Book of abstracts

PDEs on the sphere workshop

3.-7. July 2023 in Grenoble, France

Contents

1 The effect of linear dispersive errors on nonlinear time-stepping accuracy in weather and climate PDEs

Speaker: **Andrews Timothy**
Authors: Andrews timothy (1)
Institutions: 1 - University of Exeter (United Kingdom)
Type: Oral

There is an ever-increasing demand for larger time-steps in the next generation of weather and climate models-—these enable longer and higher complexity simulations to be completed within a restricted wall-clock time. However, implementing a stable and accurate large time-step is difficult, with the governing equations containing highly oscillatory linear waves. Additionally, there can be multiple time scales, such as in slower nonlinear interactions. We will examine the effect of a large time-step on the solution accuracy, with application to the Rotating Shallow Water Equations (RSWEs). To begin, a general reformulation of the equations will highlight the important interactions of three wave 'triads'. Combining numerical linear dispersion relations, obtained from the Dahlquist test equation, allows for the estimation of a nonlinear 'triadic error'. Error comparisons for selected explicit and implicit time-stepping methods (including RK4, Generalised Euler methods, and TR-BDF2) are provided for the RSWEs. Next, two test cases are presented for comparing different time-steppers in any numerical model. The first is of a reforming Gaussian height perturbation. This contains a nonlinear phase shift that can be missed with a large time-step. The second type of test case initialises specific linear waves which, via direct- and near-resonant triad interactions, construct nonlinear dynamics over a long duration. Three models are applied to these tests, including the compatible finite element code, Gusto, and the MetOffice's new LFRic model.

2 The Discontinuous Galerkin method: comparison of two Euler equation sets

Speaker: **Baldauf Michael**
Authors: Baldauf michael (1), Prill florian (2)
Institutions: 1 - Deutscher Wetterdienst (Frankfurter Str. 135 63067 Offenbach Germany), 2 - Deutscher Wetterdienst (Germany)
Type: Oral

Currently, at the Deutscher Wetterdienst (DWD) efforts are made to develop an alternative dynamical core based on the Discontinuous Galerkin (DG) approach for the weather forecast and climate model ICON. This work is organized in the internal project BRIDGE (Basic Research for ICON with DG Extension). The new dynamical core uses local coordinates to allow a uniform triangulation on the sphere and terrain following coordinates to treat orography. The time-integration uses the horizontally explicit-vertically implicit (HEVI) approach, put in an higher-order IMEX-Runge-Kutta scheme to enhance efficiency for strongly anisotropic grid cells. Furthermore, first steps are made to couple and treat complex turbulence models like the one equation TKE scheme with the DG approach, too.

Several standard idealized test case simulations are shown. In particular, two different Euler equation systems in conservation form, one using potential temperature density and the other using total energy density as the thermodynamic variable are compared. Apart from the obvious advantage to have local energy conservation, it turns out that the use of total energy possesses also some positive properties concerning well-balancing.

3 Casimir-dissipation stabilized stochastic rotating shallow-water equations on the sphere

Speaker: **Bauer Werner**
Authors: Bauer werner (1), Brecht ruediger (2)
Institutions: 1 - University of Surrey, School of Mathematics and Physics (United Kingdom), 2 - Universität Hamburg, Fachbereich Mathematik (Germany)
Type: Oral

We introduce a structure preserving discretization of stochastic rotating shallow water equations, stabilized with an energy conserving Casimir (i.e. potential enstrophy) dissipation. A stabilization of a stochastic scheme is usually required as, by modeling subgrid effects via stochastic processes, small scale features are injected which often lead to noise on the grid scale and numerical instability. Such noise is usually dissipated with a standard diffusion via a Laplacian which necessarily also dissipates energy. In this contribution we study the effects of using an energy preserving selective Casimir dissipation method compared to diffusion via a Laplacian. For both, we analyze stability and accuracy of the stochastic scheme. The results for a test case of a barotropically unstable jet show that Casimir dissipation allows for stable simulations that preserve energy and exhibit more dynamics than comparable runs that use a Laplacian.

4 Developing consistent subgrid-scale representations by multi-scale finite elements

Speaker: **Behrens Joern**
Authors: Behrens joern (1)
Institutions: 1 - University of Hamburg (Germany)
Type: Oral

When modeling global geophysical processes such as atmospheric or oceanic flows a cascade of processes acting on different scales influences the overall system behavior. In general, there is a resolved scale, determined by the discrete resolution, and an unresolved scale that is parameterized. Most parameterization schemes rely on some kind of averaging small scale processes within a grid cell. This is totally acceptable as long as there is no dominant structure in the subgrid scale process. However, in some cases the subgrid scale features structure, that imprints into the large scale. In such situations, it would be desirable to somehow lift this information into the resolved process scale. This can be achieved by multi-scale finite element methods. These methods, already in use in elliptic or parabolic problem settings, have been extended by means of semi-Lagrangian approaches for hyperbolic - i.e. transport dominated - flow regimes. This Semi-Lagranian subgrid Reconstruction (SLMsR) method has been demonstrated using linear advection-diffusion equations in multiple dimensions. Further steps have been taken to make use of such methods in more applied situations. We will introduce the main ideas and features of the method and give an outlook on possible applications.

5 A Solution to the Trilemma of the Moist Charney-Phillips Staggering

Speaker: **Bendall Thomas**
Authors: Bendall thomas (1), Wood nigel (1), Thuburn john (2), Cotter colin (3)
Institutions: 1 - Met Office (United Kingdom), 2 - University of Exeter (United Kingdom), 3 - Imperial College London (United Kingdom)
Type: Oral

The Charney-Phillips grid involves vertically staggering the nodes of the density variable with the nodes of the entropy-type variable. When moisture is included in such a model, it is either co-located with density so that moisture can be transported conservatively and consistently with dry mass, or with the entropy-type variable so that the coupling between moisture and temperature can be represented well. Both properties are desirable, yet at first it appears difficult to obtain both simultaneously!

Here we present a framework to resolve this problem, by co-locating the moisture mixing ratio with potential temperature but formulating its transport as that of a density on a vertically-shifted mesh. Within this framework, particular choices of the operators involved provide the desired conservation and consistency properties of the moisture transport. The framework is described in the context of the finite element approach used in the UK Met Office's LFRic model.

6 Analysis of Spherical Harmonic subspace related to different spherical grids

Speaker: **Brachet Matthieu**
Authors: Bellet jean-Baptiste (1), Brachet matthieu (2), Croisille jean-Pierre (1)
Institutions: 1 - Institut Élie Cartan de Lorraine (France), 2 - Laboratoire de Mathématiques et Applications (France)
Type: Poster

Spherical harmonics are useful in solving partial differential equations on a spherical grid, sometimes employing pseudo-spectral methods or quadrature formulae. These are used to interpolate data on the grid, e.g. to initiate the numerical resolution of a PDE.

In [Bellet et al.., 2022, Numerische Mathematik], a spherical harmonic subspace is introduced, allowing to obtain an unique solution to the Lagrange interpolation problem on the Cubed-Sphere within this subspace. However, the algorithm works whatever the chosen grid. It results in different subspaces for different grids.

The subspaces are analyzed when considering different grids such that the Cubed-Sphere and Icosahedron grids. Numerical results are obtained and compared to highlight the differences between the subspaces.

