Preface

Approximating the solution to the partial differential equations for atmospheric flows using numerical algorithms implemented on a computer has been intensively researched since the pioneering work of Prof. John von Neuman in the late 1940s and 1950s. Since von Neuman's numerical experimentation on the first general purpose computer, the processing power of computers has increased at a breath-taking pace. While global models used for climate modeling a decade ago used horizontal grid spacings of order hundreds of kilometers, computing power now permits horizontal resolutions near the kilometer scale. Hence, the range of the scales of motion that next-generation global models will resolve spans from thousands of kilometers (planetary and synoptic scale) to the kilometer scale (meso-scale). Hence, the distinction between global climate models and global weather forecast models is starting to disappear due to the closing of the resolution gap that has historically existed between the two. For anyone interested in the dynamics of the weather and climate problem, this is a significant milestone since two branches of modeling, previously considered two separate disciplines, have started to merge.

Making effective use of massively parallel supercomputers, that are necessary for running global models at high resolution, has forced model developers back to the drawing board. Many current numerical methods are not scalable and therefore not amenable for massively parallel processing. This has forced the community to consider novel spherical grids (in the context of atmospheric global climate/weather modeling) where the grid-cell size is globally quasi-uniform in contrast to the highly nonuniform geographical longitude–latitude grid that has been the preferred choice for decades. The higher resolutions also affect which equation set is appropriate as a basis for the numerical discretizations. Model users now also expect the numerical method to preserve key integral invariants in discretized space, demand the accurate maintenance of balances in the flow, and request a truthful representation of waves on many scales as well as realistic scale interactions. Needless to say, the breadth of the choices of the computational grids and numerical schemes that should fulfill all these requirements is daunting, to say the least, and requires insight into the multi-scale nature of the problem and the properties of the chosen numerical methods.

The NCAR[1] ASP Colloquium 2008

To start tackling the significant challenges that lie ahead in global modeling, the Editors organized a colloquium on the latest developments in numerical methods for the dynamical cores of atmospheric General Circulation Models (GCMs). Dynamical cores are the central component of every climate and weather model. Loosely speaking, they solve the equations of motion on the resolved scales and determine not only the choice of the computational grid but also the predicted variables. Research in dynamical cores faces many scientific and computational challenges as was briefly outlined above.

On 1–13 June 2008, the colloquium entitled *Numerical Techniques for Global Atmospheric Models* was held at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. The colloquium was hosted by NCAR's Advanced Study Program (ASP) that hosts colloquia on an annual basis. The colloquium had two main objectives.

First, it introduced a multidisciplinary group of graduate students to the science of dynamical cores for global weather and climate models through lectures and hands-on tutorials. The chapters of this book are based on the lectures given at the colloquium by leaders in the field of numerical techniques for global atmospheric models. Second, the colloquium brought together the global modeling community by having the GCM modeling groups port their models to NCAR supercomputers, configure the models for idealized test cases defined by the colloquium organizers and to have the students exercise their models on these test cases during the colloquium. Nine international modeling groups accepted our invitation to participate in the colloquium, and each group had at least one modeling mentor present during the entire duration of the colloquium.

The modeling groups were as follows:

- Colorado State University (CSU) with the CSU-GCM
- Max Planck Institute for Meteorology (MPI-M) with the ICON (ICOsahedral Non-hydrostatic) model
- Goddard Institute for Space Studies (GISS) and Goddard Space Flight Center (GSFC) both part of National Aeronautics and Space Administration (NASA) with ModelE
- NCAR with the CAM (Community Atmosphere Model)
- NCAR and Sandia National Laboratories with the HOMME (High-Order Method Modeling Environment) model
- Massachusetts Institute of Technology (MIT) with the MIT-GCM
- Duke University, Earth System Science Interdisciplinary Center (ESSIC, University of Maryland) with the OLAM (Ocean-Land-Atmosphere Model)
- German Weather Service (DWD) with GME[2] (Global Model for Europe)

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

[2] Before the GME became operational, GME was an acronym for Global Model 'Ersatz' (which means 'replacement' in German) as the GME was a replacement for the spectral transform Global Model (GM).

