Subcycled dynamics in the Spectral Community Atmosphere Model, version 4

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Abstract. To gain computational efficiency, a split explicit time integration scheme has been implemented in the CAM spectral Eulerian dynamical core. In this scheme, already present in other dynamical core options within the Community Atmosphere Model, version 4 (CAM), the fluid dynamics portion of the model is subcycled to allow a longer time step for the parameterization schemes. The physics parameterization of CAM is not subject to the stability restrictions of the fluid dynamics, and thus finer spatial resolutions of the model do not require the physics time step to be reduced. A brief outline of the subcycling algorithm implementation and resulting model efficiency improvement is presented. A discussion regarding the effect of the climate statistics derived from short model runs is provided.

1. Introduction

This note describes an implementation of a temporal subcycling algorithm in the Community Atmosphere Model (CAM) version 4 Eulerian dynamical core. The CAM is the atmospheric component of the Community Climate System Model (CCSM), a global Earth system model encompassing model components of the atmosphere, ocean, sea ice and land surface. The components communicate through a flux coupler that allows interactions at various time scales set to a level appropriate to capture the relevant model features with accuracy and stability. This core uses a spherical harmonic based spectral method. It requires more computational expense per grid point than other dynamical core options included in CAM, but it remains a favorable option for higher resolution studies due to its isotropic treatment of spherical geometry and the fact that it is well tested with a range of resolutions [1]. It solves the fluid dynamics equations of the model with a semi-implicit time integration scheme, which is a combination of an explicit Robert-filtered leapfrog scheme for the nonlinear terms and a Crank-Nicholson treatment of the linear terms responsible for gravity waves.

2. Subcycling Approach

We start with a high level representation of the equations,

$$\frac{\partial X}{\partial t} + D(X) = F(X) \tag{1}$$

where $X(t)$ is the state vector at time t, the dynamics terms are represented by $D(X)$ and the forcing tendency terms by $F(X)$. The Eulerian dynamical core uses a process-split approach

[2] to couple the dynamics and the forcings tendencies computed by the CAM model physics subroutines. When combined with the semi-implicit time-stepping scheme, (1) is discretized as

$$X(t+\Delta t) = X(t-\Delta t) - 2\Delta t D\Big(X(t-\Delta t), X(t), X(t+\Delta t)\Big) + 2\Delta t F\Big(X(t-\Delta t), 2\Delta t\Big). \quad (2)$$

Most of the terms in the dynamics, D, are evaluated at time t, but because of the semi-implicit scheme there are a few terms that are evaluated at $t-\Delta t$ and $t+\Delta t$. The forcing term, $F(Y, \Delta t_{\mathrm{phys}})$ arises from the model physics computed by CAM. We have added a second argument to F because CAM physics can be considered as a function of two variables: a state vector Y and the physics timestep Δt_{phys}. With the semi-implicit scheme used above, the solution is advanced from time $t-\Delta t$ to $t+\Delta t$, representing a duration of $2\Delta t$, and thus with leapfrog time-stepping, the physics timestep is $\Delta t_{\mathrm{phys}} = 2\Delta t$. The physics is computed from the state vector $X(t-\Delta t)$ instead of $X(t)$ because the physics contains many dissipative processes that would be unstable if evaluated with the leapfrog scheme. Evaluating that term at time $t-\Delta t$ results in a stable forward-Euler treatment.

For subcycling, we simply reuse the physics tendencies over multiple steps. Let n be the number of subcycled steps and introduce two timesteps, $\Delta t_{\mathrm{phys}} = n\Delta t_{\mathrm{dyn}}$. A single timestep, representing one physics evaluation and n dynamics steps is then given by
For i=1 ... n:

$$\begin{aligned} X(t+(i+1)\Delta t_{\mathrm{dyn}}) = X(t-(i-1)\Delta t_{\mathrm{dyn}}) \\ - 2\Delta t_{\mathrm{dyn}} D\Big(X(t-(i-1)\Delta t_{\mathrm{dyn}}), X(t+i\Delta t_{\mathrm{dyn}}), X(t+(i+1)\Delta t_{\mathrm{dyn}})\Big) \\ + 2\Delta t_{\mathrm{dyn}} F\Big(X(t-\Delta t_{\mathrm{dyn}}), \Delta t_{\mathrm{phys}}\Big). \end{aligned} \quad (3)$$

That Δt_{phys} is the correct physics timestep to be used as the argument to F can be seen by considering the simplified case with no dynamics D and then writing the final result after n steps in terms of the initial conditions. For n even, we have

$$X(t+(n-1)\Delta t_{\mathrm{dyn}}) = X(t-\Delta t_{\mathrm{dyn}}) + n\Delta t_{\mathrm{dyn}} F(X(t-\Delta t_{\mathrm{dyn}}), \Delta t_{\mathrm{phys}}) \quad (4)$$

$$X(t+n\Delta t_{\mathrm{dyn}}) = X(t) + n\Delta t_{\mathrm{dyn}} F(X(t-\Delta t_{\mathrm{dyn}}), \Delta t_{\mathrm{phys}}) \quad (5)$$

