Singletrack Dynamical Core Roadmap

This document outlines the development and testing necessary to evaluate and fulfill Singletrack dynamical core requirements. Based on the section 2 and 3 from the *SingleTrack Dynamical Core Requirements Report*, dynamical core evaluation and development will require some combination of the following:

(1) Testing for conservation where conservation is not exact.
(2) Testing to measure efficiency of dynamical core components.
(3) Testing of transport characteristics (some SE, FV3 and MPAS results in the literature).
(4) Development of capabilities not yet existing in the dynamical cores.
(5) Tests measuring the efficiency and scaling of the core (both transport and dynamics).

Requirements and evaluations that require atmospheric physics are not included in the dynamical core roadmap presented here; these tests and evaluations will need to be accomplished in collaboration with physics subgroup.

FV3 roadmap

FV3 is being implemented into the CESM through a NOAA funded project. The code is pulled from a common repository shared with NOAA. Since FV3 it being implemented in the CESM framework, it will require little effort to run the test case suite and evaluate the performance of FV3 (once the tests are implemented for CAM-SE under the CESM simpler models “umbrella”).

FV3 publications and documentation:

https://www.gfdl.noaa.gov/fv3/fv3-documentation-and-references/

More information being gathered.

MPAS roadmap

The latest release version of the MPAS dynamical core (MPAS Version 5.2) contains most of the major developments and optimizations except for the regional capability that exists in a development branch. The version of MPAS that exists in CAM (i.e. CIME) is from MPAS Version 4, and it does not contain many of the optimizations of MPAS-V5.2 and it does not have all the latest algorithmic upgrades. Given that Singletrack will use CIME and some version of the CESM/CAM/CIME infrastructure, engineering a build of MPAS/CAM pulling MPAS from its development or its release repository is a very high priority, but it is not listed here. Fortunately, many (perhaps all) of the dynamical core requirements considered by the Singletrack dynamical core subgroup can be evaluated using the standalone MPAS V5.2 because there should not be significant degradation of MPAS dynamical core performance with its build in CAM.

The following developments and testing needs are those identified in Table 2 in the *SingleTrack Dynamical Core Requirements Report*.

Ongoing and future MPAS dynamical core developments and testing:

(1) Testing for conservation of energy and angular momentum (requirement 4): We have preliminary results from MPAS V4 (V2?). Need to repeat with V5.2 in CAM (after further configuration and tuning of upper absorbing layer?)
(2) Efficiency of components and overall dycore efficiency (requirements 1, 2, 19 and 20): Transport, dry dycore - testing can be done in standalone version - need to determine tests or pull results from previous testing? These tests could be part of more general benchmarking for throughput and scaling. e.g. requirements 1, 19 and 20.
(3) Regional capability: The initial phase of regional MPAS testing is almost complete. The MPAS developers will be doing a code clean-up along with a cleanup of necessary utilities before a public release. The question of how CIME/CESM/CAM will accommodate regional applications needs to be addressed in other subgroups and the Singletrack group.

Geospace applications needs

(4) Geospace configuration (requirement 18): High-top thermodynamics - need to evaluate the use of coupled potential temperature (density * potential temperature) as a prognostic variable in MPAS for high-top applications. Also need to evaluate the height coordinate and upper boundary conditions, etc for these applications. Will any major changes be needed to MPAS to accommodate high-top thermodynamics?
(5) Geospace configuration (requirement 17): Deep atmosphere capability - need to implement 3D-variable gravity, complete Coriolis term (already available in MPAS) and geometry. This should be a straightforward task given the height coordinate used in MPAS.
(6) Geospace configuration (requirement 16): Species dependent mean molecular mass and specific heats - need to evaluate the inclusion of this generalization into the MPAS nonhydrostatic compressible solver. If feasible then implement.
(7) Evaluate height coordinate and upper boundary conditions, etc for these applications.
(8) Geospace configuration (requirement 15): Efficient 2 way 3D inline grid coupling - need to evaluate with the infrastructure group, consider implementation if feasible.

SE roadmap

Current status of SE:

A new version of the SE dynamical core has been committed to the CAM trunk. This version is a reformulation of the spectral-element dynamical core in dry-mass vertical coordinates with comprehensive treatment of condensates and energy (see Lauritzen et al., 2018; submitted; for details). It also contains the option of performing tracer transport with CSLAM (only uniform resolution grids are supported at this point).

