Priority Project COSMO-EULAG Operationalization (PP CELO)

Bogdan Rosa[1], Marcin J. Kurowski[2], Joanna Linkowska[1], Zbigniew P. Piotrowski[1], Damian K. Wójcik[1] and Michał Z. Ziemiański[1]

1 Instytut Meteorologii i Gospodarki Wodnej - PIB, Warsaw, Poland

2 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

1 Introduction

The progress in the convective-scale numerical weather prediction (NWP) at the beginning of 2000s motivated the COSMO Consortium to discuss and formulate an optimal model development strategy to address new challenges emerging at those scales. The strategy was formulated in the COSMO Science Plan (Arpagaus et al. 2010), which for dynamics called for high accuracy, numerical robustness and computational efficiency. Specifically, the Science Plan pointed at potential advantages of conservative properties of prospective future dynamical core in dealing with steep gradients and discontinuities (Le Veque 2003). Following the strategy, the COSMO Priority Project Conservative Dynamical Core (PP CDC) considered, in between, a conservative version of an already existing anelastic EULAG research dynamical core (Prusa et al. 2008) as a potential candidate for the new dynamical core of the operational COSMO model.

The PP CDC proved that the anelastic EULAG dynamical core is a feasible candidate for the purpose. The successful results of the core's numerous tests for a range of idealized and semi-realistic flows and new developing super-computer architectures were published by Rosa et al. (2011), Kurowski et al. (2011), Piotrowski et al. (2011), Ziemiański et al. (2011) and Baldauf et al. (2013).

Consequently, PP CDC was followed by the Priority Project COSMO-EULAG Operationalization (PP CELO), aiming to fully integrate of the EULAG dynamical core with the COSMO framework. The project work involved consolidation and optimization of the setup of the dynamical core for the high-resolution NWP, coupling with the COSMO physical parameterizations. The work was further followed by testing and exploiting the forecasting capabilities of the new integrated model: the COSMO-EULAG (CE). This article briefly summarizes the development and results of PP CELO.

2 Some Formulas

Following the PP CELO project plan, the work considered at first the implementation of the anelastic version of the EULAG dynamical core (based on the soundproof atmospheric equations of Lipps and Hemmler 1982) within the COSMO model framework. The successful results of that part of the project are documented mainly in (Kurowski et al. 2016). In the meantime, the fully compressible semi-implicit version of the EULAG dynamical core was developed (Smolarkiewicz et al. 2014 and 2016, Kurowski et al. 2014, 2015). Following that development, the Consortium decided to extend the project plan to implement the new compressible version of EULAG as the dynamical core of the COSMO model. The successful results of that work are documented in Ziemiański et al. (2021), together with the results of the Priority Task Consolidation of COSMO-EULAG (PT CCE), which followed PP CELO and which results are summarised in the companion article (Wójcik et al. 2021). The work within PP CELO was structured within five main project tasks, which are briefly discussed below.

---

doi:10.5676/dwd_pub/nwv/cosmo-nl_21_07

2.1 The integration of EULAG dynamical core with COSMO framework

Within this task, the EULAG dynamical core was re-configured to optimize the coupling with the COSMO environment. Also, a coupler between the core and the COSMO model infrastructure was constructed to account for the different native grid structures: A-grid for EULAG and C-grid for COSMO, and different prognostic variables of the Runge-Kutta and EULAG cores. The coupler allows for the communication between the dynamical core and physical parameterizations and the use of native COSMO initialization and I/O procedures. Also, it allows for EULAG physics-dynamics coupling equivalent to the integration of forcings along the flow trajectory. Two different configurations of the dynamical core were prepared and tested: first with additional EULAG mass level on the ground for a provision of the same boundary condition for vertical velocity there (finally implemented in the anelastic model version). The second configuration was without that additional level (finally implemented in the compressible version of the model), with all EULAG mass levels and points as in the Runge-Kutta dynamical core configuration.

The work needed to account for the ongoing development of the mother COSMO model. The task started with implementing EULAG into model version 4.26 and needed to follow the subsequent developments of COSMO physical parameterizations in their ongoing unification with the ICON parameterizations. Currently, the EULAG dynamical core is implemented into COSMO 6.0. The correctness of the EULAG setup and the coupler were extensively tested during the development work against the idealised benchmark experiments with moist convective flows: the supercell of Weisman and Klemp (1982) and the daytime convective development of Grabowski et al. (2006). They proved to be very useful for the task and were applied using varying horizontal resolutions. Finally, the dynamical core configuration and the coupler were extensively and successfully tested for real convective and non-convective weather forecasts, especially over the Alpine domain.