7 Physics-Dynamics-Chemistry Coupling with components of different resolutions in LFRic

Speaker: **Brown Alex**
Authors: Brown alex (1), Bendall thomas (1)
Institutions: 1 - United Kingdom Met Office [Exeter] (United Kingdom)
Type: Oral

Traditionally the dynamical core, the physical parametrisations and chemical and aerosol processes all use the same mesh. Here we present a formulation to for each of the components to use a different mesh, with different horizontal resolutions. By running different model components at different resolutions, we will be able to target computational resources where they will be most effective, allowing for improvement in model performance. Furthermore, by running some parts of the model at coarser resolutions we may in fact reduce errors by preventing the amplification of noise. Key to this new approach is the mapping of fields between meshes, which has been designed for the compatible finite element discretisation of LFRic, the next generation Met Office atmospheric model. The formulation preserves several important properties of the model with all components on the same mesh, such as positivity and mass conservation of moist species. The validity of the formulation will be demonstrated through a series of idealised test cases. Finally, we will discuss the future scope of this work and the plan for a full climate suite with coarsened aerosol and radiation schemes.

8 Status and perspectives of the temporal scheme of the AROME model

Speaker: **Burgot Thomas**
Authors: Burgot thomas (1)
Institutions: 1 - Météo-France (France)
Type: Oral

AROME is the operational limited area model of Météo-France. A Crank-Nicolson temporal scheme is currently used to integrate the fully system of Euler equations. This scheme is approached by an Iterative Centered Implicit scheme which is a fixed point method, where a linear operator is introduced to invert the implicit problem. In AROME, the linear operator of this scheme is chosen such that it does not contain orographic terms, and thus depends only on the vertical coordinate. In this case, the horizontal and vertical part are separable and a Fast Fourier Transform (FFT) algorithm can be used to compute efficiently some components in the spectral space: solving the implicit problem, adding diffusion, computing derivatives, etc. However the FFT algorithm is not fully scalable on large parallel computing architectures. To avoid calling this algorithm as much as possible, a large time step is currently used. We will show that using a large time step leads to some accuracy loss, especially on the non-hydrostatic signal at small scale. Moreover, numerical stability problems appear with the current formulation once a finer resolution is used and thus when the relief is better represented, especially the steepest slopes. We will show that none of the usual strategies tested significantly improves numerical stability without worsening efficiency or accuracy. Hence, the current formulation is probably not the most suitable for high-resolution computing. A successful strategy consists in using the same features of the current version except for the orographic terms which are implicitly treated, resulting in a linear operator which depends on both horizontal and vertical coordinates. In this case, we will show that slopes up to 70° can be easily reached. Since the FFT algorithm can no longer be used, some iterative solvers and their features are presented as an alternative.

9 Fast Summation for the Barotropic Vorticity Equations

Speaker: **Chen Anthony**
Authors: Chen anthony (1)
Institutions: 1 - Department of Mathematics - University of Michigan (United States)
Type: Oral

The barotropic vorticity equations describe the conservation of absolute vorticity in a rotating fluid. When transformed appropriately, one can discretize these equations as a N-body problem. In this talk, I present a fast summation technique to accelerate the computation of the solution with a spherical tree code.

10 A shape-preserving multi-moment advection scheme on arbitrary polygonal grids

Speaker: **Chen Chungang**
Authors: Chen chungang (1), Zhao yanfeng (1), Li xingliang (2), Shen xueshun (2), Xiao feng (3)
Institutions: 1 - Xi'an Jiaotong University (China), 2 - China Meteorological Administration (China), 3 - Tokyo Institute of Technology (Japan)
Type: Oral

In this talk, a high-order numerical scheme for calculating the advection transport on arbitrary polygonal grids is described. The proposed scheme is constructed by using the multi-moment method. Two kinds of moments, including the point-wise values (PVs) at cell vertices and volume-integrated average (VIA) over each polygonal cell, are treated as unknowns and updated independently. The spatial reconstruction can be accomplished based on the multiple degrees of freedom (DOFs) within a single-cell stencil. The resulting scheme is easy to be implemented and able to achieve the uniform high-order accuracy on various computational grids. A flux correction algorithm is designed to modify the solutions of PVs, in order to avoid that the new local extrema are generated by the high-order scheme during the simulations. As a result, the shape-preserving property of the proposed scheme can be assured when solving the non-divergent transport problems. To preserve the accuracy in smooth regions, a smoothness indicator using the WENO (weighted essentially non-oscillatory) concept is further adopted to flag the cells involving the discontinuities and the flux correction operations are then applied only in the flagged cells. The proposed scheme is verified by solving the benchmark test cases on 2D rectangular and hexagonal grids in this talk. The third-order accuracy is achieved on both grids in the tests for smooth problems, meanwhile the numerical oscillations are effectively removed around the discontinuities. A shape-preserving advection scheme in spherical geometry is under develop on the quasi-uniform cubed-sphere and icosahedral-hexagonal grids.

11 PlanetCubed: A Cubed-Sphere Dynamical Core for Simulating Planetary Atmospheres

Speaker: **Chen Sihe**
Authors: Chen sihe (1), Li cheng (2)
Institutions: 1 - California Institute of Technology (United States), 2 - University of Michigan [Ann Arbor] (United States)
Type: Poster

The current lack of convective-permitting global models for giant planets is due to the fundamental assumption of hydrostatic balance and the computational inefficiency of the conventionally used uniform longitude-latitude grids. Due to a decrease in the grid size in high latitudes, the CFL condition enforces a small time step otherwise the polar region could not be well resolved. There are two methods that are widely used to circumvent this problem: we can either transform the grids based on spherical harmonics (Eliasen et al., 1970), or we can cast the grids onto a "cubed sphere" geometry (Ronchi et al., 1996). We developed a cubed-sphere dynamical core based on SNAP (Li and Chen, 2019), which is designed for simulating planet atmospheres built upon the baseline code Athena++ (Stone et al., 2020; White et al., 2016), in which a finite volume scheme is taken. We used gnomonic equiangular coordinates, and used the fifth-order WENO scheme for Riemann solvers. In this work, we will present the equations necessary for changing the geometry into a cubed-sphere, and will present several test cases of both shallow water model simulations and 3-dimensional nonhydrostatic simulations.

12 Balanced data assimilation with a blended numerical model

Speaker: **Chew Ray**
Authors: Chew ray (1), Benacchio tommaso (2), Hastermann gottfried (3), Klein rupert (4)
Institutions: 1 - Institut für Atmosphäre und Umwelt, Goethe-Universität Frankfurt am Main (Germany), 2 - Weather Research, Danmarks Meteorologiske Institut (Denmark), 3 - GeoForschungsZentrum - Helmholtz-Zentrum Potsdam (Germany), 4 - Institut für Mathematik, Freie Universität Berlin (Germany)
Type: Oral

Physical imbalances introduced by local sequential Bayesian data assimilation pose a problem for numerical weather prediction. For example, fast-mode acoustic imbalances of the order of the relevant slower dynamics destroy solution quality. We introduce a novel dynamics-driven method that suppresses imbalances arising from data assimilation. Specifically, we employ a blended numerical model with seamless access to compressible, soundproof, and hydrostatic dynamics. After careful numerical and asymptotic analysis, we introduce a one-step blending strategy to switch between model regimes within a simulation run. Upon assimilation of data, the model configuration is switched for one timestep to the limit soundproof pseudo-incompressible or hydrostatic regime. After that, the model configuration is switched back to the compressible regime for the duration of the assimilation window. The switching between model regimes is repeated for each subsequent assimilation window. Idealised experiments involving the travelling vortex, buoyancy-driven rising thermals, and internal gravity wave pulses demonstrate that our method successfully eliminates imbalances from data assimilation, yielding up to two orders-of-magnitude improvements in the analysis fields. While our studies involved eliminating acoustic and hydrostatic imbalances, this novel dynamics-driven method of achieving balanced data assimilation can be extended to eliminate other undesired imbalances, with significant prospective applications in real-world weather prediction.

