Universidade de São Paulo
Instituto de Astronomia, Geofísica e Ciências Atmosféricas

Coupling of the physics and dynamics processes in weather and climate forecasting models

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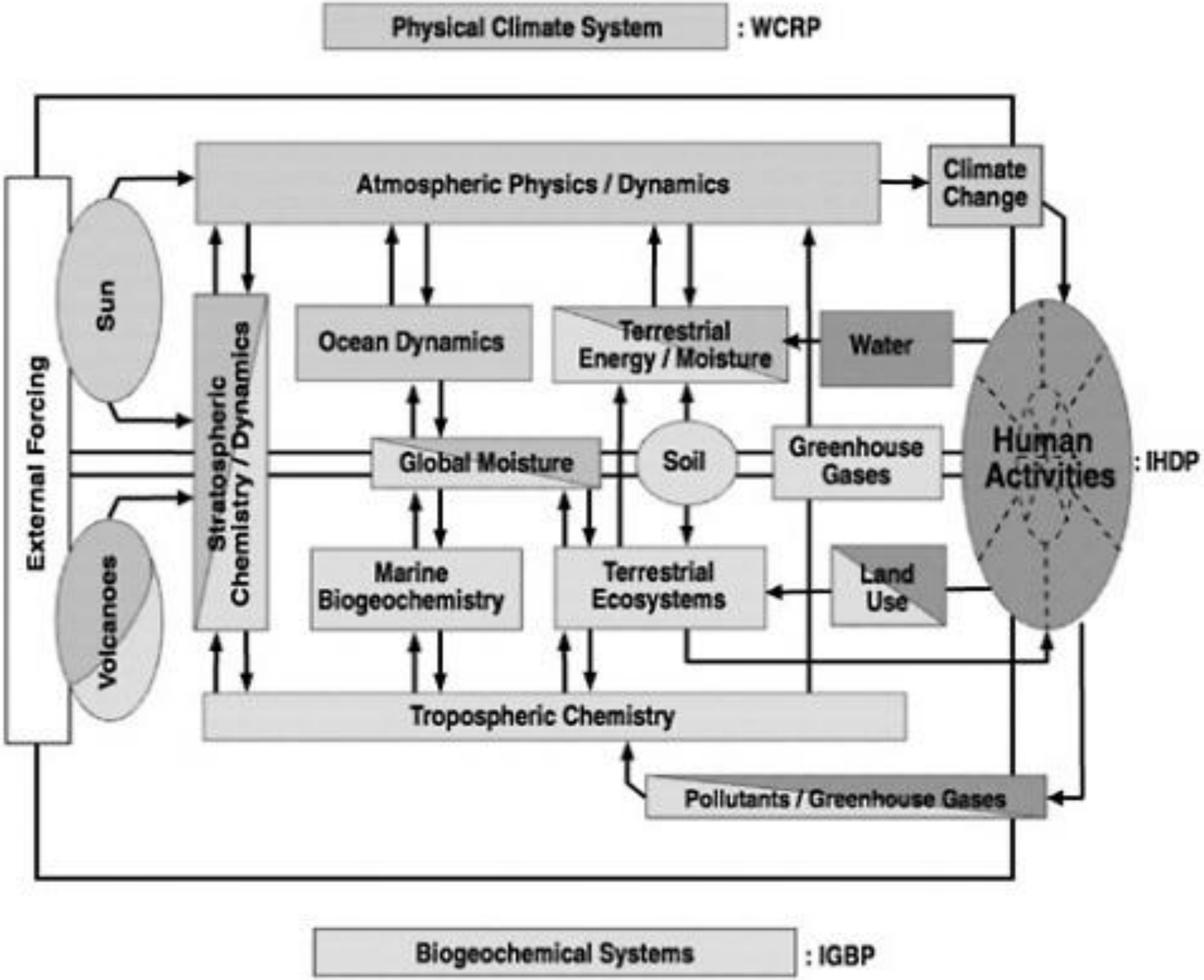
Lecture at the 2nd WCRP Summer School on Climate Model Development: Scale aware parameterization for representing sub-grid scale processes
January 22nd - 31st, 2018
Instituto Nacional de Pesquisas Espaciais, Centro de Previsão de Tempo e Estudos Climáticos, Cachoeira Paulista - SP, Brazil


Physical Climate System
: WCRP
Atmospheric Physics / Dynamics
Climate Change
External Forcing
Sun
Volcanoes
Stratospheric Chemistry / Dynamics
Ocean Dynamics
Terrestrial Energy / Moisture
Water
Global Moisture
Soil
Greenhouse Gases
Human Activities
: IHDP
Marine Biogeochemistry
Terrestrial Ecosystems
Land Use
Tropospheric Chemistry
Pollutants / Greenhouse Gases
Biogeochemical Systems
: IGBP

3D Modelling the Earth Atmosphere System ($X_i = X_i(x,y,z,t)$)

$$\frac{\partial X_a}{\partial t} + L_a X_a = N_a(X_a, X_o, X_v, X_c, X_s) + F_a(X_a, X_o, X_v, X_c, X_s)$$

atmosphere

$$\frac{\partial X_o}{\partial t} + L_o X_o = N_o(X_a, X_o, X_v, X_c, X_s) + F_o(X_a, X_o, X_v, X_c, X_s)$$

ocean+hydrology+ice

$$\frac{\partial X_s}{\partial t} + L_s X_s = N_s(X_a, X_o, X_v, X_c, X_s) + F_s(X_a, X_o, X_v, X_c, X_s)$$

soil

$$\frac{\partial X_v}{\partial t} + L_v X_v = N_v(X_a, X_o, X_v, X_c, X_s) + F_v(X_a, X_o, X_v, X_c, X_s)$$

vegetation

$$\frac{\partial X_c}{\partial t} + L_c X_c = N_c(X_a, X_o, X_v, X_c, X_s) + F_c(X_a, X_o, X_v, X_c, X_s)$$

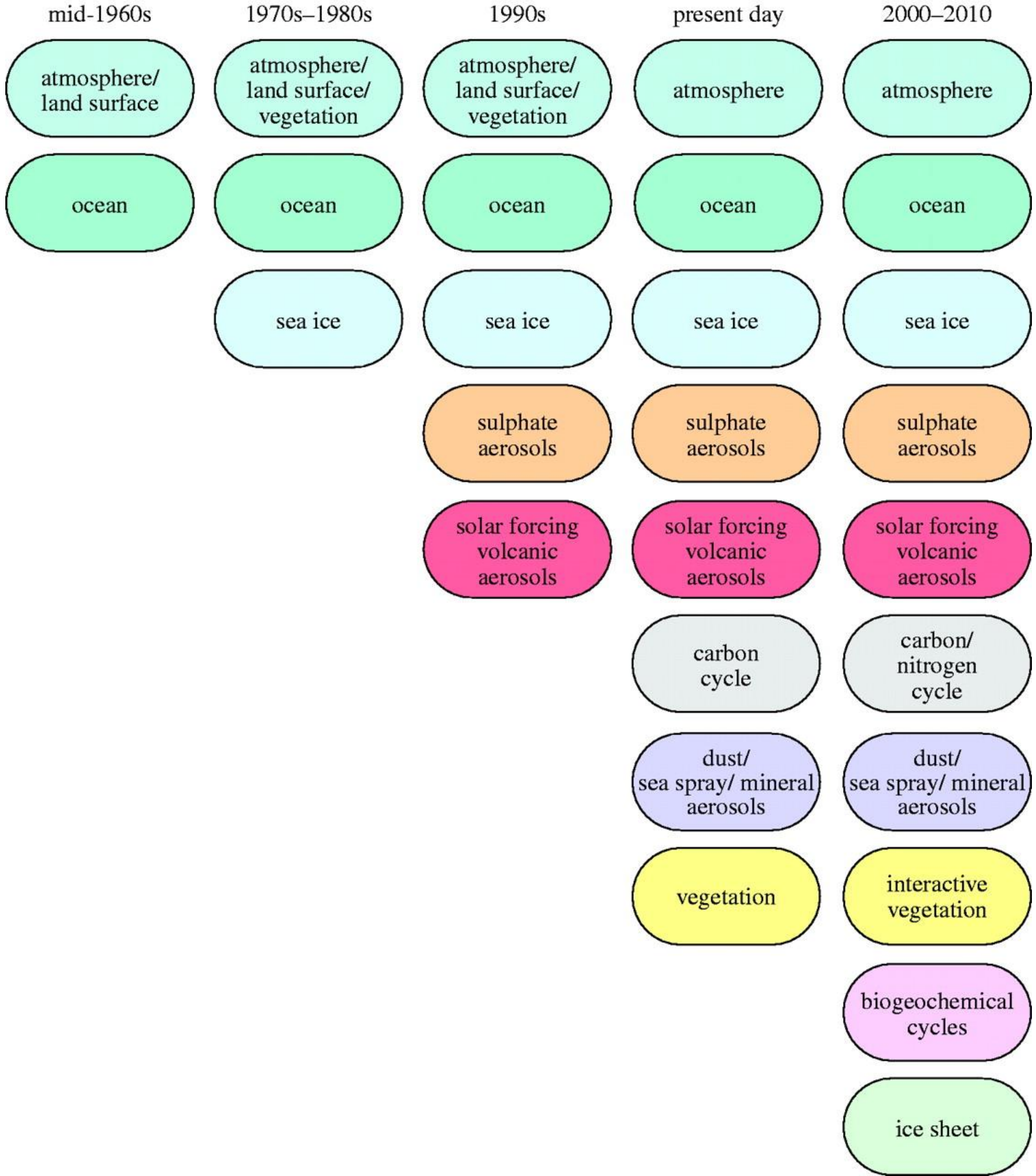
chemical species

$X_a = (u, v, w, T, q_v, q_l, q_r, q_i, \ldots.)$ $\quad X_o = (u, v, w, T, s_v, \ldots)$ $\quad X_s = (T^{i\,s}, W^{i\,s}, N^{i\,n}, \ldots.)$

$X_v = (lai^i, sig^{i\,v}, root^{i\,d}, stom^{i\,c}, VOC^i, C^i, N_i, \ldots.)$

$X_c = (CO_2, CH_4, O_3, NO_x, VOC's, SO_2, \ldots)$

Coupling of the sub-components of the climate system


mid-1960s
1970s–1980s
1990s
present day
2000–2010
atmosphere/ land surface
ocean
atmosphere/ land surface/ vegetation
ocean
sea ice
atmosphere/ land surface/ vegetation
ocean
sea ice
sulphate aerosols
solar forcing volcanic aerosols
atmosphere
ocean
sea ice
sulphate aerosols
solar forcing volcanic aerosols
carbon cycle
dust/ sea spray/ mineral aerosols
vegetation
atmosphere
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carbon/ nitrogen cycle
dust/ sea spray/ mineral aerosols
interactive vegetation
biogeochemical cycles
ice sheet

