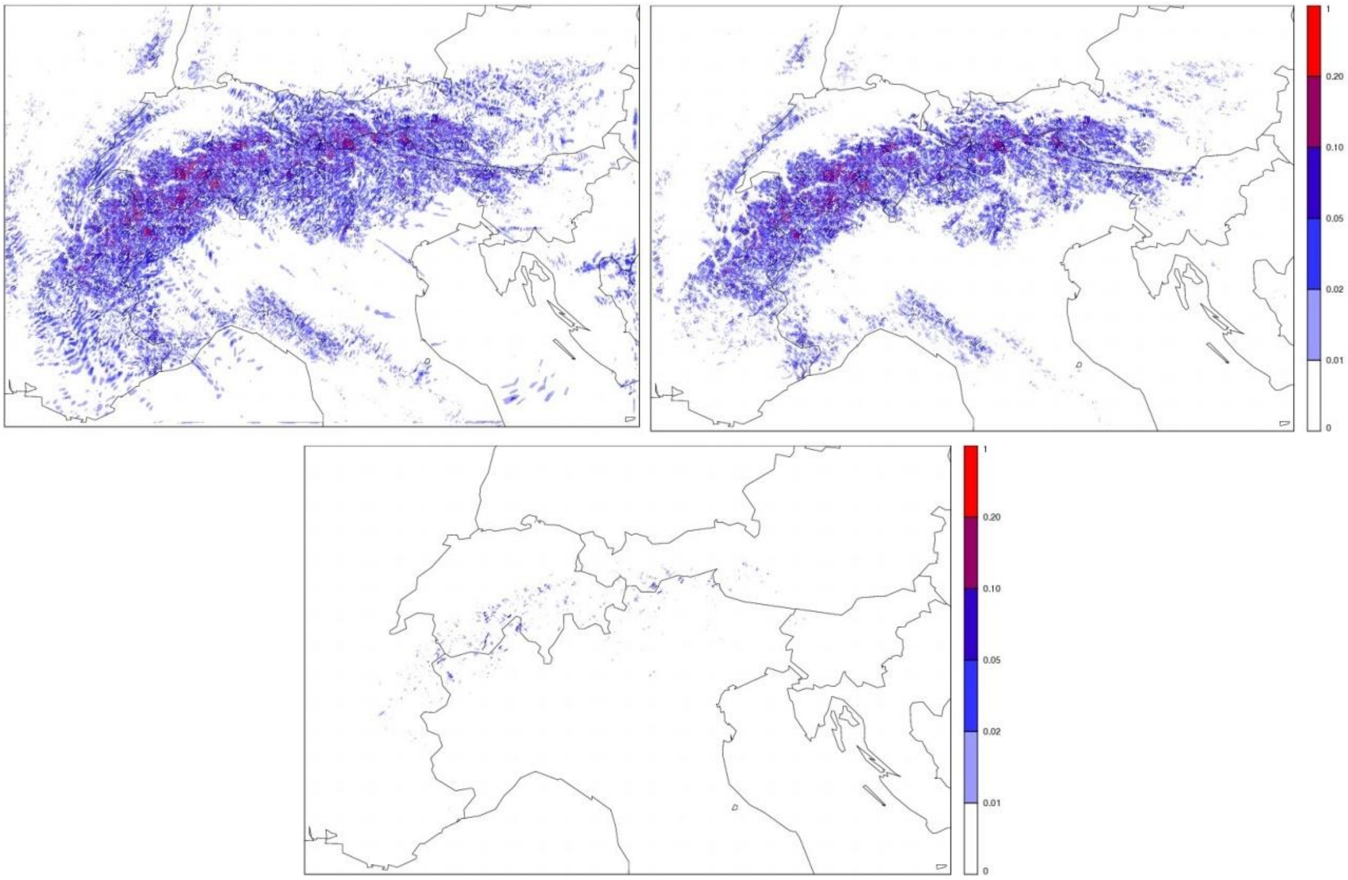

Figure 2: The norms for consecutive iterations of the trajectory search algorithm at 50th model layer: iteration 2-1(top left); iteration 3-2 (top right); iteration 4-3 (bottom); forecast from 31 March 2015 00 UTC for 24 hours.

algorithm was applied separately for horizontal and vertical components. The number of iterations was increased to 5. The testing environment was applied on several real cases.

