JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Computational Science Mainz

4th International EULAG Workshop

Forward-in-time Differencing for Earth-System Models

20 – 24 October 2014, Mainz, Germany

LIST OF ABSTRACTS

Large Eddy Simulation of turbulent urban flows in a fractal model city

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complex media and topologies, urban flows, porous media analogy, darcy's law, immersed boundaries

The majority of human activities and their impacts (e.g. pollution emission) takes place in the lowermost part of the atmosphere, especially in the extensively growing cities. Knowledge about the flow field and its modification through urban areas is essential for numerical weather and air quality predictions. The questions, how to describe an urban area, and how to parameterise its impact on the atmosphere in numerical prediction models must be considered (Martilli, 2007).
In our work, we treated a city as a porous medium with a fractal geometry. Fractal geometry describes the irregular and fragmented forms of nature and can also be used to describe urban areas. We created an idealised model city out of the Sierpinski triangle, a self-similar fractal with a fractal dimension of ≈ 1.585, and implemented it in EULAG using the immersed boundary method.
In analogy to Darcy's law, which describes the flow through a porous medium at low Reynolds numbers (Bear, 1972), we seek the relationship between the mean horizontal flow and the horizontal pressure gradient for our high Reynolds number (turbulent) flow. We used the eddy viscosity determined by the turbulent kinetic energy closure according to Schumann to calculate a proportionality factor K_t in the modified Darcy's law:

$$K_t = -\frac{\langle u - u_0 \rangle^v}{\langle \frac{\Delta \tilde{p}}{\Delta x} \rangle^i} \langle \rho k_m \rangle^i,$$

where u_0 is the initial velocity, $\tilde{p}$ the pressure perturbation, ρ the density, k_m the eddy viscosity, and $\langle\rangle^v$ and $\langle\rangle^i$ are volume and fluid mean, respectively. The proportionality factor K_t replaces the permeability K in the original Darcy's law. Simulations in a small scale Sierpinski city ($12.75\,\mathrm{m}\times 12.75\,\mathrm{m}\times 3.2\,\mathrm{m}$, obstacle height $1\,\mathrm{m}$, $\Delta x = \Delta y = 0.05\,\mathrm{m}$) revealed that the proportionality factor is independent from flow velocity when using the eddy viscosity instead of the kinematic viscosity. In conclusion the proportionality factor K_t is like the permeability only a function of the geometry of the medium and the modified Darcy's law is valid for the turbulent flow through this fractal city.
In the current work we exceed the domain size ($1022\,\mathrm{m}\times 1022\,\mathrm{m}\times 254\,\mathrm{m}$, obstacle height $80\,\mathrm{m}$, $\Delta x = \Delta y = 4\,\mathrm{m}$) to receive a more realistic relationship between obstacle size and flow velocity. Again it was found, that K_t does not change with the flow velocity and is quite constant below the top of the obstacles. Further simulations attend the question, how the grid resolution affects these findings. First analysis of simulations with a coarser grid ($\Delta x = \Delta y = 8\,\mathrm{m}$), show a dependency from the resolution caused by the subgridscale model. This will be investigated more precisely, in particular the reliability of the LES for these resolutions will be considered. Furthermore the impacts of the porosity and other parameters will be examined.

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Propagation of gravity waves through the tropopause

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gravity waves, tropopause, tropopause inversion layer

The thermal tropopause constitutes a sharp boundary between troposphere and stratosphere. It is characterized by a strong change in the lapse rate. Often, an inversion layer can be found (tropopause inversion layer, TIL, see e.g. Birner etal, 2002), characterised by a strong maximum in Brunt-Vaisala frequency just above the thermal tropopause. In addition, the horizontal wind shear usually has its maximum close to the tropopause. Vertically propagating gravity waves have to pass the tropopause region, before entering the stratosphere. Their properties are changed drastically by the changing stratification and strong wind shear. In this contribution we investigate the impact of the tropopause on vertically propagating gravity waves, as excited by flows over topography. We investigate different idealized scenarios of vertical profiles of Brunt-Vaisala frequency (step-wise vs. continuos change, including TIL) and wind shear in order to determine the impact of environmental conditions on vertically propagating waves.

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The sensitivity of mesoscale heavy precipitation on atmospheric boundary layer over complex orography

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precipitation physics, atmospheric modeling, atmospheric boundary layer

Heavy precipitation at the atmospheric mesoscale is among the important hazardous meteorological phenomena. Every year, at mid latitudes flash floods cause a considerable amount of damages, injuries and casualties, see e.g. UNISDR-UNEP/GRID-Geneva (2014) and EEA rep. 13/2010 (2010). Furthermore the simulation of high efficiency precipitation weather events is a challenge for numerical models because it is expected they grasp both the microphysical and the dynamical processes involved in the rain formation. Nowadays operational weather numerical models aim to reproduce the precipitation rates and patterns measured during local extreme precipitation events. In this work we show the application of the WRF (2014) model to the September 2013 flash flood that interested a few square kilometers in the NE Italy, recording precipitation rates of 15 mm/5min lasting for two hours. The computational approach to generate and compare a large number of high resolution (< 2 km) simulations, which were performed on a medium size High Performance Computing infrastructure, is described in detail. Such simulations were carried out to investigate the sensibility of the model on boundary layer parametrization schemes, orographic effects, initial and boundary conditions. From the meteorological point of view, results show that the boundary layer plays a significant role in maintaining deep atmospheric convection stationary for several hours over the same geographical area, furthermore it is evident the supporting effect given by the interaction between synoptic moist flows and the orography as pointed out by Miglietta and Rotunno (2012). The WRF model is running operationally at the Regional Center for Environmental Modeling of ARPA FVG.

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Simulations of the solar magnetic cycle with EULAG-MHD

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magnetohydrodynamics; turbulent convection; solar cycle

Using the magnetohydrodynamical extension of EULAG (Smolarkiewicz and Charbonneau, 2013), we have succeeded in producing simulations of the sun's magnetic activity cycles that exhibit a number of features that resemble observed evolutionary patterns of the large-scale solar magnetic field, most notably regular magnetic polarity reversals occurring on a decadal timescale (Ghizaru et al., 2010; Beaudoin et al., 2013; Charbonneau and Smolarkiewicz, 2013; Passos and Charbonneau, 2014). These simulations solve the anelastic form of the ideal magnetofluid equations in a thick, rotating shell of electrically conducting fluid, the outer two thirds of which being unstably stratified and subjected to thermal forcing. In this presentation, the design of these simulations is briefly reviewed, and recent results and comparison with observed characteristics of the solar cycle are described in some detail. Evidence will also be presented supporting the idea that the stable fluid layers underlying the convection zone develops non-axisymmetric magnetohydrodynamical instabilities, in response to the buildup of magnetic fields accumulating there by turbulent magnetic pumping operating throughout the convection zone.

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Towards efficient implementation of EULAG elliptic solver on GPU architectures

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large scale computing, GPGPU computing, elliptic solver, stencil computations

Novel multi- and many- core hardware architectures offers possibility to run scientific codes at greater precision and speed than before. Howover, their complexity requires developing and integrating various adaptation strategies, taking into consideration every level of parallel hierarchy. An extra care must be taken for communication-intensive algorithms which may be a botleneck for fortcomming exascale era of computing. The variational generalized conjugate residual, GCR, elliptic pressure solver (Smolarkiewicz et al. (2011)), a part of latest version of EULAG model (Piotrowski et al. (2011)), is a great example of such algorithm. In this research we focus on adaption of this algorith to novel GPU architectures, taking into acoount complex memory hierarchy, topology of compute resoruces and efficient load-balancing to find the best trade-off between computation and communication. We discuss various adaptation strategies for paralleisation, e.g. pipelining, communication overlapped with computations, stencil and block decomposition, cache reusing and others. Preliminary results of performance of the new implementation show promising increase of computational efficiency (Ciznicki et al. (2014)).

