Improved model performance through parallel coupling of physics and dynamics

AMWG Winter Meeting – February 12, 2018
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Introduction

• Coupling paradigms
  – Approaches
  – Implementation
• Results
  – Improved Performance (The Good,)
• Problems and Strategies
  – Mass Conservation (the Bad,)
  – Stability Concerns (and the Ugly)
• Climate Impact
• Conclusions
(A) The Earth is divided into a cubed sphere of quadrilateral elements.

Figure 1: Dynamics and physics domains for the ACME model. (A) cubed sphere
(A) The Earth is divided into a cubed sphere of quadrilateral elements.

(B) Dynamics is solved on individual spectral elements.

$$(1^\circ) \approx 5.4K \text{ elements}$$

$$(1/4^\circ) \approx 86.4K \text{ elements}$$

Figure 1: Dynamics and physics domains for the ACME model. (A) cubed sphere, (B) example spectral element.
Process Splitting: Domain Decomposition

(A) The Earth is divided into a cubed sphere of quadrilateral elements.

(B) Dynamics is solved on individual spectral elements.

(C) Physics is solved over a set of columns defined by the Gauss-Labatto points of a spectral element.

\[(1^\circ) = 5.4K \text{ elements, } 48.6K \text{ columns} \\
\left(\frac{1}{4}\right)^\circ = 86.4K \text{ elements, } 777.6K \text{ columns}\]

Figure 1: Dynamics and physics domains for the ACME model. (A) cubed sphere, (B) example spectral element, (C) example physics column. Image credit: Dennis et al. (2012) Int. J. of High Performance Computing Applications (A and B) and Neale et al. (2010) CAM 4.0 (C)
- Sub-grid scale processes
- Includes updates from surface model components
- Produces tendencies in $T$, $U$, $V$ and $Q$
- Handled by `phys_run1` and `phys_run2`

- Solves equations of state
- Produce a model state in $T$, $U$, $V$ and $Q$, and...
  - $ps$, $phis$, $omega$, $pint$, $pmid$, $pdel$, $rpdel$, $exner$, and $s$
- Handled by `stepon_run3`
Process Splitting

**"Physics" (Phys)**
- Sub-grid scale processes
- Includes updates from surface model components
- Produces tendencies in T, U, V and Q
- Handled by `phys_run1` and `phys_run2`

**"Dynamics" (Dyn)**
- Solves equations of state
- Produce a model state in T, U, V and Q, and...
  - `ps`, `phis`, `omega`, `pint`, `pmid`, `pdel`, `rpdel`, `exner`, and `s`
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**Fluid “Dynamics”:**
- there are `qsplit` dynamics steps per tracer step

**“Tracer” Advection:**
- there are `rsplit` tracer steps per remap step

**Vertical “Remap”:**
- there are `nsplit` vertical remap steps per physics step
“Physics” (Phys)

- Sub-grid scale processes
- Includes updates from surface model components
- Produces tendencies in T, U, V and Q
- Handled by phys_run1 and phys_run2

“Dynamics” (Dyn)

\[ \frac{\partial (T, U, V, Q)}{\partial t} \]

- Solves equations of state
- Produce a model state in T, U, V and Q, and...
  - \( ps, phis, omega, pint, pmid, pdel, rpdel, exner, \) and \( s \)
- Handled by stepon_run3

Vertical “Remap”:

- there are nsplit vertical remap steps per physics step

Fluid “Dynamics”:

- there are qsplit dynamics steps per tracer step

“Tracer” Advection:

- there are rsplit tracer steps per remap step
Coupling: Sequential Splitting

- Sequential-tendency-splitting (STS), $se_{ftype}=0$
- Sequential-update-splitting (SUS), $se_{ftype}=1$
- Hybrid-tendency-update-splitting (HUS), $se_{ftype}=2$