Hence, the differences between distances (arrival - departure) were checked for consecutive iterations: 2 - 1, 3 - 2, 4 - 3, 5 – 4. These values, referred as norms, proved to have very small values (most of them between 0 and 0.1, in horizontal). As expected, these differences show (Figure 2) some decrease after each iteration.

The next step was to compute the convergence rate of each grid point, defined as the ratio of the above defined norms for successive iterations. When this value is bigger than 0.5, it is considered that the departure point has diverged. For the cases chosen, we found several points excessing this value spread over the whole domain. Even for these points the difference between departure and arrival point was not changing much even for the second iteration. Hence for our purposes another definition of the convergence rate is needed. This will be subject of future work. Moreover, we envisage more systematic testing for an appropriate and longer time period.

The topic is ONGOING.

Contributors: Alexandra Craciun (Meteo Romania), Petra Smolíková (CHMI)

Executed efforts: 1 PM – research stay at CHMI, Prague, 3 PM of local work

Documentation: report on the LACE web pages

Subject: 3.3 Dynamic definition of the iterative time scheme

Description and objectives: Tests in higher horizontal resolutions then those used currently in operational applications (being close or less than 1km) reveal that in most of the cases the SETTLS time scheme is enough to deliver stable solution while there appear some cases when at least one iteration of the iterative centred implicit scheme is needed. When going to higher resolutions it may happen that even one iteration is not enough as reported by Karim Yessad. The idea of this topic is to determine a condition which will evaluate the stability of the integration and in case there is an indication of poor stability the iteration will be started. Ones such condition defined, the time scheme would become more efficient and the computer time will be invested only when needed. Iterative time stepping procedure could be used as well regularly every Nth time step (N>1) to better balance the cost/stability properties of the whole scheme. Implementation of such choice would require careful allocation of corresponding buffers and thorough handling of the data flow between consequent time steps treated in a different way.

Status: A simplified approach was applied to define a complete set of semi-Lagrangian advection schemes that are second order in time accurate and that use the information from the three consecutive time levels and the spatial location of departure and arrival point. This set includes the currently implemented SETTLS scheme. A stability analysis of the 1d horizontal advection problem for the proposed time schemes lead to the definition of a new time scheme with possibly beneficial properties. See Figure 3 for some details. It was shown theoretically that schemes with explicit guess may be even more stable than SETTLS. A combined scheme was proposed writing the so called NESC scheme as a departure from SETTLS scheme and enabling different combinations of these two schemes depending on a chosen parameter. This reflects the experience showing that SETTLS scheme is less stable in real simulations than NESC scheme, while the latter is less accurate (only first order accuracy in time). Hence, the aim is to run SETTLS whenever possible while keep stable integration. See Figure 4 for an illustration.