This work is a part of joint efforts that aim in adapting two mains modules of EULAG (Prusa et al. (2008)), namely advection algorithm MPDATA (Rojek et al. (2014); Szustak et al. (2014)) and GCR iterative pressure solver (**?**) to modern CPU and GPU architectures (Rosa et al. (in press)).

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Towards efficient implementation of EULAG elliptic solver on ccNUMA architectures

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large scale computing, ccNUMA, elliptic solver, stencil computation, multi-level parallelism

Adaption of scientific codes to novel hardware architectures offers a unique opportunity for modelling complex physical phenomenas at greater scale and speed.The modern multi- and many-core architectures provide additional levels of parallelism, thus requiring additional effort to achieve proper scalability. Cache-coherent non uniform memory access (ccNUMA) is a popular architecture for multisocket shared memory systems today (Broquedis et al. (2010)). As the amount of memory and number of processors is still growing, the bandwidth between processors and memory may become soon a scalability bootleneck. The ccNUMA architectures aims to address the problem by providing separate memory for each processor, thus avoiding performance degradation when several processes attempts to access the same memory address. The price is that memory access times depands on location of memory against processor - the longer the distance, the slower access times. The increasing diversity of multi-core processor architectures introduce another aspects to be considered in order to achieve good scalability, e.g. bandwidth bottlenecks caused by improper page placement, non-local memory access larger latencies and lower bandwidths. This paper presents challenge to adapt variational generalized conjugate residual, GCR, elliptic pressure solver (Smolarkiewicz et al. (2011)), a part of latest version of EULAG model (Piotrowski et al. (2011)) to ccNUMA architectures, taking into accout data locality, page migration, underlying hardware information that describe the distance between processors and memory, presence of multi-level thread scheduler (see e.g. Bircsak et al. (2000); Terboven et al. (2008); Wittmann et al. (2011)).

This work is a part of joint efforts that aim in adapting two mains modules of EULAG (Prusa et al. (2008)), namely advection algorithm MPDATA (Rojek et al. (2014); Szustak et al. (2014) and GCR iterative pressure solver (Ciznicki et al. (2014)) to modern CPU and GPU architectures (Rosa et al. (in press)).

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A massively-parallel framework for finite-volume simulation of global atmospheric dynamics

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Large scale computing, unstructured meshes

A computational environment is being developed that aims at integrating — within a single mathematical/numerical framework — PDE's of global atmospheric dynamics. The paper reports an essential step towards this goal. It presents massively-parallel non-oscillatory forward-in-time finite-volume integrators for PDE's on the sphere, cast in the anholonomic geospherical framework. Spatial discretization employs bespoke unstructured meshes built about the vertices of the reduced Gaussian grid employed in the ECMWF's Integrated Forecast System (IFS). Such arrangement allows using a domain decomposition identical to IFS and opens avenues to the future high fidelity comparisons with IFS' solutions of primitive equations. Furthermore, it allows for model hybridization where selected elements can be directly exchanged between the two models, without interpolation.

The reported development operates on flexible dual meshes with an efficient parallel edge-based data structure and a non-staggered arrangement of flow dependent variables. The paper will discuss aspects of implementation on shared/distributed memory machines with MPI and OpenMP parallelization, in the context of efficiency and portability on supercomputing architectures. Selected canonical benchmarks of global shallow-water flows are used to illustrate the approach.

Sensitivity of Banner Cloud Formation to Mountain Geometry

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flow past complex orography, implicit LES

Banner clouds occur in the immediate lee of steep mountains on otherwise cloudfree days. Their formation is most likely due to strong vertical uplift in the lee of the mountain (Voigt and Wirth, 2013). However, it is not known to what extent their formation depends on the properties of the flow and on the shape of the mountain. The present work investigates the sensitivity of banner cloud formation on the mountain geometry as well as on wind shear.

To address these issues we used the EULAG model, in order to simulate flow over an isolated mountain. The model is run in an implicit Large Eddy Simulation (I-LES) mode with terrain following coordinates. The model configuration includes idealized, pyramid-shaped orography of constant height (1000 m) and the wind being specified at the inflow boundary.

In our sensitivity experiments we vary both the width of the mountain and the inflow profile. Changing the shear of the inflow profile has a large impact on the flow geometry behind the mountain. Our key diagnostic is the Lagrangian vertical displacement of the air, as this is an important prerequisite to cloud formation. The vertical displacement is obtained with the help of a materially conserved tracer. To the extent that the Lagrangian uplift is larger on the leeward side of the mountain than on the windward side, this represents favorable conditions for banner cloud formation.

For the runs without shear, the simulations indicate a strong dependence of banner cloud likeliness on the aspect ratio of the mountain. Mountains with an aspect ratio around 1 are optimal for banner clouds, confirming an earlier study by Reinert (2010). On the other hand, the dependence on the mountain aspect ratio is much smaller for the runs with shear. The simulations will be used in order to understand the differences regarding the sensitivities in the two sets of simulations.

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A novel methodology for testing multiscale moist atmospheric models

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atmospheric dynamics, moist processes, numerical model

Validation of numerical design and physical consistency is an important part of model development. Many numerical tests used by the atmospheric modeling community have been designed in the past targeting various scales of motion, from small-scale to global. Examples of such tests include small-scale thermals rising from rest, mesoscale flows over idealized topography, moist deep convection tests (e.g., the supercell), idealized synoptic baroclinic waves, and the Held-Suarez climate benchmark. With a few exceptions, these tests are designed as dry problems, and their extension to moist processes is often cumbersome. This is because moist dynamics involve conditional instability (i.e., moist convection) and documenting physical and/or numerical convergence of moist solutions is practically impossible. This is especially true for large-scale flows where the model has to be either capable of high-spatial-resolution nonhydroststic simulation to allow moist convection (computationally intensive) or it has to include convective parameterization (highly uncertain). Here we present a novel methodology inspired by the Bryan and Fritsch (2002; BF02 hereafter) unstratified moist-saturated small-scale benchmark case. The BF02 case is designed in such a way that moist model solutions have to exactly match dry solutions thus ensuringthe efficacy of the moist model physics; see discussion in Kurowski et al. (2014). Since the unstratified case has little relevance to multiscale atmospheric dynamics, we extend BF02 test into the stratified atmosphere. The new test is applied to compare dry and moist solutions for the small- and mesoscale stratified flows over topography, one of canonical tests of a small-scale numerical model. Perhaps more importantly, the new methodology allows developing moist-saturated synoptic-scale baroclinic wave test and compare moist solutions to their dry counterparts. Details of the test and examples of numerical solutions will be presented at the meeting.

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Simulation of Deep Internal Gravity Wave Propagation Using EULAG

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deep gravity wave, transient topography

Atmospheric gravity waves are triggered by different sources all around the globe, e.g., mountains, convective systems, jet streams and fronts. They affect short-term evolution of weather systems as well as long-term climate, but with spatial scales from ≈ 5 to 500 km in the horizontal, they can't be fully resolved in prediction models (Kim et al., 2003). To develop appropriate parametrizations, knowledge about gravity wave properties and propagation is essential.

In the current work different model setups and options are tested to find the best way of simulating and studying deep internal gravity wave propagation with EULAG. First, classical setups for which analytical solutions are available are simulated. For example, the numerical solutions of the flow over sinusoidal ridges and flow over isolated hills are compared with analytical solutions for a height range up to 80 km altitude. Furthermore, different flow regimes (hydrostatic, non-hydrostatic, potential flows) are considered and compared to analytical solutions.

Second, the propagation of deep gravity waves is simulated employing different sets of equations: the solutions of the Boussinesq equations, anelastic equations (Clark-Farley and Bacmeister-Schoeberl versions), and pseudo-incompressible equations are assessed and an intercomparison will be presented. Another aspect considered is the effect of viscosity on the deep wave propagation up to a height of 200 km.

The impact of the initial conditions on the solutions in the middle atmosphere are investigated. Two approaches are juxtaposed. To reduce initial transients of the solution, simulations with a time-dependent topography are performed: beginning with a flat surface, the orography establishes as a transient lower boundary growing to its final amplitude in a given time period. Results of this approach are compared with simulations based on a steady lower boundary.