13 Recent progress in discrete exterior calculus for GFD models

Speaker: **Christopher Eldred**
Authors: Christopher eldred (1), Waruszewski maciej (1), Bauer werner (2)
Institutions: 1 - Sandia National Laboratories [Albuquerque] (United States), 2 - University of Surrey (United Kingdom)
Type: Oral

Structure-preserving discretizations such as discrete exterior calculus (DEC) provide a powerful means of constructing numerical models with many desirable properties, including discrete conservation laws, steady geostrophic modes and freedom from spurious computational modes. An important example for GFD applications is TRiSK-type schemes (a type of DEC), which are widely used in both atmospheric and ocean models. However, most existing DEC approaches suffer from low order of accuracy, inability to handle arbitrary boundary conditions and poor transport operators. In this talk, we will discuss recent work in DEC towards addressing these concerns: 1) Development of a consistent treatment of arbitrary boundary conditions on unstructured meshes 2) Development of high-order Hodge star operators 3) Development of structure-preserving, high-order, oscillation limiting (SPHOOL) transport operators; including optional positivity preservation through flux-corrected transport (FCT) Together, these developments make DEC a viable approach for struture-preserving next generation atmosphere and ocean models. These advances will be demonstrated in the context of the thermal shallow water equations with boundaries, as a simplified setting that still encompass most of the spatial discretization difficulties that occur for a full atmospheric or oceanic model. However, these spatial numerics are also being used in an operational cloud resolving model (PAM, the Portable Atmospheric Model), which will be briefly discussed if time permits.

14 Towards a finite volume discretization of the atmospheric surface layer consistent with physical theory

Speaker: **Clement Simon**
Authors: Clement simon (1), Lemarie florian (1), Blayo eric (1)
Institutions: 1 - Université Grenoble Alpes (France)
Type: Oral

We study an atmospheric column and its discretization. Because of numerical considerations, the column must be divided into two parts: (1) a surface layer, excluded from the computational domain and parameterized, and (2) the rest of the column, which reacts more slowly to variations in surface conditions. A usual practice in atmospheric models is to parameterize the surface layer without excluding it from the computational domain, leading to possible consistency issues. We propose in this talk to unite the two representations in a Finite Volume discretization. In order to do so, the reconstruction inside the first grid cell is performed using the particular functions involved in the parameterizations and not only with polynomials. Using a consistency criterion, surface layer management strategies are compared in different physical situations.

15 Towards thermodynamics-agnostic dynamical cores and test cases

Speaker: **Dubos Thomas**
Authors: Dubos thomas (1), Christopher eldred (2), Lauritzen peter (3), Demaine léo (4)
Institutions: 1 - Laboratoire de Météorologie Dynamique / IPSL (France), 2 - Sandia National Laboratories [Albuquerque] (United States), 3 - National Center for Atmospheric Research [Boulder] (United States), 4 - Laboratoire de Météorologie Dynamique / IPSL (France)
Type: Oral

Dynamical cores often make hard-coded assumptions regarding the thermodynamics of the simulated fluid, such as assuming an ideal perfect gas or an ideal mixture of perfect gases. They also typically make a single choice of thermodynamic prognostic variable, such as some variant of potential temperature. For practical and aesthetical reasons it is desirable to relax these assumptions. This goal is relatively easy to achieve for the vector-invariant formulation of the equations of motion provided the thermodynamics assumptions are consistent, in the sense that all thermodynamic functions can be derived from a single thermodynamic potential, especially enthalpy. We illustrate how this program can be implemented with the dynamical cores DYNAMICO and PAM. In both cases, thermodynamics assumptions affect a small number of thermodynamics routines that form a mostly model-independent package, while the rest of the dynamical core is indifferent to those assumtions and to the choice of a specific prognostic variable. To exercise the dynamical cores, we also address the question of turning standard test cases, especially from the DCMIP suite, into thermodynamics-agnostic equivalents. We hope that this work invites a discussion on the prospects for more flexible models, possibly including community-driven components, and for future work, especially with respect to simple physical parameterisations.

16 Tracer advection tests using a non-interpolating semi-Lagrangian scheme with forward trajectories and cascade interpolation

Speaker: **Enomoto Takeshi**
Authors: Enomoto takeshi (1) (2), Okazaki kohei (3)
Institutions: 1 - Kyoto University (Disaster Prevention Research Institute, Kyoto University, Uji Japan), 2 - Japan Agency for Marine-Earth Science and Technology (Japan), 3 - Kyoto University (Japan)
Type: Poster

Semi-Lagrangian advection schemes are widely used in atmospheric general circulation models to allow longer time steps and to better represent frontal structures. Semi-Lagrangian schemes require interpolation to compute off-grid tracer values with the notable exception of the non-interpolating semi-Lagrangian (NISL) scheme. Despite small dissipation and dispersion errors the NISL scheme has limited adoption probably due to computational cost. NISL requires three time levels and interpolation of residual advection terms at the midpoint. We present modifications to NISL that reduce the computational cost and increase accuracy. Centred three time levels are replaced by forward two time levels. Forward trajectories are accordingly calculated as Taylor series truncated to the third order. One-dimensional cascade interpolation is adopted to compute the residual terms. The centred finite difference is used to compute derivatives to avoid spherical harmonic transforms. Two and three dimensional tests on the sphere are conducted to validate the forward-trajectory NISL (FNISL) scheme. The FNISL scheme exhibits a convergence, a 'minimal' resolution and mixing properties comparable to interpolating semi-Lagrangian scheme with spectral bicubic interpolation. The FNISL outperforms other interpolating and non-interpolating schemes in the advection of slotted cylinders and in computational cost. These tests show that FNISL is a practical alternative approach to advection in two and three dimensions.

17 Data-driven spectral stochastic modeling for ideal hydrodynamics

Speaker: **Ephrati Sagy**
Authors: Ephrati sagy (1), Luesink erwin (1), Franken arnout (1), Cifani paolo (1), Geurts bernard (1) (2)
Institutions: 1 - University of Twente (Netherlands), 2 - Eindhoven University of Technology (Netherlands)
Type: Oral

A characteristic feature of two-dimensional ideal hydrodynamics is the formation of both large vorticity structures through the inverse energy cascade and small-scale vorticity filaments through the enstrophy cascade. The large-scale features dominate the qualitative dynamics of the flow, which can be captured using coarse, computationally inexpensive grids. The small-scale dynamics is expensive to compute and has been subject of explicit modeling approaches that enable accurate simulation on coarse grids. Additionally, the use of coarse grids introduces inaccuracies in the numerical solution. A promising way to compensate for these inaccuracies is by means of data-driven forcing. We will present a general methodology that allows computing an online stochastic forcing term for coarse-grid numerical simulations, based on measurements obtained from an offline fine-grid reference simulation. The forcing is designed to reproduce the kinetic energy spectrum of the reference solution in the coarse numerical simulations, up to the smallest resolvable spatial scales. Previous results have shown that this method produces qualitatively accurate large-scale dynamics for the two-dimensional Euler equations on the sphere. Additionally, it is stable by design and computationally cheap, making it a suitable surrogate for long-time simulations. In this work, we will present the results of coarse-grid simulations of quasi-geostrophic flow, where we demonstrate the capability of the model to reproduce zonal vorticity structures.