Fluid "Dynamics": there are $qsplit$ dynamics steps per tracer step
"Tracer" Advection: there are $rsplit$ tracer steps per remap step
Vertical "Remap": there are $nsplit$ vertical remap steps per physics step

Equations:
\[
0: \frac{\partial (T,U,V,Q)}{\partial t}
\]
\[
1: (T, U, V, Q)^*
\]
\[
2: \frac{\partial (T,U,V)}{\partial t}, Q^*
\]

Deep Convection
CLBB = Shallow Convection, Microphysics, and Turbulence
Dry Adjustment
Surface Coupling
Microphysics
Radiation
Motivation

- Both the physics parameterization suite and the SE-dycore have near perfect scalability.
- The scalability of the atmosphere model is limited by the total number of dynamics elements.
- There are ~9X more physics columns than dynamics elements.
- Running physics and dynamics in parallel has the potential to speed up the ATM model by ~2X, even without unlocking more physics parallelism.

Coupling: Parallel Splitting

- **Parallel-splitting (PS),** \( se_{ftype}=3 \)

\[ \frac{\partial (T, U, V, Q)}{\partial t} \]_{phys}

\[ [(T, U, V, Q)^*]_{dyn} \]

- **Physics and Dynamics are run in parallel.**
- **Physics passes tendencies, and Dynamics passes an intermediate state, to a coupling routine.**

**State Update**
Combine tendencies from Phys and Dyn
Tracer Advection: there are \( rsplit \) tracer steps per remap step

Fluid "Dynamics": there are \( qsplit \) dynamics steps per tracer step

Dry Adjustment

Deep Convection

Deep Clouds

Mesoscale Clouds

Microphysics

Turbulence

Convection

CLUBB = Shallow Convection, Macrophysics, and Turbulence

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"Dynamics" (Dyn)

Deep Convection

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State Update

Combine tendencies from Phys and Dyn

\[
\frac{\partial (T, U, V, Q)}{\partial t}_{\text{Phys}} \\
(T, U, V, Q)^{n+1}
\]

\[
(T, U, V, Q)^{n+1}
\]

\[
((T, U, V, Q)^{*})_{\text{Dyn}}
\]

Parallel Splitting (PS), \( se_{\text{ftype}}=3 \)

- Physics and Dynamics are run in parallel.
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- Physics tendencies are combined with the dynamics state.
- The updated state is passed back to Physics and Dynamics.

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- Physics passes tendencies, and Dynamics passes an intermediate state, to a coupling routine.
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Results: (The Good,)

**Sequential-Split**
- The option to run more physics cores than dynamics cores in the SE dycore has been fixed.
- Degraded scalability for runs with more cores than dynamics elements.

Fig: Scalability of EAM v1 on 7.5 degree (ne4) mesh for sequentially split physics/dynamics coupling.
Results: (The Good,)

**Sequential-Split**
- The option to run more physics cores than dynamics cores in the SE dycore has been fixed.
- Degraded scalability for runs with more cores than dynamics elements.

**Parallel-Split**
- Extended scalability of the model (2.5X more cores!).
- Improved performance at high core counts (~40% better performance).

Fig: Scalability of EAM v1 on 7.5 degree (ne4) mesh for sequentially split (top) and parallel-split (bottom) physics/dynamics coupling.
Problems: (the Bad, and the Ugly)
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Mass conservation becomes a concern
Problems: (the Bad,)

Impact of overconsumption by parallel splitting:

- Negative water, energy, or aerosol species. Fixing this often violates conservation
- Overstabilized atmosphere due to competition between resolved and parameterized convection
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- Negative water, energy, or aerosol species. Fixing this often violates conservation
- Overstabilized atmosphere due to competition between resolved and parameterized convection

Mass conservation strategies:
- Hole filling, ”clipping”
- More sophisticated local and global mass borrowing algorithms, e.g. QUILT
Problems: (and the Ugly)

1-Degree simulations go unstable for $\Delta t > 300s$
Problems: Possible Causes (and the Ugly)

a) Inconsistencies in derived variables passed between physics and dynamics.

b) Inconsistencies between physics and dynamics states.