2.2 Consolidation and optimization of the formulation of the Eulag dynamical core

As the anelastic dynamical core provides information on pressure perturbations, the problem of recovering of the full pressure from the anelastic system was analysed. The idealized experiments have shown that the anelastic pressure perturbations are comparable with their compressible analogs (Kurowski et al. 2013) while Kurowski et al. (2016) have shown for realistic flows that moist processes are weakly sensitive to various alternative methods of full pressure recovery and used the time-dependent pressure from the driving model.

Further work concerned a consistent formulation of the dynamical core for different versions of the vertical coordinates, handled by the COSMO model options, and a correct implementation of the boundary conditions for the advection operator MPDATA, consistent with the anelastic integrability condition. In addition, an alternative preconditioner for the solution of the elliptic pressure equation was developed, implemented, and tested (Piotrowski et al. 2016).

2.3 Eulag DC code restructuring and engineering

The task was focused on the optimization and further consolidation/integration of the EULAG dynamical core with the COSMO numerical framework. Its code was restructured for a more transparent exposition of its algorithmic foundation, optimized for minimizing the need for communication and overlapping of communication and computation. In addition, flexible parallelization subdomains were implemented and tested.

Further work concerned an assessment of the feasibility of transforming the EULAG code into a stencil library in the context of potential code adaptations to the emerging computer architectures. The work included porting of EULAG dynamical core and especially its crucial MPDATA and iterative elliptic solver procedures to GPU and MIC architectures. The results show a potential speedup that can be achieved on modern architectures and were published in several articles: (Rosa et al. 2014 and 2015), and (Rojek et al. 2015).

2.4 Optimization and testing of COSMO with EULAG dynamical core

The finally developed CE was thoroughly tested for its anelastic and compressible versions. At first, the tests involved moist idealized flows (Weisman and Klemp 1982, and Grabowski et al. 2006) followed by realistic weather simulations. The model was tested for different horizontal resolutions with grid sizes ranging between 2.2 and 0.1 km. The sensitivity of model solutions to different values of tunable parameters of physical parameterizations was tested. For convective flows, a strong sensitivity was found for the varying turbulent diffusivity of the model. Also, different microphysical setups were tested, from a rain scheme to a more complicated setup involving a groupel presence. The majority of advanced experiments for realistic weather were performed for realistic Alpine domains to provide a demanding environment for testing model numerical robustness and physics-dynamics coupling. The tests involved both analyses of case studies and more extended periods for standard verification studies.

2.5 Integration and consolidation of the EULAG compressible DC with COSMO framework

The task was added to the project plan after the anelastic version of the CE was developed. The semi-implicit compressible EULAG dynamical core was integrated with the COSMO framework. The main work in this task involved an introduction of two-level density and pressure as new prognostic variables throughout the code, new formulations for ambient profiles (including ambient pressure and density) and appropriate boundary conditions, and extending the existing elliptic solver formulation for new Helmholtz operators and custom preconditioner. In general, the compressible variables add considerable complexity to the model formulation. This development aims at convective-scale NWP regional applications and, as such, supplements the ECMWF studies on the implementation of the semi-implicit compressible EULAG for global applications within the Finite Volume Module of IFS (Kühnlein et al. 2019).

Before the compressible CE was tested for moist flows and realistic weather scenerios, as described in section 2.4, it was first successfully tested for standard benchmark idealized experiments including cold density currents (Straka et al. 1993), inertia-gravity waves (Skamarock and Klemp 2004), and mountain flows (e.g., Bonaventura 2000). In view of potential future applications in diverse High Performance Computing environments, the dynamical core was tested on a variety of standard compilers used for CPU architectures.

3 Conclusion

The project delivered its main expected result: the fully-operational COSMO-EULAG weather prediction package, without data assimilation, for two variants of the dynamical core: anelastic and semi-implicit compressible. Furthermore, as shown by Kurowski et al. (2016) and Ziemiański et al. (2021), the COSMO-EULAG is numerically stable over Alpine domains even for very high resolutions. Its verification results are similar or competitive when compared to the standard COSMO model employing the Runge-Kutta dynamical core.

Acknowledgments

Support of Piotr Smolarkiewicz and Wojciech Grabowski in the development of COSMO-EULAG is gratefully acknowledged. The implementation of the compressible EULAG benefitted from the exchange od ideas with ECMWF's group working on the Finite Volume Module of IFS. We acknowledge the help of MeteoSwiss in providing initial and boundary conditions for realistic weather simulations and observational data for verification studies. The computational resources were partly provided by the Swiss National Supercomputing Centre (CSCS) under ID d25 and PRACE projects.