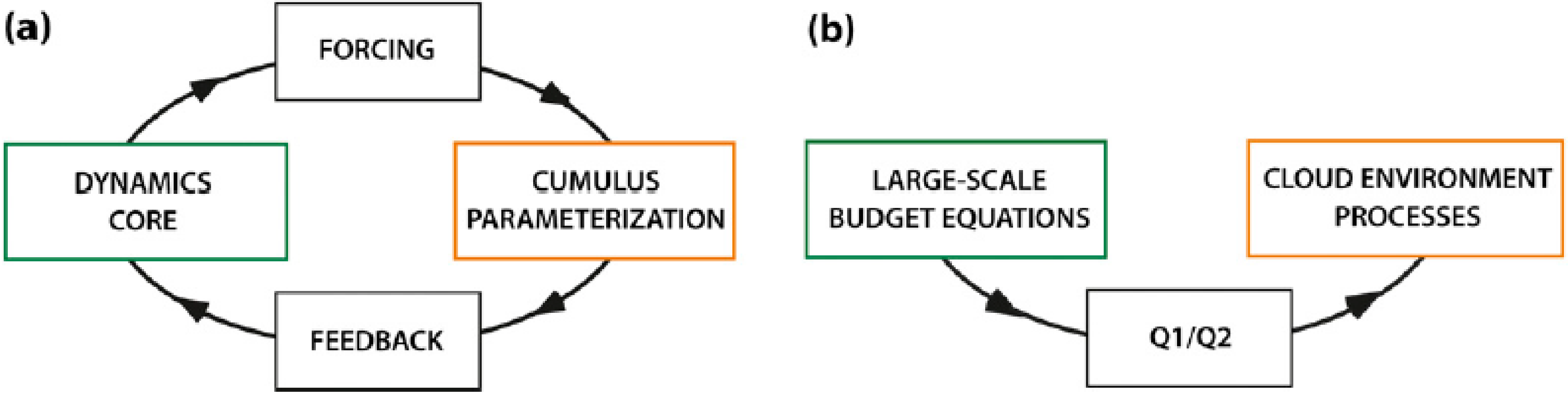

FIG. 16-1. (a) A schematic diagram showing the two-way interaction between the dynamics core and cumulus parameterization. (b) A schematic diagram showing the logical structure of the analysis performed by Yanai et al. (1973).

Chapter 16

Multiscale Modeling of the Moist-Convective Atmosphere

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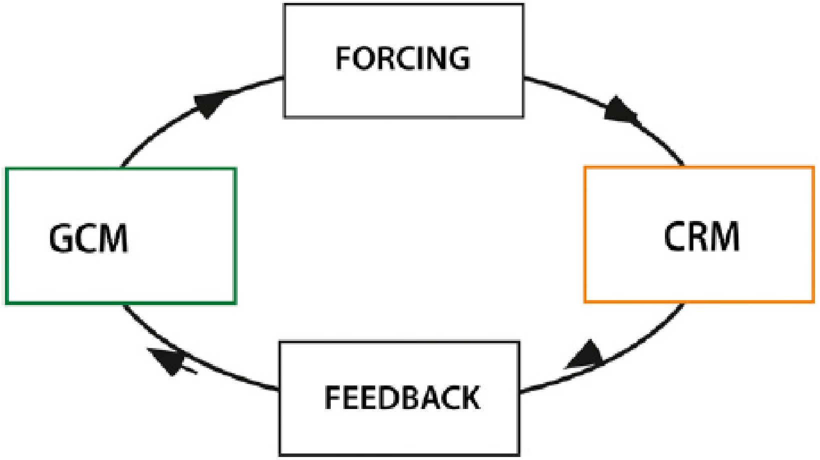
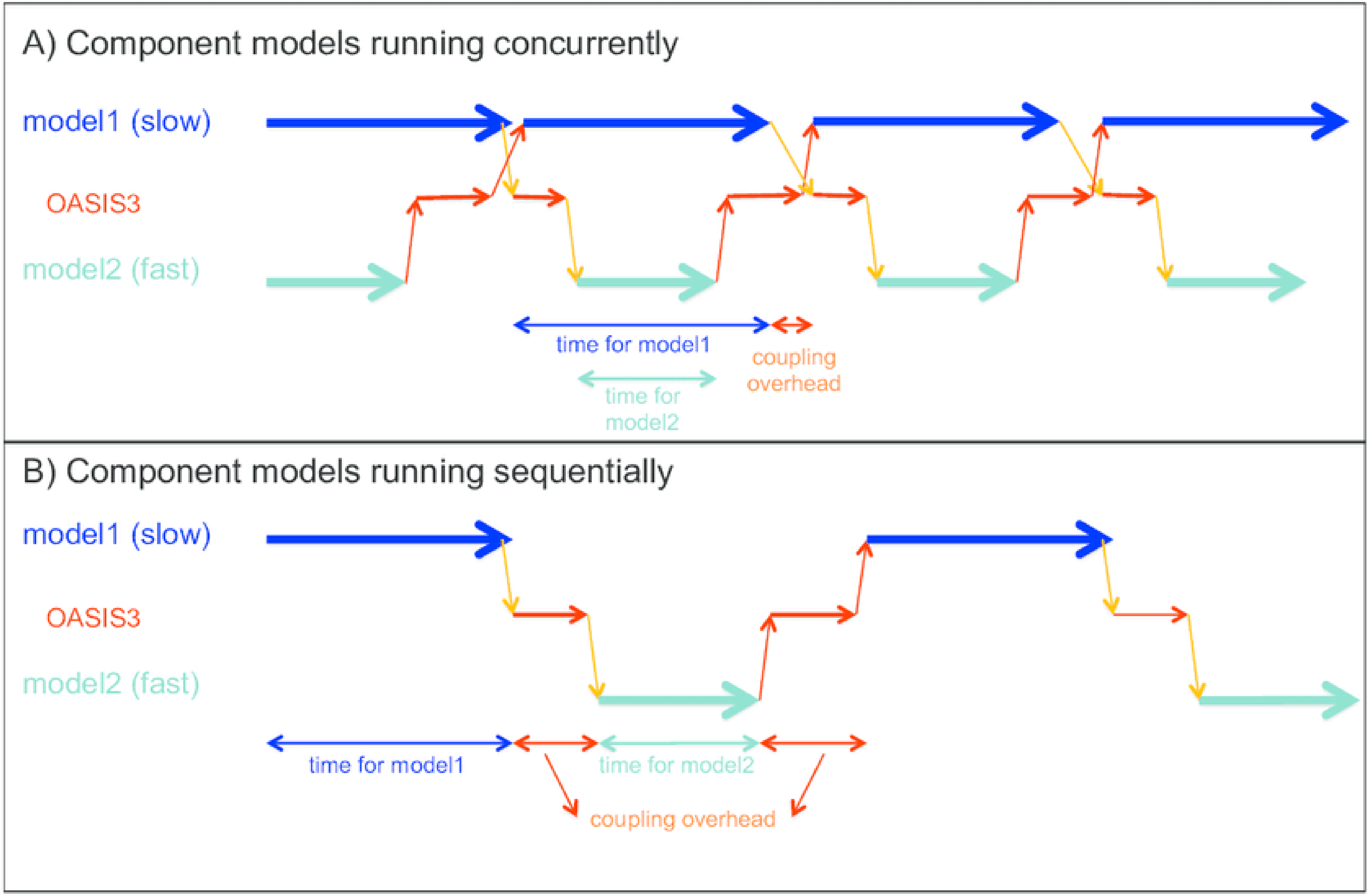
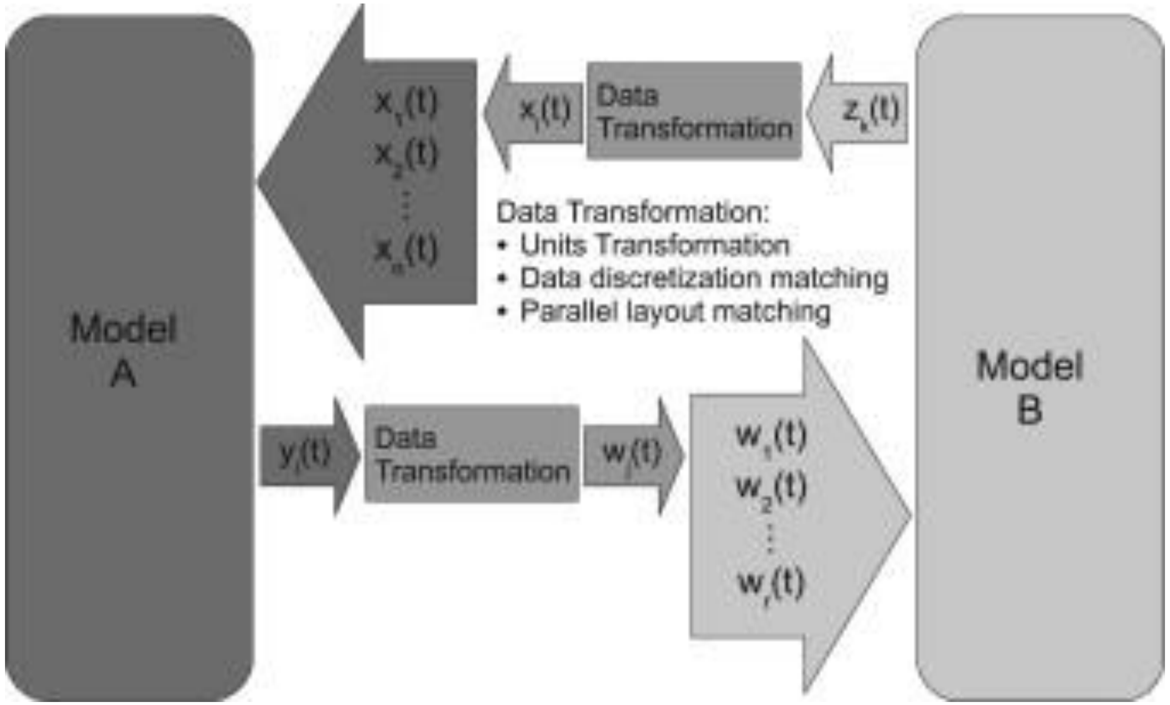
JOON-HEE JUNG
Colorado State University, Fort Collins, Colorado

