Working Area Dynamics & Coupling

Progress Report

Prepared by:	Area Leader Petra Smolíková
Period:	2019
Date:	6/3/2019

Progress summary

This report summarizes the work done in the Area of Dynamics and Coupling of RC LACE during 2019. One topic was added on top of what has been planned for the year 2019. It is denoted as 6.1. "Reformulation of the NH system as a departure from HPE". The idea has emerged in spring 2019 and the local work was started immediately. The topic was mention at the LSC in September 2019 and it was agreed that the topic will enter the report for 2019 and the plan for 2020.

1. Scientific and technical main activities and achievements

Let us mention the biggest achievements in the tasks planned for the year 2019.

Task 1. Vertical discretization

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). We plan to study the compatibility of direct inversion in the Helmholtz solver done after elimination of all variables but horizontal divergence (solution proposed by Voitus) with finite element vertical discretization.

Status: The compatibility of VFE with direct inversion Helmholz solver is planned for the end of year since the elimination of variables implemented by Fabrice Voitus is now available in the official cycle CY46T1. On top of that the formulation of vertical discretization in case of VFE was revised. The explicit definition of vertical coordinate was modified with several new options enabling to choose the density of vertical levels close to the bottom and top domain boundary. See Figure 1 for an illustration. Then the definitions of A and B coefficients needed for pressure based vertical coordinate definition ensure mass conservation. It was shown experimentally that the proposed solution results in purely imaginary eigenvalues of the operator representing the linear model which property is a necessary condition for the scheme numerical stability.

The vertical FE discretization designed primarily for NH model version was tested in global hydrostatic model IFS. It was shown that even with B-splines of high order (7) used in the FE basis the proposed discretization results in stable integration.

Moreover, the full level variant of the vertical velocity was implemented on top of the already existing half level version. In both cases, the integral and the derivative in the vertical are not inverse of each other, but it does not seem to affect the results detrimentally. See Figure 2 for an illustration of results.

The topic is ONGOING.

Contributors: Jozef Vivoda (SHMU)

Executed efforts: 1 PM

Documentation: presentation

Subject: 1.2 Modularization of vertical discretization

Description and objectives: The influence of a vertical discretization on stability and accuracy of the model integration is still not well understood. This task incorporates two parts, one technical – to modularize the vertical discretization from other parts of the dynamics; and second scientific, to understand better the influence of vertical levels definition on the behaviour of the model. It is a known fact that SL interpolations are less accurate when applied in terrain following vertical coordinates then in smooth pressure levels (Park et al., 2019). The usage of hybrid levels up to the stratosphere is a common practise in our community. However, it can be a source of noise in the upper model levels. This undesirable phenomenon can be simply pacified by using pressure levels already from the middle troposphere and higher. Such a choice could have a positive influence on the quality of the upper level turbulence (CAT) prediction and also it could possibly avoid the generation of vertical chimneys in the vertical velocity field observed often over an orography. This could have as well a positive impact on precipitation field which may become smoother. Hence, we propose to investigate the influence of “hybridism” on the quality of the model prediction and to try to find an optimal choice for vertical coordinate setting.

[S.-H. Park, J. B. Klemp, and J.-H. Kim, *Hybrid mass coordinate in WRF-ARW and its impact on upper-level turbulence forecasting*, MWR, in press, 2019]

The topic is PENDING.

Contributors: none

Executed efforts: none

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 be well working 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 was redesigned. Two domains were prepared for clean tests covering roughly the same territory and differing in the resolution. We will continue the work.

Status: RESEARCH STAY at the first part of 2019. Described in the report from September 2019. **The topic is ONGOING.**

Contributors: Mario Hrastinski (DHMZ), Petra Smolíková (CHMI)

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

Documentation: The report from the stay is available 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 PENDING.**

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 produces 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 Lipschitz criteria may be broken locally. Then the trajectory search may become divergent and 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. First tests were started in 2017 which did not reveal any serious problem with the convergence. The prepared environment will be used for systematic testing on longer period.