Finally, a two-step approach using a split domain for deep wave-propagation is investigated: waves in a lower domain (up to 40 km) are simulated, and a time-dependent material surface in the upper part of the domain is stored periodically. In a subsequent simulation, this transient surface serves as the lower boundary of the upper domain (up to 100 km height), causing waves to establish. Results are compared and issues of this approach are discussed.

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Hyperbolic Regions in Flows Through Three Dimensional Pore Structures

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immersed boundary method, finite time Lyapunov exponents, flow through porous media

Finite time Lyapunov exponents are used to determine expanding, contracting, and hyperbolic regions in computational simulations of laminar steady-state fluid flows within realistic three dimensional pore structures embedded within an impermeable matrix. These regions correspond approximately to pores where flow converges (contraction) or diverges (expansion), and to throats between pores where the flow mixes (hyperbolic). The regions are sparse and disjoint from one another, occupying only a small percentage of the pore space. Nonetheless, nearly every percolating fluid particle trajectory passes through several hyperbolic regions indicating that the effects of in-pore mixing are distributed throughout an entire pore structure. Furthermore, the observed range of fluid dynamics evidences two scales of heterogeneity within each of these flow fields. There is a larger scale that affects dispersion of fluid particle trajectories across the connected network of pores and a relatively small scale of non-uniform distributions of velocities within an individual pore.

Testing a Phase Transition Theory for Convective Organisation

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Cloud/precipitation physics, Large scale computing

Convection over the tropics shows organisation on large scales. It is known from numerical model simulations that even in the absence of large-scale instabilities or external forcings convection organises itself. The mechanism responsible for the self-aggregation of convection is not well understood up to now. However, one particular theory has been proposed describing the organisation as a coarsening process and the simple model from Craig and Mack (2013) has been developed for this purpose.

We investigate in our work the self-aggregation of tropical convection in a radiative-convective equilibrium over a constant sea surface temperature (SST) without large-scale forcings. Idealised simulations with different SSTs, different initial moisture conditions, as well as with and without the cloud-radiative feedback are performed with the numerical model EULAG over a 510 km x 510 km domain on an f plane with periodic boundary conditions and no wind shear. The simulations are comparable to Bretherton et. al. (2005), Khairoutdinov and Emanuel (2010), Mueller and Held (2012) or Wing and Emanuel (2014).

According to our simulations, the values of the critical temperature (SST_c) depend on the initial conditions of the simulations, resulting in a subcritical pitchfork bifurcation, which is unstable to large amplitude perturbations. Further, self-organisation is also possible without the cloud-radiative feedback, unlike to Wing and Emanuel (2014). In accordance with the coarsening process, the potential function V has a bistable character only for organising simulations and close to SST_c V confirms the theory of an abrupt phase transition, stated by Craig and Mack (2013).

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Observations from the construction of two time level integrators for compressible and sound-proof models

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compressible and pseudo-incompressible models, time integration, finite volume schemes

The authors have been developing two time level, forward in time, finite volume discretizations for compressible and sound-proof flow models in recent years (Klein , 2009; O'Neill and Klein , 2013; Klein et al. , 2014; Benacchio et al. , 2014). We will report on a model family that allows for a seamless blending between the compressible and pseudo-incompressible models. To allow for future applications to fluids with general equations of state the schemes do not utilize Exner pressure but work with thermodynamic pressure, and we will report on the consequences of this choice for model formulation and discretization. An interesting potential application of the blended formulation concerns balanced data assimilation.

We will also summarize theoretical and empirical insight into the stability properties of these schemes and their dependence on several optional variants of the discretization starting from (Vater and Klein , 2009).

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Physics of Stratocumulus Top: results of large eddy simulations sampled with a virtual aircraft method compared to airborne data

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cloud physics, large scale computing

All-scale EULAG model parallelized in three dimensions was used to perform high-resolution large eddy simulations of stratocumulus topped marine boundary layer. Setup was based on research flight TO13 of Physics of Stratocumulus Top field campaign (Gerber et al., 2010, 2013). Virtual aircraft sampling method (i.e. sampling the model domain in the course of the simulation along a path similar to the trajectory of the research aircraft in the field campaign) was used to compare simulations and in-situ measurements. Cloud top layer division, proposed by Malinowski et al. (2013), was applied to both kind of data. Statistical properties of turbulence and cloud thermodynamics in each layer collected in nature and in virtual reality were compered.

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Impact of wind shear on the top of stratocumulus cloud

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cloud physics, entrainment, large scale computing

In the course of Physics of Stratocumulus Top (POST) campaign CIRPAS Twin Otter research aircraft performed 17 flights in the region of Monterey Bay in July and August 2008. Data analysis revealed two different types of stratocumulus:

(i) "classical", under strong temperature inversion, dry air above the cloud top and thin wind shear layer in the cloud top region and

(ii) "non-classical" under weak temperature inversion, humid air above and deep shear layer.

In "non-classical" cases conditions prohibit Cloud Top Entrainment Instability (CTEI). One of such "non-classical" cases (TO13) was used to prepare setup for high resolution LES (Large Eddy Simulation). The focus of the presentation would be on sources of turbulence responsible for entrainment and mixing process. A series of simulations was performed varying wind shear and radiative cooling in a cloud-top region in order to understand formation of layers in the cloud top region reported by Malinowski et al. (2013).

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Application of EULAG to the simulation of flow through the urban structure in Warsaw

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city ventilation, urban canopy, voxelization

To recognize the problems of a possible limitation of city ventilation by the growing urban structure in Warsaw, a numerical study of the flow through the urban canopy has been undertaken. The supporting data base available for this project contains a detailed description of individual building planes, with resolution of an order of a meter. To be useful for simulations with substantially lower spatial resolution, these data must be aggregated; because of their volume, automatic methods must be applied. Having these capabilities, it would be desirable to determine the effect of reducing the spatial resolution of urban structure representation on the results of flow simulation, under different atmospheric conditions.

A voxelization (Lee, Requicha, 1982) algorithm has been constructed and implemented, to allow for a flexible projection of the database objects onto a structured EULAG mesh. The method inherits from the ideas previously applied in computer graphics and uses fairly simple techniques such as ray tracing or angle summation. In EULAG, the immersed boundary method has been chosen for building representation. We would like to present the voxelization techniques along with preliminary results from the study, including simulations of flow around selected major structures under various meteorological conditions.

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Combining a conservative non-oscillatory forward-in-time solver for soundproof and compressible PDEs with moving meshes

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Terrestrial weather and climate, Stratified flows, Large scale computing

As part of our efforts towards a future non-hydrostatic dynamical core at the European Centre for Medium-Range Weather Forecasts, we present an extension of the semi-implicit forward-in-time solver for soundproof and compressible PDEs Smolarkiewicz et al. (2014) to time-dependent generalised coordinates. The current work unifies the solver of Smolarkiewicz et al. (2014) with the time-dependent generalised coordinate formulation of the soundproof PDE solver developed in Prusa et al. (2003); Wedi and Smolarkiewicz (2003); Kühnlein et al (2012). Here, special attention is given to the accurate transport with the MPDATA scheme (Smolarkiewicz and Margolin , 1998) when solving the soundproof and compressible PDEs under time-dependent meshes. Furthermore, given the capability to integrate the governing PDEs on general meshes, the solver is enhanced with a mesh adaptation apparatus based on the moving mesh approach (Huang et al., 2009; Kühnlein et al , 2012). Applications of the combined soundproof and compressible PDE solver with moving meshes to atmospheric flow problems of varying complexity will show the fidelity of the approach.

