Final summary of the EX-CELO Priority Project

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September 8, 2020

Overview of EX-CELO Priority Project

- Overarching goal: extend capabilities and provide optimal accuracy of the EULAG dynamics within COSMO
- Realization: March 2017 - March 2020 (including extension)
- FTEs: planned - 3.775, realized - about ~ 1 FTE senior and ~ 1 junior)
- Fully externally funded by the research grant of Foundation for Polish Science, complementary to the state-funded efforts of CELO Priority Project at IMGW.

Scientific and practical questions addressed

- What is the gain in accuracy from dispensing 'gentle slope' approximations in diffusion ?
- What is the optimal numerical strategy for realizing turbulent surface fluxes (with or without mass model level at 0 m) ?
- Given the fully explicit advection of EULAG, what is the way to achieve long timesteps, necessary for timely forecast delivery ?
- How to apply ensemble data assimilation capabilities of COSMO to EULAG numerics ?

EX-CELO Task 1 - diffusion-related advancements

What has been done ?

- Refactoring and optimization of EULAG diffusion operator to modern Fortran(in connection with CEL-ACCEL Priority Project), benchmarking of computational performance.
- Performing idealized tests, validating the implementation in a series of 1D and 3D tests
- Performing analytical stability analysis of the explicit vertical diffusion scheme, which involves horizontal components (note that *horizontal* $\neq$ *flat* in terrain following coordinates).
- Preparation of NWP test setup of the foehn flow past Tatra mountain range in southern Poland.

Example idealized study - cold bubble "Straka" test

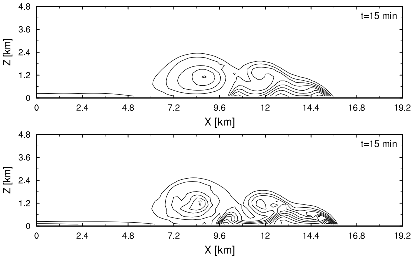

Figure: COSMO EULAG(top) and Runge-Kutta, $dx = 200m$

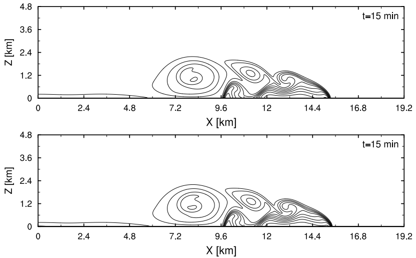

Figure: COSMO EULAG(top) and Runge-Kutta, $dx = 25m$

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Isolines of potential temperature at 200 m and 25 m for the two dynamical cores are presented after 15 min of simulated time.

Difference in pure EULAG and mixed: vertical COSMO+horizontal EULAG diffusion. Note the different set of variables diffused (T vs. θ)

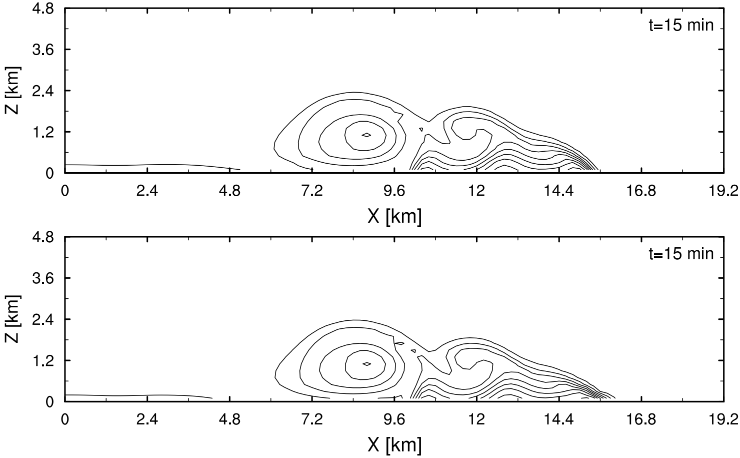

Figure: COSMO EULAG(top) and COSMO-EULAG with COSMO vertical implicit diffusion, $dx = 200m$