18 A Comparison of Spectral Deferred Correction, Multistep and Runge-Kutta Methods for the Rotating Shallow Water Equations

Speaker: **Fregin Joscha**
Authors: Fregin joscha (1), Lunet thibaut (1), Ruprecht daniel (1), Götschel sebastian (1)
Institutions: 1 - Hamburg University of Technology, Institute of Mathematics, Chair Computational Mathematics, 21073 Hamburg (Germany)
Type: Oral

Atmospheric motion covers a broad range of time- and spatial scales. Low and high pressure systems can influence us for days or even weeks and they extend up to hundreds of kilometers. In contrast, sound waves pass by in seconds with wavelengths of centimers to meters. Implicit-explicit (IMEX) time stepping methods can help to avoid drastic limitations on the time step induced by the variety of scales without requiring computationally expensive fully nonlinear implicit solves. In our talk, we compare IMEX- Spectral Deferred Correction (SDC), multistep and Runge-Kutta time integrators for the Galewsky test case using the Python spectral method framework Dedalus. We demonstrate that SDC methods have superior stability properties and can provide shorter time to solution for comparable errors. In addition, we outline strategies that could further reduce simulation times by using the SDC residual to minimise the computational effort and by parallelising SDC "across the method".

19 Upstream biased momentum advection on a Voronoi C-staggered mesh

Speaker: **Gassmann Almut**
Authors: Gassmann almut (1)
Institutions: 1 - no affiliation (Germany)
Type: Oral

Voronoi C-staggered meshes are attractive for ocean and atmospheric modeling. Then, the momentum advection is given in vector invariant form. The TRiSK energy conserving scheme is usally the method of choice. But, this scheme cannot be cast in advection form. Gassmann (2018) demonstrated that, when using the same vector reconstruction as TRiSK, but different usages of the vorticities, an approximate second order advection formulation of momentum advection can be given. Based on this ground, this talk aims at three goals: (1) It demonstrates that the remaining non-cancellation terms between the vector-invariant and the advection form have different character than those known to give raise to the Hollingsworth instability on quadrilateral grids. Especially they do not give raise to stationary non-isotropic modes. Those terms rather represent a kind of very slowly traveling isotropic waves. Thus, the classical Hollingsworth instability does not occur on such meshes. (2) Based on the higher order advection scheme for scalars of Skamarock and Gassmann (2011), a similar scheme is developed for momentum advection. The upstream biased third order version mitigates numerical dispersion errors effectively. As a consequence, the spurious excitation of gravity waves is largely reduced near fronts. This is of importance when studying natural and artificial mechanisms of gravity wave excitation. This is discussed in the context of the baroclinic wave test. (3) A new tangential wind vector reconstruction is discussed, which employs a purely geometric view on the problem, rather than a view which puts the consistency with the vorticity equation in the center. Thus, a given constant vector field is correctly reconstructed on a deformed mesh. This feature was found to be important in previous studied by Peixoto. The new reconstruction coincides with TRiSK in the limit of an equilateral mesh.

20 Moisture with Gusto: test cases in moist shallow water models using the Gusto dynamical core toolkit

Speaker: **Hartney Nell**
Authors: Hartney nell (1), Shipton jemma (1), Bendall thomas (2)
Institutions: 1 - University of Exeter (United Kingdom), 2 - Met Office (United Kingdom)
Type: Oral

The rotating shallow water equations are widely used in the development of weather and climate models. Being a simpler equation set than the full 3D atmospheric equations they are computationally cheap, but they still retain many pertinent features of atmospheric dynamics. The usual shallow water equations model a 'dry' atmosphere and so neglect moist processes and moisture effects. Including moisture in the shallow water system not only extends the modelling potential of the equations, but also introduces numerical complexities that are of interest in the development of time-stepping schemes. These include features such as new timescales related to moist physics processes, and discontinuities introduced by the notion of boundaries between 'precipitating' and 'non-precipitating' regions. In this way the moist shallow water equations provide a simplified equation set for exploring physics-dynamics coupling

and how this coupling is handled by different time steppers. This talk will discuss the implementation of moist shallow water models in the dynamical core toolkit Gusto, which follows the same compatible finite element approach being taken in the next-generation UK Met Office model. We will highlight the advantages Gusto offers for rapid prototyping and flexible implementation of different moist shallow water models and describe progress towards running moist shallow water tests cases (both from the literature and newly-devised for this purpose) in Gusto.

21 Test Results from the Deep-atmosphere Configuration of the HOMME Dynamical Core

Speaker: **Hughes Owen**
Authors: Hughes owen (1), Jablonowski christiane (2), Taylor mark A. (3), Guba oksana (3)
Institutions: 1 - Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor (United States), 2 - Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor (United States), 3 - Sandia National Laboratories (United States)
Type: Oral

The Higher Order Methods Modeling Environment (HOMME) dynamical core simulates atmospheric fluid flow using the non-hydrostatic shallow-atmosphere Euler equations. We introduce a new method for augmenting this dynamical core with a configuration that solves the deep-atmosphere Euler equations. The horizontal spectral finite element discretization and Lorenz-staggered vertical discretization in shallow-atmosphere HOMME are designed to obey discrete analogues of continuous conservation identities. Our method for treating the deep atmosphere equations in HOMME ensures that these identities are still satisfied with respect to the shallow-atmosphere differential operators. Modifications are made to the specific form of the prognostic equations and the prognostic variables. We present results from idealized test cases. They demonstrate that desirable conservation properties are preserved in the deep-atmosphere configuration.

22 Causes and Effects of Dissipation in Dynamical Cores

Speaker: **Jablonowski Christiane**
Authors: Jablonowski christiane (1), Hughes owen K. (1), Limon garrett C. (1)
Institutions: 1 - University of Michigan (United States)
Type: Oral

All dynamical cores of atmospheric General Circulation Models need dissipation processes to avoid an accumulation of energy at the grid scale and enable numerically stable integrations. In addition, dissipation processes are needed in the upper-level sponge layer to slow down the wind speeds and dampen wave reflections near the model top. These dissipation processes come in many forms and are typically hand-tuned in each dynamical core. Often, the lost energy is even returned via local dissipative heating processes or global energy fixers. The talk uses examples from various dynamical cores to shed light on the causes and effects of selected dissipative processes. The selected models include the Spectral Element (SE) dynamical core used at the Department of Energy (DoE) and the National Center for Atmospheric Research (NCAR) as well as the NOAA cubed-sphere finite volume model FV3. A portfolio of dry and moist idealized test cases is used to illustrate the impacts of the dissipation. It is shown that the dissipation can even act as a moisture transport mechanism and impacts the precipitation efficiency, thereby mimicking the effects of physics parameterizations. In addition, and as an aside, the pros and cons of machine learning techniques for physical parameterizations are briefly characterized which provides pointers for future model designs.