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Modelling air quailty in urban canyons

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Complex media and topologies, EULAG, urban modelling, air quality, traffic emissions, street canyons

The increased traffic emissions and reduced natural ventilation in urban canyons can lead to increase in pollution levels. It is then of great importance to assess urban air quality and support decision-making for pollution control strategies and trafic planning to help local citizens. In this paper we present approach to model air quality in urban canyons using the EULAG model (Prusa et al. (2008)). This model is able to to quantify airflow characteristics under various meteorological conditions, with emphasis on predicting the concentration levels of hazardous contaminants as they disperse and collect in recesses (see Smolarkiewicz et al. (2004, 2007)). Various scenarios are discussed to compare differences in flow characteristic in street canyons at small scale, taking into account canyon parameters and mean wind speed and direction.

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Formation of current sheets and magnetic ejecta: A numerical study

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Keywords: Magnetohydrodynamics, Current Sheet, Solar Corona, EULAG

The solar corona is characterized by a magnetic Reynolds number $R_M \approx 10^{10}$. Such high value of R_M renders the coronal magnetofluid to be near-ideal in a sense that the condition of flux-freezing holds to a good approximation. Under this condition of flux-freezing the coronal magnetofluid can be partitioned into contiguous subvolumes of fluid each of which entraps its own subsystem of magnetic flux. During any dynamical evolution, these subvolumes are expected to press into each other and in the process two subvolumes can come arbitrarily close by ejecting the interstitial fluid (Bhattacharyya et al., 2010). Then, depending on the orientations of magnetic field lines on the two interacting subvolumes, the magnetic field at the common surface of interaction may become discontinuous and a current sheet (CS) is formed there (Parker, 1994). In a near-ideal system this discontinuity in magnetic field never attains its true mathematical limit, since the current sheets decay through magnetic reconnection as a minimum threshold in local R_M is achieved where the otherwise negligible Ohmic dissipation becomes important. The above process of CS formation and its subsequent decay is responsible for a multitude of eruptive phenomena observed in the solar corona and provides a possible explanation for the corona to be at million degree Kelvin temperature (Parker, 1994).

In this work, we numerically demonstrate the formation of CSs and their subsequent decay through magnetic reconnection using the Implicit Large Eddy Simulation (ILES) mode of the numerical model EULAG-MHD (Smolarkiewicz and Charbonneau, 2013)— a magnetohydrodynamic extension of the standard EULAG (Prusa et al., 2008). We present two different sets of simulations toward an illustration of CS formation utilizing the physical scenario of viscous relaxation. The first set utilizes periodic boundary conditions and confirms the formation of CSs near the three-dimensional and two-dimensional magnetic nulls (Kumar et al., 2013). In the second set, we have an open boundary in the vertical (z-direction) whereas the horizontal directions (x and y) are chosen to be periodic. The results show development and subsequent ejection of magnetic islands which are widely observed at the solar atmosphere. In both sets, the initial magnetic field is a superposition of linear force-free magnetic fields and has the same morphological structure as the coronal magnetic field.

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Formation of magnetic discontinuities through viscous relaxation

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Keywords: Magnetohydrodynamics, Current Sheet, Magnetic Flux Surface, EULAG

According to Parker's magnetostatic theorem, formation of tangential discontinuities in magnetic field, or current sheets (CSs), are unavoidable in an equilibrium magnetofluid with infinite electrical conductivity and complex magnetic topology. This inevitable formation of CSs is attributed to a general failure of topologically complex equilibrium magnetic field in maintaining the two stringent conditions of local force balance and global preservation of magnetic topology while simultaneously being spatially continuous everywhere. In a recent work (Kumar et al., 2013), the possibility of CS formation has been demonstrated in a magnetofluid undergoing topology-preserving viscous relaxation utilizing the standard approach of advecting the vector magnetic field. Here, we complement the above work by exploring the formation of CSs through a novel approach based on the advection of local magnetic flux surfaces instead of the vector magnetic field. A successful numerical demonstration of spontaneous CS formation demands the frozen-in condition to be satisfied with a high fidelity such that the identity of a fluid surface as a magnetic flux surface is maintained to a reasonable accuracy during magnetofluid evolution. For our calculations we adapt the MHD version (Smolarkiewicz and Charbonneau, 2013) of the well established general-purpose numerical hydrodynamic model EULAG predominantly used in atmospheric and climate research (Prusa et al., 2008) which is based entirely on the spatio-temporally second order accurate nonoscillatory forward-in-time advection scheme MPDATA (Multidimensional Positive Definite Advection Transport Algorithm) (Smolarkiewicz, 2006). The initial non-equilibrium magnetic field is intricately associated with a linear force-free field through the vertical extension of the computational domain and the magnetic topology of the two fields are in close proximity. The magnetic flux surfaces being the sites on which CSs develop, following their evolution provides a direct visualization of the process of CS formation and hence a better understanding of the governing dynamics. In this particular set of computations, we report the development of magnetic discontinuities through a favorable contortion of magnetic flux surfaces. A crucial finding of this work is in its demonstration of CS formation at spatial locations away from the magnetic nulls.

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Towards high-resolution simulation of moist global flows

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Cloud/precipitation physics, moist non-hydrostatic modeling

This presentation will take you on a journey through the soundproof (e.g. anelastic) and compressible moist modeling across scales: from small-scale cloud dynamics to planetary flows. Following current trends in non-hydrostatic modeling, we aim at a high-resolution simulation of global atmospheric flows with a long-term objective to develop and examine soundproof alternatives to the compressible approach. A special emphasis will be given to the discussion of soundproof moist modeling at different scales and the importance of pressure perturbations (diagnosed/prognosed in the anelastic/compressible systems) for the saturation adjustment. All these considerations will be supported by a set of numerical examples carried out within a consistent numerical framework of the anelastic/compressible EULAG model – the tool that allows unification of numerical methodologies and credible comparisons of the models' results. A recently developed implicit compressible version of the model facilitates the use of large (i.e. anelastic) timesteps in the large-scale simulations. Perhaps surprisingly, a demonstrated consistency of soundproof and compressible solutions goes beyond typical notions, although significant differences are also documented.

High resolution modeling of flows over Tatra mountains

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orographic flows, large scale computing

As operational mesoscale numerical weather prediction models go to and beyond 1 km horizontal resolutions, know-how on modeling flows over steep orography becomes increasingly important. Here we present the results of very high horizontal resolution (960 m - 60 m) modeling of flows in foehn wind conditions over Tatra mountains with EULAG model. We investigate the impact of orography filtering on the power spectra of kinetic energy, the optimal distance of the mountain range to the domain boundary and the possibility to model the actual foehn conditions within the simplified model setup. We compare the solutions of anelastic and implict compressible core of EULAG.

Multi-scale behavior in vortical flows: a numerical approach

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EULAG has been successfully applied to a plethora of environmental systems, a recent example being the solar dynamo (Charbonneau & Smolarkiewicz, 2013). Various temporal and spatial scales are involved and pose new challenges that simulations can help to resolve. Our focus lies on vortical flows in the atmosphere, comprising a wide range of scales as well. We present a numerical approach with EULAG that addresses the multi-scale behavior of the flow. A series of tests for two-dimensional setups is conducted first, borrowed from Klein (2009) and Kadioglu *et al.* (2008) to double-check EULAG's performance on concentrated vortical flows. A first application is the numerical implementation of precessing quasi-modes of three-dimensional atmospheric vortices. The results are compared to the linear small-displacement theory by Reasor *et al.* (2004) and to the nonlinear matched asymptotic analysis for vortices with large tilt by Paeschke *et al.* (2012).

Key words: atmospheric vortices, multi-scale analysis, terrestrial weather and climate

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EULAG 2014 model with three-dimensional MPI decomposition

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Eulag 2014, large scale computing

We present the newly developed restructured version of EULAG model with the three-dimensional MPI decompostion. Initialization and the time integration loop of the model are restructured to accommodate growing number of options and modules of EULAG, which include the latest developments of Smolarkiewicz et al. (2014). We discuss the debugging tools recently incorporated in the EULAG code, and provide brief tutorial on the new model options and the three-directional parallelisation available in EULAG 2014.

