The transition of Climate Models into Earth System Models

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Outline

• Introduction

• “Coupling”: An attempt to classify different methods

• Examples, challenges (and solutions)
  1. Atmospheric Chemistry in the Earth System
  2. Atmosphere – Ocean System
  3. On-line nesting: an alternative way to higher resolution

• Summary and Outlook
Computational Earth System Science
(numerical weather prediction and climate simulations)
was from the beginning on exploiting HPC up to the limits …
1950 (Charney, Fjørtoft, von Neumann): first numerical weather forecast on ENIAC (Electronic Numerical Integrator and Computer)

- forecast time: 24 hours
- computation: 24 hours
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forecast time: 24 hours
computation: 24 hours

2008 (Lynch & Lynch): reconstruction on mobile-phone (JAVA-application):

forecast time: 24 hours
computation: < 1 second (!!!)

http://mathsci.ucd.ie/~plynch/eniac/phoniac.html
Deutsches Klimarechenzentrum (DKRZ)

June 2009:
no. 27 of top500
8448 Cores
158 TFlops/s

http://www.dkrz.de
Computational Earth System Science
(numerical weather prediction and climate simulations) was from the beginning on exploiting HPC up to the limits ...

... mainly for two reasons:

• increasing resolution of numerical discretisation(s) (i.e., finer “grids”)  

• increasing complexity by incorporating more and more processes
Computational Earth System Science (numerical weather prediction and climate simulations) was from the beginning on exploiting HPC to the limits …

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“coupling”
The development of climate models, past, present and future

Mid-1970s
Atmosphere
Land surface
Ocean & sea-ice

Mid-1980s
Atmosphere
Land surface
Ocean & sea-ice

Early 1990s
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol

Late 1990s
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Non-sulphate aerosol

Present day
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Non-sulphate aerosol
Carbon cycle

Early 2000s?
Atmosphere
Land surface
Ocean & sea-ice
Carbon cycle
Dynamic vegetation
Atmospheric chemistry

Ocean & sea-ice model
Sulphur cycle model
Non-sulphate aerosols
Land carbon cycle model
Ocean carbon cycle model
Dynamic vegetation
Dynamic vegetation
Atmospheric chemistry

IPCC
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
"coupling": circulation of energy, momentum, constituents

change of "state variables" by physical, chemical, biological, socio-economic processes
Coupling ...

... the prerequisite is the *operator splitting* concept

(Jöckel et al., ACP, 2005)
Coupling ...

... the prerequisite is the *operator splitting* concept

Example:
X = air
temperature

\[ \frac{\partial X}{\partial t} \]

\[ X(t-1) \]

\[ \text{radiation} \quad \text{convection} \quad \ldots \quad \text{diffusion} \]

\[ \text{time integration} \]

(Jöckel et al., ACP, 2005)
Coupling ...

... the prerequisite is the *operator splitting* concept

different numerical algorithms (discretisation, parallel decomposition, cache/vector blocking, ...)

(Jöckel et al., ACP, 2005)
Coupling ...

Example:

basic (dynamical) equations → coupled PDE system

reaction kinetics (chemistry) → coupled ODE system

spectral transform

Rosenbrock-3 (auto)

\( \frac{\delta X}{\delta t} \)

\( X(t-1) \)

(Jöckel et al., ACP, 2005)
Coupling ... a classification (of the “way” how operators “communicate”)

- Internal coupling:
  - Os are part of the same program unit ("task")
  - Data exchange via working memory

- External coupling:
  - Os are split into different program units ("tasks")
  - Data exchange via external storage (files)
  - Data exchange via working memory
  - Involves an add. external program ("coupler")
Coupling … a classification

- **internal coupling**
  - Os are part of the *same program unit* (“task”)
  - data exchange via *working memory*

- **external coupling**
  - Os are split into *different program units* (“tasks”)
  - data exchange via *external storage* (files)
  - data exchange via *working memory*

- **on-line**
  - direct
  - indirect

- **off-line**
  - on-line

choice depends on:
- application
- implementation effort (legacy code!)
- desired sustainability, flexibility, re-usability
→ compromise in minimizing computational and communication overheads

(of the “way” how operators “communicate”)

→ involves an *add. external program* (“coupler”)
Example 1: **internal coupling**

Language level:

\[
\begin{align*}
&\text{CALL subroutine}_1(\ldots, A, \ldots) \quad \text{[INTENT(OUT)]} \\
&\text{CALL subroutine}_2(\ldots, A, \ldots) \quad \text{[INTENT(IN)]}
\end{align*}
\]

more formal: standard model infrastructure + coding standard

- Earth System Modeling Framework (ESMF)  
  \[http://www.earthsystemmodeling.org\]
- Modular Earth Submodel System (MESSy)  
  \[http://www.messy-interface.org, Jöckel et al., ACP, 2005\]
- … (many others)

key: strict separation of *model infrastructure* (4 layer!)