References

[1] Arpagaus, M., H. Asensio, M. Baldauf, J.-M. Bettems, U. Blahak, P. Eckert, F. Grazzini, J. Helmert, H.-J. Koppert, D. Majewski, C. Marsigli, D. Mironow, R. Potthast, M. Raschendorfer, A. Raspanti, B. Ritter, M. W. Rotach, U. Schättler, C. Schraff, F. Schubiger, A. Seifert and S. Theis, 2010: COSMO Science Plan 2010-2014, Consortium for Small-scale Modeling, 79pp, *www.cosmo-model.org/content/consortium/reports/sciencePlan_2010-2014.pdf*

[2] Baldauf, M., O. Fuhrer, M. J. Kurowski, G. de Morsier, M. Muellner, Z. P. Piotrowski, B. Rosa, P. L. Vitagliano, D. K. Wójcik and M. Z. Ziemiański, 2013: The COSMO Priority Project Conservative Dynamical Core Final Report, Consortium for Small-scale Modeling, 118pp, *https://doi.org/10.5676/DWD_pub/nwv/cosmo-tr_23.*

[3] Bonaventura, L., 2000: A semi-implicit semi-Lagrangian scheme using the height coordinate for a nonhydrostatic and fully elastic model od atmospheric flows, *J. Comput. Phys.*, 152, **186–213**, *https://doi.org/10.1006/jcph.1999.6414.*

[4] Grabowski, W. W., P. Bechtold, A. Cheng, R. Forbes, C. Halliwell, M. Khairoutdinov, S. Lang, T. Nasuno, J. Petch, W.-K. Tao, R. Wong, X. Wu, K.-M. Xu, 2006: Daytime convective development over land: A model intercomparison based on LBA observations, *Quart. J. Roy. Meteor. Soc.*, 132, **317–344**, *https://doi.org/10.1256/qj.04.147.*

[5] Kurowski, M. J., B. Rosa and M. Z. Ziemiański, 2011: Testing the anelastic nonhydrostatic model EULAG as a prospective dynamical core of a numerical weather prediction model. Part II: Simulations of supercell, *Acta Geophys.*, 59, **1267–1293**, *https://doi.org/10.2478/s11600-011-0051-z.*

[6] Kurowski, M. J., W. W. Grabowsk and P. K. Smolarkiewicz, 2013: Toward multiscale simulation of moist flow with soundproof equations, *J. Atmos. Sci.*, 70, **3995–4011**, *https://doi.org/10.1175/JAS-D-13-024.1.*

[7] Kurowski, M. J., P. K. Smolarkiewicz and W. W. Grabowski, 2014: Anelastic and Compressible Simulations of Moist Deep Convection, *J. Atmos. Sci.*, 71, **3767–3787**, *https://doi.org/10.1175/JAS-D-14-0017.1.*

[8] Kurowski, M. J., D. K. Wójcik, M. Z. Ziemiański, B. Rosa and Z. P. Piotrowski, 2016: Convection-Permitting Regional Weather Modeling with COSMO-EULAG: Compressible and Anelastic Solutions for a typical Westerly Flow over the Alps, *Mon. Wea. Rev.*, 144, **1961–1982**, *https://doi.org/10.1175/MWR-D-15-0264.1.*

[9] Kühnlein, C., W. Deconinck, R. Klein, S. Malardel, Z. P. Piotrowski, P. K. Smolarkiewicz, J. Szmelter and N. P. Wedi, 2019: FVM 1.0: a nonhydrostatic finite-volume dynamical core for IFS, *Geosci. Model Dev.*, 12, **651–676**, *https://doi.org/10.5194/gmd-12-651-2019*

[10] LeVeque, R. J., 2002: Finite Volume Methods for Hyperbolic Problems, *Cambridge University Press*, pp. **580**

[11] Lipps, F.B. and R.S. Hemler, 1982: A scale analysis of deep moist convection and some related numerical calculations, *J. Atmos. Sci.*, 39, **2192–2210**, *https://doi.org/10.1175/1520-0469(1982)039¡2192:ASAODM¿2.0.CO;2.*

[12] Piotrowski, Z. P., A. A. Wyszogrodzki and P. K. Smolarkiewicz, 2011: Towards petascale simulation of atmospheric circulation with soundproof equations, *Acta Geophys.*, 59, **1294–1311**, *https://doi.org/10.2478/s11600-011-0049-6.*