CHIEN-MING WU
National Taiwan University, Taipei, Taiwan





A) Component models running concurrently
model1 (slow)
OASIS3
model2 (fast)
time for model1
coupling overhead
time for model2
B) Component models running sequentially
model1 (slow)
OASIS3
model2 (fast)
time for model1
time for model2
coupling overhead



ELSEVIER

Mathematical and Computer Modelling

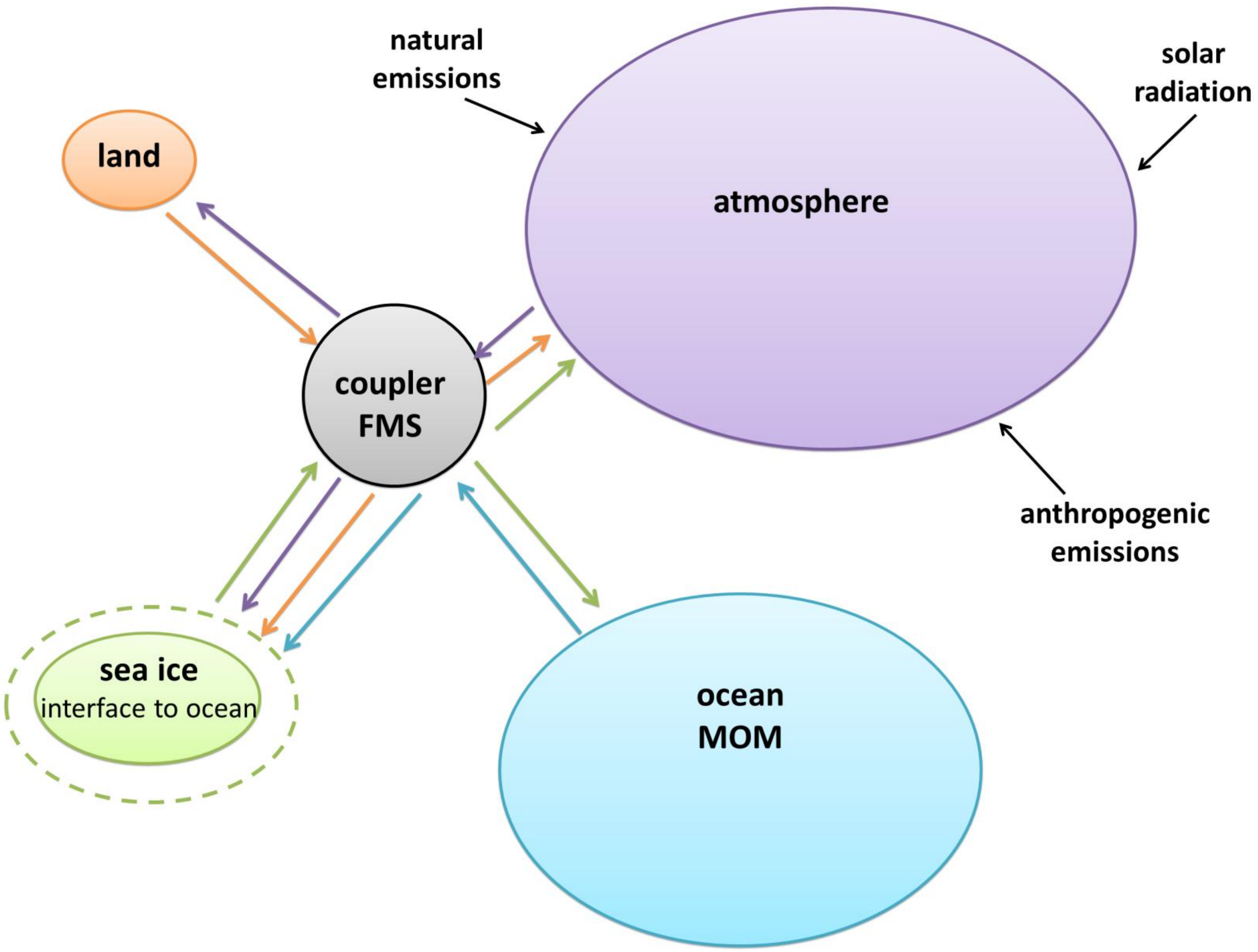
Volume 57, Issues 9–10, May 2013, Pages 2267-2278

Design of a Distributed Coupling Toolkit for High Performance Computing environment

D. De Cecchis [a, c], L.A. Drummond [b], J.E. Castillo [a]

Show more

https://doi.org/10.1016/j.mcm.2011.07.002


natural emissions
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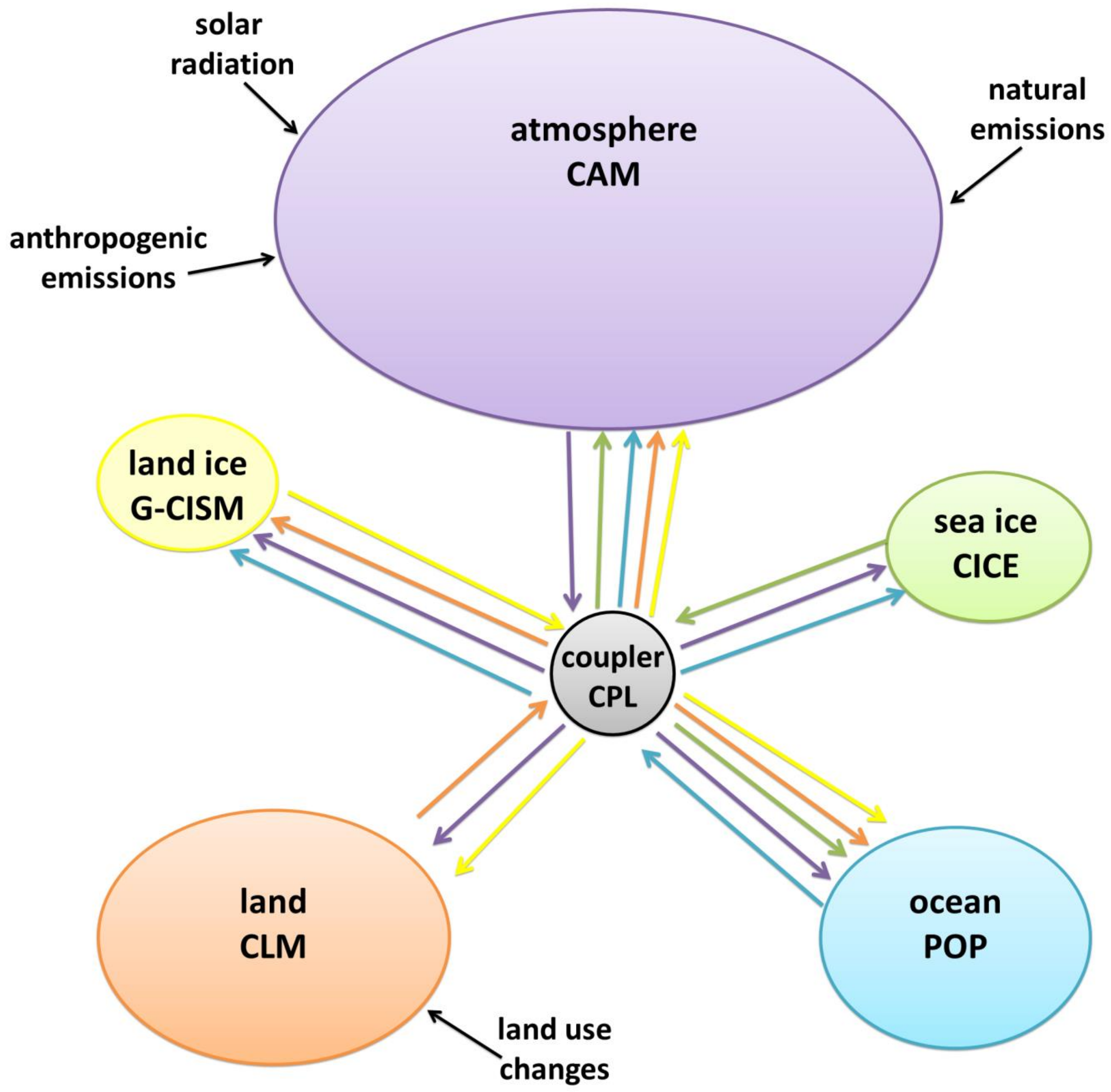
coupler FMS
anthropogenic emissions
sea ice
interface to ocean
ocean MOM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POP
land use
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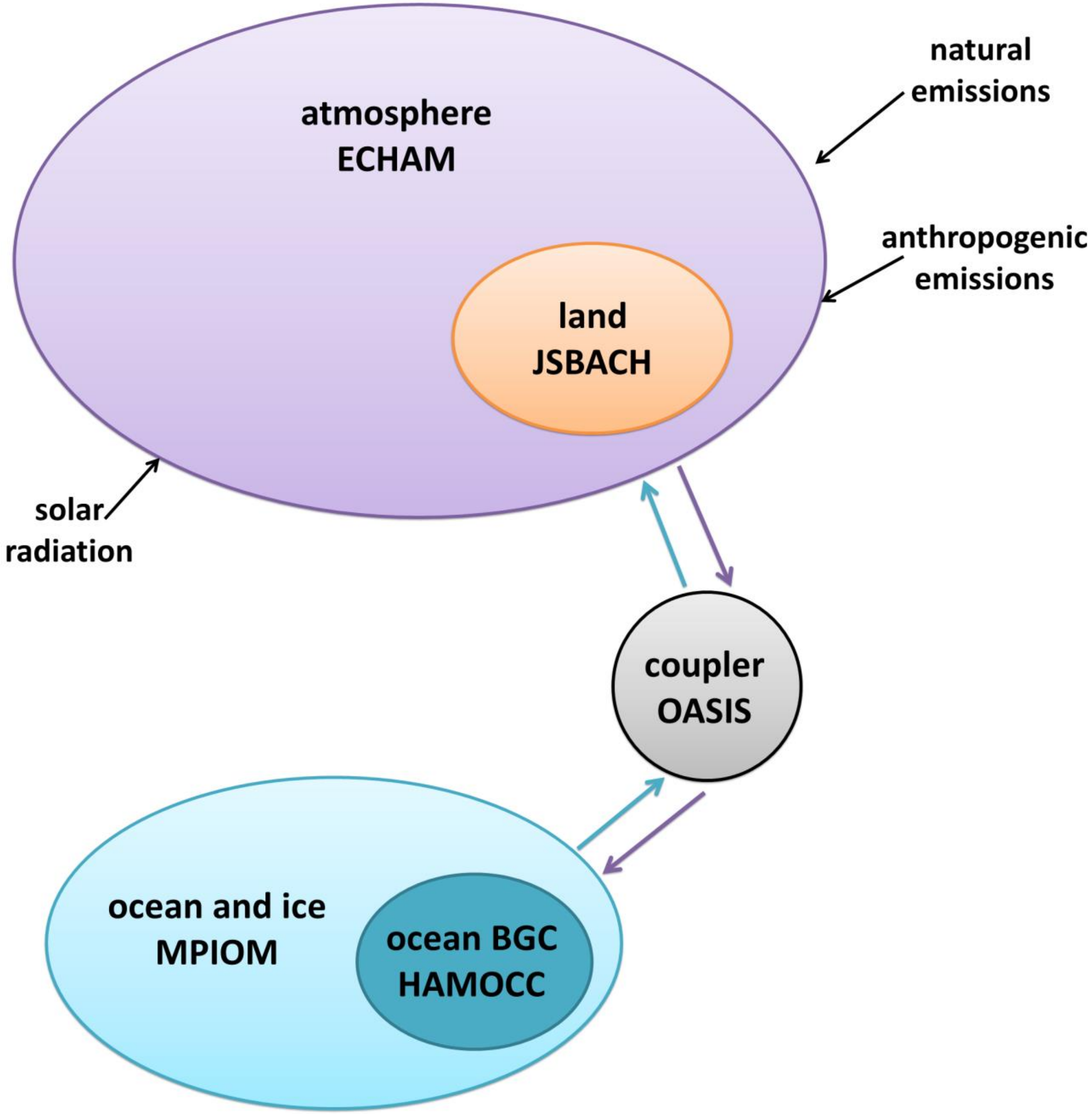
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OASIS
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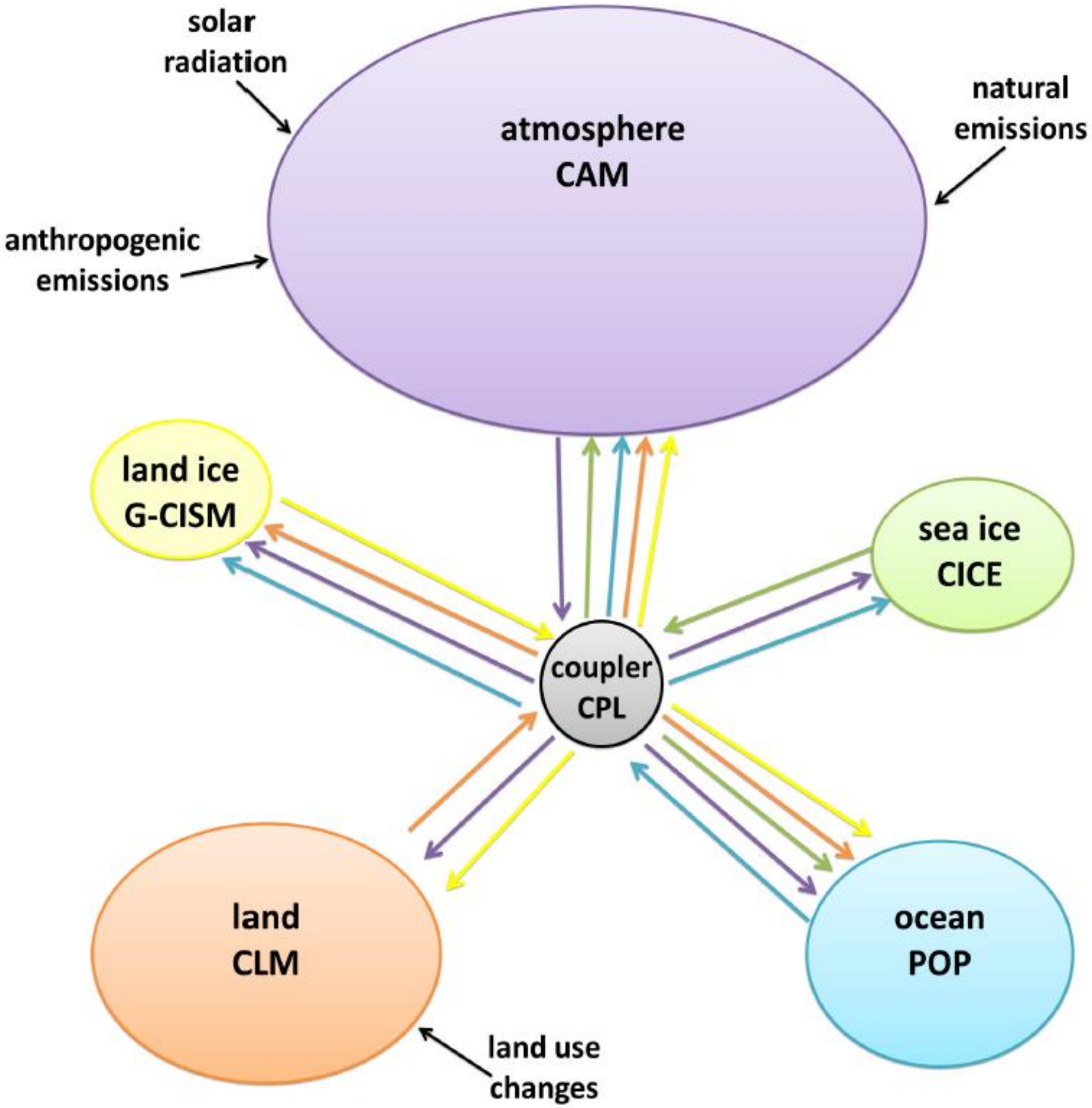
ocean BGC
HAMOCC