For both final time values $t+(n-1)\Delta t_{\mathrm{dyn}}$ and $t+n\Delta t_{\mathrm{dyn}}$, the forcing is applied over a time interval of length $n\Delta t_{\mathrm{dyn}}$, and thus it is appropriate to compute the physics with $\Delta t_{\mathrm{phys}} = n\Delta t_{\mathrm{dyn}}$. For n odd, the situation is slightly different, resulting in

$$X(t+(n-1)\Delta t_{\mathrm{dyn}}) = X(t) + (n-1)\Delta t_{\mathrm{dyn}} F(X(t-\Delta t_{\mathrm{dyn}}), \Delta t_{\mathrm{phys}}) \quad (6)$$

$$X(t+n\Delta t_{\mathrm{dyn}}) = X(t-\Delta t_{\mathrm{dyn}}) + (n+1)\Delta t_{\mathrm{dyn}} F(X(t-\Delta t_{\mathrm{dyn}}), \Delta t_{\mathrm{phys}}) \quad (7)$$

and now the forcing is applied over a time interval of length $(n-1)\Delta t_{\mathrm{dyn}}$ in (6) and an interval of length $(n+1)\Delta t_{\mathrm{dyn}}$ in (7). For this case, we take the average of these two time intervals and set $\Delta t_{\mathrm{phys}} = n\Delta t_{\mathrm{dyn}}$, matching what was used in the n-even case.

For moisture advection there is one complication due to the fact that the CAM physics returns an adjusted field instead of tendency terms. Let q represent one of the advected moisture fields, such as specific humidity. An implied tendency F_q can be computed from the adjusted field by defining

$$q^-(t) = q(t) + \Delta t_{\mathrm{phys}} F_q\Big(X(t), \Delta t_{\mathrm{phys}}\Big)$$

where $q^-(t)$ is the adjusted field computed by the CAM physics. With this definition, the original advection scheme

$$\frac{\partial q}{\partial t} + U \cdot \nabla q = F_q(X)$$

is discretized by

$$\begin{aligned} q^-(t-\Delta t) &= q(t-\Delta t) + 2\Delta t F_q\Big(X(t-\Delta t), 2\Delta t\Big) \\ q(t+\Delta t) &= q^-(t-\Delta t) - 2\Delta t U \cdot \nabla q \end{aligned}$$

which can be written as

$$q(t+\Delta t) = q(t-\Delta t) - 2\Delta t U \cdot \nabla q + 2\Delta t F_q\Big(X(t-\Delta t), 2\Delta t\Big). \tag{8}$$

This equation is now in the same form as (2), and thus to introduce subcycling we follow the identical procedure as was used above.

3. Efficiency Gains with Subcycling

The motivation to incorporate subcycling is to increase efficiency for a forward-in-time simulation with multiple, weakly interacting time scales. Unlike the stability constrained fluid equations in the model, the subgrid scale physics parameterizations can utilize a larger time step size appropriate for capturing the time evolution of a wide range of parameterized physical processes, which for the global atmospheric model in the hydrostatic regime is generally no greater than 30 minutes. The efficiency gain for a simulation using subcycling depends upon the ratio of the size of the dynamics and physics time steps, n, and the percent of time spent evaluating the physics versus dynamics. Simulations of the CAM spectral model run with active atmosphere and land surface components with subcycling have been performed for two resolutions, T85 and T341. T85 and T341 have spatial resolutions about the same as the CAM finite volume dynamical core at one and one-quarter degree resolutions respectively [3]. When T85 and T341 are run with the most favorable configuration for efficiency, which for each is n=3 and 12, the simulations exhibit a decrease in runtime of about 30% and 20% respectively. For the finer T341 resolution, the dynamics portion of the model becomes computationally more expensive although it is being subcycled to a greater degree.

When CAM is used within the fully prognostic Community Climate System Model (CCSM), the efficiency benefit is not simply in the gain of the atmosphere and land model but in the increased efficiency gained by coupling the subcycled model with the rest of the Earth system components. Like the land surface, the sea ice component of the CCSM, CICE [4], is iterated forward in time at the physics time step of the atmospheric model, so CCSM efficiency is gained by the increase in the time step size of the sea ice component. When a fully coupled CCSM version 4 configured for high resolution (T341 atmosphere, quarter-degree finite volume land surface, tenth-degree ocean and sea ice) is run for one full month, the simulation time is reduced from 7.44 hours to 2.97 hours on 6924 processors. Additional gains could be attained by reorganizing processors allocated to each CCSM component now that CICE has become relatively less expensive than the ocean.