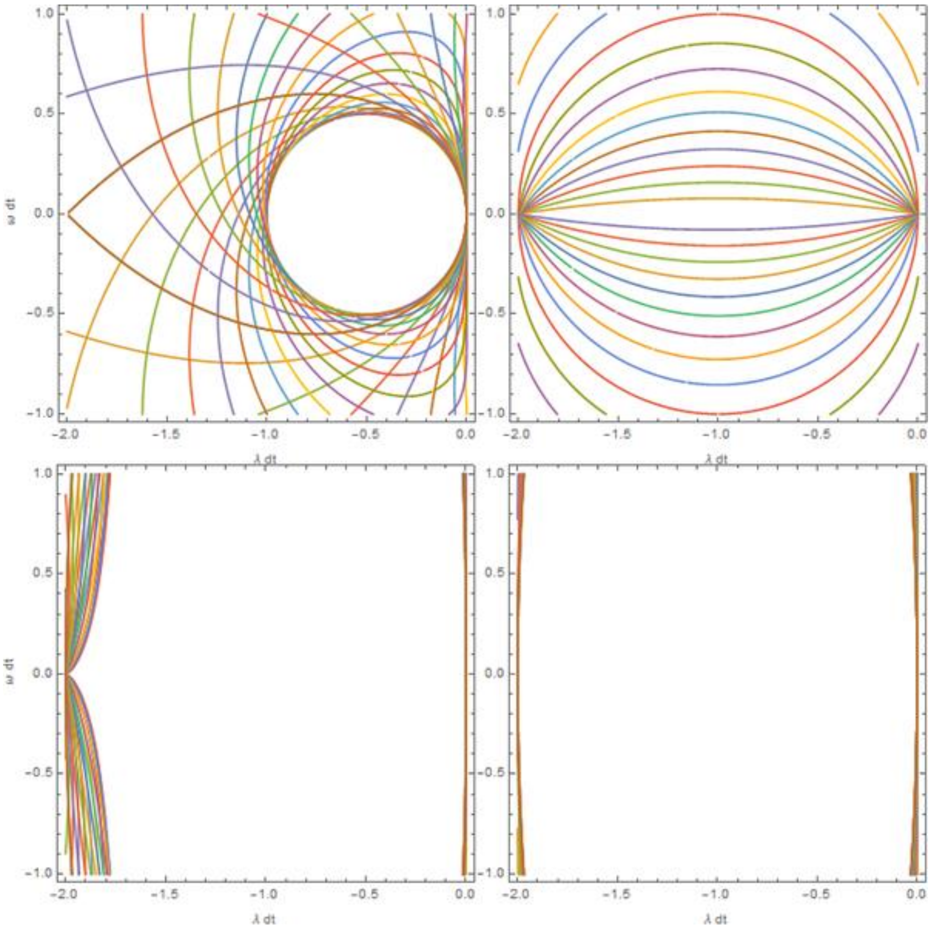

Figure 3: Stability of (a) SETTLS, (b) NESC, (c) PC with SETTLS in predictor and one corrector, and (d) PC with NESC in predictor and one corrector; depending on wave parameters ωΔt, λΔt. Contour lines for several CFL numbers show the threshold for stability (amplitude evolution =1).

The proposed scheme was implemented in the code on the base of CY43 and tested in a simplified context. For the successful implementation it was necessary to harmonize the usage of SETTLS with the key LPC_CHEAP of the PC scheme. The final combined scheme may use either NESC or SETTLS extrapolation for the non-linear residual in the predictor step of the PC scheme depending on a stability measure, and then the global information about the usage of SETTLS/NESC scheme is calculated for each prognostic variable and each vertical level and gathered together to indicate the number of consecutive corrector steps needed for a stable integration. The drawback of the method is the loss of possibility to predict in advance the CPU time needed for model integration. The time of results delivery may be only limited through some threshold value. On the other hand, the stability of time integration is enlarged and in most of the cases the time of results delivery is much smaller