solar
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G-CISM
sea ice
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CLM
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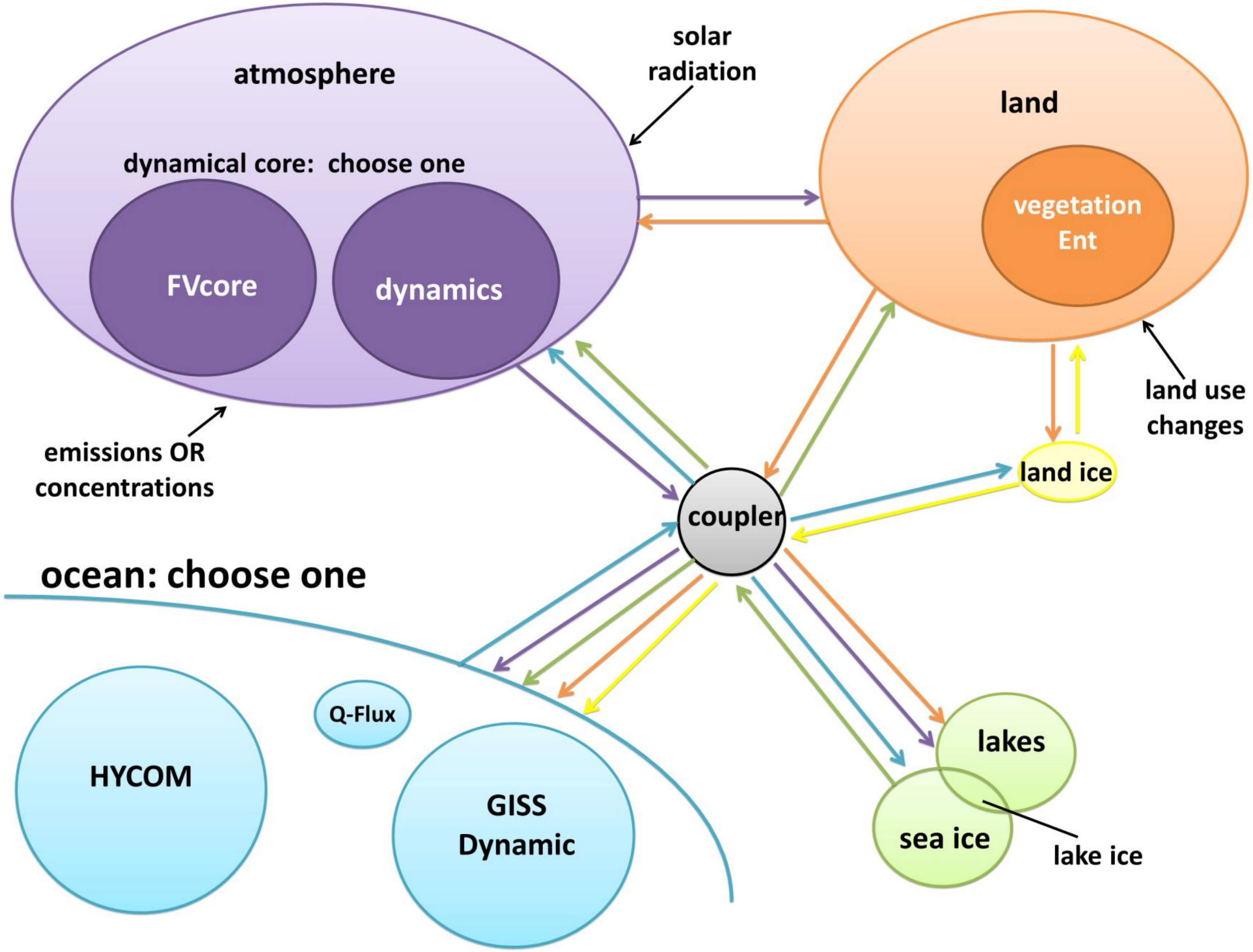
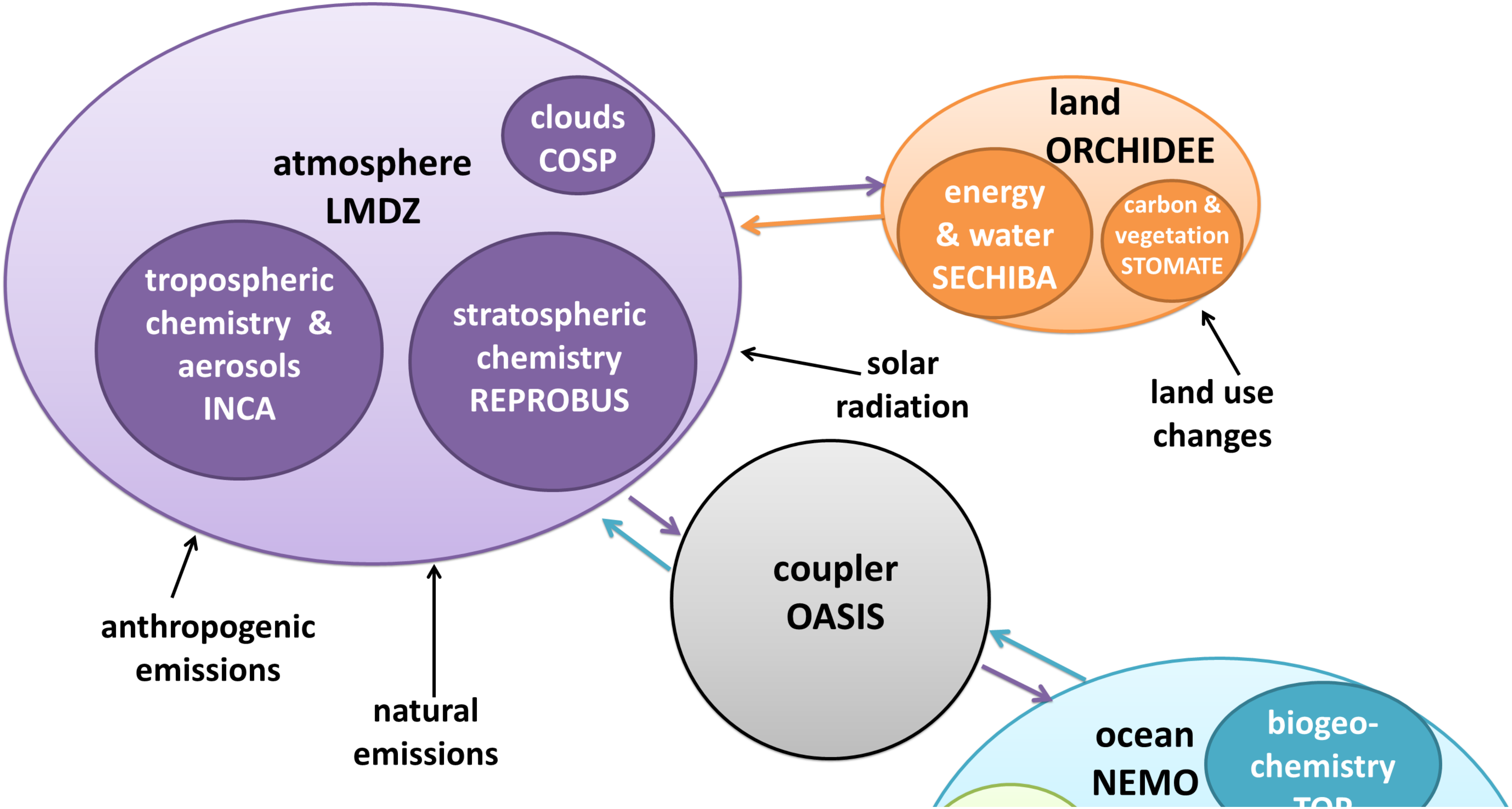
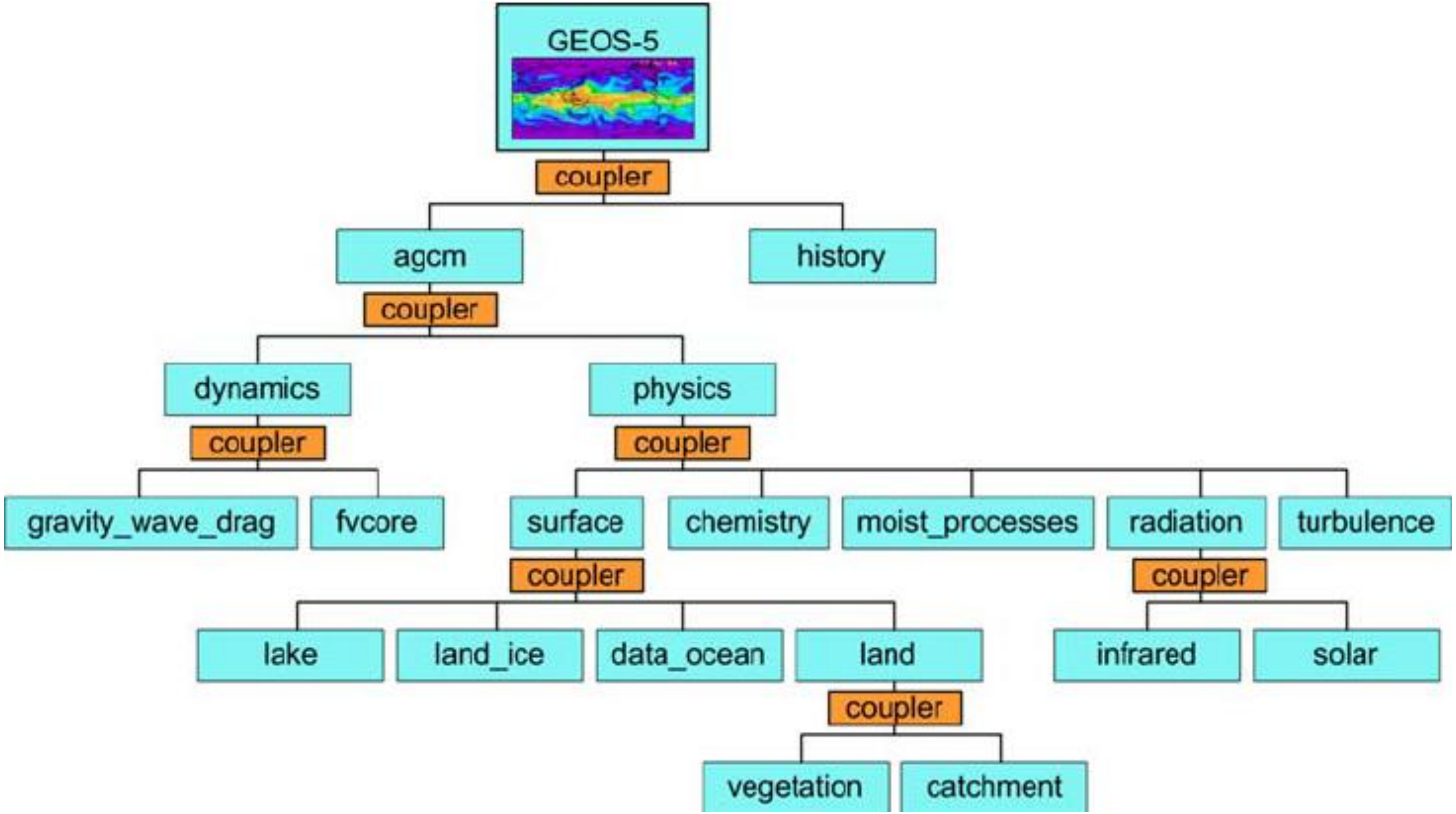
POP
land use
changes