23 Finite-Volume Transport in GungHo

Speaker: **Kent James**
Authors: Kent james (1)
Institutions: 1 - United Kingdom Met Office [Exeter] (United Kingdom)
Type: Oral

GungHo is the dynamical core of the Met Office's next generation weather and climate model, called LFRic. The aim of GungHo is to maintain the accuracy, stability and mimetic properties of the existing Met Office model while improving the conservation properties and the scalability. It uses a mixed finite-element spatial discretization, an iterated semi-implicit time stepping scheme, and the cubed sphere grid. Finite-volume methods are used for transport within GungHo to ensure conservation of mass. The method-of-lines approach separates the spatial and temporal transport components, using a finite-volume spatial reconstruction with a strong stability preserving Runge-Kutta time stepping scheme. This presentation details the modifications made to the method-of-lines scheme to improve the accuracy and efficiency of the transport in GungHo. This includes: horizontal-vertical dimensional splitting, the use of limiters, conservative semi-Lagrangian vertical transport, and an efficient semi-implicit transport update. Results will be presented from standard transport test-suites, along with results from the LFRic atmospheric model, to demonstrate the improvements to the method-of-lines transport scheme in GungHo.

24 Coupling simple dry physics to a dynamically adaptive global atmosphere model

Speaker: **Kevlahan Nicholas**
Authors: Kevlahan nicholas (1), Dubos thomas, Ching-Johnson gabrielle (1)
Institutions: 1 - Department of Mathematics and Statistics, McMaster University (Canada)
Type: Oral

Adaptive global circulation models (GCMs) have the potential to significantly improve the computational efficiency and accuracy of climate simulations by dynamically adjusting the local grid resolution to ensure a specified numerical tolerance or to track features of interest. We have developed the global dynamical cores WAVETRISK-ATMOSPHERE and WAVETRISK-OCEAN to explore the strengths and weaknesses of dynamical GCMs. The main open challenge of adaptive climate modelling is how to appropriately couple the dynamical core to the physics. The physics should ideally be "scale-aware": adjusting the parameterization as necessary based on the current local resolution (or disabling it entirely if the physical phenomenon becomes fully resolved). A related question is whether the grid adaptation criteria should be based on the physics as well as the dynamics. Such scale-aware physics parameterizations remain poorly understood. In this talk we report on initial progress in coupling WAVETRISK-ATMOSPHERE to Hourdin's (1992) "simple dry physics". A better understanding of scale-aware physics will also improve non-adaptive climate modelling, since such models currently require extensive tuning each time the resolution is increased. An additional goal of this project is to develop a set of test cases for the simple physics that could be used to compare dynamical cores using a well-understood and standardized physics package. This is joint work with Gabrielle Ching-Johnson (MSc student, McMaster University, Canada) and Thomas Dubos (LMD, École Polytechnique, France)

25 CGDycore - A continuous spectral element dynamical core in Julia

Speaker: **Knoth Oswald**
Authors: Knoth oswald (1)
Institutions: 1 - Leibniz Institute for Tropospheric Research (D-04318 Leipzig, Permoserstraße 15 04318 Leipzig Germany)
Type: Oral

I will present a dynamical core written in Julia on arbitrary conforming quad grids on the sphere or a cartesian plane. The grid is then extruded in the vertical direction. The standard implementation uses continuous spectral elements in the horizontal and differencing in the vertical with a staggered arrangement of variables. The code includes different time stepping schemes, special limiters for positive tracer transport and rudimentary microphysics. Also you can choose between different type of thermodynamic variables. The second part of the talk is devoted to the construction of conforming adaptive quad grids. Finally we will present numerical results for two standard test cases, the baroclinic wave test case and the Held-Suarez example in the dry and moist setup.

26 Compatible finite elements for terrain following meshes

Speaker: **Kowalczyk Karina**
Authors: Kowalczyk karina (1)
Institutions: 1 - Imperial College London (United Kingdom)
Type: Poster

We are presenting a new approach for compatible finite element discretisations for atmospheric flows on a terrain following mesh. In classical compatible finite element discretisations, the H(div)-velocity space involves the application of Piola transforms when mapping from a reference element to the physical element in order to guarantee normal continuity. In the case of a terrain following mesh, this causes an undesired coupling of the horizontal and vertical velocity components. We are proposing a new, Piola-map free finite element space for the velocity. In order to solve the equations of interest, we introduce a hybridisable formulation with trace variables supported on horizontal cell faces in order to enforce the normal continuity of the velocity in the solution. Alongside the discrete formulation for various fluid equations we discuss solver approaches that are compatible with them and present our latest numerical and analytical results.

27 Entropy and energy conservation for thermal atmospheric dynamics using mixed compatible finite elements

Speaker: **Lee David**
Authors: Ricardo kieran (1), Lee david (2), Duru kenneth (1)
Institutions: 1 - Australian National University (Australia), 2 - Bureau of Meteorology (Australia)
Type: Oral

Atmospheric systems incorporating thermal dynamics must be stable with respect to both energy and entropy. While energy conservation can be enforced via the preservation of the skew-symmetric structure of the Hamiltonian form of the equations of motion, entropy conservation is typically derived as an additional invariant of the Hamiltonian system, and satisfied via the exact preservation of the chain rule. This is particularly challenging since the function spaces used to represent the thermodynamic variables are typically discontinuous at element boundaries, and so their derivatives are not defined. In the present work we negate this problem by constructing our equations of motion via weighted averages of Hamiltonian formulations using both flux form and material form advection of thermodynamic variables, which allow for the necessary cancellations required to conserve entropy without the chain rule. We show that such formulations allow for the stable simulation of both the thermal shallow water equations and the 3D compressible Euler equations on the sphere using mixed compatible finite elements without any entropy damping.

28 A well-balanced multi-moment constrained finite volume method for nonhydrostatic atmospheric flow

Speaker: **Li Xingliang**
Authors: Li xingliang (1), Zhang yinzheng (1), Chen chungang (2), Shen xueshun (1), Xiao feng (3)
Institutions: 1 - CMA Earth System Modeling and Predication Center (China), 2 - Xi'an Jiaotong University (China), 3 - Tokyo Institute of Technology (Japan)
Type: Oral

A well-balanced multi-moment constrained finite volume method (MCV) for nonhydrostatic atmospheric flow is presented in this talk. The compressible Euler equations with gravitational force can govern the dynamics of local atmospheric flow if the Coriolis force is neglected. Improper handling of the gravitational force can lead to a solution which either oscillates around the equilibrium, or deviates from the equilibrium after a long integration. A 3rd order well-balanced MCV method for nonhydrostatic atmospheric flow is designed, which can keep the exact hydrostatic balance at rest and maintain the high order accuracy. One-dimensional testcases have verified that the well-balanced MCV method can achieve the numerical errors of the hydrostatic reference state up to machine round off errors. The resulting well-balanced MCV nonhydrostatic model has been verified by widely used standard benchmark tests and is competitive to the existing ones.