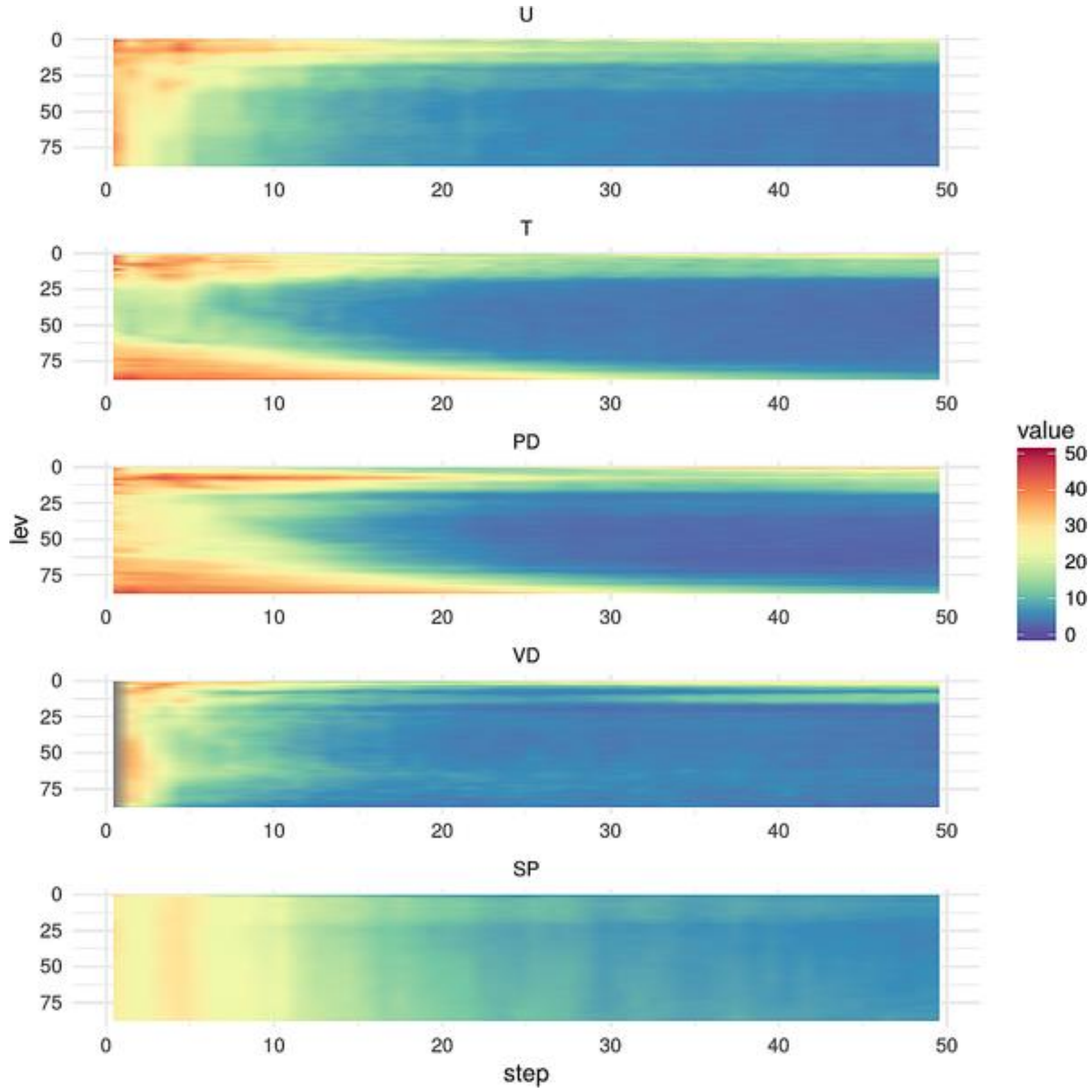

Figure 4: The time evolution of the percentage of points in each model level where NESC scheme was used instead of SETTLS in a real case over Czech territory. Red color means more NESC, blue color indicates less NESC scheme used. Horizontal axis shows the model time step, vertical model levels are on vertical axis. Statistics is calculated for meridional wind component U, temperature T, pressure departure variable PD, vertical motion based variable VD and 3D part of continuity equation SP.

then with the safe choice of PC with one iteration (one corrector step) used in all the time steps.

A real simulation revealed that NESC scheme may be necessary in the whole domain at the beginning of integration and on the bottom and the top boundary of the domain even later. The calculated stability measure differs for different prognostic variables. See Figure 4 for illustration of the results.

The topic is ONGOING.

Contributors: Jozef Vivoda (SHMU)

Executed efforts: 1 PM – research stay at CHMI, Prague, 1 PM of local work

Documentation: A detailed report in two parts may be found on the LACE web pages.

Subject: 3.4 ENO/WENO technique in SL advection

Status: The ENO (Essentially non-oscillatory)/WENO (Weighted Essentially non-oscillatory) technique was implemented in the ALADIN dynamical core in 2014-2016. After idealised tests in 2D academic framework it was desided that the potential benefit of the method may not outweight the increase in the computational cost. Nevertheless, the ENO/WENO technique was implemented in the vertical interpolations done in the semi-Lagrangian advection calculations of IFS by Filip Váňa during 2017 based on our implementation. This method will be tested in long runs and compared with runs where conventional interpolations are applied using objective scores. The WENO technique will be tested in tangent-linear model for 4DVAR assimilation.

Contributors: none

Executed efforts: none, the topic is mentioned for information about connected work done at ECMWF.

Documentation: none

Task 4. Evaluation of the model dynamical core in very high resolutions

Subject: 4.1 Upper boundary condition

Description and objectives: There are some indications that upper boundary may cause a problem in higher resolutions. There could be a big jump in vertical levels needed which may destabilize the whole model as it was observed for finite elements used in the vertical discretization of ALADIN-NH.

In general, on the top boundary there is no material surface contrary to the bottom boundary and vertically unbounded atmosphere may be undesirable in some applications. In practice, velocity normal to the upper boundary is set to zero causing wave reflection similar to lateral boundaries. Free-slip conditions are used for other variables. This means that the vertical derivatives of these variables are equal to zero and there is no mass and heat transfer across the boundary. Radiation boundary condition can be imposed by diagnostic relationship between pressure and vertical velocity at the top (Klemp, Durran 1983; Bougeault 1983). However, it is formulated in terms of vertical wavenumbers and frequencies and is difficult to be implemented. To overcome this problem an explicit absorbing layer is applied for example in SLHD (semi-Lagrangian horizontal diffusion) where spectral diffusion works only when approaching to the top, and an implicit absorbing layer is applied through the coarsening of the vertical resolution when approaching to the top. It should be investigated if there are some new or enhanced problems at the model top in horizontally or vertically higher resolutions and solutions could be proposed if needed.