What’s your favorite state format?

1. $\frac{\partial p}{\partial \eta}$
2. $q$
3. All the way!!!
Strategies: Derived Variables (and the Ugly)

- Variables such as $\omega$ are derived in dynamics, but are based on variables which are updated by physics tendencies.
- There may be an inconsistency between the variables updated by physics tendencies and those derived by dynamics.

$$\omega = \vec{u} \cdot \nabla p - \int_{\eta_{top}}^{\eta} \nabla \cdot \left( \frac{\partial p}{\partial \eta'} \vec{u} \right) d\eta'$$
• Dynamics works on a $\eta$-coordinate system, with dependent variable $\frac{\partial p}{\partial \eta} q$.
• Physics updates $q$ directly.
• In order for the two to “talk” the physics tendencies are converted to the $\eta$-coordinate system using $\left(\frac{\partial p}{\partial \eta}\right)^n$.
• In the application of parallel coupling the physics tendencies are applied to the $\left(\frac{\partial p}{\partial \eta} q\right)^*$, the state passed by dynamics.
• There may be an inconsistency in $\eta$-coordinate space between the state that the physics tendencies are applied to.
What is the model impact? ($\Delta t = 300s$):

<table>
<thead>
<tr>
<th>Variable</th>
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<th>Sequential-Split ($\Delta t = 300s$)</th>
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<tr>
<td>PRECT</td>
<td>3.142</td>
<td>3.145</td>
<td>3.074</td>
</tr>
<tr>
<td>FLNT</td>
<td>242.763</td>
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*Based on AMWG Diagnostics

- At fine temporal resolution ($\Delta t = 300s$), the parallel-split coupling behaves well.
What is the model impact? ($\Delta t = 300s$):

The table below shows the global annual average values of various variables for a 1-year simulation under parallel-split and sequential-split coupling at a temporal resolution of $\Delta t = 300s$.

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- At fine temporal resolution ($\Delta t = 300s$), the parallel-split coupling behaves well.
- Comparison between parallel-split and sequentially-split diagnostics shows very little difference between the two solutions.
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*Global Annual Average Values (1-year simulation)*

*Based on AMWG Diagnostics

- At fine temporal resolution ($\Delta t = 300s$), the parallel-split coupling behaves well.
- Comparison between parallel-split and sequentially-split diagnostics shows very little difference between the two solutions.
- There is a greater difference for switching to a smaller timestep from the default of ($\Delta t = 1800s$)
Conclusions:

• We have accomplished parallel-split physics/dynamics coupling,
  • Extends the range of scalability by 2X.
  • A 40% performance boost observed at maximum core counts.
• Climate impact from switching to parallel split is minimal.

• Still have a few issues to resolve,
  • Mass conservation always a concern when coupling in parallel.
  • Address stability issues at higher time steps.
QUESTIONS?
Extra Slides
$\omega$

Sequentially Split

Parallel Split

Difference

$t = 15\text{hr}$

$\Delta t = 1800\text{s}$

$z = 937\text{hPa}$
$q$

Sequentially Split

Parallel Split

Difference

$t = 15\, hr$

$\Delta t = 1800\, s$

$z = 937\, hPa$
Sequentially Split

Parallel Split

Difference

\[ \frac{\partial p}{\partial \eta} q \]

\[ t = 15\text{hr} \]

\[ \Delta t = 1800\text{s} \]

\[ z = 937\text{hPa} \]
$p_s$

Sequentially Split

Parallel Split

Difference

$t = 1800s$
$\Delta t = 1800s$
$z = surface$
Sequentially Split

Parallel Split

Difference

$p_s$

$t = 15\text{hr}$

$\Delta t = 1800\text{s}$

$z = \text{surface}$