A next generation Earth System Model (ESM): The atmospheric component

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1. Introduction

Increasing supercomputer capabilities expected in the near future provide an opportunity for substantial improvements to models employed in simulations for weather and climate research. For example, we expect that global atmospheric simulation using non-hydrostatic resolutions (horizontal grid spacing of significantly less than 10 km) will be common within the next ten years. We know that our current climate and weather modeling systems are not at present suitable for these high-resolution applications on the new massively parallel processing (MPP) architectures that are expected to use anywhere from 10^4 to 10^6 processors, both on the computational side (our solvers are not expected to scale well to these processor counts) and on the model formulation side (a number of model physics and solver discretization problems will be exacerbated). Additionally, many significant simplifications are made to physical and chemical processes important for climate and weather (the *model physics*) in atmospheric models because of limited computer capabilities. We know how to represent many of these processes more accurately, but presently cannot afford to do so. These high-resolution simulations will also provide new challenges in terms of data storage and analysis. Given the problems our current modeling systems face, and given the 5 to 10 year timeframe it takes to develop and test new modeling systems, it is appropriate to begin now to develop a new system that can overcome these problems.

The charge to our working group is to facilitate the development of the atmospheric component of a next generation Earth System Model. This new atmospheric component should surpass the simulation capabilities currently fulfilled by the Community Atmosphere Model CAM (climate applications) and the Advanced Research WRF (ARW) model (weather and regional climate applications). It should also provide improved capabilities in the areas of chemical weather prediction, observational campaign support, data assimilation and simulating atmosphere-geospace interactions. It is expected that the modeling system will be configurable for these many different applications, that is, it will have a sufficiently flexible dynamical core (Navier-Stokes solver) and representations for physical processes for coarse resolution long-timescale climate simulations and for high-resolution short-timescale NWP simulations.

For simplicity, we divide the atmospheric component into two components (1) a module used to solve the Navier Stokes equations for fluid flow (often called the atmospheric dynamical core), and (2) modules representating all the processes important in the atmosphere but not simulated by the dynamical core (often called the model physics). The model physics may contain representations for fluid flow occurring on time and space scales below the model resolution (e.g. turbulence, gravity waves, etc.), or process components that are not explicitly represented by fluid flow (e.g. chemistry, radiative transfer, cloud and aerosol microphysics, etc). In the following sections we outline the needs and requirements for these atmospheric model components, and we suggest near and long term plans for accomplishing our goal of constructing the new atmospheric core of the ESM.

2. The dynamical core.

Over the past 18 months, a group of atmospheric modelers from NCAR have met periodically to discuss the needs of both the weather and climate modeling communities and the approaches being used in existing models, specifically in the dynamical cores. One result of these meetings was a general consensus on required and desirable features for a dynamical core suitable for both weather and climate applications. The list of necessary features includes:

1. The solver should be capable of producing reasonably accurate solutions for small-scale flows (Large Eddy Simulation scales) and large scale flows (synoptic and global scales). This will require a solver capable of integrating the fully compressible non-hydrostatic equations of motion.

2. The module should be applicable to both global domains and also suitable for regional (limited area) modeling using prescribed boundary conditions.

3. The model should have local refinement capability on both regional and global applications.

4. The module should satisfy a number of conservation properties that are present in the continuous equations for fluid flow, namely the solver should conserve air and trace constituent mass and do so in a consistent manner.

5. Shape preserving numerical techniques should be available for use where needed.

6. The atmospheric core should support relatively uniform horizontal resolution (grid-cell area should not vary significantly), and the horizontal grid should be relatively isotropic ($\Delta x \sim \Delta y$).

7. The model should be reasonably efficient on various existing and proposed supercomputer architectures (time to solution for a given accuracy, understanding that specific efficiency and accuracy measures may be application dependent).

Other features were discussed that are generally desirable, for example various levels of energy conservation and monotonic transport options.

A more detailed discussion of these features and the reasons for including them in this list are discussed in a companion report of the dynamics working group - *ESM Dynamical Core Evaluations*, but what should be appreciated here is that the list is fairly complete and takes into account the needs of both the climate and weather applications.

This consensus came as somewhat of a surprise because less than 5 years ago a similar exercise resulted in little consensus. In addition to this consensus, two other points should be appreciated. First, the existing dynamical cores in CAM (FV core) and in ARW share a number of features, most notably, both cores are based on finite-volume discretization techniques and both use latitude-longitude grids. The cores are in many ways more similar than different. Second, neither of these solvers possesses all the necessary features listed above, nor do they scale well to projected MPP architectures in global configurations. In addition, it is not obvious that simple extensions of the FV or the ARW core address the shortcomings in any significant way.

Common needs and similar existing cores suggest that a general module for atmospheric dynamics is feasible, but we do not yet know whether any existing cores satisfy all the above needs. Limited personnel and resources suggest that leveraging is crucial for NCAR and the wider community.

3. Model physics

A significantly greater fraction of resources both within NCAR and in the model development community around the world is spent developing model physics compared to that used to develop dynamical cores. There is good reason for this – there are many processes other than fluid flow important in the atmosphere, there is much more uncertainty in the physics controlling those processes than that inherent in the Navier-Stokes solver, and the problems in model physics are much more varied and complex than those associated with building discrete NS solvers.

There has not yet been the organic evolution of ideas within the groups responsible for the physics components comparable to the dynamics group effort. Our first task will be to try to seed such an effort. Our goal is to identify a very small group of scientists inside and outside of NCAR with expertise in the areas mentioned below, and a willingness to contribute to the ESM. We will ask those people to lead activities tasked to:

1. identify deficiencies in current formulations for small and large scale modeling problems
2. identify common needs in small and large scale modeling problems
3. identify areas where different approaches are likely to be required.