atmosphere
dynamical core: choose one
FVcore
dynamics
solar
radiation
land
vegetation
Ent
land use
changes
emissions OR
concentrations
coupler
land ice
ocean: choose one
HYCOM
Q-Flux
GISS
Dynamic
lakes
sea ice
lake ice



atmosphere
LMDZ
clouds
COSP
tropospheric chemistry & aerosols
INCA
stratospheric chemistry
REPROBUS
land
ORCHIDEE
energy & water
SECHIBA
carbon & vegetation
STOMATE
solar radiation
land use changes
coupler
OASIS
anthropogenic emissions
natural emissions
ocean
NEMO
biogeo-chemistry


GEOS-5
coupler
agcm
history
coupler
dynamics
physics
coupler
coupler
gravity_wave_drag
fvcore
surface
chemistry
moist_processes
radiation
turbulence
coupler
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lake
land_ice
data_ocean
land
infrared
solar
coupler
vegetation
catchment

Now, let's go back to the dynamical core requirements and to a critical point concerning coupling:

- nonlinearity and multiscaling

In a simplified form: an initial value problem:

$$\frac{\partial x}{\partial t} + Lx = F - N - kx - n\nabla^4 x \qquad (1)$$

ξ = (u,v,w, ρ , θ),

L is a linear operator,

N represents the non-linear terms,

κ e *ν crudely represents dissipation*

F is the forcing (e.g. physics)

Nonlinearity => energy transfer among scales

$$u = u^{(0)}(x,y,p,t,\varepsilon t) + \varepsilon u^{(1)}(x,y,p,t,\varepsilon t) + O(\varepsilon^2)$$

$$v = v^{(0)}(x,y,p,t,\varepsilon t) + \varepsilon v^{(1)}(x,y,p,t,\varepsilon t) + O(\varepsilon^2)$$

$$\phi = \phi^{(0)}(x,y,p,t,\varepsilon t) + \varepsilon \phi^{(1)}(x,y,p,t,\varepsilon t) + O(\varepsilon^2)$$

$$\omega = \omega^{(0)}(x,y,p,t,\varepsilon t) + \varepsilon \omega^{(1)}(x,y,p,t,\varepsilon t) + O(\varepsilon^2)$$

$$\begin{bmatrix} u^{(0)}(x,y,p,t,\tau) \\ v^{(0)}(x,y,p,t,\tau) \\ \phi^{(0)}(x,y,p,t,\tau) \end{bmatrix} = \sum_a A_a(\tau)\xi_a(y)e^{ik_a x + i\varpi_a t}G_a(p) + c.c.$$

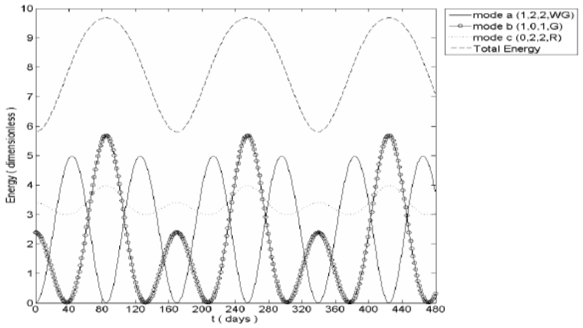
Dynamics of resonant interaction

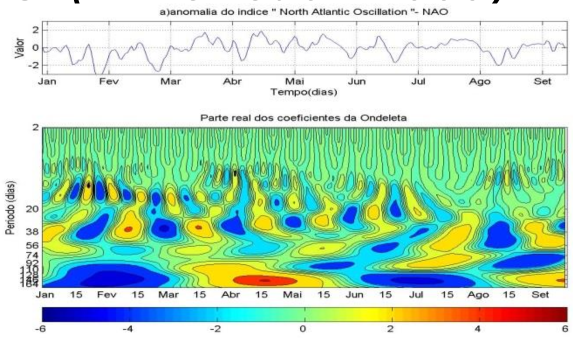
- *Examples:*
    - *Interaction between slow (O(5-7days)) and fast modes (O(1 day or less)) => intraseasonal scales (20-60 days) Raupp et al. (2008)*
    - *Importance of diurnal variation leading to energy in intrasesonal time scales (Raupp and Silva Dias, 2009)*
    - *Coupled ocean/atmosphere simplified models: interaction between intraseasonal scale (O(20-60d)) with interannual (El Nino/La Nina) - O (2-3 yr) => decadal/multidecadal time scales (Enver et al. 2009)*

$$c_a^{\,2}\frac{dA_a}{d\tau} = A_b A_c \eta_a^{bc} + q_a\,\delta\left(\frac{\varpi_a \pm \nu_j}{\varepsilon}\right)$$

$$c_b^{\,2}\frac{dA_b}{d\tau} = A_a A_c^{*} \eta_b^{ac} + q_b\,\delta\left(\frac{\varpi_b \pm \nu_i}{\varepsilon}\right)$$

$$c_c^{\,2}\frac{dA_c}{d\tau} = A_a A_b^{*} \eta_c^{ab} + q_c\,\delta\left(\frac{\varpi_a \pm \nu_l}{\varepsilon}\right)$$