(memory management, I/O, parallel decomp., time control, etc.)

from “process” (and “diagnostic”) formulations
Example 1a: **internal coupling** of Atmospheric Chemistry in MESSy coupling via model infrastructure (nearly object oriented)

- TIMER
- CHANNEL (pointer based memory management and I/O)
- TRACER (special for chemical constituents)
- ...

“operators” = “processes” = “submodels”
Emission

Transformation

Deposition

natural emissions

anthropogenic emissions

Emission

Transport

Deposition

sedimentation

advection

convection

diffusion

Dynamics

radiation

gas phase

aerosol

clouds

dry deposition

wet deposition

scavenging

OCEAN AND BIOSPHERE
photo-chemistry:

\[
A + B \rightarrow C + D \quad : \quad J(\text{light}, \ldots)
\]

\[
B + E \rightarrow F + G \quad : \quad k(p, T, \ldots)
\]

\[
\ldots
\]

\[
\Rightarrow \text{ODE system}
\]
Number* of sub-time steps of the ODE solver for the kinetic system

T106L90MA → \(~ 1.125^\circ \times 1.125^\circ \times 90 (~80 \text{ km}) \); \Delta t = 6 \text{ min}

*vertical average
Number* of sub-time steps of the ODE solver for the kinetic system

T106L90MA → ~ 1.125° x 1.125° x 90 (~80 km) ; Δt = 6 min

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Number* of sub-time steps of the ODE solver for the kinetic system

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*vertical average

Load imbalance due to time dependent stiffness of kinetic (ODE) system → possible solution: dynamic parallel decomposition
Example 2: **internal coupling** *versus* **indirect external coupling**

of an Atmosphere – Ocean System (domain coupling)

MPIOM as MESSy submodel
“coupled to” ECHAM5

MPIOM – OASIS3 – ECHAM5

**task**

(MPIOM as MESSy submodel “coupled to” ECHAM5)

data exchange

atmosphere

ocean
Example 2: **internal coupling** versus **indirect external coupling**

of an Atmosphere – Ocean System (domain coupling)

Processor ID # for 4 x 4 decomposition
Example 2: **internal coupling** versus **indirect external coupling**

of an Atmosphere – Ocean System (domain coupling)

- grid-trafo (semi-parallel)
- “all-gather”

- “gather”
- incl. grid-trafo (serial)
- “scatter”
Example 2: Performance (seconds per simulated month)

The performance depends on:
- HPC system
- Model setup

Indirect external coupling

\[ Y = 0.89207 \times X \]
\[ R^2 = 0.9984 \]

Number of tasks (cores)

(Pozzer et al., GMD, 2011)
Example 3: On-line nesting: an alternative way to higher resolution

- 1-way on-line nested global-regional atmospheric model system (zoom)
- multiple instances possible due to client – server architecture of MMD ...

MECO(n): MESSy-fied ECHAM and COSMO models n-times nested

(Kerkweg & Jöckel, GMDD, 2011a,b; Hofmann et al., GMDD, 2011)
MECO(2) simulation of Eyjafjallajökull eruption plume 2010

TIME: 17–APR–2010 00:00 column density [arbitrary units]

EMAC T106L31ECMWF
(1.125° x 1.125°, 6 min)

COSMO/MESy–EU
(40 km, L40, 3 min)

COSMO/MESy–DE
(7 km, L40, 40 sec)

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Example 3: On-line nesting: an alternative way to higher resolution

**MMD-Server**  
(ECHAM5 or COSMO)

**MMD-Client**  
(COSMO)

MPI based, single sided “point-to-point” communication between c&s tasks with overlapping grids
Example 3: On-line nesting: an alternative way to higher resolution

(Kerkweg & Jöckel, GMDD, 2011b)
Example 3: On-line nesting: an alternative way to higher resolution

no. of tasks
ECHAM-COSMO-40 km
COSMO-7 km

4-4-56 is most efficient!

additional effort to optimize efficiency!
Summary

• ESMs are computationally demanding due to continuously increasing complexity

• Operator splitting is basis for coupling of model components

• Different coupling methods exist; challenge: efficiency – computation versus communication

• Exemplary challenges:
  - Atmospheric Chemistry: internal coupling
    → Load Imbalance (parallel decomp.)
  - Atmosphere – Ocean System: internal vs. indirect external coupling
    → both feasible, best choice depends on model (legacy code!), model setup, HPC-system
  - Global – Regional Nesting: direct on-line coupling
    (client – server approach)
    → complex timing, add. effort to achieve efficiency

• (exascale parallelisation, parallel I/O, memory/core reduction)