Status: **The topic is FINISHED.**

Contributors: none

Executed efforts: none

Documentation: none

Subject: **3.3 Dynamic definition of the iterative time scheme**

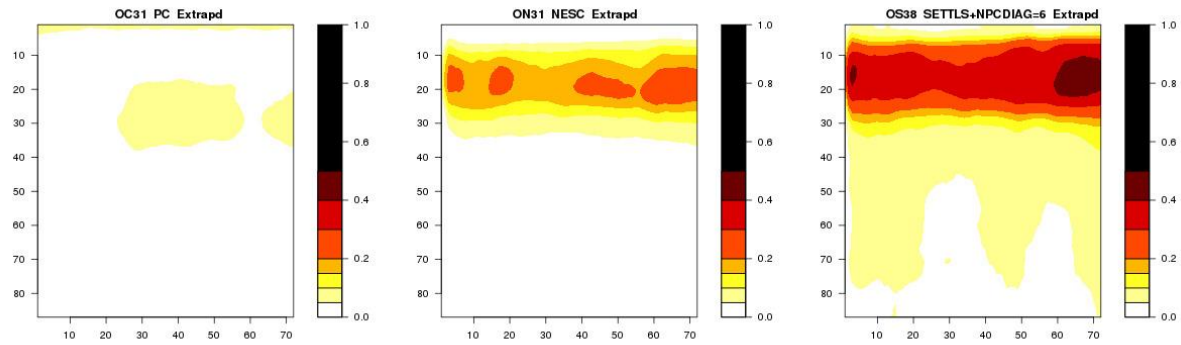

Figure 1: The proportional part of grid points in one vertical layer with broken "stability criterion", here the criterion is based on the change of non-linear residuum in pressure departure equation between consecutive time steps. Left: predictor corrector with one iteration applied as a reference solution; middle: NESC time scheme; right: NESC applied only when "stability criterion" is broken.

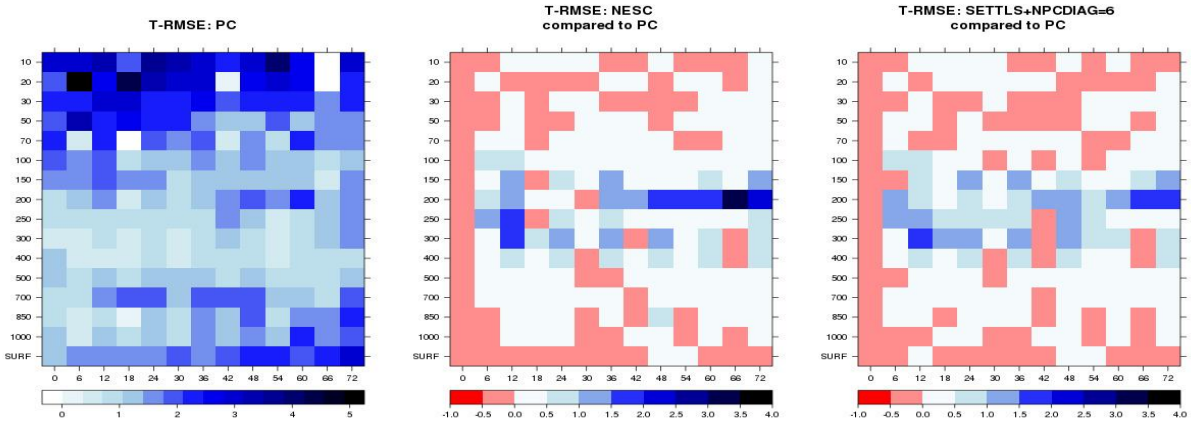

Figure 2: RMSE for temperature. Left: PC (predictor corrector with one iteration) as a reference solution; middle: NESC - PC; right: NESC applied only when "stability criterion" is broken - PC. On the x-axis is the time range, on the y-axis is the vertical extent of the domain.

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 additional iteration (corrector) 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: We started with a less ambitious idea, to find a balance between less accurate/more stable nonextrapolating scheme NESC and second order accurate/less stable scheme SETTLS for each grid point. Moreover, a combined scheme allowing to use a linear combination of these two approaches for each grid point was proposed and implemented in 2018. We were investigating which condition could serve as a good weight for this linear combination. Several possible formulae were proposed and tested. Since the stability issues appear usually at the top of the domain, we tried as well to apply NESC scheme in upper layers and SETTLS scheme in lower levels and the combined scheme in between.