29 Structure-preserving numerical methods for quasi-geostrophy on the sphere

Speaker: **Luesink Erwin**
Authors: Franken arnout (1), Luesink erwin (1), Ephrati sagy (1), Cifani paolo (1), Geurts bernard (1) (2)
Institutions: 1 - University of Twente (Netherlands), 2 - Eindhoven University of Technology (Netherlands)
Type: Oral

Recent numerical developments have enabled discretisations of incompressible fluids on the sphere that preserve the energy and enstrophy, as well as all other Casimir invariants associated with such flows. Previous work has shown that preserving structure is beneficial in showing the double cascade mechanism in the kinetic energy spectrum for the Navier-Stokes equations on the sphere. In this presentation we focus on quasi-geostrophic equations on the sphere with full nonlinear Coriolis parameter. Quasi-geostrophy on the sphere with nonlinear Coriolis parameter enjoys a Hamiltonian formulation. We show that these equations can be simulated at high resolution with efficient isospectral Lie-Poisson methods. Numerical results will be demonstrated comparing the rotating Euler equations and the quasi-geostrophic equations, showing qualitative features such as strong zonal jet formation that becomes weaker towards the poles for quasi-geostrophy. Moreover, this approach permits easy extensions towards the multilayer setting.

30 Novel grid capabilities in GFDL's dynamical core FV3

Speaker: **Mouallem Joseph**
Authors: Mouallem joseph (1) (2), Harris lucas (2), Benson rusty (2)
Institutions: 1 - Atmospheric and Oceanic Sciences Program, Princeton University (United States), 2 - NOAA Geophysical Fluid Dynamics Laboratory (United States)
Type: Oral

We present the latest grid-related capabilities implemented in Geophysical Fluid Dynamics Laboratory (GFDL)'s Finite-Volume Cubed-Sphere Dynamical Core (FV3): multiple nested grids and the Duo-Grid. First, two-way multiple same-level and telescoping grid nesting allows simulating various independent weather events in greater detail by resolving smaller-scale flow structures. Nested grids run concurrently on different sets of processors to optimize the overall computational performance. Second, a Duo-Grid system is implemented to reduce cubed-sphere grid imprinting in FV3. The Duo-Grid algorithm consists of remapping a tile's halo data from neighboring tiles from kinked to natural locations along great circle lines. Results from idealized test cases show that error norms are greatly reduced and grid imprinting is practically eliminated in the numerical solutions. This comes at the expense of an increase in computational cost.

31 Baroclinic instability tests using a global primitive equation model based on radial basis functions generated finite difference discretizations

Speaker: **Ogasawara Koji**
Authors: Ogasawara koji (1), Enomoto takeshi (1) (2)
Institutions: 1 - Kyoto University (Japan), 2 - Japan Agency for Marine-Earth Science and Technology (Japan)
Type: Poster

Radial basis function (RBF) methods can achieve high order convergence without any grid or mesh. RBF-generated finite difference (RBF-FD) methods have been developed for large scale problems and applied to shallow water equation models. In this study, the RBF-FD approach is applied to the horizontal discretization of a primitive equation model on maximum determinant or icosahedral nodes. The number of nodes is up to 163842 and the number of levels is fixed to 20. The vertical discretization adopts a finite difference scheme that conserves energy and potential temperature. Our dynamical core is validated in baroclinic instability tests and is compared against a counterpart using spherical harmonics. The reference solution with triangular truncation at 341 is interpolated from the Gaussian grid to the RBF-FD nodes using spectral bicubic interpolation. The global l2 and l-infinity norms of vorticity indicate that the RBF-FD model converges to the reference solution and is competitive with the spectral transform model.

32 An IMEX-DG solver for atmospheric dynamics based on deal.II framework

Speaker: **Orlando Giuseppe**
Authors: Orlando giuseppe (1), Benacchio tommaso (2), Bonaventura luca (1)
Institutions: 1 - MOX, Dipartimento di Matematica, Politecnico di Milano (Italy), 2 - Danish Meteorological Institute (Denmark)
Type: Oral

In this talk, we propose an efficient and accurate compressible flow solver for atmospheric dynamics simulations that allows for Adaptive Mesh Refinement (AMR). The model equations considered are the classical Euler equations in conservation form. The method is based on an h-adaptive Discontinuous Galerkin spatial discretization and on a second order Additive Runge Kutta IMplicit EXplicit (ARK-IMEX) numerical approach for time discretization. The scheme has been implemented in the framework of the deal.II library and AMR is employed to enhance efficiency and to increase resolution in the regions of interest. Reasonably good strong scaling is obtained, showing that no relevant scaling problems are induced by h-adaptivity as compared to unrefined grids. The choice of an open-source environment allows us to enhance the portability and to embed the code into a the continuously updated framework. The proposed solver constitutes therefore a starting point for the development of a proper dynamical core within a publicly available finite element environment. A number of numerical experiments based on classical benchmarks for atmosphere dynamics without and with orography demonstrate the properties and advantages of the proposed method. Ongoing work for the extension of the proposed techniques to spherical geometry for global atmospheric dynamics will be also discussed.

33 Wind driven transport at the ocean surface on a sphere

Speaker: **Paldor Nathan**
Authors: Paldor nathan (1)
Institutions: 1 - Fredy and Nadine Herrmann Institute of Earth Sciences, The Hebrew University of Jerusalem (Edmond J. Safra Campus Givat Ram, Jerusalem Israel)
Type: Oral

The fundamental oceanographic theory of wind driven transport was developed in 1905 by V. W Ekman on the f-plane i.e. in Cartesian coordinates and for constant Coriolis frequency, f. The theory provides explicit expressions for the trajectory of a water column below the ocean's surface forced by the overlying wind stress. In the nearly 120 years that elapsed from the publication of the theory it was not extended to more realistic setup where i.e. either to a plane with variable f or to spherical coordinates. My talk will focus on extensions of Ekman's theory both to the b-plane and to the sphere based on tools adapted from the theory of Dynamical Systems. The theoretical advances are achieved by: 1) Substituting the angular momentum (or pseudo angular momentum in the case of the beta-plane). 2) Filtering out the inertial oscillations using the adiabaticity paradigm. The results of the extensions show that while some aspects of the dynamics can be anticipated by varying the value of f in Ekman's simple solutions, other aspects cannot. In particular, for zonally directed wind stress the original, f-plane, theory does not provide any information on the zonal component of the water column trajectory. The results have important implications for the wind stress dynamics in simulations by Eulerian numerical methods on a sphere and can applied to wind forced trajectories on the continental shelf where the stretching vorticity associated with the sloping bottom plays the role of planetary vorticity changes on the sphere and beta-plane.

34 Rossby wave nonlinear interactions and the generation of low-frequency atmospheric oscillations

Speaker: **Peixoto Pedro**
Authors: Raphaldini breno (1), Peixoto pedro (2), Teruya andré (2), Raupp carlos (2), Bustamante miguel (3)
Institutions: 1 - National Center for Atmospheric Research [Boulder] (United States), 2 - Universidade de São Paulo = University of São Paulo (Brazil), 3 - University College Dublin [Dublin] (Ireland)
Type: Oral

The dynamics of the Earth's atmosphere is characterized by a wide spectrum of oscillations, ranging from hourly to interdecadal and beyond. The low-frequency component of the atmospheric variability cannot be understood solely in terms of linear atmospheric waves that have shorter timescales. Here, we discuss the role of a recently proposed nonlinear precession resonance, and the alignment of dynamical phases, in the generation of low-frequency oscillations and the redistribution of energy/enstrophy in the spectral space using the barotropic vorticity equation. The results suggest that the organization of the dynamical phases plays a key role in the redistribution of energy in the spectral space, as well as the generation of low frequencies in the barotropic vorticity equation.