Status: The topic is POSTPONED.

Executed efforts: none

Documentation: none

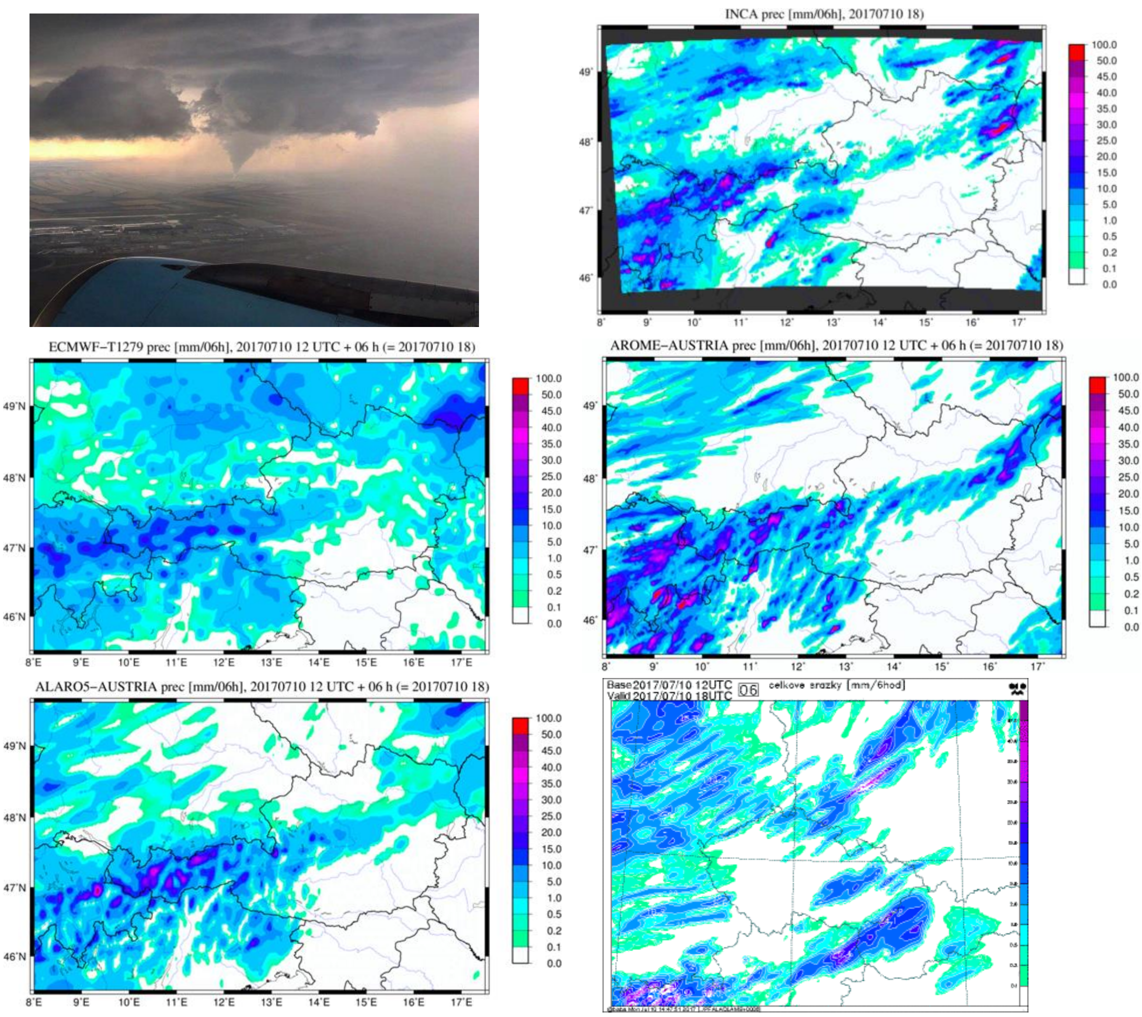

Figure 5: Tornado case from 10 July 2017, forecast from 12UTC valid for 18UTC. Top: INCA; middle: ECMWF and AROME-AUSTRIA; bottom: ALARO-AUSTRIA/5km and ALARO-CZ/4.7km (shifted domain) .