EX-CELO Task 1 - deadlock

- While idealized tests with prescribed diffusion coefficient worked fairly well, extraction of the turbulent fluxes from COSMO in order to link it to new diffusion operator seemed next to impossible.
- COSMO documentation was insufficient, and, effectively, no assistance could be reached from COSMO.
- The hired PhD student was unable to perform reverse engineering of the COSMO code.
- For the hope of better documentation, the decision was made to wait for the new COSMO release with unified COSMO-ICON physics, which was severly delayed.
- As a result, this development was not continued as the human resources were no longer available at the later date.
- One more attempt beyond EX-CELO is planned with the newest COSMO and EULAG codebase, to exclude or correct possible programming error.
- Technical developments aiming at COSMO infrastucture extension to embrace extra mass level at 0 m became unfeasible with the decsision to phase-out COSMO.

EX-CELO Task 2 - Enhance the efficiency of COSMO-EULAG algorithms.

Actions considered the two pillars of EULAG numerics - explicit advection and implicit solver.

- At first, substepping of advection was developed, that allowed for executing two or more dynamics steps per physics step, if needed for numerical stability.
- This easily allowed to match the timestep of COSMO-EULAG with the timestep of Runge-Kutta core.
- Forecasting scores does not seem to be negatively affected.
- Further development included the transfer of the adaptive timestep capability from IFS-FVM, which allows for integrations with the Courant number kept close to unity, optimal in terms of performance and accuracy for MPDATA family.
- Synchronization with I/O is ensured with smooth limitation of the timestep over three timesteps to match the desired I/O time
- Within the COSMO context, as the code is not ready for adaptive timestepping, this development seem to only make sense when employing main timestep much larger than the dynamics step, e.g. 80 s for $\sim$ 2 km grid spacing.

Lowest level of advection substepping - split MPDATA scheme.

The vertical Courant number, in the context of regional NWP, typically exceeds the horizontal Courant number up to several times. This justifies the splitting approach typically employed in NWP, but has numerical consequences. The strategy is as follows:

- First perform vertical advection of density with half timestep, followed by horizontal advection with full timestep, then again vertical advection of rho with half timestep; intermediate results stored.
- Evaluate advection of a prognostic variable with the same three steps, using respective densities.
- Allows for twice larger Courant number in the vertical (horizontal variant possible as well, e.g. twice larger Courant in x direction as well if needed)
- Somewhat more diffusive than regular MPDATA due to effectively larger stencil as a result of full sequence (even though particular operators remain the same)

Further developments and technology transfers

- Originally planned multigrid preconditioner implementation was dropped, as the benefit for IFS-FVM seemed insufficient.
- Instead, new extended implicit formulation of pressure solver was implemented.
- New features include, among others, integration of solution in fully perturbed form, i.e. advection of perturbations around known solution.

EX-CELO Task 3 - data assimilation.

- Nudging data assimilation seemed working well during the pre-operational phase of COSMO-EULAG at IMGW
- EX-CELO aimed at implemenation of KENDA for EULAG dynamical core, however, no human resoures could be found and this development was eventually dropped in the perspective of COSMO phase-out

Summary and conclusions

- The project success is limited to the implementation of novel algorithms, which should be employed pre-operationally this autumn.
- The new algorithms already found their way to fundamental research. Experimentation on nudging and diffusion supported the COSMO-EULAG operationalization at IMGW to some extent.
- Level of difficulty with respect to the COSMO source code modifications was underestimated.
- Hiring capable young researchers extremely difficult for the IMGW, as links to universities are very loose.
- Overall, I have imposed too much dependence on the project leader (myself). I have underestimated technical difficulties as well.
- Major practical outcome is the open way to very high resolution simulations through the long-timestep capabilities.
- COSMO-EULAG operationalization is a success, but it came far too late. Strong, multicompetent research group are needed to attack problems at this level of difficulty.