Dynamics of resonant nonlinear interactions in the atmosphere-ocean system:

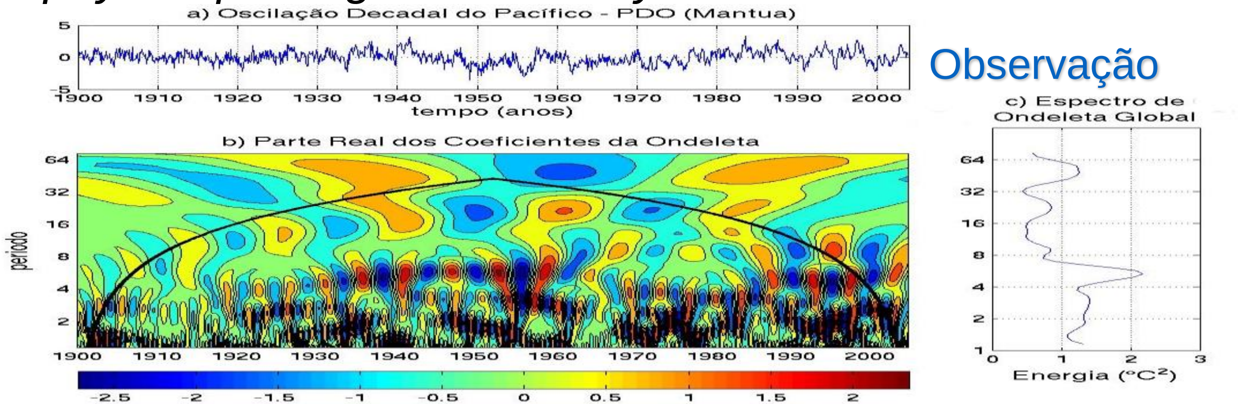
•*Numerical evidences: Misra et al (Mon. Wea. Rev. 2005) -> models with strongest diurnal cycle show strongest intraseasonal cycle – closer to observations; difficulty with slow modes.*

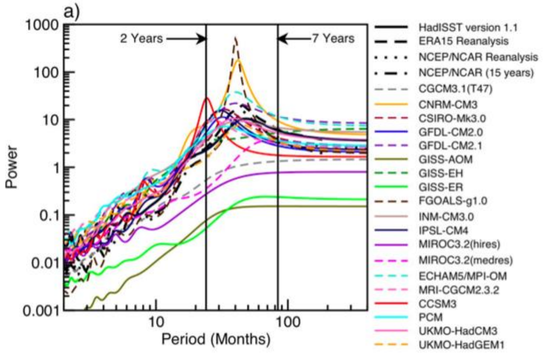
•*Climate models typically have low resolution (computational cost) - order 50-200 km*

•*Need parameterization of smaller scale => upscaling*

•*Lack of success in accurately representing smaller scales => higher resolution models (costly)*

•*Understanding of preferred spatial and temporal time scales helps establishing physics packages and the dynamical core of climate/weather models.*





www.cambridge.org
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Application to the dynamics/physics coupling:

- Use of too long dt for fast physical processes : temptation in view of the numerical stability of implicit squemes .
- Possible influence of high frequency numerical solutions in 3 time level squemes on the slower modes through nonlinear interactions

- In principle, all processes evolve simultaneously.

- However, the numerical time integration generally is based on 2 or three level time schemes.
    - In some specific cases, we find the use of a 4th order numerical scheme for very particular fast evolving processes (such as a Runge Kutta 4th order).

- Given the fact that different processes use different numerical time integration schemes, it is necessary to order the processes during the numerical integration.

- The impact of the order of integration will be discussed in terms of the effects of the physical implications and impact in the final solution.

Traditional experience with Atmospheric Models

Different Types of Atmospheric Models

- Cloud-Resolving Models (CRMs)
- Mesoscale Models
- Numerical Weather Prediction (NWP) Models
- Regional Climate Models (RCMs)
- Global Circulation Models (GCMs)

Numerical Representation

- **Finite difference**
  - Pointwise representation on a grid mesh
- **Galerkin**
  - Representation of dependent variables by a finite series of linearly-independent basis functions, transforming the PDE into a set of ODE for the coefficients
    - Spectral method
      - orthogonal basis functions (e.g. spherical harmonics)
    - Finite elements method
      - piecewise basis functions that are 0 everywhere except in a limited region

Pros and Cons of the Different Approaches

- **Finite-difference:**
    - Simplicity
    - Nonlinear instability and aliasing problems - could be minimized by using special techniques like Arakawa Jacobian
- **Spectral Method:**
    - More accurate than F-D for same degree of freedom
    - No aliasing problem (as in F-D) since shorter waves are truncated and their interactions are excluded
    - No "polar problem" in global applications
    - "Spectral ringing" (e.g. in mountainous regions)
    - Complexity in implementation and solution
- **Finite-elements Method:**
    - Flexibility in grid structure for irregular domain or variable resolution
    - Complexity in implementation and solution

Time-integration Schemes

- **Eulerian:**
  - Fixed grid points and fields evolve around them
  - *Explicit:* Two-level (e.g., Forward) or Three-level (e.g., Leapfrog)
    - Stringent stability criteria: timestep dictated by phase speeds of fast moving gravity waves
  - *Semi-implicit (SI):*
    - Explicit for advective terms and implicit for linear terms governing fast-moving waves
    - Relaxed numerical stability criteria
- **Semi-Lagrangian (SL):**
  - Fields evolve following fluid particles
  - Chose different set of particles at each timestep so that a regular mesh can be used
  - Relaxed numerical stability criteria
- **Semi-implicit Semi-Lagrangian (SISL)** schemes provide the most efficient method: SI for fast moving waves and SL for advection. The maximum timestep can be chosen as a function of the physics, rather than the stability of the numerical method.

SL & SI schemes requires more computations per timestep - SISL schemes typically provide a 4 -6 fold gain in computational efficiency despite overhead.

Computational Stability

Consider the Linear Advective Equation:

$$\frac{\partial F}{\partial t} = -c\frac{\partial F}{\partial x}$$

Leapfrog Scheme:

$$F^{n+1} = F^{n-1} - c\frac{\Delta F^{n}}{2\Delta x}2\Delta t$$

Courant-Friedrichs-Lewy (CFL) Stability Criteria:

$$c\Big/\frac{\Delta x}{\Delta t} \leq 1$$

i.e. if the true wave speed c is greater than the speed at which information propagates in the numerical scheme, instability occurs.

Implicit Scheme:

$$F^{n+1} = F^{n} - c\frac{\Delta F^{n+1/2}}{2\Delta x}\Delta t$$

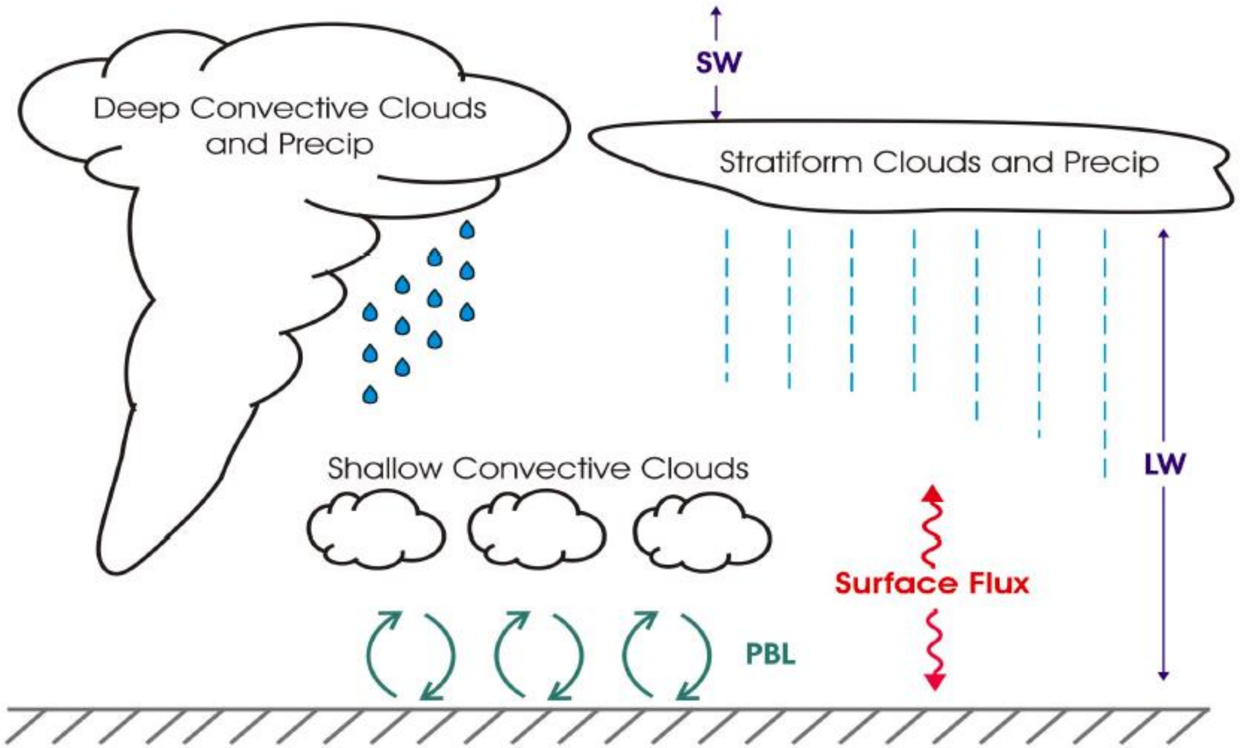
$$F^{n+1/2} = (F^{n+1} + F^{n})/2$$

Effectively slows down the wave propagation speed and thereby permitting longer Δt.