35 Development of a Global-regional-unified Model for the Atmosphere on the Yin-Yang Grid

Speaker: **Peng Xindong**
Authors: Peng xindong (1), Chen siyuan (2), Zhao yifan (2), Li xiaohan (2)
Institutions: 1 - CMA Earth System Modelling and Prediction Centre (China), 2 - Chinese Academy of Meteorological Sciences (China)
Type: Oral

A global-reginal-unified atmospheric model, the Yin-Yang-grid Unified Model for the Atmosphere (YUNMA), is developed on the quasi-uniform Yin-Yang grid for flexible weather simulation using a semi-implicit semi-Lagrangian solver, which aims to reconstruct a unified core for global and limited-area selections in GRAPES model at CMA. Arbitrary coordinate rotation and multi-level nesting are entrusted to the model for easy configuration and mesh refinement. Several idealized numerical benchmarks have been tested with global or regional configuration with or without nesting grid on sphere. An average convergence rate of the dynamical core is 2.43 in the balanced flow test, and rotation of the Yin-Yang grid makes the selection of computational domain convenient even though generally dose no matter on numerical results, as shown in the balanced flow test and the terminator chemical reaction test. Coordinate rotation makes the present dynamical core suitable for polar region application. Local refinement and limited-area high-resolution simulation improves the numerical results in the baroclinic wave test, and achieved similar development of baroclinic waves as in the global high-resolution run with significantly low cost. Transport of vortices in the colliding

modons test shows unique features in comparison with existing simulations. Travel distance and vorticity amplitude vary with model resolution and time step explicitly in the global model, which is consistent with published results. In a nested model, however, the vortex enhances just the same as in the global high-resolution model, but travels a distance the same as in the low-resolution global (parent) model, which illustrates the impact of lateral boundary condition on the modons propagation. The development of topographic gravity wave and topographic Rossby wave is shown quite well in the YUNMA dynamic core with different coefficients in the implicit algorithm.

36 Derivation and calibration of consistent Eddy-Diffusivity Mass-Flux parameterizations for ocean models

Speaker: **Perrot Manolis**
Authors: Perrot manolis (1), Lemarie florian (1)
Institutions: 1 - Laboratoire Jean Kuntzmann (France)
Type: Oral

The mass-flux (MF) concept itself, then combined with an Eddy-Diffusivity (ED) approach, has been extensively studied and used in global and regional atmospheric models to parameterize dry and cloudy convection at various scales. The EDMF closure relies on a decomposition of vertical turbulent fluxes into a diffusion term - accounting for local small-scale mixing in a near isotropic environment - and a mass-flux transport term - accounting for the non-local effects of vertically coherent structures (called plumes) embedded into the environment. In this talk we examine how and why such an approach can be adapted to parameterize the mixing phase of oceanic deep convection. First we will recall how to derive EDMF schemes from a conditional averaging of the reference fluid equations, with special attention on assumptions leading to EDMF schemes. The validity of these assumptions will be discussed with respect to oceanic Large Eddy Simulations (LES). The derivation of the MF formulation from a multi-fluid perspective allows to lucidly interpret terms of the parameterization and keep track of energy exchanges between resolved and unresolved part of the flow which is not feasible with the usual schemes used in the ocean to take non-local effects into account (e.g. within the K-Profile Parameterization; KPP). An other advantage of the mass flux approach, which to our knowledge has not yet been exploited, is the possibility to consistently account for the tilting of convective plumes due to nontraditional Coriolis terms and its effect on the mean circulation (oceanic LES simulations have already illustrated that this effect can be substantial). Finally, the proposed EDMF formulation requires the determination of free parameters to close the system. We show a novel method to estimate the probability distribution of these parameters against LES data.

37 An iterative Method for the elliptic equation in the GEM Model

Speaker: **Qaddouri Abdessamad**
Authors: Qaddouri abdessamad (1), Aider rabah (2)
Institutions: 1 - Environement Canada (2121, route Transcanadienne, Dorval, Quebec, H9P1J3, Canada Canada), 2 - Environement Canada (Canada)
Type: Oral

The dynamical core of GEM model in operation at the Canadian Meteorological Center uses an implicit semi-Lagrangian time discretization method on a global Yin-Yang and a limited area spatial grid. Therefore, we must solve in an efficient way, a tri-dimensional elliptic equation four times at each time step. Two different elliptic solvers are developed and implemented in the GEM model: a parallel direct solver currently used in operations, and a parallel iterative elliptic solver. Matrices inversion in the direct solver involves the Fast Fourier Transform (FFT) and the numerical solution of a series of independent uni-dimensional boundary value problems. The parallel implementation of the direct solver requires data transpositions, i.e. global redistribution of data between processes that necessitates global communications resulting in scalability deterioration, as the number of processor cores becomes large.This makes the direct solver less suitable for future generations of massively parallel supercomputers and thus underlines the importance of developing a performant alternative solver. Our Iterative solver is based on the flexible generalized minimal residual (FGMRES). Among the different preconditioners tested, the one based on the Restricted Additive Schwarz (RAS) method proved to be the one that improved the scalability and efficiency of the FGMRES algorithm the most. Furthermore, with the RAS preconditioner the iterative solver outperforms the direct solver for high rank problems. In this presentation, we discuss the direct and iterative solvers, and report comparisons of the efficiency and the scalability of the dynamical core of GEM model using the two kinds of the elliptic equation solvers.

38 Coordinate independent formulation of the NEPTUNE global atmospheric model

Speaker: **Reinecke Alex**
Authors: Reinecke alex (1), Nair ramachandran
Institutions: 1 - Naval Research Laboratory (Monterey, CA United States)
Type: Oral

Over the last decade the Naval Research Laboratory has developed a new global numerical weather prediction model based on an Earth-centric three dimensional Cartesian coordinate system in order to solve a compressible form of the Navier-Stokes equations. Although the three-dimensional Cartesian formulation provides a robust and simplistic framework for solving these equations, it does not lend itself to implementing efficient time-integration methods based on dimensional-split approaches, such as Horizontally Explicit, Vertically Implicit (HEVI) methods. This is due to the fact that the Jacobian associated with the spatial discretization of the three-dimensional Cartesian coordinate system is not separable into a horizontal and vertical component. However, casting the three-dimensional equations momentum equations in the vector-invariant form sets the stage for using various geometries, such as the cubed sphere or other horizontally non-orthogonal curvilinear coordinates. The vector-invariant form corresponds to the covariant form of the momentum equations in a general curvilinear geometry and are free from explicit metric terms, such as the Chrisoffel symbols. The three-dimensional spherical domain is split into a two-dimensional horizontal component that follows the cubed-sphere topology and a one-dimensional radial component. This dimension split approach facilitates efficient implementation of HEVI time-integration schemes. The new formulation will be presented along with a series of hierarchical numerical simulations comparing the three-dimensional Cartesian geometry against the new formulation.