[13] Piotrowski, Z. P., B. Matejczyk, L. Marcinkowski and P. K. Smolarkiewicz, 2016: Parallel ADI Preconditioners for All-Scale Atmospheric Models, *In: Wyrzykowski R., Deelman E., Dongarra J., Karczewski K., Kitowski J., Wiatr K. (eds) Parallel Processing and Applied Mathematics. Lecture Notes in Computer Science*, vol 9574. Springer, Cham. *https://doi.org/10.1007/978-3-319-32152-3_56.*

[14] Prusa, J. M., P. K. Smolarkiewicz and A. A. Wyszogrodzki, 2008: EULAG, a computational model for multiscale flows, *Computers and Fluids*, 37, **1193–1207**, *https://doi.org/10.1016/j.compfluid.2007.12.001.*

[15] Rojek, A. and Coauthors, 2015: Adaptation of fluid model EULAG to graphics processing unit architecture, *Concurr. Comput.*, 27, **937–957**, *https://doi.org/10.1002/cpe.3417.*

[16] Rosa, B., M. J. Kurowski and M. Z. Ziemiański, 2011: Testing the anelastic nonhydrostatic model EULAG as a prospective dynamical core of a numerical weather prediction model. Part I: Dry benchmarks, *Acta Geophys.*, 59, **1236–1266**, *https://doi.org/10.2478/s11600-011-0041-1.*

[17] Rosa, B., M. Ciznicki, A. Rojek, D. K. Wójcik, P. K. Smolarkiewicz and R. Wyrzykowski, 2014: Porting multiscale fluid model EULAG to modern heterogenous architectures, *Int. J. Appl. Phys. Math.*, 4, **188–195**, *https://doi.org/10.7763/IJAPM.2014.V4.281.*

[18] Rosa, B., L. Szustak, A. A. Wyszogrodzki, A. Rojek, D. K. Wójcik and R. Wyrzykowski, 2015: Adaptation of Multidimensional Positive Definite Advection Transport Algorithm to modern high-performance computing platforms, *Int. J. Model. Optim.*, 5, **171–176**, *https://doi.org/10.7763/IJMO.2015.V5.456.*

[19] Skamarock, W. C. and J. B. Klemp, 1994: Efficiency and accureacy of the Klemp-Wilhelmson time-splitting technique, *Mon. Wea. Rev.*, 122, **2623–2630**, *https://doi.org/10.1175/1520-0493(1994)122¡2623:EAAOTK¿2.0.CO;2.*

[20] Smolarkiewicz, P. K., C. Kühnlein and N. P. Wedi, 2014: A consistent framework for discrete integrations od soundproof and compressible PDEs of atmospheric dynamics, *J. Comput. Phys.*, 263, **185–205**, *https://doi.org/10.1016/j.jcp.2014.01.031.*

[21] Smolarkiewicz, P. K., W. Deconinck, M. Hamrud, C. Kühnlein, G. Mozdzynski, J. Szmelter and N. P. Wedi, 2016: A finite-volume module for simulating global all-scale atmospheric flows, *J. Comput. Phys.*, 314, **287–304**, *https://doi.org/10.1016/j.jcp.2016.03.015.*

[22] Straka, J. M., R. B. Wilhelmson, L. J. Wicker, J. R. Anderson, K. K. Droegemeier, 1993: Numerical solutions of non-linear density current: A benchmark solution and comparison, *Int. J. Numer. Methods Fluids*, 17, **1–22**, *https://doi.org/10.1002/fld.1650170103.*

[23] Weisman, M. L. and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy, *Mon. Wea. Rev.*, 110, **504–520**, *https://doi.org/10.1175/1520-0493(1982)110¡0504:TDONSC¿2.0.CO;2.*

[24] Wójcik, D. K., B. Rosa and M. Z. Ziemiański,, 2021: Priority Task Consolidation of COSMO-EULAG , *COSMO Newsletter*, 21, **xx–xx**, *https://doi.org/xxxx.xxxx.xxxx*

[25] Ziemiański, M. Z., M. J. Kurowski, Z. P. Piotrowski, B. Rosa and O. Fuhrer, 2011: Toward very high resolution NWP over the Alps: Influence of increasing model resolution on the flow pattern, *Acta Geophys.*, 59, **1205–1235**, *https://doi.org/10.2478/s11600-011-0054-9.*

[26] Ziemiański, M. Z., D. K. Wójcik, B. Rosa, Z. P. Piotrowski, 2021: Compressible EULAG dynamical core in COSMO: convective-scale Alpine weather forecast, *Mon. Wea. Rev*, 149, **3563–3583**, *https://doi.org/10.1175/MWR-D-20-0317.1.*