Subject: 4.2 High resolution experiments with AROME

Status: Tests with AROME on 2.5km, 1.2km and 500m were performed with the focus on options in dynamics (diffusion strength, COMAD, PC,..) to learn and gather experiences with the behavior of model on different resolution. The dynamic setting was based on the recommendations from RC LACE web sites and on the information from Météo-France on their AROME 500m setup.

Contributors: Phillip Scheffknecht (ZAMG)

Executed efforts: 1PM

Documentation: none

Subject: 4.3 Testing COMAD in high resolution AROME

Status: COMAD weights were tested in AROME high resolution runs prepared for Subject 4.2. The example on Figure 6 shows that COMAD removes the unrealistic persisting convergence over some mountain peaks. It helps a lot to get rid of grid point storms but it worsens objective scores for near surface variables, e.g. t2m, rh2m, in the 2.5km run. As consequence, it is not recommended for operational setting and tests wil continue in 2018.

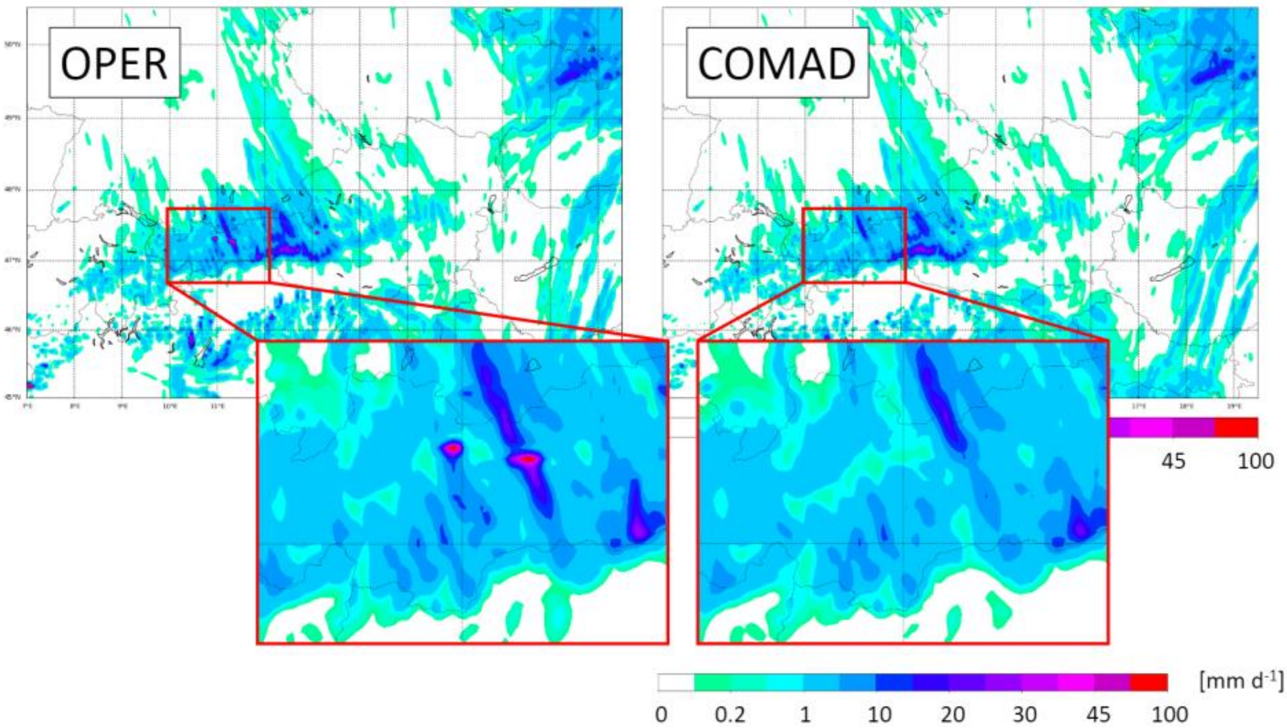

Figure 6: COMAD weights in SL scheme helping to get rid of grid point storms in AROME.