39 New Version of the GRAPES_GFS Dynamic Core Based on the Predictor–Corrector Time Integration Scheme

Speaker: **Su Yong**
Authors: Su yong (1), Shen xueshun (1), Zhang hongliang (1)
Institutions: 1 - China Meteorological Administration (China)
Type: Oral

The operational Numerical Weather Prediction (NWP) systems established by China Meteorological Administration (CMA) based on the Global/Regional Assimilation and Prediction System (GRAPES) model adopts the classical Semi-Implicit Semi-Lagrangian (SISL) time integration algorithm. This paper describes a major upgrade to the dynamic core of the global forecast system GRAPES_GFS (Global Forecast System), which was successfully incorporated into operation in 2020. In the upgrade, the classical SISL is further developed into a predictor-corrector scheme, a 3D (3-dimensional) reference profile is applied when implementing the SI algorithm instead of the original isothermal reference profile, a hybrid terrain-following vertical coordinate and a mass conservation correction scheme are also applied. The new version of the dynamic core greatly improves the model performance, the time integration reaches second order accuracy, the time step can be extended 50% larger, and the efficiency is greatly improved by about 30%. Simulation of the atmospheric circulation is systematically improved, and deviations for temperature, wind, humidity are reduced. The new version of the dynamic core provides a solid foundation for further development of the entire CMA operational systems.

40 Algorithmic and code improvements in the SL-AV global atmosphere model

Speaker: **Tolstykh Mikhail**
Authors: Tolstykh mikhail (1) (2), Shashkin vladimir (3), Goyman gordey (3), Fadeev rostislav (3), Biryucheva ekaterina (2)
Institutions: 1 - Marchuk Institute of Numerical Mathematics, RAS (Russia), 2 - Hydrometcentre of Russia (Russia), 3 - Marchuk Institute of Numerical Mathematics, RAS (Russia)
Type: Oral

The recent works on improving the efficiency of SL-AV global atmosphere model used for medium-range and long-range numerical weather prediction are described. The algorithmic improvements of SL-AV dynamical core are presented. The implementation of parallel I/O, code optimizations and single precision implementation are briefly overviewed. The reduced lat-lon grid is now implemented in the 3D SL-AV dynamical core. The results for some

tests with the reduced grid are shown. The algorithmic improvements have allowed to increase the time step of the model by a factor of 2.25 to 270 s for the version having about 10 km horizontal resolution and 104 vertical levels. All abovementioned optimizations have further reduced the elapsed time by a factor of 1.8. As a result, only 13 minutes are required to compute 24-hour forecast for the model version using 2916 processor cores of Cray XC40 system. The partial utilization of single precision computations in dynamics and some parts of parameterizations produces approximately the same model climate as the version with fully double precision computations. The study is supported with RSF grant No 21-71-30023.

41 Data driven stochastic primitive equations with dynamic modes decomposition

Speaker: **Tucciarone Francesco**
Authors: Tucciarone francesco (1), Mémin Étienne (1), Li long (1)
Institutions: 1 - Inria Rennes – Bretagne Atlantique (France)
Type: Poster

Despite the growth of computational power in the last years, the full resolution of planetary flows is beyond reach. Representation of the complex interdependence of mesoscale and sub-mesoscale dynamics is often done through parameterization of the scales smaller than the grid resolution. The correct representation of oceanic features is crucial for climate models, however there is no agreed-upon procedure to choose the parameterization. This work investigates the benefits of a stochastic decomposition of the Lagrangian trajectory into a smooth-in-time large scale velocity and a random fast-evolving uncorrelated part, ideally accounting for mesoscale and submesoscale processes. This approach, named Location Uncertainty (LU), is built upon a stochastic version of the Reynolds Transport Theorem allowing us to cast the classical physical conservation laws into this scale-separated framework. This framework has been proven to be successful in several large-scale models for ocean dynamics. The stochastic hydrostatic primitive equations has been derived through physical reasoning and classical scaling. More recently, the same equations were re-derived by means of rigorous stochastic calculus as a particularization of the general compressible Navier-Stokes equations. The first experiments were conducted adopting an Empirical Orthogonal Function (EOF) method to define the spatial correlation of the noise field. If on one hand, this approach was found to be beneficial to the dynamical variables of the model such as energy and vorticity, on the other it was driving excessive mixing in the tracer component. A novel approach, based on Dynamical Mode Decomposition (DMD), combined with an isopycnal constraint on the noise, is shown to enhance the large scale representation while not driving any spurious mixing. Both of these previous studies rely on High Resolution data to be treated offline. Novel solutions not relying on offline data but on the current state of the simulations are being performed.

42 Energy-Conserving Time Integration in a Cloud-Resolving Atmospheric Model

Speaker: **Waruszewski Maciej**
Authors: Waruszewski maciej (1), Eldred christopher (1), Norman matthew (2), Taylor mark (1)
Institutions: 1 - Sandia National Laboratories (United States), 2 - Oak Ridge National Laboratory (United States)
Type: Oral

Portable Atmospheric Model (PAM) is a new atmospheric model being developed for the superparametrized configuration of the Energy Exascale Earth System Model. In this configuration each global model column embeds a cloud-resolving model (CRM) to better represent moist convection. The CRM has to robustly and accurately handle a wide range of atmospheric convective motions, from shallow convection to severe storms. Efficiency of the CRM on modern computing architectures is paramount, as it is usually the dominant cost of the global model.

The C-grid dynamical core of PAM is designed to solve multi-species compressible and anelastic Euler equations using structure-preserving numerical methods. Specifically, it combines a quasi-Hamiltonian formulation with mimetic discrete exterior calculus operators to create a semi-discretization that is stable, energy-conserving, and has good wave propagation properties. The dynamical core is formulated on a structured grid, which enables construction of higher-order Hodge stars with improved accuracy. To capture sharp gradients, the model incorporates high-order WENO reconstructions and optional FCT limiting, carefully done in a way that maintains energetic consistency.

The choice of time integration scheme is crucial for the CRM efficiency. To avoid a stringent CFL condition based on physically insignificant acoustic waves, PAM considers either semi-implicit time integration of the fully compressible equations, or the use of anelastic approximation that filters sound waves. Energy-conserving time integration is achieved through the use of Poisson integrators. However, the model also implements more standard methods, such as explicit SSPRK schemes for the anelastic equations. After presenting an overview of PAM, this talk will focus on its time integration options. Validation of the large-time-step integrators with respect to explicit solution of the compressible equations will be presented. Lessons learned in efficient implementation of energy-conserving time steppers will be shared. Comparisons of energy-conserving time integrators with more standard approaches will be shown.

43 Implicit Time Stepping for Advection and Gravity Waves

Speaker: **Weller Hilary**
Authors: Weller hilary (1)
Institutions: 1 - University of Reading (The University of Reading, Whiteknights, PO Box 217, READING, Berkshire, RG6 6AH, United Kingdom United Kingdom)
Type: Oral

Implicit time stepping for advection is not popular in atmospheric science because of the cost of the global matrix solution and the phase errors for large Courant numbers. However, implicit advection is simple to implement, conservative on any grid structure and can exploit improvements in solver efficiency and parallelisation. I will describe an implicit version of the MPDATA advection scheme and show that it is accurate for low Courant numbers, stable for very large Courant numbers and locally high Courant numbers (such as occur over the poles of a latitude-longitude grid) do not harm the accuracy.

Implicit treatment of advection is particularly useful for the large Courant numbers associated with strong updrafts. This talk will also describe how implicit advection is used for advecting vertical velocity and how this interacts with the implicit treatment of gravity waves.