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Boundary layer separation in the lee of steep mountains

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Cloud physics, Stratified flows

Boundary layer separation in the lee of steep mountains can be observed either right at the top of the mountain or it can be delayed, further into the lee depending on the steepness of the mountain and the stratification of the oncoming flow. Boundary layer separation at the top of the mountain leads to flow reversal and strong upwelling on the leeward side in the vicinity of the mountain top on the leeward side. In previous large eddy simulations it was found that this lifting of air is the main formation mechanism for banner clouds (Voigt and Wirth, 2013). Therefore boundary layer separation is essential for banner cloud formation.

In the present work we want to answer the following question: under what conditions can one expect banner clouds to form most readily? In other words: under what conditions does the flow separate right at the top of the mountain, leading to flow reversal and upwelling on the leeward side of the mountain?

To elucidate these questions, we carried through a series of numerical simulations using a cosine-shaped mountain and varying both the aspect ratio (steepness) of the mountain as well as the Froude number (stratification) of the oncoming flow. This is motivated by earlier studies of flow over two-dimensional orography that identified essentially three different regimes: lee side separation, no separation and post wave separation (Ambaum and Marshall, 2005). However, banner clouds imply fully three-dimensional orography by necessity, and the questions remains as to what extent these two-dimensional results remain valid.
Our simulations show that even in the case of three-dimensional orography there are essentially the same three regimes as for two-dimensional orography. It turns out that banner clouds prefer steep mountains (large aspect ratio) in combination with weak stratification (low Froude number), corresponding to the regime of lee-side separation.

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Baroclinic Dynamics in the Atmosphere: Soundproof vs. Compressible Computations

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KEYWORDS: baroclinic dynamics, soundproof equations, climate

Soundproof equation sets have been used extensively and successfully in computational models for global applications ranging from simulations of the geodynamo (Glatzmaier and Roberts 1996), to idealized climate problems (Smolarkiewicz et al. 2001; Prusa and Gutowski 2010, 2011) as well as more realistic ones (Abiodun et al. 2011) in atmospheric physics, to simulations of solar and stellar convection zones (Lantz and Fan 1999; Elliot and Smolarkiewicz 2002) and the solar magnetic cycle (Charbonneau and Smolarkiewicz 2013). They are also of interest in the ocean modeling community as a possible upgrade path from Boussinesq models (Chu and Fan 2002). In addition to to the filtering of sound waves, sound-proof models lead to incompressible-like forms for the the continuity equation that can be used to generate elliptic boundary value problems for pressure. Combining Krylov solvers for pressure with NFT (non-oscillatory-forward-in-time) solvers for advection allows models of high accuracy (Smolarkiewicz et al. 2014) to be constructed, as especially evinced by the the above references where multiscale wave-wave interactions are paramount in the simulated (geo and solar dynamo) physics. Successes to date notwithstanding, it is still important to explore the differences between soundproof and compressible solutions.

This talk will present and analyse results of idealized global simulations in which baroclinic instability is the main element of atmospheric forcing. Such simulations are especially revealing because soundproof models may suffer from truncated representations of baroclinicity– the anelastic model (Lipps and Hemler 1982) is an example. Linear modal analysis (Davies et al. 2004) clearly reveals that soundproof waves can suffer from phase and growth rate errors. Yet the set of soundproof global simulations shows a more nuanced set of results such that even anelastic simulations of baroclinic instability can show credible results early in the linear growth phase and later in the chaos of extensive wavebreaking. The simulations are made using a new version of EULAG in which a major advance has been implemented– the approach to setting up boundary value problems for pressure in soundproof models has been generalized to also include fully compressible equations (Smolarkiewicz et al. 2014). For the first time, this allows a systematic soundproof vs. compressible comparison to extend well beyond the linear regime and into that of strong nonlinearity (wave breaking and ensuing mixing) using virtually the same numerical algorithm.

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Largy-Eddy Simulation of Gravity-Wave Breaking: Validation against DNS

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ABSTRACT

The breaking of gravity waves plays an important role in the dynamics of the atmosphere and ocean, in particular in helping control the large-scale circulation in the middle atmosphere. It is also a highly complex and nonlinear (i.e. turbulent) process that is represented in weather and climate models using extremely simplified and highly tuned parameterizations.

In order to be trusted, especially for use in, for example, modelling climate scenarios different from today's, these parameterizations should be tested against simulations that can accommodate both the propagation of the waves (requiring domains of tens to hundreds of kilometres in all three spatial dimensions) and their breaking (requiring resolutions of between centimetres and a few metres, depending on the altitude). Only large-eddy simulation (LES) is suited for this task. On the other hand, since LES treats the the small-scale turbulence by parameterizing the sub-gridscale (SGS) physics, it too needs to be validated against turbulence-resolving direct numerical simulation (DNS).

Recent work (1; 2) has produced fully resolved DNS of breaking monochromatic inertia-gravity waves under conditions appropriate to the upper mesosphere. Three test cases were considered, each exhibiting turbulence with varying degrees of intensity and intermittency in time and space. These DNS are used as reference cases for testing two LES schemes: the dynamic Smagorinsky method and the implicit Adaptive Local Deconvolution Method (ALDM) (3), originally developed for modelling isotropic incompressible turbulence but adapted for use with stratified turbulence (4). The schemes are compared in terms of how well they reproduce the decay of the wave and the energy dissipation as functions of time during the breaking process, with results varying considerably with the type of wave-breaking event considered. For a case involving strong turbulence ALDM turns out to be the better choice, while for cases with weak turbulence and a partially laminar flow field the dynamic Smagorinsky method has advantages. With all methods, a higher resolution is required in the vertical direction than in the horizontal directions.

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Modeling of daytime convective development over land with a new prototype model COSMO-EULAG

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COSMO-EULAG, boundary layer, diurnal cycle, moist convection

EULAG has been recently implemented as a new dynamical core of the COSMO (Consortium for Small-scale Modeling) weather prediction model. The primary motivation for employing EULAG to weather forecasting results from the fact that EULAG has considerable advantages concerning conservation properties and does not impose severe constraints on the maximal allowable steepness of the surface orography. In addition, EULAG features a high numerical robustness confirmed in a number of benchmark tests.

To date the new prototype model COSMO-EULAG has been successfully tested in several idealized dry experiments including stationary flow over mountains, expansion of linear gravity waves, strongly nonlinear and non-stationary falling bubbles. Current efforts are focused on accurate modeling of convective processes such as cloud and precipitation formation and further optimization of the prototype model. In particular, our goal is to calibrate coupling between the dynamical core and COSMO physical parameterizations to make the code suitable for resolving explicitly convective processes. The optimizations involve tuning of turbulence scheme, shallow convection parameterization, moist processes and other cloud processes. The efforts made allow more deeply to explore the numerical features of the COSMO-EULAG model.

Setup of the numerical experiments is similar to the study by Grabowski et al. (2006) and is based on observations of the diurnal cycle and convection during rainy season in Amazonia. The focus is on the 6 hour period between sunrise and early afternoon. A number of simulations have been performed for different parameterization of moist processes, different resolutions of computational grids (up to 100m horizontally) and available subgrid scale parameterizations of COSMO. The simulations evaluate model's capabilities for modeling the transition from shallow to deep convection. The study involves also the comparison of COSMO-EULAG results with results of standard compressible COSMO-Runge-Kutta model to test the suitability of an anelastic dynamical core for operational mesoscale high-resolution numerical weather prediction.