- NASA GSFC joint with Geophysical Fluid Dynamics Laboratory (GFDL) run by National Oceanic and Atmospheric Administration (NOAA) with the GEOS5 (Goddard Earth Observing System model version 5)
- Joint Center for Earth Systems Technology (University of Maryland) with the GEF (Global Eta Framework) model

Some groups participated with several model versions.

A total of six test cases with several variants were used. Two of the test cases are described in Jablonowski and Williamson (2006, Quarterly Journal of the Royal Meteorological Society) and Lauritzen et al. (2010, Journal of Advances in Modeling Earth Systems), and the remaining four in Jablonowski et al. (submitted, Geoscientific Model Development). These papers also show results from the model simulations.

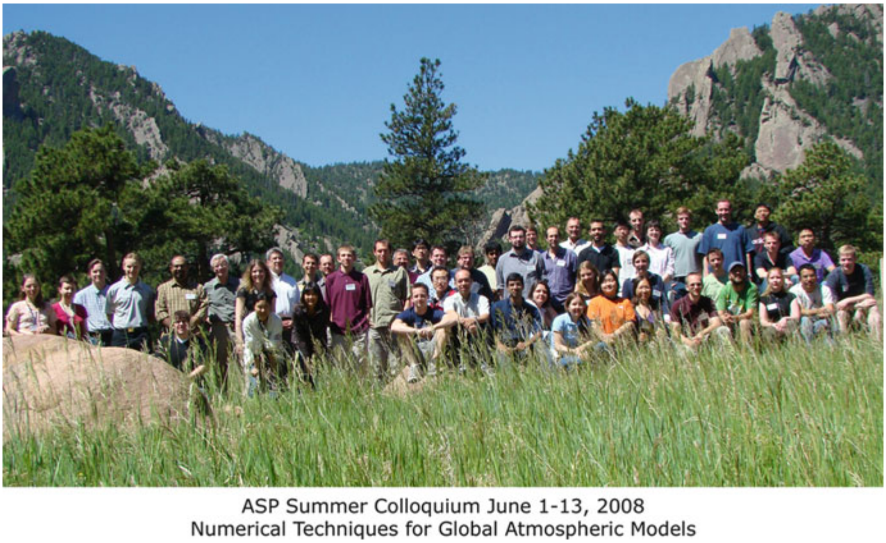

Fig. 1 NCAR ASP 2008 summer colloquium group picture behind NCAR's Mesa Laboratory. From left to right (in order of increasing x-coordinate if photo was overlaid by a Cartesian coordinate system): Svetlana Dubinkina, Oksana Guba, Mark A. Taylor, Peter Hjort Lauritzen, Ramachandran D. Nair, Paul Ullrich, Dale Durran, Christiane Jablonowski, Jin-Young Kim, Richard Rood, Jasper Kok, Jung-Eun Kim, Todd Ringler, Lucas Harris, Matthew Long, Detlev Majewski, Hajoon Song, Dustin Williams, Sean Crowell, Junsu Kim, Jairo Gomes, Jochen Förstner, Aneesh Subramanian, Atul Kapur, David Devlin, Willian Sawyer, Verica Savic-Jovcic, Alberto Casado, Angela Marie Zalucha, Robert Walko, Marcia DeLonge, Matthew Norman, Guan Song, Qiang Deng, Colm Clancy, Almut Gassmann, Lin Su, Priscilla Mooney, Lee Murray, Jared Pierce Whitehead, Joakim R. Nielsen, Benjamin Kravitz, Ole-Kristian Kvissel, Lantao Sun, Brian Sørensen, Ayoe Buus Hansen, Cheng Zhou, Prabhakar Shrestha, Allan Christensen. Photo courtesy of Kathleen Barney (ASP)

About This Book

The chapters in this book collectively address almost every step in the development of dynamical cores for global atmospheric models. The 16 chapters have been divided into three parts: (1) equations of motion and basic ideas on discretizations, (2) conservation laws and traditional finite-volume as well as emerging numerical methods, and (3) practical considerations for dynamical cores in weather and climate models.