Contributors: Phillip Scheffknecht (ZAMG)

Executed efforts: 1PM

Documentation: none

Task 5. Optimization of the model code to better balance computer resources/results achieved

Subject: 5.1 Single precision

Description and objectives: We propose to investigate the impact of limiting the precision of real-number variables used in the model code to only 32 bits (single precision) in most of the calculations instead of commonly used 64 bits (double precision). The results from annual integration of IFS and from medium range ensemble forecasts indicate no noticeable reduction in accuracy and an average gain in computational efficiency by approximatively 40%. We would like to carefully check the limited area model dedicated part of the code to obtain similar results in CPU reduction while keeping reasonable accuracy level. The envisaged code changes would be rather technical including replacement of hard coded thresholds with intrinsic precision functions, avoiding divisions by floating point numbers that may become zero etc.

Status: The topic is POSTPONED.

Executed efforts: none

Documentation: none

Documents and publications

Six reports describing the results achieved in 2017 are published on the RC LACE web pages:

1) Jozef Vivoda, Dynamical PC scheme for NH kernel of AAA models, Part 1: Theoretical considerations and implementation of LSETTLS residual extrapolation into LPC_CHEAP scheme

2) Jozef Vivoda, Dynamical PC scheme for NH kernel of AAA models, Part 2: Time stepping strategy, implementation and first tests

3) Jozef Vivoda, Vertical finite element scheme in dynamical core of ALADIN

4) Petra Smolíková, Phasing VFE NH to CY45t1

5) Alexandra Craciun, The trajectory search in the iterative time schemes
6) Viktoria Homonnai, Ideal share between horizontal turbulence and numerical diffusion, Testing different parts of SLHD on 1km resolution.

One paper was submitted for publication:

Jozef Vivoda, Petra Smolíková, Juan Simarro, Finite elements used in the vertical discretization of the fully compressible core of the ALADIN system.

Activities of management, coordination and communication

1) **Joint 27th ALADIN Workshop & HIRLAM All Staff Meeting 2017**, 3-7 April , Helsinki, Finland – presentation of Petra Smolíková "LACE - problems in dynamics & coupling and some solutions"
2) **39th EWGLAM and 24th SRNWP EUMETNET Meetings**, 2-5 October 2017, Reading, UK – presentation of Petra Smolíková "Dynamics in LACE"

LACE supported stays in 2017

1) Viktória Homonnai (Hu) - Ideal share between horizontal turbulence and numerical diffusion, 1 month in Prague (15.5.2017-11.6.2017)
2) Alexandra Craciun (Ro) - The trajectory search in the SL advection scheme, 1 month in Prague (12.2.2017-12.3.2017)
3) Jozef Vivoda (Sk) - Dynamic definition of the iterative time scheme, 1 month in Prague (15.5.2017-11.6.2017)
4) Jozef Vivoda (Sk) - Design of vertical finite elements scheme for NH version of the model, 1 month in Prague (30.10.2017-26.11.2017)

Summary of resources/means for the whole year 2016

The total effort invested into the area of Dynamics&Coupling in frame of LACE in 2017 is 17 PM, 4 PM from that as scientific stays. This represents roughly 80% of planned efforts and full accomplishment in scientific stays. Some topics, especially tests of AROME in high resolutions, have been done on top of planned work.

Task	Subject		Resources		
			Planned	Executed	Stays (Executed /Planned)
1. VFE NH	1.1	Design of VFE in NH model	6	6	1/1
2. Horizontal diffusion	2.1	Tuning and redesign of the horizontal diffusion depending on the scale	3	3	1/1
3. Time scheme	3.1	Generalization of the semi-implicit reference state	2	0	0
	3.2	The trajectory search in the SL advection scheme	4	4	1/1
	3.3	Dynamic definition of the iterative time schemes	2	2	1/1
	3.4	ENO/WENO technique in SL advection	-	-	-
4. Evaluation of the dynamical core in very high resolutions	4.1	Upper boundary conditions	2	0	0
	4.2	High resolution experiments with AROME	0	1	0
	4.3	Testing COMAD in high resolution AROME	0	1	0
5. Optimization of the model code	5.1	Single precision	2	0	0
Total manpower			**21**	**17**	**4/4**

Problems and opportunities

We have started interesting and promising topics and expect to be able to do valuable work in case the dedicated workforce will be available.