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Resolution Dependence of Cumulus Statistics in Radiative-Convective Equilibrium

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Cloud resolving simulations, Convection, Radiative-convective equilibrium

In numerical modeling of atmospheric processes on global and mesoscales it is necessary to parameterise the effects of moist convection as they cannot be adequately represented by the resolved-scale motions. With the Plant-Craig stochastic parameterization for deep convection the theoretical basis is given by statistics of equilibrium fluctuations of a cumulus cloud ensemble under homogeneous large-scale forcing. It was derived by Craig and Cohen (2006) that in the limit of non-interacting convective cells, statistics of the convective fluctuations can be written in terms of the large-scale, externally constrained properties of the system and that the probability density function of individual cloud mass fluxes is exponential. This theory was validated at a horizontal resolution of 2 km and the distribution was observed to be insensitive to changes in the magnitude of forcing (Cohen and Craig, 2006). However, at this horizontal resolution convective cells are only partially resolved and mostly collapse to the grid-scale. In our project we reproduced the exponential distribution at 2 km horizontal resolution for horizontally homogeneous forcings from -2 K/day to -12 K/day on a 128 km x 128 km x 20 km domain. Increasing horizontal resolution to 1 km and 500 m revealed a trend towards clouds occuring with a size and mass flux larger than predicted by the theoretical distributions. Further evaluation showed these large clouds to be made up of several smaller clouds which suggests an increasing trend of clouds to develop in near-cloud environments. Convergence of these preliminary results will be investigated by further increasing horizontal resolution.

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Computational Fluid Dynamics Simulations to Understand Mass Transport in Major Vessels of the Heart and Brain

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Mass Transport, Heart, Brain

Vascular disease is the number one cause of mortality in industrial nations. In severe cases, infarction may occur, i.e. the brain or heart tissue may die because of blocked or severely reduced blood supply to an organ because of an acute thrombotic or a chronic process like atherosclerosis. Therefore, there is an urgent need for understanding and diagnosis of the development and progression of these diseases, i.e. using non-invasive image based techniques like computed tomography and magnetic resonance imaging (MRI). The key problem for an accurate diagnosis is question if transport of diagnostic molecules and particles along the major feeding arteries of the heart and brain, i.e. the coronary and the carotid arteries, introduces systematic errors. It is the aim of this study to investigate the transport of typical contrast agents used in imaging based diagnostics along the major feeding arteries, and to predict potential systematic errors.

Computational fluid dynamics simulations based on the Navier Stokes Equations are a powerful technique to understand blood flow in such vessels. Although they are well established to predict blood flow and shear stress in major arteries, little is known about the transport of tracer substances along these vessels. Moreover, experimental validation of CFD in-vivo is largely nonexisting.

As the basis of CFD simulations, computed tomography of vessel casts, or imaging microcryotome data of the heartâs epicardial vessels were used. For the brainâs feeding arteries (i.e. the carotid vessels) magnetic resonance imaging data were used. From those data, the vessel lumen was segmented out to be used as input data for generation of a 3D mesh which is later used for the CFD simulations. Rather than the widely used tetrahedral meshes, hexahedral mesh elements were found to be necessary to suppress the occurrence of unphysiological numerical diffusion effects in the later steps of the simulations. Currently, the analysis is limited to the larger vessels. Nevertheless, meshing takes at least one week per dataset. The 3D mesh is then used to simulate the periodic spatiotemporal blood flow profile in the arteries. After that, the transport equation is used to predict the transport of molecules and particles, the latter being characterized by their diffusion coefficient. Simulations are performed using Ansys Fluent or Openfoam software. Depending on the number of mesh elements, total computing time on the Elwetrisch (Kaiserslautern) or Mogon (Mainz) high-performance computing clusters is on the order of one week. Based on the results of these simulations, predictions of the systematic error of MRI were made.

It was found that blood flow velocity, curvature of the blood vessels and tissue perfusion state, as well as degree and shape of vessel narrowing (stenosis) strongly influence the transport of molecules along the arteries. In the normal heart, systematic errors of up to 25% may occur. Initial results indicate that in the brain errors are much smaller. Measurements based on tracer molecules with a high diffusion coefficient such as water induce less systematic errors than those based on chelates like Gd-DTPA or Gd-DOTA, or ultrasmall superparamagnetic iron oxide particles. Moreover, current results predict systematic errors depending on the anatomical position within the heart.

In the future, it is planned to extend the analysis to smaller vessels and to patients with coronary or carotid vessel stenosis, and to include fluid-structure interaction in the simulations. For this, further developments are required, in particular the automated generation of hexahedral meshes is a currently unsolved problem. Moreover, a one-to-one experimental validation of the results of the simulations with real MRI data will be performed using latest MRI technology.

Meandering of a wind mill wake vortex

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vortex instability, wake meandering, wind energy

A meander in nature commonly refers to a sinuous watercourse or river. Here it denotes the sinusoidally shaped transverse oscillation of a wind mill wake. This oscillation occurs a few rotor diameters downstream of the turbine (1). Periodic vortex shedding (2) or the advection of the wake by large upstream eddies (3) have been discussed as causes for the meandering motion.

We approach the wind mill wake vortex tube with diameter D from a theoretical perspective and conduct a linear stability analysis of a Rankine vortex in shear flow using the vorticity equation (Fig. 1). Corresponding idealized numerical simulations show the onset of the meandering motion for $1/f$-*noise* of different intensities and spectral properties (4).

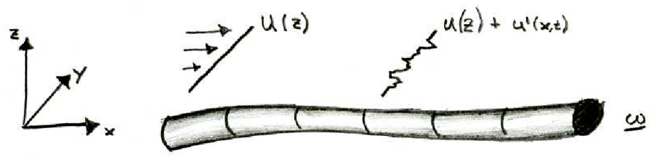

Figure 1: Vortex tube with vorticity $\boldsymbol{\omega}$ in strong shear flow $U(z)$ with perturbations u'.

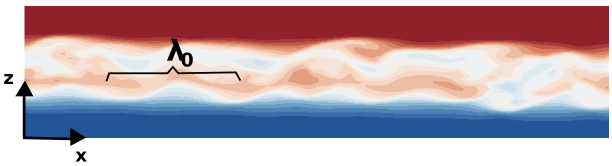

Figure 2: Streamwise velocity field $\tilde{u}(x, z)$ after onset of instability.

Strong background shear initiates and sustains the meandering in the stability analysis and in the simulations (Fig. 2). The scale where instabilities arise depends on the initial noise. For *one-dimensional* noise, meanders evolve with a wavelength $\lambda_0 \geqslant D$ in the perturbed velocity field.

Finally, we implement an actuator disk (2) by immersed boundary methods in a large-eddy simulation code. The actuator disk represents a rotating wind turbine in the atmospheric surface layer. Passive tracers are used to illustrate the wind turbine wake dynamics. A spectral analysis of the turbulent kinetic energy reveals a maximum at the scale of the wavelength λ_0 of the meanders. Our results suggest strong shear as a third cause for the meandering motion.

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A consistent framework for discrete integrations of all-scale atmospheric dynamics

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atmospheric models, geophysical turbulence, terrestrial weather and climate

A consistent framework is developed for discrete integrations of soundproof and the fully compressible nonhydrostatic equations of motion for all-scale atmospheric dynamics (Smolarkiewicz et al., 2014). The reduced soundproof and compressible Euler PDEs are formulated as a generalised system of conservation laws for mass, momentum and entropy. This facilitates the design of a sole principal algorithm for discrete integration. The development relies on non-oscillatory forward-in-time transport methods, applied consistently to all dependent variables of the generalised system (Prusa et al., 2008). Semi-implicit time-discretisation of the buoyant and rotational forces enhances the stability and the accuracy of integrations. Furthermore, when the compressible equations are solved, the framework allows for either an explicit or implicit representation of acoustic modes, thus providing, respectively, the reference and two large-time-step variants of the compressible solutions. The latter is competitive in computational efficiency with soundproof schemes. In essence, the differences between the soundproof and large-time-step compressible integrators reduce to the selection of either a prescribed or a numerically prognosed density, and extension of the generalised Poisson solver (Prusa et al., 2008) to a bespoke Helmholtz solver. The numerical advancements and merits of the approach are illustrated with canonical simulations of planetary baroclinic instability and the breaking of a deep stratospheric gravity waves, archetypes of planetary weather and nonhydrostatic mesoscale dynamics.

