Improving the Numerical Accuracy and Physical Realism of Process Coupling in an Atmospheric General Circulation Model

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A quote from Beljaars et al. (2004, 2018)

“Numerics of parametrization is perhaps less developed as it is neither pure numerics nor parametrization. Traditionally the numerics of parametrization is handled by parametrization experts and they focus on the formulation of the equations. Solving them is often considered to be a secondary issue. Recently, the topic has received more attention, as it is realized that parametrization assumptions can be completely overwhelmed by errors in the numerical approximation.”


An example of numerical error overwhelming physics assumptions

Annual and zonal mean H$_2$SO$_4$ gas concentration (modules cm$^{-3}$) in ECHAM5-HAM2

Change aerosol nucleation parameterization

Change time integration scheme for H$_2$SO$_4$ gas

Zhang et al. (2012, ACP, doi: 10.5194/acp-12-8911-2012, Figure 2)
Convection-permitting simulations are not exempt from time integration problems

Impact of changing $\Delta t$ between 1 s and 15 s in the limited-area model COSMO (1 km resolution)

Barrett et al. (2019, JAMES, doi: 10.1029/2018MS001418)
In EAMv1, shortening time steps to 1/6 of the default leads to 20%-50% reduction in the subtropical low-cloud amount and total cloud radiative effect.

Relative differences in 10-year averages, $\Delta t/6$ vs. v1_CTRL

EAMv1 results at 1-degree horizontal resolution. See Wan et al. (2021, GMD, DOI: 10.5194/gmd-14-1921-2021)
Shortening the time steps results in systematic increases in model biases, suggesting non-negligible error compensation in the default configuration.

Model biases in 10-year mean present-day climate

(a) Relative error in global mean

(b) Relative error in global pattern

Simulation setup
- Active atmosphere and land
- Year 2000 forcing
- ne30_ne30 (1-degree)

Source of obs. data: NCAR AMWG diagnostics package
Reducing time-step sensitivity can have practical benefits for multi-resolution configurations, e.g., the Regionally Refined Model (RRM)

- EAMv2 RRM uses high-res $\Delta t$ for the dycore but low-res $\Delta t$ for the parameterizations (Tang et al. 2020)
- Shorter $\Delta t$ for parameterizations has been found to result in
  - Significant changes in the atmospheric energy balance
  - Need for re-tuning of empirical parameters (tedious!)

Figures from Qi Tang et al., “Regionally refined model updates for the E3SMv2 atmosphere model”, Oct. 2020, ESMD/E3SM PI Meeting. Courtesy Qi Tang @LLNL
Reducing time-step sensitivities in EAM is necessary. Revealing the sensitivities is only the start

Steps needed

1. **Attribution**
   - Which parts of the model are the culprits?

2. **In-depth understanding**
   - Why does the model behave this way?
   - How does the model physics and numerics interact with each other?

3. **Improvement**
   - How to reduce the undesirable sensitivities at reasonable computational costs?

Methods we find effective

- Sensitivity experiments using sub-stepping and alternative process coupling methods
- Budget analysis
- Sub-time-step behavior of solution and processes
- Idealized models
- A new theoretical error analysis
1. Attribution Time Integration Error

Wan et al. (2021, GMD, doi: 10.5194/gmd-14-1921-2021)
See also: Santos et al. (2021, JAMES, doi: 10.1029/2020MS002359)
We make use of flexibilities in CAM/EAM’s code and data structures

- Subcycles have been implemented for various parameterizations and the dynamical core
- Many are configurable via namelist

- Primary method for process coupling is sequential splitting (time splitting), but
  - All parameterizations return tendencies
  - Physics driver is responsible for updating model state
  - “Physics buffer” provides a flexible data structure to save states or tendencies if needed

- Sensitivity experiments with sub-stepping and/or alternative coupling methods can be tested without a huge amount coding
Process coupling is a significant source of time-step sensitivity in the subtropics.
Impact of process coupling on subtropical marine stratocumulus