But... Problems with fast physical processes.

Model Physics

- Deep and shallow convection
- Stratiform clouds & precipitation (resolved or large-scale condensation)
- Microphysics
- Surface fluxes
- PBL processes, turbulence & diffusion
- Radiation
- Cloud-radiation interaction
- Gravity wave drag



Lateral Boundary Conditions and Model Nesting

- Lateral B.C. not needed in global models but essential in LAMs

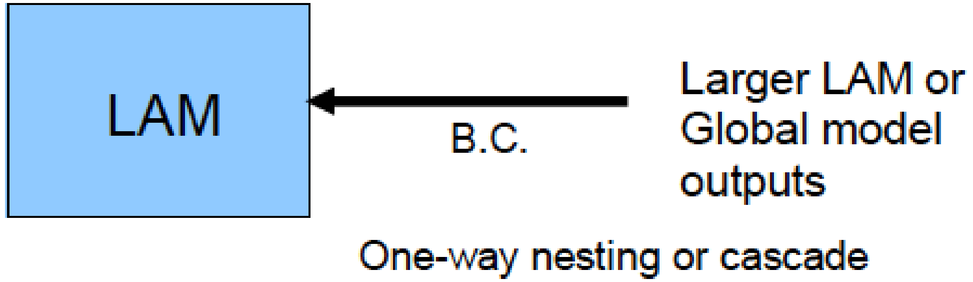
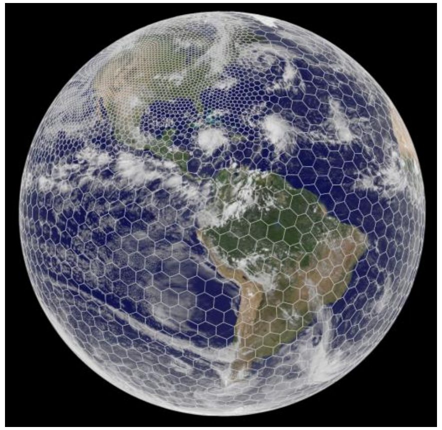


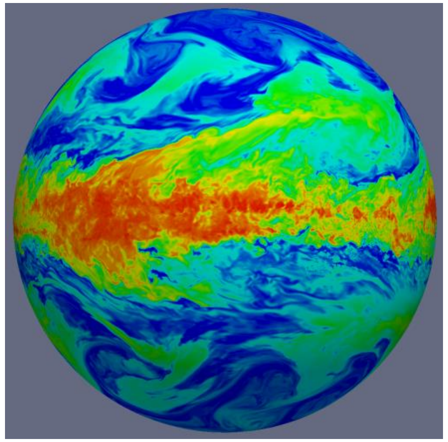
Figure 3: Schematic showing the "forcing" of a LAM by specifying the lateral B.C. with outputs from models with larger or global domains.

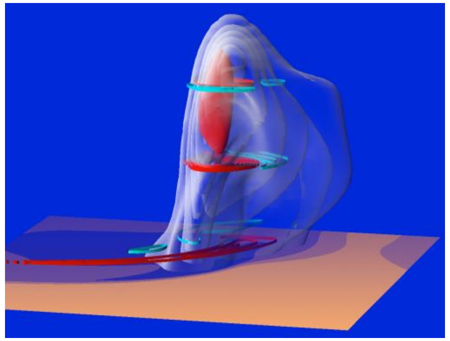
- Waves generated inside the LAM must be able to propagate freely out of the lateral boundary or be dampened; otherwise they will be artificially reflected back into the domain and ruin the simulation.

Alternative procedure: variable resolution global grids

The Model for Prediction Across Scales





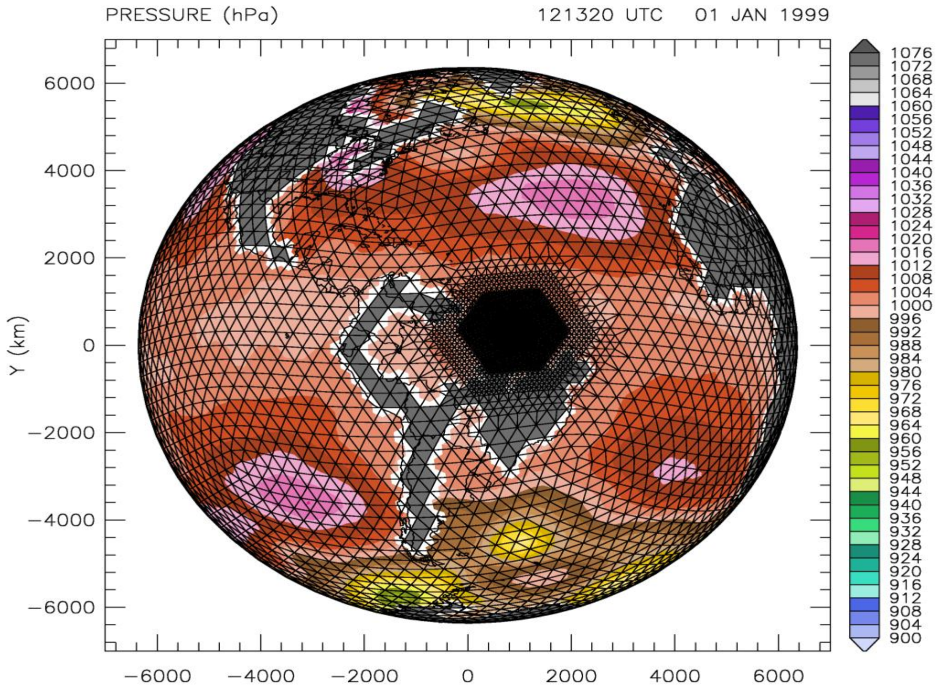


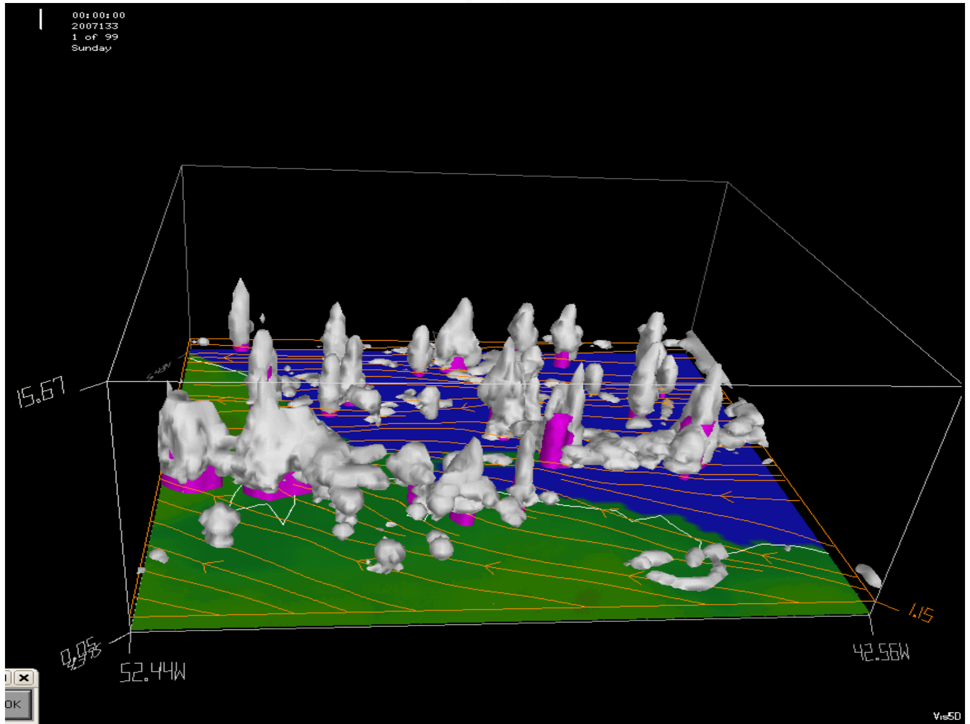
- The next-generation Model for Prediction Across Scales
- *Based on high spectral models or unstructured Voronoi (hexagonal) meshes and selective grid refinement with finite volume differencing scheme. Grid refinement is implemented.*
- To be utilized for operational weather, regional and global climate applications.
- Finite volume versions allows for non-hydrostatic (< 10 km horizontal resolution)
- Work towards exascale computing – very costly

https://mpas-dev.github.io/atmosphere/atmosphere.html

- ***Where are we:***

- ***Avoid use of different models for each spatial scale;***
- ***Multiscaling modeling;***
- ***Numerical challenge: efficiency/precision***
- ***Example:Global grid structure in OLAM - successor of RAMS/BRAMS***





Considerations in Building Different Types of Models

- **Purposes:**
  - NWP, climate simulation, climate and weather case and process studies etc.
- **Efficiency vs. Accuracy:**
  - NWPs need to be produced in a timely manner but efficiency is not a main concern for a research model
  - Available computer resources?
- **Domain and Resolution:**
  - Global vs. regional
  - Domain must be large enough to protect the main region of interest from boundary effects
  - Resolution should be fine enough to resolve the phenomena of interest
- **Appropriate Model Physics and Assumptions:**
  - Scale (model resolution) dependency of physical parameterizations?
  - Appropriate assumptions used in simplifying the equation sets?
  - All factors are inter-related.

Errors in Models

- Errors in the initial and boundary conditions (observational or analysis errors)
- Errors in the assumptions used in development of the model equations
- Errors in the numerics
- Errors in the parameterization of subgrid scale processes
- Errors can be random and/or systematic errors
- Different sources of error will have more affect on different models
    - Errors in I.C. will have more effects on NWP model than on climate models (more dependent on the accurate specifications of the B.C.)
- Intrinsic predictability limitations (scale dependent) due to the chaotic nature of the atmosphere
- The inevitability of errors from different sources along with the chaotic nature of the atmosphere suggest the need for prediction of uncertainties in the forecast (e.g. by using the ensemble forecast or dynamical-statistical approaches)

An example of how dynamics and physics are coupled:

- Offline and online coupling of chemical module in WRF (CMAQ)

Offline CMAQ

- WRF and CMAQ are run sequentially.
- WRF data is input to CMAQ, and the chemistry does not affect the weather.
- The model is useful in many applications, for example, emissions-control studies and data sharing/collaboration.