Tests were performed on a severe case of 30.10.2017 over the Czech operational domain, in 2.3km horizontal resolution and with 87 vertical levels. Simple SETTLS is in this case unstable. We were able to stabilize the integration through the application of NESC scheme in points where a “stability criterion” was broken, or with a combined scheme. But the objective scores (RMSE, STDEV, BIAS) for basic variables revealed that the precision was lowered to be close to the case with pure NESC scheme applied and diagnostic showed that huge portion of grid points was involved in the NESC scheme. Similarly, the application of NESC only in upper levels is not enough and the stable case with NESC being applied in the big part of domain is not accurate enough. The results are illustrated in Figure 2. We plan to continue in the work just started.

The topic is ONGOING.

Contributors: Alexandra Craciun (ANM), Petra Smolíková (CHMI)

Executed efforts: 1 pm research stay of Alexandra Craciun at CHMI, 1 pm local work

Documentation: none

Subject: 3.4 Terms redistribution through new vertical motion variables

Description and objectives: Motivated by the work of Fabrice Voitus being presented at the ALADIN Workshop in Toulouse in April 2018 we started this new subject. The aim is to

reformulate the nonhydrostatic nonlinear model to obtain simple bottom boundary condition which is easily fulfilled. This aim may be reached only for restricted choices done in the dynamics of the ALADIN system. In particular, only the case when vertical velocity variable is used in the nonlinear nonhydrostatic model in the two-time level SI SL scheme. The bottom boundary condition was proven to be very important for the stability and accuracy of the whole discretization of the system of prognostic equations.

Status: The cooperation with Fabrice Voitus has been established and the implemented options will be tested in 2D and 3D cases. **The topic is ONGOING.**

Contributors: none

Executed efforts: none

Documentation: none

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

Subject: 4.1 Tuning of dynamical adaptation of the wind field at different resolutions

Description and objectives: The quality of the wind field forecast may be improved in case of strong wind and rugged terrain through a dynamical adaptation to high resolution topography by running short range forecast of the ALADIN system in higher than standard operational resolution. Wind field from the dynamical adaptation may be used as well to evaluate local wind climatology. This strategy was applied on Croatian domain to better capture the local wind “bura” being developed due to large gradients of pressure over the coastal mountains having large spatial variability and local terrain dependence. The influence of non-hydrostatic dynamics setting in several high resolution experiments (500m, 250m) will be studied.

The work is connected to physics, since the influence of parameters of the turbulence scheme is being questioned as well.

Status: Described in the report from September 2019. **The topic is ONGOING.**

Contributors: Mario Hrastinski (DHMZ)

Executed efforts: 1 PM of local work

Documentation: The report is available on the LACE web pages.

Subject: 4.2 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 PENDING.**

Executed efforts: none

Documentation: none

Subject: **4.3 Experiments in very high resolution**

Description and objectives: As reported by Fabrice Voitus (Météo France) the numerical stability of the ALADIN nonhydrostatic dynamical core is endangered as soon as the horizontal resolution of 350m is approached above steep orography. To be able to test this statement and to analyse the model dynamical core behaviour we have to start experiments in the very high resolution. For these goal the climate files have to be prepared from a fine database. We started with the domain covering Central Europe including Alps in 500m horizontal resolution. We solved problems connected to memory requirements in the procedure e923.

Status: It has revealed that the high resolution experiments are very sensitive to the distribution of vertical levels. It has consequences in the stability and accuracy of the results. We plan to continue the work with increased vertical resolution.

The topic is ONGOING.