Weakened SWCRF due to a proportional shortening of all major time steps

Coupling between stratiform cloud parameterizations and rest of model

Step size used by shallow cumulus and stratiform cloud parameterizations

Deep convection and its coupling with other processes

Coupling of radiation and deep convection

$\Delta t/\tau$ in deep convection

Residuals attributable to the coupling frequency and closure formulation for deep convection
2. Understanding the Interplay Between Physics and Numerics
Background: the “mac-mic” subcycles in EAM

“Physics time step”
- The primary coupling time step (deep convection, radiation, aerosols, etc.)
- 30 min in 1-degree simulations

CLUBB
- Unified parameterization for turbulence, shallow convection and condensation (“mac”)
- Subcycled together with microphysics (“mic”)
- Default is 6 subcycles per “physics time step”
The “mac-mic” sub-cycles in EAM, a simplified view

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

- **EAMv1 CNTL**
- **30 min**
- **5 min**

![Graph showing the concentration of stratiform cloud liquid over 5 time steps with 30 min and 5 min intervals.](image-url)
The original schemes subcycles sources and sinks together for cloud liquid. "Dribbling" does that for supersaturation, too.
For subtropical marine stratocumulus, in addition to a smoother evolution, dribbling also leads to a drift of the mean state – why?

Figure 1: EAMv1 results. Left: time series of global mass-weighted mean stratiform cloud liquid mixing ratio in two simulations using 1 degree horizontal resolution, showing the changes from sub-cycle to sub-cycle and after different physical processes (CLUBB and MG). Red is the default EAMv1. Blue is with "dribbling". Right: same as left panel but for the average between 700 hPa and 1000 hPa over the Peruvian stratocumulus region. Green is a reference simulation that uses small step sizes and no sub-cycling.

Global mean of vertically integrated CLDLIQ

Peruvian stratocumulus region,
4-hour time series of CLDLIQ (700-1000 hPa)
The impact of dribbling on marine stratocumulus depends on geographical location - why?

![10-year mean ΔCRE caused by dribbling](image)

10-year mean ΔCRE caused by dribbling

90N 60N 30N 0 30S 60S 90S

90E 135E 180 135W 90W 45W 0 45E

-15 -10 -5 0 5 10 15

Figure 13. Attribution of the 10-year mean CRE differences shown in the left column of Figure 11. Left: differences between v1_Dribble and v1_CTRL revealing the impact of coupling between the subcycled cloud macro-/microphysics and the rest of EAM. Right: differences between v1_CPL+DeepCu_Shorter and v1_Dribble revealing the impact of step sizes used by various other parameterizations (deep convection, gravity wave drag, various aerosol processes) and the coupling among them. White indicates statistically insignificant differences. The simulation setups are summarized in Tables 1 and A1. Flowcharts are shown in Figures 1, 12, and A2b.
...and we also saw seasonal differences

Annual cycle of CRE over the Peruvian stratocumulus region

Seasonal averages of out-of-mac-mic $dT/dt$

Peru

California
Impact of dribbling appears to be strongly correlated to cloud-top dT/dt

Monthly mean out-of-subcycle dT/dt v.s. impact of dribbling

Seasonal averages of out-of-mac-mic dT/dt
Sequential splitting results in a direct impact of coupling step size on the atmospheric state seen by CLUBB

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

- Shorter coupling interval
- Less cloud-top cooling applied to the state seen by CLUBB
- Weaker turbulence
- Reduced stratocumulus amount, less cloud liquid
Weaker TKE and buoyancy flux in the PBL seem to support our hypothesis.
How can we further verify the hypothesis?