4. Climate simulation variation with subcycling

The climate produced by CAM is especially sensitive to the physics timestep [5]. Below we demonstrate this sensitivity using the subcycling capability in T85 CAM spectral Eulerian simulations. The model was tuned without subcycling and using minimum relative humidity thresholds for the formation of low and high stable clouds of 0.915 and 0.68, respectively. The

Table 1. The physics time step size Δt_{phys} is varied for a series of T85 simulations to isolate the its effect on the simulation statistics. 'Nosub' refers to the simulation performed without any subcycling. The number of subcycled dynamics steps, n, are 3, 2, and 3, for Δt_{phys}=600, 1200, and 1800 s, respectively. RESTOM, FSNT, CLDLOW, and LWCF refer to the residual energy flux at the model top, the net absorbed shortwave energy flux at the model top, the vertically integrated factional coverage of low clouds, and the longwave cloud forcing respectively (units of W/m^2). 'PBLH' and 'TS' refer to the global annually averaged planetary boundary layer height (m) and surface temperature (degrees K), respectively.

Variable	Nosub (Δt_{phys}=1200)	Δt_{phys}=600	Δt_{phys}=1200	Δt_{phys}=1800
RESTOM	-0.239	-2.131	0.247	1.613
FSNT	236.634	233.134	236.737	238.705
CLDLOW	34.252	34.755	33.610	32.897
LWCF	28.185	29.719	28.452	27.694
PBLH	609.21	621.93	609.09	599.66
TS	287.406	287.460	287.465	287.390

model was run from specified initial conditions for the land surface model rather than a spun up state, which is available with the finite volume land model resolution. The rest of the cloud physics parameters used the default settings for CAM version 4 for all the simulations presented here. Table 1 displays several parameters of interest for two years of simulation using a range of physics time step sizes, Δt_{phys}, of 600 s, 1200 s, and 1800 s. Δt_{phys}=1200 s matches the physics time step size of the unsubcycled simulation and Δt_{phys}=1800 s is used in the default finite volume CAM configuration. The global annual net energy exchange at the model top (RESTOM) for 2 years of simulation without subcycling is -0.239, and this was the base value from which we explored variations present in the other model runs. Without subcycling, the physics time step is twice the dynamics time step as explained in Sec. 2. Since only two years are analyzed, an overall energy balance climate model in this range is reasonable.

For the range of physics time step sizes analyzed, RESTOM and several related variables, such as the net shortwave energy out of the model top (FSNT), the low cloud amount (CLDLOW), and the longwave cloud forcing (LWCF), are linearly dependent on the time step of the physics parameterization scheme. As expected, Δt_{phys}=1200 s is close to the nonsubcycled model. The physics and dynamics time step sizes are the same, so only differences associated with the different algorithm for subcycling outlined in section 2 and interannual variability are present. The global annual surface temperature (TS) of each simulation is presented to verify that it is invariant to the time step size of the physics and dynamics time step size within expected internal variability of the model (the root mean square of the observational TS error is about 0.7 K). Because TS is not influenced measurably by a variation in the physics time step size and the agreement between the Δt_{phys}=1200 subcycled and nonsubcycled solutions, we are confident the subcycling algorithm is working as expected.

The origination of this variation of cloud physics parameters with time step size is certainly of interest, and an exhaustive investigation of the details of this dependence would be worthwhile in the improvement of physics parameterization schemes. For our purposes, the source of variations in the fields displayed in Table 1 likely trace back to the planetary boundary layer height (PBLH), which is sensitive to and decreasing with larger physics time step size. Thus, the implied connection between time step size and RESTOM is that the longer time step size results in a lower PBLH, and thus fewer low clouds, which creates a lower albedo and correspondingly a higher absorbed shortwave term and lower value for RESTOM. The less understood feature of these connections is the reason for the lower PBLH with longer time step sizes. One hypothesis is that the longer time step size results in slightly different estimates of boundary layer height (a consequence of the linearizations in the boundary layer parameterization) which can strongly affect the exchange of heat, moisture, and momentum between the surface and free atmosphere. This exercise uncovered unusual behavior in the physics package, specifically wavelike behavior in the instantaneous precipitable water fields, when very short time steps are used.

As with other dynamical cores in CAM, the subcycling introduced into the spectral Eulerian core does require changes to the cloud physics parameters to reproduce the same climate statistics. zonal wind (not shown), vary with physics time step size as well but are expected Thus, the simulations can produce consistent climate results with the nonsubcycled simulation once the physics parameterization is tuned to account for the longer time step sizes of the physics. In sum, the subcycled physics time step allows more efficient coupled climate simulations without appreciably affecting the climate statistics as defined within the existing CAM physics parameterization scheme.

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