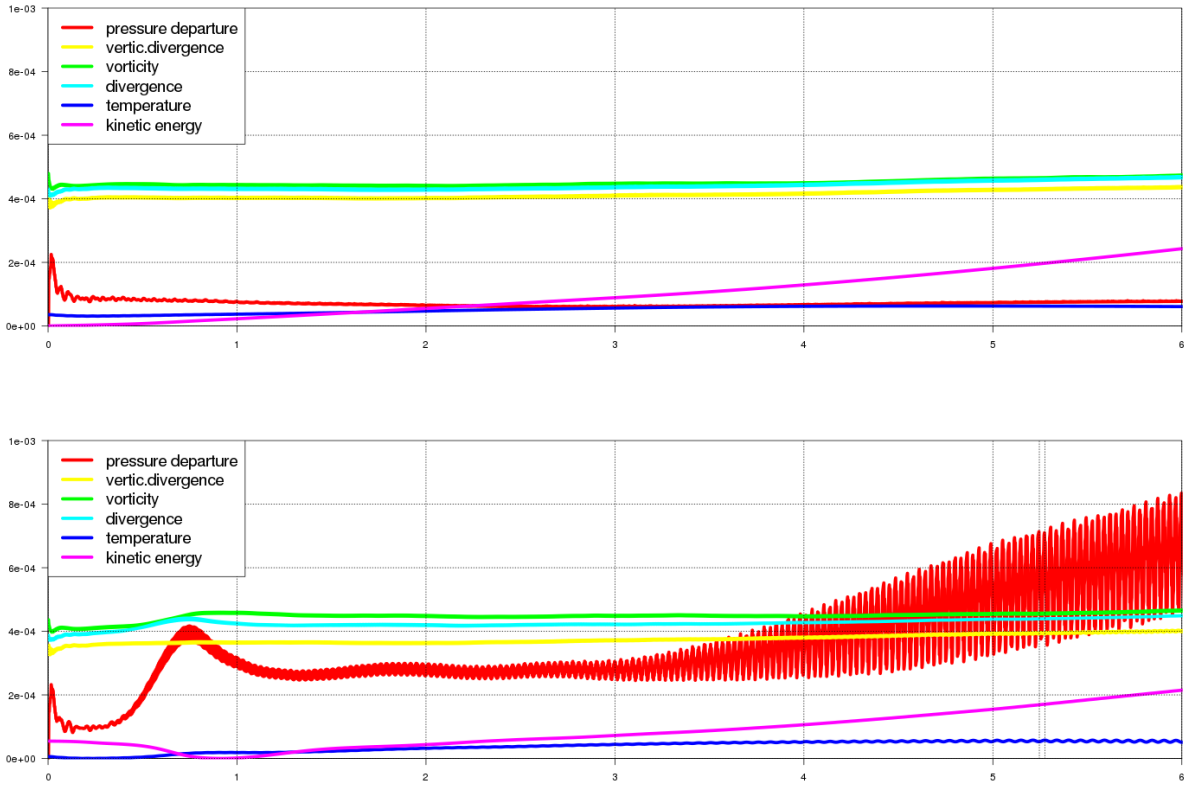

Figure 3: Spectral norms averaged over the whole domain for the experiment over Occitania with the horizontal resolution of 375m, and top: 90 vertical levels of the AROME operational application at Meteo-France; bottom: 87 vertical levels of the operational Czech application. The length scale of the pressure departure oscillation is 7 full time steps.

Contributors: Petra Smolíková (CHMI)

Executed efforts: 2 PM of local work

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-numbers 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 LAM model configuration CY46t1 was compiled in single and double precision. The model integration was run in the adiabatic, nonhydrostatic context. The comparison of results from runs in single and in double precision indicated problems which were tracked to the calculation of interpolation weights in the semi-Lagrangian scheme. The problem was found and fixed through changed calculation of these weights. Its influence is restricted to case LSLHDQUAD=T being switched on either through the choice of SLHD for at least one variable, or through non-zero SLHDKMIN, the choice which influences the properties of the high order semi-Lagrangian interpolator. The work must continue step by step.

The topic is ONGOING.