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Subvisible cirrus clouds driven by slow updrafts

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cirrus clouds, large-scale dynamics, ice nucleation

Thin cirrus and so-called subvisible cirrus (i.e. optical thickness < 0.03) are found very often in the tropopause region. However, the dominant formation mechanism of these clouds remains unclear. Recent theoretical investigations with a simple analytical cloud model showed that thin cirrus might be formed via homogeneous nucleation in slow synoptic updrafts. The interaction between nucleation, growth and sedimentation leads to damped oscillations and finally to very small ice crystal number concentrations. In this study the formation of thin cirrus clouds is investigated using the full 2D/3D setup of EULAG as a cirrus LES. In addition to thermodynamic boundary conditions, the impact of small scale perturbations in potential temperature and vertical velocity are investigated.

An unstructured-mesh nonhydrostatatic model for orographic flows

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stratified flows, ILES, non-oscillatory forward-in-time, MPDATA, edge-based finite volume schemes

A three-dimensional semi-implicit edge-based unstructured-mesh model (Smolarkiewicz and Szmelter, 2011; Smolarkiewicz et al., 2013) is developed that integrates non-hydrostatic anelastic equations, suitable for simulation of small-to-mesoscale atmospheric flows. The model builds on non-oscillatory forward-in-time (NFT) Multidimensional Positive Definite Advection Transport Algorithm (MPDATA) approach (Smolarkiewicz and Szmelter, 2005) using finite-volume discretization, admitting unstructured meshes with arbitrarily shaped cells. Implicit large eddy simulation exploits properties of MPDATA.

Applications to weekly and strongly (stably) stratified orographic flows are discussed. The latter epitomise diverse aspects of highly nonlinear non-hydrostatic dynamics. The solutions are obtained on fully unstructured-meshes and compared to equivalent results generated with an established structured-grid model and observation. A further, quantitative study examines simulations of stratified flow past a sphere and a hemisphere for a range of stable stratifications and both laminar and turbulent boundary layer flow regimes, followed by a selection of examples illustrating applicability of the method to engineering flows.

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The Lagrangian ice microphysics code LCM within EULAG: Introduction, current developments and applications

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Lagrangian ice microphysics, cirrus clouds, contrails

The Lagrangian Cirrus Module (LCM) is a Lagrangian ice microphysics code (**?**) that is fully coupled to EULAG. The ice phase is described by a large number of simulation particles (order $\mathcal{O}(10^6) - \mathcal{O}(10^8)$) which act as surrogates for the real ice crystals. The simulation particles (SIPs) are advected and microphysical processes like deposition/sublimation and sedimentation are solved for each individual SIP. More specifically, LCM tracks ice nucleation, growth, sedimentation, aggregation, latent heat release, radiative impact on crystal growth, and turbulent dispersion. The aerosol module comprises an explicit representation of size-resolved non-equilibrium aerosol microphysical processes for supercooled solution droplets and insoluble ice nuclei.

First, an introduction to LCM is given focusing on the implementation of a Lagrangian model within the grid-based EULAG framework. Incorporating dynamic data management and improving numerical implementations substantially reduce computing time and memory consumption (**??**). Applications of LCM include simulations of the dispersion of aircraft exhaust (**?**) and of the formation of contrail clusters and their competition with natural cirrus.

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Formation of thin cirrus clouds: Homogeneous or heterogeneous nucleation?

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cirrus, large-scale dynamics, small scale instabilities, ice nucleation

There are two different pathways of ice crystal formation at low temperatures: Homogeneous freezing of aqueous solution droplets and heterogeneous nucleation, involving solid aerosol particles. For thin and subvisible cirrus clouds, the dominant formation mechanism is still unknown. During the aircraft campaign AIRTOSS-ICE in Spring 2013, the rare case of in situ formation of thin cirrus clouds was measured. Thus, we use the in situ measurements, METEOSAT images and complementary model simulations to test different hypotheses about the formation of thin cirrus clouds.

In a first step the meteorological conditions leading to the cirrus formation are analyzed using meteorological analyses as obtained from the European Centre for Medium-Range Forecasts (ECMWF). The ECMWF wind fields are then used to calculate backward trajectories with the Lagrangian analysis tool LAGRANTO. From these investigations the large-scale/mesoscale motions are derived and analyzed. Finally, the meteorological analyses and measurements (temperature, wind, humidity) are used as initial conditions for cirrus cloud simulations. We used EULAG as LES model, including a state-of-the-art ice microphysics scheme for 2D and 3D idealized and quasi-realistic simulations. In order to address the impact of dynamics vs. aerosols (i.e. heterogeneous nucleation), we investigated different environmental conditions. The microphysical and macrophysical properties of the simulated cloud are finally compared to the measurements, in order to get some information about the most probable scenarios.

Modeling baroclinic driven flows with the immersed boundary method

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stratified flows, immersed boundaries, baroclinic driven flows, rotating annulus

We present a numerical study of baroclinic driven flows in the thermally driven rotating annulus using the geophysical flow solver EULAG. The Navier-Stokes equations in the Boussinesq approximation are solved in the Eulerian flux-form advection scheme. The cylindrical research cavity is embedded in a cartesian grid and boundaries of the model set-up are defined with the immersed boundary method. We, first, test our approach against an appropriate laboratory experiment and directly aim at the wavy flow regime where complex flows and regular wave patterns are observed. Multivariate statistical methods are used for analyzing time series of computed temperature and velocity data. We present the realization of the model set-up in the EULAG framework and show the results of our study, specifically the outcome of the time series data analysis at particular parameter points where complex wave-wave interactions are found. The numerical results are consistent with the findings of the laboratory reference experiment. That encourage us for the attempt to investigate chaotic flow patterns usually found at higher rotation rates where large-scale and small-scale flow patterns coexist. In that region, centrifugal effects become increasingly important.

libmpdata++: library of parallel MPDATA-based solvers built with emphasis on maintainability

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MPDATA, code maintainability, object-oriented programming, C++

Clear separation of concerns is one of the core principles of modern software engineering (Hürsh and Lopes, 1995). In the context of atmospheric science, it is beneficial to separate code describing the numerics, physics and technical constructs. Code separation yields a significant added value if the separated parts constitute standalone packages that can be independently tested. Releasing these packages as free and open source software (FOSS) brings additional advantages of facilitating code reuse and helping with result reproducibility.

This talk will present libmpdata++: a new library of solvers based on MPDATA family of schemes (Smolarkiewicz and Margolin, 1998). It is implemented in C++ using object-oriented paradigm (see Arabas et al., 2014, for discussion of this choice). The core of the library consists of a hierarchy of solvers that can be chosen depending on its user's needs. The solvers are highly customizable with options to perform integration in curvilinear coordinate system, to choose among different algorithms for integrating source terms, and to control MPDATA variants. The implemented MPDATA options include the flux-corrected transport formulation guaranteeing monotonic solutions, and the infinite-gauge version of the algorithm for handling variable-sign fields. Integration in one, two and three dimensions is supported. Support of parallel execution is provided within shared-memory model through domain decomposition.

The library is designed with focus on maintainability, ease of use and productivity. Each of the solvers and each algorithm variant is implemented as a separate component susceptible to unit testing. Employment of external libraries and object-oriented constructs resulted in succinct code. The whole codebase totals less than 10 kLOC.

During this talk we will give a tour of the library highlighting its features and design choices. Provided examples of use will be compared to previous MPDATA benchmarks in order to assert correctness of the implementation. Presented examples will illustrate how libmpdata++ can be used in several diverse contexts with no modifications of its code, thus enabling the user to easily (i.e., automatically) benefit from the library updates. The examples include solutions of shallow water equations, homogeneous advection in spherical coordinates, buoyant convection in a Boussinesq fluid and kinematic cloud model implemented using a sister library libcloudph++ that is being developed in our group using analogous principles (Arabas et al., 2013).

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Increasing horizontal resolution in global NWP and climate simulations – illusion or panacea ?

