Quantifying, Attributing, and Understanding Time Step Sensitivities in the E3SMv1 Atmosphere Model

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Background and motivation

Various significant, undesirable numerical artifacts noticed in E3SM and similar models, both global and regional, at traditional and much higher resolutions

SciDAC project aiming at reducing time-stepping error and in atmospheric physics parameterizations in E3SM

• Investigations using simplified models demonstrated the feasibility and benefits of addressing time-step convergence issues

• From proofs of concept to the “real EAM”
  ○ Priorities?
  ○ Relevance to day-to-day development focused on reducing model biases?

See also Wan et al. (2015, JAMES)
Shortening EAMv1’s time steps to 1/6 of the default causes a systematic increase in model biases.

Model biases in 10-year mean present-day climate

- (a) Relative error in global mean
- (b) Relative error in global pattern

Simulation setup
- F_2000 compset
- ne30_ne30 (1-degree)

Source of obs. data: AMWG diagnostics
The degradation in model fidelity is comparable in magnitude to the improvement from v0 to v1.
Key signatures of sensitivity include systematic drying of the troposphere and decreases in cloud fraction when time steps are shortened.

Differences in zonal mean 10-year averages, $\Delta t/6 - v1_{CTRL}$
Significant changes are seen in subtropical low-clouds, which has potential implications on the prediction of climate change.

Differences in 10-year averages, $\Delta t/6 - v1_{\text{CTRL}}$

Total cloud cover

Net cloud radiative effect (CRE)

Wan et al. (2020, GMD Discussion, doi: 10.5194/gmd-2020-330)
“Perhaps unsurprisingly to those familiar with model development, the largest deviations can be attributed to the parametrizations of clouds and moist convection. Perhaps less predictable is how and where these deviations are...” — anonymous reviewer

- “How and where”
- “By what and why”

Our experiments: time step sizes in various components of EAMv1 are varied separately or in combination to attribute time step sensitivities
These simulations reveal key impactors in different cloud regimes

Differences in 10-year averages of shortwave cloud radiative effect

- Shallow cumulus and stratiform cloud macro/microphysics
- Deep convection and its interaction with dynamics etc.
- Coupling between cloud macro-/microphysics and rest of model

All major processes
These simulations reveal key impactors in different cloud regimes (cont’d)

Differences in 10-year averages of longwave cloud radiative effect

All major processes

Coupling between cloud macro-/microphysics and rest of model

Shallow cumulus and stratiform cloud macro/microphysics

Deep convection and its interaction with dynamics etc.
Going beyond attribution — understanding and addressing the root causes

This presentation: discussing process coupling as an example

10-year mean total CRE differences caused by more frequent coupling between cloud macro/microphysics and rest of model.
Sequential splitting is the primary process coupling method used in EAM

We start the description with simpler cases where different processes are integrated using the same step size $t$. Denoting the discrete solution at time instances $t = n$ and $t = (n + 1)t$ by $n$ and $n + 1$, respectively, the following methods can be used to advance the solution from time level $n$ to $n + 1$:

- **Parallel splitting** (Figure 1a), also referred to as process splitting in Williamson (2002) and parallel splitting in Beljaars et al. (2004), Beljaars et al. (2018), and Donahue and Caldwell (2018), is the method of discretizing different processes independently, all starting from the same model state:
  
  Discretizing process $A$ in isolation:
  
  $A_n, n,t = A_n, n$
  
  Discretizing process $B$ in isolation:
  
  $B_n, n,t = B_n, n$
  
  Advancing solution in time:
  
  $n + 1, ⇤ = n + ⇤ A_n, n + B_n, n$
  
  Applying limiter if needed:
  
  $n + 1 = L n + 1, ⇤$

Two time levels of $n$ are listed in the parentheses following $A$ or $B$ in the equations above to reflect the fact that each process can be integrated using an explicit or implicit method. Numerical error resulting from discretizing the individual processes can lead to unphysical features in the numerical solution of equations (2) or (3), for example negative tracer concentrations or spurious maxima or minima. Numerical treatments like limiters, clipping or fixers that are used to avoid such artifacts can be employed as part of the discretization methods used for the individual processes; those limiters etc. not explicitly spelled out in the equations above as the focus of the paper is on process coupling. On the other hand, an additional limiter might be needed when tendencies from $A$ and $B$ are added together to update $n$, as the individual processes are discretized independently. This need of an additional limiter is highlighted by equation (5).
Sequential splitting can cause strong oscillation of atmospheric state within each time step

Global mean concentration of stratiform cloud liquid (CLDLIQ) over 5 time steps (30 subcycles)

EAMv1 default

B = CLUBB + MG2
A = all other processes (grid resolved and unresolved)
Tighter coupling can help alleviate the problem

Global mean concentration of stratiform cloud liquid (CLDLIQ) over 5 time steps (30 subcycles)

- **MG2**
- **DRIB**
- **CLUBB**
- **CNTL**

Number of steps (#)

(10^{-6} \text{ kg kg}^{-1})

24 25 26 27 28 29

Intermediate state

State n

Tendency

State n
Change in coupling frequency can lead a shift of the mean state

Why decreases in stratocumulus?
Sequential splitting results in a direct impact of coupling step size on the atmospheric state seen by CLUBB

Shorter coupling interval

Less cooling applied to the state seen by CLUBB
Positive feedback between cloud-top cooling and stratocumulus amount enhances the model’s response to coupling frequency

- Shorter coupling interval
- Less cooling applied to the state seen by CLUBB
- Weaker turbulence
- Reduced stratocumulus amount, less cloud liquid
Diagnostics from inside CLUBB support our hypothesis

- Weaker turbulence and buoyancy flux in the boundary layer
- Decreased convective stability at cloud top

Single-column simulation further confirms the role of radiation

- DYCOMS-II RF01 case
- No deep convection
- No horizontal advection
- With or w/o microphysics, with or w/o shortwave radiation, model shows the same qualitative behavior
Impact of process coupling appear to be time and location dependent - why?

10-year mean ΔCRE caused by more frequent coupling between cloud macro/microphysics and rest of model.
The proposed mechanism is expected to be valid only when radiative cooling is sufficiently strong to result in a negative out-of-subcycle T-tendency.

Seasonal averages of out-of-subcycle T-tendency

Monthly mean out-of-subcycle T-tendency v.s. ∆CRF
Conclusions so far

• Time step sensitivity is non-negligible in EAMv1’s present-day climate simulations
  ▪ Inconvenient for model developers focusing on model fidelity
  ▪ Indication of significant time-stepping error needing to be addressed

• Sources and root causes of time step sensitivity can be identified and addressed
• Process coupling is an important area to put more efforts in
On-going and future work

Figure 11. As in Figure ??, but showing the longwave (LW, top row), shortwave (SW, middle row), and total (bottom row) CRE.

Coupling between cloud macro-/microphysics and rest of model

More advanced process coupling methods

Shallow cumulus and stratiform cloud macro/microphysics

Numerics inside CLUBB; macro-/microphysics time steps

Deep convection and its interaction with dynamics etc.

Closure assumption and numerical coupling
Can the $\Delta t / \tau$ ratio explain our observed time step sensitivities? Yes, but there is more to it.