Geophysical Research Abstracts,
Vol. 10, EGU2008-A-09883, 2008
SRef-ID: 1607-7962/gra/EGU2008-A-09883
EGU General Assembly 2008

A massively parallel finite elements approach to the solution of the Navier-Stokes equations in mesoscale atmospheric dynamics for numerical weather prediction

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Within the framework of atmospheric dynamics in numerical weather prediction (NWP) models, a massively parallel algorithm for the numerical solution of the variational formulation of the Navier-Stokes equations based in the Finite Element Method (FEM) is presented. Only a limited amount of atmospheric models resolves the complete atmospheric equation of compressible viscous flows because of the limitations imposed in many respects; the difficult treatment of high-frequency oscillation of the pressure field is one of them, being these inherent in the solution. Moreover, the common use of explicit, split-explicit or semi-implicit time integration schemes is a major limitation that NWP models carry.

The problem of stratified, nonhydrostatic, low Mach number flows is of particular interest in mesoscale atmospheric dynamics. Hence, the use of different numerical schemes is proposed, all of them based in a FEM formulation, assessing one against each other. Incompressibility limit and thermal coupling is treated in different ways, ranging from a compressible formulation with low-Mach treatment up to incompressible one with a Boussinesq approximation. In the first case, fractional step strategies are used to cope with the low-Mach limit combined with a special diagonal preconditioner to speed-up convergence allowing larger CFL numbers. In the second one, either fractional or monolithic schemes are used depending on the case solved. In all cases variational sub-scale stabilization deal with the numerical stabilization of the NS equations.

The use of a non-Cartesian grid is one of the main features of a space FEM-based formulation. It can intrinsically incorporate the definition of the orography, avoiding the inefficient transformation into terrain-following coordinates in the vertical direction, as typical of most atmospheric codes. Furthermore, the ability for local grid refinement allows for better resolution of important physical features over a wide spectrum of spatial scales. Finally, the local nature inherent to these kinds of methods make the parallelization highly efficient. All the algorithms and schemes proposed here are programmed in the same multi-purpose in-house code, attaining more than 95% of scalability in all schemes (implicit and explicit) for up to 5000 processors either in Marenostrum supercomputer or a Blue Gene cluster. Parallelization is based in mesh partition techniques and MPI, specially well suited for both distributed or shared memory facilities.

The proposed schemes in their different forms have been (and are continually being) successfully evaluated. Both the accuracy and efficiency attained render them key tools for simulating 3D complex atmospheric flows without any additional hypothesis appart from the Navier-Stokes equations, which are difficult enough to load with supplementary approximations. In this work, the algorithms proposed are assessed through a range of classical benchmarks. Among them are the 2D density driven flow, a 3D larger example to show the performance in parallel and hydrostatic and nonhydrostatic mountain waves simulations with highly resolution-sensitives.