- Piggybacking a second, diagnostic calculation of CLUBB would be useful but tricky to implement
- Construct an idealized (toy) model to mimic the mac-mic subcycles

\[
\frac{ds}{dt} = D + F - C
\]

\[
\frac{dl}{dt} = C - I
\]

Two unknowns
- s: supersaturation (kg/kg)
- l: cloud water mixing ratio (kg/kg)

Two constant sources of condensable water
- D: dynamics and radiation
- F: surface evaporation and turbulence

Parameterized condensation (linear)
\[
C' = \frac{s}{\tau_s} \quad \tau_s = 1 \text{ s} \ll \Delta t.
\]

Parameterized microphysics (rain formation): KK2000 autoconversion
\[
I = \alpha l^{2.47}
\]
Adding terms to include positive feedback

\[ \frac{ds}{dt} = D + F - C \]
\[ \frac{dl}{dt} = C - I \]

More cloud liquid leads to more radiative cooling \( \Rightarrow \) higher supersaturation

\[ \frac{ds}{dt} = D + \gamma \left( \frac{l}{l_{ref}} - 1 \right) D + F - C \]
\[ \frac{dl}{dt} = C + \beta \left( \frac{s}{s_{ref}} - 1 \right) C - I \]

More radiative cooling \( \Rightarrow \) stronger turbulence, more condensation
Numerical simulations using the toy model

\[ \frac{ds}{dt} = D + F - C \]

\[ \frac{dl}{dt} = C - I \]

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**GdB region: Feedback off with KKG2000 mic. (Euler forward) and Instant mac. Integration**

No feedback, no drift

**Sc region: Feedback on with KKG2000 mic. (Euler forward) and Instant mac. Integration**

30 min

\[ \frac{ds}{dt} = D + \gamma \left( \frac{l}{l_{\text{ref}}} - 1 \right) D + F - C \]

**5 min**

\[ \frac{ds}{dt} = D + \gamma \left( \frac{l}{l_{\text{ref}}} - 1 \right) D + F - C \]

\[ \frac{dl}{dt} = C + \beta \left( \frac{s}{s_{\text{ref}}} - 1 \right) C - I \]
Dribbling provides more frequent process coupling and more accurate results

The purpose of constructing the first model (or, the one special, simpler case of model #2) is to explain that, while sub-cycling CLUBB and MG2 together seem to have provided an apparent tight coupling between the direct source and sink of stratiform cloud water, the ultimate (primary) source of cloud water is the processes outside the sub-cycles that lead to supersaturation of water vapor. Hence "dribbling" is necessary for achieving a tight coupling between cloud liquid sources and sinks and for avoiding the distinct strong increase of liquid water mixing ratio seen in the red time series in Figure 1 after the first call of CLUBB in each time step.

The purpose of constructing the second model is to explain the systematic decrease of the cloud liquid water seen in the subtropical marine stratocumulus regions. The key point we make is that cloud radiative cooling, especially its role of driving the boundary layer turbulence and hence providing a substantial small-scale source of cloud liquid in the stratocumulus clouds, is the key mechanism that leads to the systematic shift of time series in the right panel of Figure 1.

See also Chris Vogl’s presentation on a new theoretical error analysis (Friday morning)
3. Reducing Time-step Sensitivities Using Revised Coupling

Our recipe

• Perform budget analysis for prognostic variables of interest
• Identify strong sources and sinks
• Combine physical intuition with theoretical error analysis to review current coupling method and develop alternative schemes
• Assess old and new schemes in EAM
Example 1: Trade Cumulus
When investigating time-step sensitivities in the Peruvian stratoculumus region, we noticed strong near-surface dT/dt gradient

Seasonal mean out-of-mac-mic dT/dt profiles in the Peruvian stratocumulus region, default EAMv1

- Attributable to longwave radiation
- Also seen in global average and in averages over other regions
- Seen in L72 runs but not in L30 runs
- Is physical: L72 grid starts to resolve surface layer
Which process could be sensitive to near-surface heating gradients?
Parallel splitting of radiation and deep convection is expected to affect regions where radiation has a significant role in the CAPE budget.
This revision + the “dribbling” substantially reduces time-step sensitivity in subtropical low clouds in EAMv1

Differences in annual mean low-cloud fraction

- Negligible computational cost
- Very simple, non-intrusive code changes at the physics driver level
Example 2: Dust Life Cycle
Dust aerosol in EAMv1

Global mean dust lifetime from Feng et al. (2021, in review)