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spectral transform, numerical weather prediction, large scale computing

The steady path of doubling the global horizontal resolution approximately every 8 years in numerical weather prediction (NWP) at the European Centre for Medium Range Forecasts (ECMWF) may be substantially altered with emerging novel computing architectures. It coincides with the need to appropriately address and determine forecast uncertainty with increasing resolution, in particular, when convective-scale motions start to be resolved. Blunt increases in the model resolution will quickly become unaffordable and may not lead to improved NWP forecasts. Consequently, there is a need to accordingly adjust proven numerical techniques. An informed decision on the modelling strategy for harnessing exascale, massively parallel computing power thus also requires a deeper understanding of the sensitivity to uncertainty — for each part of the model — and ultimately a deeper understanding of multi-scale interactions in the atmosphere and their numerical realisation in ultra-high resolution NWP and climate simulations. Here we explore opportunities for substantial increases in the forecast efficiency by judicious adjustment of the formal accuracy or relative resolution in the spectral and physical space. One path is to reduce the formal accuracy by which the spectral transforms are computed. The other pathway explores the importance of the ratio used for the horizontal resolution in gridpoint space versus wavenumbers in spectral space. This is relevant for both high resolution simulations as well as ensemble-based uncertainty estimation.

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The development and testing of EULAG version for numerical weather prediciton

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COSMO-EULAG, convective storm, numerical weather prediction, Alpine summer convection

Research conducted at Institute of Meteorology and Water Management within the Consortium for Small Scale Modeling (COSMO) resulted in the development of a new prototype model COSMO-EULAG. In the new model the anelastic dynamical core of EULAG in Eulerian form, translated to Fortran 90, is a part of software environment of the COSMO modeling framework. The dynamical solver is coupled, with the 1st degree of accuracy, to the basic COSMO physical parameterizations involving turbulence, friction, radiation, moist processes and surface fluxes. The model is capable to compute weather forecast in mountainous area for the horizontal resolution of 0.28 km and with slopes reaching 60 degrees of inclination. An employment of EULAG allows to profit from its desirable conservative properties and numerical robustness confirmed in number of benchmark tests and widely documented in scientific literature. The model development is naturally linked with idealized testing in order to assure realistic representation of basic meteorological flows. In this study we show results of a convective storm benchmark of Weisman and Klemp (2014). The study presents life cycle of a single storm structure in COSMO-EULAG and compares it to the complementary results achieved with the standard compressible COSMO-Runge-Kutta model and with the EULAG stand-alone version. In the second part of presentation a realistic case study of Alpine summer convection simu- lated by COSMO-EULAG with very high horizontal resolutions are presented. While the simu- lations, even with the highest resolution, do not require any artificial orography smoothing, the influence of such smoothing on simulation is in the field of interest. The study shows a comparison of flows, cloud and precipitation structures, and power wind spectra. The COSMO-EULAG forecast is also compared with available meteorological information and with the standard operational COSMO forecast.

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Using GPU and Intel Xeon Phi coprocessors to accelerate computations in 3D MPDATA algorithm

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Large scale computing, parallel programming, GPU, Intel Xeon Phi, stencils, MDATA

The multidimensional positive defined advection transport algorithm (MPDATA) is among the most time-consuming components of the EULAG model. At previous EULAG Workshop, we presented preliminary results of parallelization of 2D MPDATA computations on multicore architectures with GPU accelerators. In the succeeding paper [1], we investigated key aspects of an optimal parallel version of the 2D MPDATA algorithm on modern hybrid architectures with GPU accelerators, where computations are distributed across both GPU and CPU components. In a development of these research, in this work we outline our approaches to adapt computations in the 3D MDATA algorithm to clusters with GPU and Intel Xeon Phi accelerators.

The general purpose programming on graphics devices is currently supported by two main vendors of GPUs. AMD and NVIDIA deliver powerful platforms, which peak performance exceeds a few Tflop/s. The goal of research presented in this work is to develop an efficient and portable adaptation of stencil-based 3D MPDATA algorithm to both types of GPUs. Differences between these architectures force users to develop distinct approaches and optimizations for each of them, including algorithm configuration, memory management and organization of computation. For this aim, we propose a performance model, which allows for the efficient distribution of computation across GPU resources. Since MPDATA is strongly memory-bounded, the main challenge of providing a high-performance implementation is to reduce GPU global memory transactions. For this purpose, our performance model ensures a comprehensive analysis of transactions based on local memory utilization, sizes of halo areas (ghost zones), data dependencies between and within stencils. The proposed model is one of the key components for developing an autotuning mechanism dedicated not only to the MPDATA computations, but also to the whole family of stencil algorithms. This mechanism aims at providing the performance portability for parallel codes across different GPU architectures. We also discuss preliminary performance results achieved on the NVIDIA Geforce GTX Titan GPU, as well as on clusters with NVIDIA GPUs (Fermi and Kepler architectures).

The Intel Xeon Phi coprocessor is the first product based on the Intel Many Integrated Core (MIC) architecture. This architecture offers notable performance advantages over traditional processors, and supports practically the same traditional parallel programming model. The Intel MIC architecture combines more than 50 cores (200 threads) within a single chip, it has at least 25 MB aggregated L2 cache, and 6 GB of on-board memory. Our approach to adaptation of the 3D MPDATA algorithm to this architecture is based on combination of loop tiling and loop fusion techniques, and allows us to ease memory and communication bounds and better exploit the theoretical floating point efficiency of target platforms. The proposed approach is than extended on clusters with Intel Xeon Phi accelerators, using a mixture of MPI and OpenMP programming standards. For this aim, we use a hierarchical decomposition of MPDATA, including level of cluster as well as distribution of computation across cores of Intel Xeon Phi. Preliminary performance results are finally discussed.

References

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Surface-layer flux-gradient relationships over inclined terrain: implementation in EULAG

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atmospheric surface layer, surface fluxes, EULAG

Despite the significant achievements of the atmospheric surface-layer theory, the effects of terrain inclination on surface fluxes remain poorly understood. Extending the Monin-Obukhov similarity theory via empirical approach poses difficulties due to a number of additional factors that would need to be included, as the terrain slope and wind angle with respect to the slope. Recently, a theoretical prediction of the Monin-Obukhov similarity (MOS) functions with an inclusion of terrain slope effects has been attempted by solving Reynolds-stress model equations in slope coordinates (Łobocki, 2014; LŁ14). Although this method delivers the desired solution, it should be treated as a first approach to the problem, where the majority of important questions still remains open; for example â the issue of choosing an appropriate turbulence model, or the applicability limitations.

Efforts have started on implementing the new slope aware MOS approach to the EULAG model, and to assess method applicability in LES over the idealized and realistic orography. We would like to present the current status of these efforts, including the formulation of lower boundary conditions, bulk formulations of surface-layer exchange coefficients based upon LŁ14, and the response of modelled flows to changes in terrain inclination.

References

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Large time step discontinuous evolution Galerkin methods for multiscale atmospheric flow

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Cloud physics, Stratified flows, Large scale computing

We present a new adaptive genuinely multidimensional method within the framework of the discontinuous Galerkin method [Yelash et al. (2014)]. The discontinuous evolution Galerkin (DEG) method couples a discontinuous Galerkin formulation with approximate evolution operators. The latter are constructed using the bicharacteristics of multidimensional hyperbolic systems, such that all of the infinitely many directions of wave propagation are considered explicitly. In order to take into account multiscale phenomena that typically appear in atmospheric flows nonlinear fluxes are split into a linear part governing the acoustic and gravitational waves and a nonlinear part that models advection. Time integration is realized by the IMEX type approximation using the semi-implicit second-order backward differentiation formula (BDF2). Moreover in order to approximate efficiently small scale phenomena, adaptive mesh refinement using the space filling curves via the AMATOS function library is employed. Four standard meteorological test cases are used to validate the new discontinuous evolution Galerkin method for dry atmospheric convection. Comparisons with the Rusanov flux, a standard one-dimensional approximate Riemann solver used for the flux integration, demonstrate better stability and accuracy, as well as the reliability of the new multidimensional DEG method. Aplications for the shallow water equation has been done in [Bispen et al. (2014)].

References

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