Current development of SE:

- Testing of CAM-SE and WACCM-SE with CAM6 physics (including using CSLAM for tracer transport) – some “tweaking” of viscosity and/or changes in topography smoothing is being investigated; this work is scheduled to be part of the CESM2.1 release.

  This work is primarily done by Lauritzen (CGD) with some software engineering support.

- Implementation of the existing SE dycore in WACCM-X, including mapping capability needed to couple with the ionosphere dynamics module (the coupling is funded by HAO). Include major species transport (variable M, R and C_p) in the SE dycore, providing the current WACCM-X capability with SE instead of FV.

  This work is primarily done by Liu (HAO) and Lauritzen (CGD) with some software engineering support.

Possible future development of SE (non-hydrostatic and deep atmosphere version):

For high horizontal resolution applications (~<10km) a non-hydrostatic version of SE is necessary. For high-top applications a deep atmosphere formulation is highly desirable. Such a formulation is much simpler in a ‘z’-based vertical coordinate system than hybrid-sigma (Yessad and Wedi; ECMWF, 2011). Hence it is recommended to implement a non-hydrostatic shallow-atmosphere version of SE based on a terrain-following height coordinate first.

More specifically, CISL’s Ram Nair wrote a roadmap for the non-hydrostatic version of SE (see Appendix). The following are the main design considerations as laid out by Nair:

- Use CAM-SE framework as much as possible and exploit the present parallel software infrastructure of the hydrostatic code. The horizontal aspects of the SE discretization will

remain the same, this includes cubed-sphere grid system, local mesh refinement, tracer transport and hyperviscosity (biharmonic) operations.
- Fully compressible 3D Euler system of equations suitable for spherical curvilinear grids and deep atmospheric domain. Momentum equations in the vector invariant form, flux-form equations for the continuity and transport equations.
- Terrain following height-based vertical z-coordinates with staggered FD/FV discretization. This is a major change to the present CAM-SE design.
- Time integration will be based on classical split-explicit Runge-Kutta formulation combined with an implicit treatment of acoustic terms in the vertical direction. This will alleviate the stringent CFL stability requirement resulting from tiny grid spacing in the vertical, while being parallel efficient.

The details of the deep extension of CAM-SE are given by Ram Nair's roadmap (see Appendix). A significant advantage of the gnomonic cubed-sphere approach in SE is that the metric terms for the deep atmosphere extension are exact; hence gradient, curl and divergence operators easily extend to deep atmosphere metrics. This may not be true for other dynamical cores.

In Nair's roadmap, Liu and Lauritzen have recommended to change the prognostic variable from potential temperature (theta) to temperature to accommodate high-top thermodynamics, as theta becomes ill-defined above the homopause (~110km). Nair responded that such a change could be accommodated.

It is important to realize that the development of a deep non-hydrostatic dynamical core with consistent thermodynamics is a basic research topic and therefore has a longer time-scale.

<u>Expertise and staffing considerations</u>

With the termination of CISL's Ram Nair position, the expertise in non-hydrostatic deep atmosphere modeling with the SE dycore is no longer available internally at NCAR. So either NCAR would have to form partnerships with external institutions or build up the expertise in-house.

DOE has independently developed a non-hydrostatic version of SE based on the 'Laprise' formulation i.e. using a pressure coordinate (Mark Taylor; personal communication). The DOE non-hydrostatic SE core is planned to replace the hydrostatic SE code after version 1 release of E3SM after which it would be publicly available (planned this summer; Mark Taylor personal communication). As mentioned above however, a pressure-based coordinate is not recommended for deep atmosphere extension.

References

Lauritzen, P.H. and co-authors, 2017: NCAR CESM2.0 release of CAM-SE: A reformulation of the spectral-element dynamical core in dry-mass vertical coordinates with comprehensive treatment of condensates and energy: *J. Adv. Model. Earth Syst.*, submitted (December 8, 2017)

Lauritzen, P.H. M.A. Taylor, J. Overfelt, P.A. Ullrich, R.D. Nair, S. Goldhaber and R. Kelly, 2016: CAM-SE-CSLAM: Consistent finite-volume transport with spectral-element dynamics.: *Mon. Wea. Rev.*. DOI:10.1175/MWR-D-16-0258.1

Yessad, K. and N.P. Wedi, 2011: The hydrostatic and non-hydrostatic global model IFS/ARPEGE: deep-layer model formulation and testing, ECMWF Technical Memorandum No. 65

Appendix: Roadmap written by R. Nair (CISL)