<table>
<thead>
<tr>
<th></th>
<th>CAM5 L30</th>
<th>EAMv1 L30</th>
<th>EAMv1 L72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burden</td>
<td>22.4 Tg</td>
<td>28.3 Tg</td>
<td>22.2 Tg</td>
</tr>
<tr>
<td>Lifetime</td>
<td>2.6 days</td>
<td>2.4 days</td>
<td>1.9 days</td>
</tr>
</tbody>
</table>
Budget analysis reveals primary sources and sinks

One month mean dust mixing ratio tendency profiles averaged over dust source regions

- Emission
- Dry removal
- Large-scale transport
- Turbulent mixing
- Wet removal

- Strongest sources and sinks occur in the lowest model layer
- Instantaneous, column-by-column data also show the same feature
Sequence of calculation in the default EAMv1 is problematic

- Dust emission in the real world happens in turbulent environments
- Particles are emitted to – and temporarily trapped in – the bottom layer
- Dry removal is calculated before turbulent mixing and is strongly overestimated

- Better approach is to numerically solve all three processes together
- Quick and easy revision: use parallel splitting for emission and dry removal
The simple revision substantially increases dust loading, as expected.
Dust lifetime is substantially increased. Sensitivity to vertical resolution is largely removed.

- No additional computational cost
- Very simple, non-intrusive code changes at the physics driver level
Remarks on vertical resolution

• Both examples appeared to be vertical resolution issues at a first glance
• Real culprit was suboptimal process coupling (i.e., thin model layer only exacerbated the problem)

• L72 grid has a 20-m thick bottom layer
• Is EAM ready to resolve the surface layer? Perhaps not.
  ▪ Might have similar coupling problems elsewhere in the time loop
  ▪ Likely have assumptions of bottom layer thicker than canopy height in various parameterizations
Remarks on budget analysis

- A key element in our toolkit
- Coding can be tedious; code maintenance can be an issue
- Conditional sampling can be important, but
  - Online sampling can pose code development and maintenance challenges
  - Sampling during postprocessing can require a huge amount of instantaneous output

We felt the pain in our earlier investigations, so we wrote a new online diagnostics tool to address these issues for EAM.
Model developer/user’s perspective

- General-purpose tool, motivated by numerics work but can be used for physics-focused studies
- Budget analysis or conditional sampling, or combined
- Single or multiple sampling conditions in one run
- Online vertical integral
- Runtime configurable through namelist variables; requires no or minimal code changes from the user

Software developer’s perspective

- Uses new data structures to track model state and processes during time integration
- Uses generalized algorithms for budget analysis and conditional sampling
- Currently assumes model uses sequential splitting but possibly adaptable to other coupling methods
- Will be further extended and improved
Conclusions
“…In other words the physics of the numerical solution may be different from the parametrized equations due to numerical errors. In that case the choice of numerical scheme and its optimization has become part of the parametrization assumptions which is undesirable. From the model development point of view, a more attractive approach is to have a numerical scheme that solves the parametrized equations with an accuracy that is better than the uncertainty of the parametrization. In this way, parametrization questions can be separated from numerical issues.”


Reducing time-step sensitivities in EAM is necessary. We have found some effective methods and obtained encouraging results.

- **For error attribution**
  - Sensitivity experiments using sub-stepping and alternative process coupling methods

- **To obtain in-depth understanding and make improvement**
  - Budget analysis
  - Sub-time-step behavior of solution and processes
  - Idealized models
  - Theoretical error analysis
Future work

Near-term: address EAM's urgent needs
• Reduce time-step sensitivities related to deep convection and ice clouds
• Perform comprehensive budget analysis for all prognostics variables to identify process coupling issues

Longer-term: explore more advanced, cost-effective process coupling methods
• Rearrange some parameterizations based on budget analysis results and characteristic time scales
• Explore multirate time integration methods

In addition to process coupling
• Improve numerical accuracy of individual parameterizations (e.g., turbulence, cloud microphysics)
• Improve time-step convergence of parameterizations (and eventually, the full model)