In the first chapter, Prof. J. Thuburn gives an introduction to the equations of motion for the atmosphere and commonly applied assumptions that are used to render the equations numerically more tractable and/or understand the types of waves supported by the equations of motion. Also the multiscale nature of atmospheric dynamics is introduced. Dr. J. Tribbia continues the theoretical discussion on the three-dimensional equations of motion through a mode decomposition analysis. In Chaps. 3 and 4, we leave the continuous equations behind and start exploring the properties of some basic horizontal and vertical numerical discretizations, and discuss the consequences of colocating and staggering prognostic variables. Thereafter some basic ideas on time-discretizations are introduced in Chap. 5 followed by a discussion on how to control fast waves through appropriate time-differencing (Chap. 6). The latter two chapters were written by Prof. D. R. Durran and conclude part I of this book.

In part II, Dr. T. D. Ringler discusses in detail the finite-volume advection of momentum and its relationship with other kinematic relationships such as conservation of vorticity (Chap. 7). Momentum advection is a key to the overall accuracy of any dynamical core as it determines the transport of mass and tracers. Chapter 8 focuses on transport, in particular finite-volume transport schemes, and reviews them from a semi-Lagrangian perspective. It presents an in-depth discussion on desirable properties for transport operators intended for global atmospheric models (Dr. P. H. Lauritzen). While most global models today use the spectral transform method or the finite-volume method, emerging new algorithms that are local but posses spectral convergence properties are at the time of writing being tested and integrated into atmospheric models. Such methods are being reviewed in Chap. 9 by Dr. R. D. Nair. To conclude part II, Prof. L. Ju gives an introduction to Voronoi diagrams that may be used to construct global spherical meshes with very flexible options for variable resolution.

After the discussion of the continuous equations of motion and basic discretization techniques in part I and the discussion of some classes of numerical schemes and spherical meshes in part II, we turn our attention to the properties of the dynamical core that are considered important in global atmospheric models (part III). Prof. J. Thuburn discusses conservation issues in Chap. 11 followed by a discussion on how to enforce key integral invariants numerically on unstructured grids (Dr. M. A. Taylor's Chap. 12). Almost all models need some level of filtering or damping to render the computed solutions physically realizable and smooth. Although these are rarely documented in the literature, they are paramount in model applications. Prof. C. Jablonowski reviews the pros and cons of these diffusion mechanisms, filters, and fixers in Chap. 13 and provides many illustrating examples from GCM runs. Continuing the filtering discussion, Dr. W. C. Skamarock focuses on the kinetic energy spectra in atmospheric models and how the tail of such spectra is influenced by discretization techniques and filtering. In Chap. 15 Prof. R. B. Rood gives a perspective on the dynamical core and its place in full model systems that include parameterizations of sub-grid-scale processes, data-assimilation, surface models, and others. Finally, Dr. J. M. Dennis discusses the many challenges in designing and implementing models for massively parallel supercomputers with concrete examples from NCAR's Coupled Climate System Model (CCSM).

The complex topic of dynamical cores, which includes choices between hundreds of numerical methods and half a dozen spherical grids as well as variable staggering options, offers an endless set of combinations and choices. Exploring all options is simply not feasible, and it is therefore necessary to make intelligent selections among the many choices. In the research community, there is, however, no consensus regarding a particular numerical method or spherical grid being superior for all applications (or even for a single application). The careful reader will find such differences among some chapters in this book, as different authors advocate particular approaches. It is deliberate that such diversity, which was discussed intensively during the 2008 ASP colloquium, is represented in this book as it depicts state-of-the-art knowledge in the field of dynamical cores. Despite this lack of collective agreement on numerical methods and grids, there seems to be broad consensus regarding dynamical core properties such as conservation, consistency, scalability, accuracy, energy spectra, and capabilities. In other words, the goal seems clear, but the optimal avenue to get there remains an open research question. We hope this book can contribute to this quest and enlighten the interested reader in the many deliberations that are an integral part of dynamical core development.

Acknowledgments

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