Contributors: Oldřich Španiel (Sk)

Executed efforts: 1 PM of local work

Documentation: none

Task 6. Basic equations

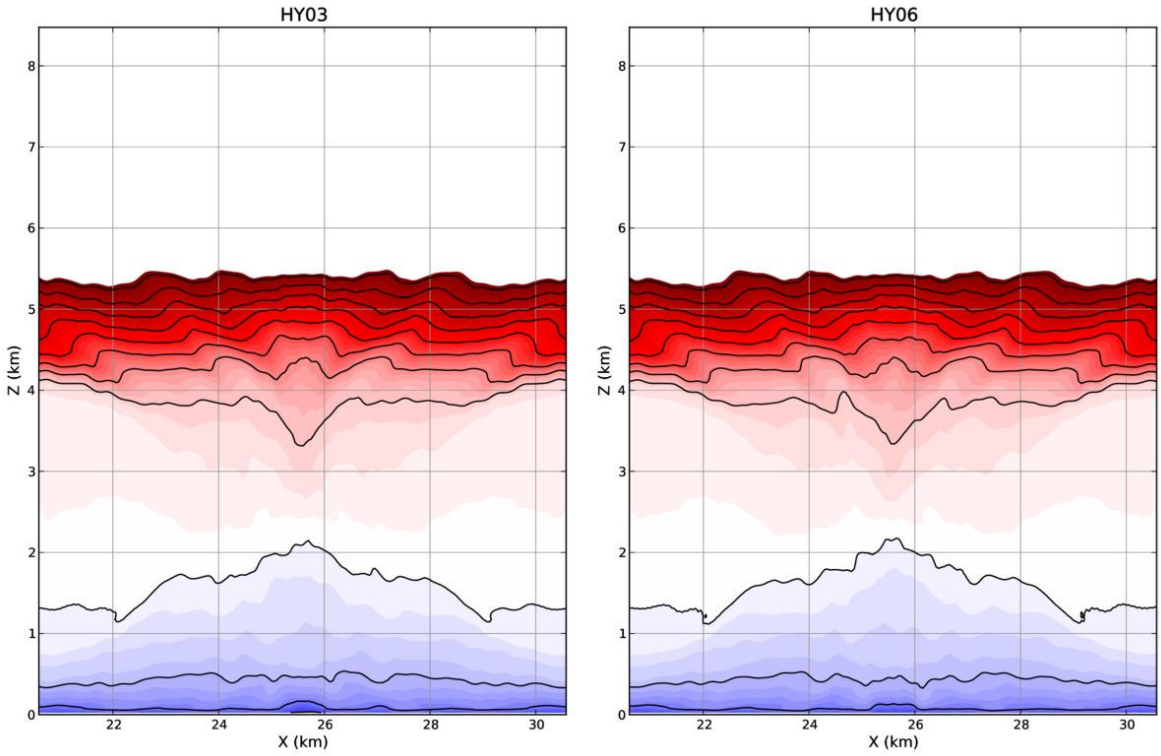

Figure 4: Straka test: the central part of the domain after 300 time steps. Left: hydrostatic run with HPE solved traditionally. Right: hydrostatic run emulated from NH code through parameter ε=0.

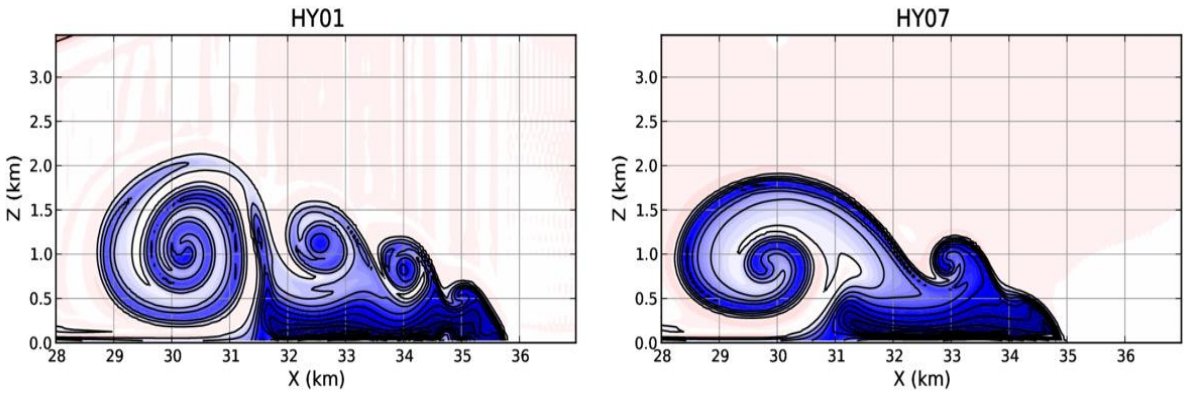

Figure 5: Straka test: the right-hand part of the domain after 300 time steps. Left: NH run. Right: hybrid run with constant parameter ε=0.5. The small features have disappeared, but the basic shape is well pronounced.