We hope that a brief writeup of these items will form the basis for a report similar to that authored by the dynamics working group, and groups of people willing to work together to make progress on their components. We will encourage the groups to produce 2-4 chairs representing communities inside and outside NCAR, with expertise relevant to small and large scale problems that can help to organize the activity and coordinate with the larger ESM goals.

We have chosen to group the atmospheric model physics into seven rough categories that are common to both the WRF and CAM atmospheric models, and are likely to be present in varying degrees of complexity in all comprehensive weather and climate models:

1. Radiation
2. Planetary boundary layer (PBL)
3. Convective parameterization
4. Clouds and cloud microphysics
5. Aerosols, aerosol-cloud, aerosol-chemistry interactions
6. Subgrid-scale dynamics and turbulent processes (those not considered as PBL physics)
7. Chemistry

These components have similar constraints to those identified for the dynamical core. They should conserve thermodynamic quantities (energy, enthalpy), mass, and stoichiometry. Fluxes in and out of the system should balance changes within the system. Components should produce positive definite values where appropriate.

There are other applications for an atmospheric model that require a representation of processes falling outside the current list (e.g. the need for a full treatment of magneto-hydrodynamics, plasma dynamics equations, non-local thermodynamic equilibrium for the radiation. etc). We anticipate that these needs will be addressed as ESM development progresses. In addition, we expect an ESM to be utilized in the study of planetary atmospheres, and Earth-specific quantities within physics modules should be abstracted to the greatest extent practical.

Physics parameterizations exist in both CAM and WRF, but different parameterizations are usually used even when run at similar resolutions. It is also the case that representations appropriate for one application are not optimal for another. For example, it is easier to treat cloud droplet growth in a model with high temporal and spatial resolution, allowing explicit treatment of vertical motions of an air parcel, than it is in models with relatively low resolution (10s of km and lower) where the vertical motions relevant to drop growth are not resolved.

Within NCAR and in the wider community, there are a number of ongoing efforts in each of these areas focused on climate applications (CAM) or weather (WRF) with, at present, little overlap between the weather and climate efforts. In many cases these efforts involve extensive collaborations between groups, and the community is much larger than that developing the dynamical cores. All the parameterizations employ substantial simplifications in their representation of these processes. Much better formulations for many of these processes are available but they are too costly to be used in current climate and NWP models. The advent of more computer power will provide us with new opportunities.

As with the dynamics section, we plan accompanying *brief* documents discussing needs for development in physics components addressing the above mentioned items, and providing a plan for progress in each area.

4. A path forward

Our mission is to develop a single atmospheric dynamical core and, where possible, common representations for physical processes (parameterizations) to satisfy both climate and weather prediction needs. We recognize that there may be the need for options within the dynamical core, and for different model physics representations, to satisfy these needs. Importantly, by focusing on common physics and common core configuration where possible, we highly leverage development resources and maximize benefits to the large community of users and developers.

Our goals are

1. to develop a new atmospheric dynamical core that satisfies the requirements outlined in section 2,
2. to develop improved physics to meet the requirements of a next generation Earth System Model, and
3. to combine the new dynamical core and model physics to form a flexible atmospheric component that provides significant increase in performance over the previous generation of models.

This work will be carried out by subgroups of our working group that will focus on the dynamical core and the different categories of model physics. Thus at this time we anticipate that there will be a number of subgroups; the dynamics subgroup, and some number of subgroups to address the physics component defined above (possibly one for each of the components.)

Once formed, we want the subroups to help organize and coordinate evaluation and development efforts, to collect and disseminate information and results related to these efforts, to provide a forum for discussion of these results, and to make recommendations concerning atmospheric model components for the new ESM.

We are in the process of inviting members of the community to participate in our atmospheric component working group and subgroups. We anticipate that the full working group and many of the subgroups will be functioning within the next few months. The first task for these subgroups will be to identify needs and requirements in their area and briefly summarize the state of the art with respect to these needs and requirements. Many of these summaries should be available by the end of this summer (2008). Possible timelines for the development and evaluation efforts should shortly follow these summaries, and at this point we will be able to assess the feasibility of or ESM atmospheric component development goals. Ideally this process will lead to more coordination among active development and evaluation efforts, but much will depend on the level of consensus and coordination we can achieve.

As an overall objective, we would like to have a viable ESM atmospheric component within the next 5 to 7 years. In order to meet this goal, we believe that we need to move forward with a viable atmospheric dynamical core candidate within 2 to 3 years, along with identification of physics that can be used for both climate and weather. Thus we expect to have the atmospheric core evaluation largely complete within approximately two years, along with an evaluation of physics.

5. Other issues

There are other issues we have not directly addressed here that will need attention by our working group or by the larger ESM development group.

With respect to developing the atmospheric component of the ESM, it is not immediately obvious what the relationship of our efforts will be to those of CCSM and WRF. Does ESM represent the future of CCSM and WRF? If so, it is not clear whether a gradual transition from the current frameworks or a fresh start is optimal. These question require conversations with the WRF and CSM communities. Working groups and subgroups similar to those we are forming already exist within the CCSM and WRF communities. How do we integrate with them? It is also important to define the communities that we are interacting with. How do we plan to interact with outside communities. It is also not clear what our ability will be to meet timelines and goals - there is only a small amount of support for this development effort within NCAR, and similarly little direct support in the community.

There are also development issues that intersect the atmospheric component development that are not currently addressed within the present ESM development plan. The identification and development of a suitable model software framework, and needs and requirements for data assimilation, are two examples.

These issues will all need to be addressed as the concept evolves.