Subject: 6.1 Reformulation of the NH system as a departure from HPE

Description and objectives: The aim of the topic is to reformulate the compressible nonhydrostatic system of equations as the departure from the hydrostatic system which may allow later to introduce nonhydrostaticism in dependence on the vertical coordinate and keep hydrostatic formulation close to the model top where stability plays the most important role. The implementation is possible only with the use of the direct Helmholtz solver after elimination of all variables except horizontal divergence proposed by Fabrice Voitus being implemented in CY46t1.

Status: **The topic is NEW.**

Contributors: Jozef Vivoda

Executed efforts: 2 pm local work, 1pm research stay at CHMI (November 2019)

Documentation: The report from the stay is available on the LACE web pages.

2. Documents and publications

Several reports already are or will be soon published on the RC LACE web pages:

1) Alexandra Craciun, Dynamic definition of the iterative time schemes, 6pp.
2) Mario Hrastinski, Testing the performance of Semi-Lagrangian Horizontal Diffusion (SLHD) at different horizontal resolutions, 16 pp.
3) Mario Hrastinski, Dynamical adaptation related work at DHMZ, 3pp.
4) Jozef Vivoda, NH system as departure from HY system. Unification of HY and NH code, 16pp.

Activities of management, coordination and communication

1) **Joint 29th ALADIN Workshop & HIRLAM All Staff Meeting 2019**, 1-5 April 2019, Madrid, Spain – presentation of Petra Smolíková "Dynamics in LACE"
2) **Dynamics Working Day**, 28 May 2019, Toulouse, France – presentation of Jozef Vivoda "Contribution of RC LACE into development of HY and NH dynamical core"
3) **EWGLAM/SRNWP 2019,** 30 Sep - 03 Oct 2019, Sofia, Bulgaria – presentation of Petra Smolíková "RC LACE advances in dynamics"

LACE supported stays in 2019

1) Mario Hrastinski (Cr) - Tuning and redesign of the horizontal diffusion depending on the scale, May-June 2019 at CHMI, 4 weeks

2) Jozef Vivoda (Sk) – NH as a departure from HY dynamics, Nov 2019 at CHMI, 4 weeks

3) Alexandra Craciun (Ro) – Dynamic definition of the iterative time schemes, Oct-Nov 2019 at CHMI, 4 weeks

Summary of resources/means

The effort invested into the area of Dynamics&Coupling in frame of LACE in 2019 is more restricted then in the previous years. Three research stays were executed. For one of them there was a shift in the topic to a newly proposed promising subject of "Reformulation of the NH system as a departure from HPE". One stay was cancelled and the topic 3.2 was closed.

Task	Subject		Resources		
			Planned	Executed	Stays
1. Vertical discretization	1.1	Design of VFE in NH model	2	2	-
	1.2	Modularization of vertical discretization	2	0	-
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	-
	3.2	The trajectory search in the SL advection scheme	3	0	1/0
	3.3	Dynamic definition of the iterative time schemes	3	3	1/1
	3.4	Terms redistribution through new vertical motion variables	3	0	1/0

4. Evaluation of the dynamical core in very high resolutions	4.1	Tuning of dynamical adaptation of the wind field at different resolutions	2	1	-
	4.2	Upper boundary condition	2	0	-
	4.3	Experiments in very high resolution	0	2	-
5. Optimization of the model	5.1	Single precision	2	1	-
6. Basic equations	6.1	Reformulation of the NH system as a departure from HPE	0	3	0/1
Total manpower			**24**	**15**	**4/3**

Problems and opportunities

This year even persistent contributors were occupied with other tasks connected to local operational activities, computer procurements etc. Consequently, some topics appeared to be pending or making only slow progress. Even in these hard conditions we did valuable work.