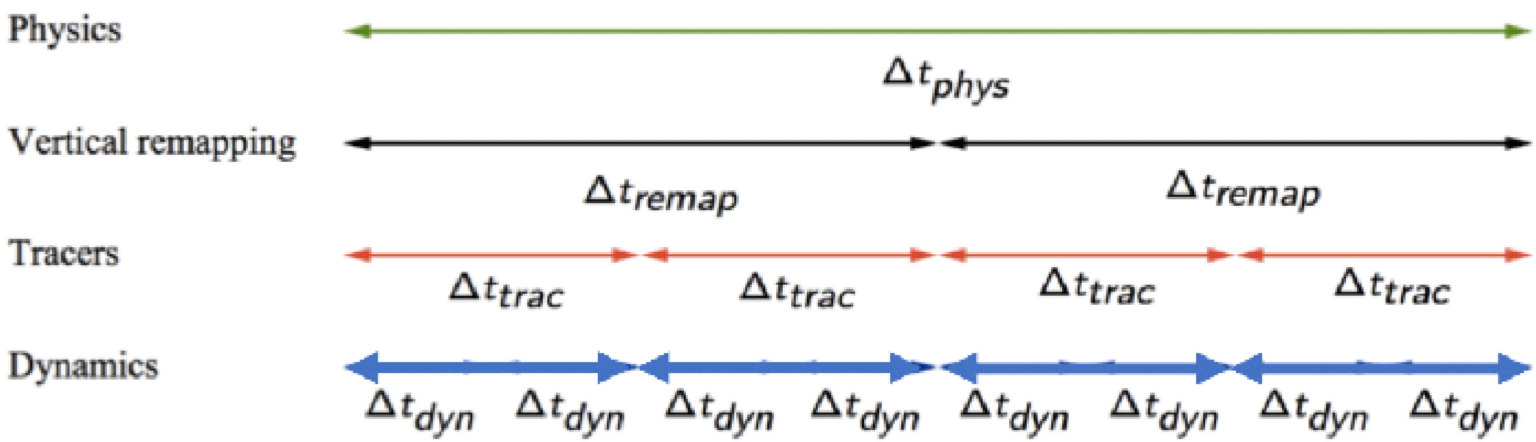
Coupled WRF–CMAQ

- WRF and CMAQ run simultaneously.
- Changes in atmospheric chemistry can impact weather.
- The results are important for studying chemistry-weather interactions. For example, aerosols may influence formation of the boundary layer due to altering the radiation reaching the surface.

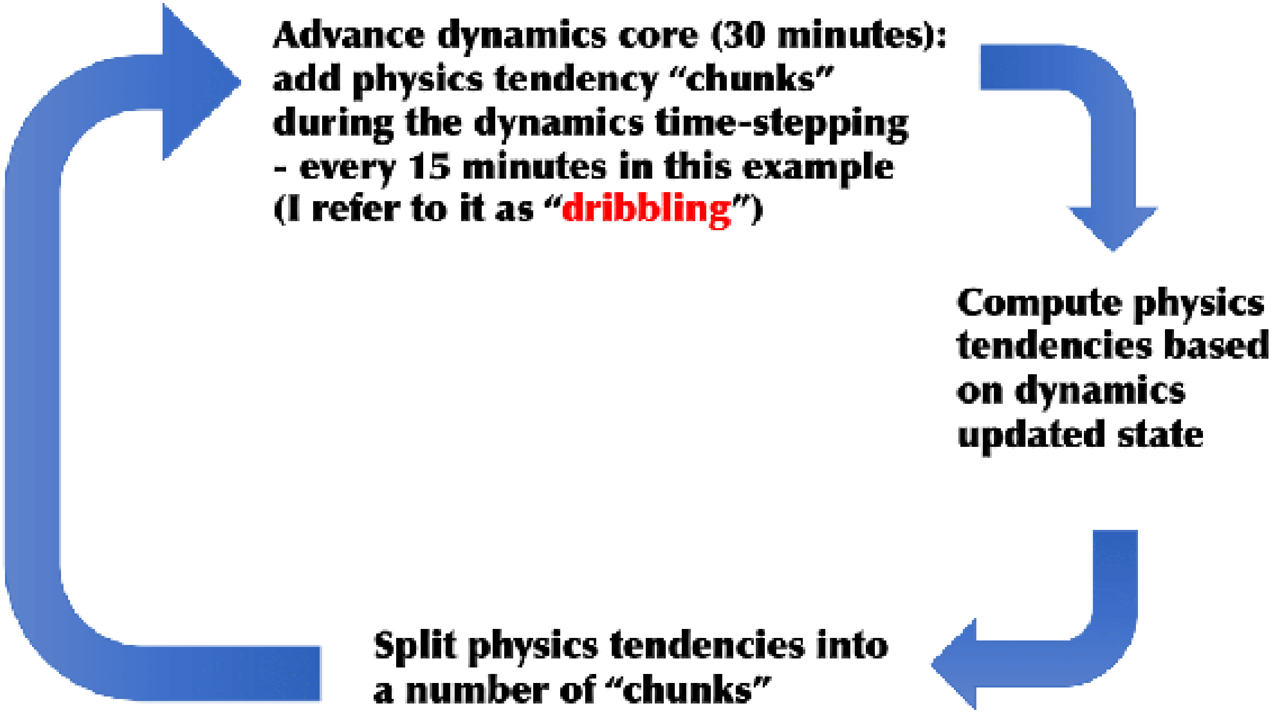
An example from CAM

(Paul Lauritzen Class)

Time-steps in CAM-SE



Physics dynamics coupling methods in CAM-SE: se_ftype=0



Physics dynamics coupling methods in CAM-SE: se_ftype=1

Advance dynamics core (30 minutes)

Compute physics tendencies based on dynamics updated state

Update dynamics state with physics tendencies

For long physics time-steps and less diffusive dynamical cores this can create spurious noise!

Noise can be detected by computing

$$\frac{d}{dt}|p_s|$$

Physics dynamics coupling methods in CAM-SE: se_ftype=2

Advance dynamics core (30 minutes): for (u,v,T) add physics tendency "chunks" during the dynamics time-stepping
- every 15 minutes in this example
(I refer to it as "dribbling")

Compute physics tendencies based on dynamics updated state

Split physics tendencies into a number of "chunks" for u,v,T
Update tracer state with physics tendencies

JUNE 1998 CAYA ET AL. 1707

1708 MONTHLY WEATHER REVIEW VOLUME 126

Consequences of Using the Splitting Method for Implementing Physical Forcings in a Semi-Implicit Semi-Lagrangian Model

ALAIN CAYA, RENÉ LAPRISE, AND PETER ZWACK

Cooperative Centre for Research in Mesometeorology and Sciences de l'Atmosphère, Université du Québec à Montréal, Montreal, Quebec, Canada

(Manuscript received 17 January 1997, in final form 18 July 1997)

- Any comprehensive numerical model is composed of two parts:
  - a dynamical kernel solving for the fluid mechanical field equations and
  - a physical package to parameterize the ensemble effect of subgrid-scale processes upon the resolved scales of the model.

- There are a number of techniques that can be used for combining the dynamics and physics contributions.
  - One such method called ‘‘splitting’’ is used in some models because of its simplicity and stability property.
  - splitting method may introduce serious truncation errors when used in conjunction with long time steps that are permitted by semi-implicit and semi-Lagrangian marching algorithms.

$$\frac{d\Psi}{dt} = L(\Psi) + R(\Psi) + P(\Psi), \qquad (1)$$

where $L(\Psi)$ is a linear function of Ψ, $R(\Psi)$ a nonlinear function of Ψ, and $P(\Psi)$ a (physical parameterization) forcing applied to the system. Integrating (1) with a

Traditional way to integrate:

$$\frac{\Psi(t + \Delta t) - \Psi(t - \Delta t)}{2\Delta t} = L\left[\frac{\Psi(t + \Delta t) + \Psi(t - \Delta t)}{2}\right] + R[\Psi(t)] + P[\Psi(t - \Delta t)]. \qquad (2)$$

The splitting method operates in two steps:
step 1:

$$\frac{\Psi^*(t + \Delta t) - \Psi(t - \Delta t)}{2\Delta t} = L\left[\frac{\Psi^*(t + \Delta t) + \Psi(t - \Delta t)}{2}\right] + R[\Psi(t)]; \qquad (3)$$

step 2:

$$\Psi(t + \Delta t) = \Psi^*(t + \Delta t) + 2\Delta t P[\Psi^*(t + \Delta t)], \qquad (4)$$

where $\Psi^*(t + \Delta t)$ is an interim result of the inviscid time step.

$$\frac{dF(t)}{dt} + \beta F(t) = G, \qquad (7)$$

The steady-state analytical solution of (7) is

$$F_A = \frac{G}{\beta}. \qquad (8)$$

A -> analytical

Now, if (7) is integrated using a semi-implicit time scheme, treating the forcing G in the traditional way, we get

$$\frac{F(t + \Delta t) - F(t - \Delta t)}{2\Delta t} + \beta\left[\frac{F(t + \Delta t) + F(t - \Delta t)}{2}\right] = G. \qquad (9)$$

The resulting recursive formula is

$$F(t + \Delta t) = \frac{F(t - \Delta t)(1 - \beta\Delta t) + 2\Delta t G}{(1 + \beta\Delta t)}. \qquad (10)$$

➔

To find the steady-state solution, we put $F(t + \Delta t) = F(t - \Delta t) = F_{\mathrm{SIT}}$, a constant (the subscript SIT stands for semi-implicit and traditional, i.e., non-SM). Thus,

$$F_{\mathrm{SIT}} = \frac{G}{\beta}, \qquad (11)$$

which is identical to the analytical solution.

Now, if the SM is used instead of the traditional way to treat the forcing G, we get

step 1:
$$\frac{F^*(t+\Delta t) - F(t-\Delta t)}{2\Delta t} + \beta\left[\frac{F^*(t+\Delta t) + F(t-\Delta t)}{2}\right] = 0; \quad (12)$$

step 2:
$$F(t+\Delta t) = F^*(t+\Delta t) + 2\Delta t G. \quad (13)$$

Eliminating F^*, we get the recursive formula
$$F(t+\Delta t) = \frac{F(t-\Delta t)(1-\beta\Delta t)}{(1+\beta\Delta t)} + 2\Delta t G. \quad (14)$$

SISM – semi-implicit and splitting method (SM)

The steady-state solution resulting from this method is
$$F_{\mathrm{SISM}} = \frac{G(1+\beta\Delta t)}{\beta} \quad (15)$$

depends on dt and converges to the exact equation!!!.

Amplifies response!!!

Compare with

Semi-implicit traditional $$F_{\mathrm{SIT}} = \frac{G}{\beta}, \quad (11)$$

A -> analytical $$F_A = \frac{G}{\beta}. \quad (8)$$

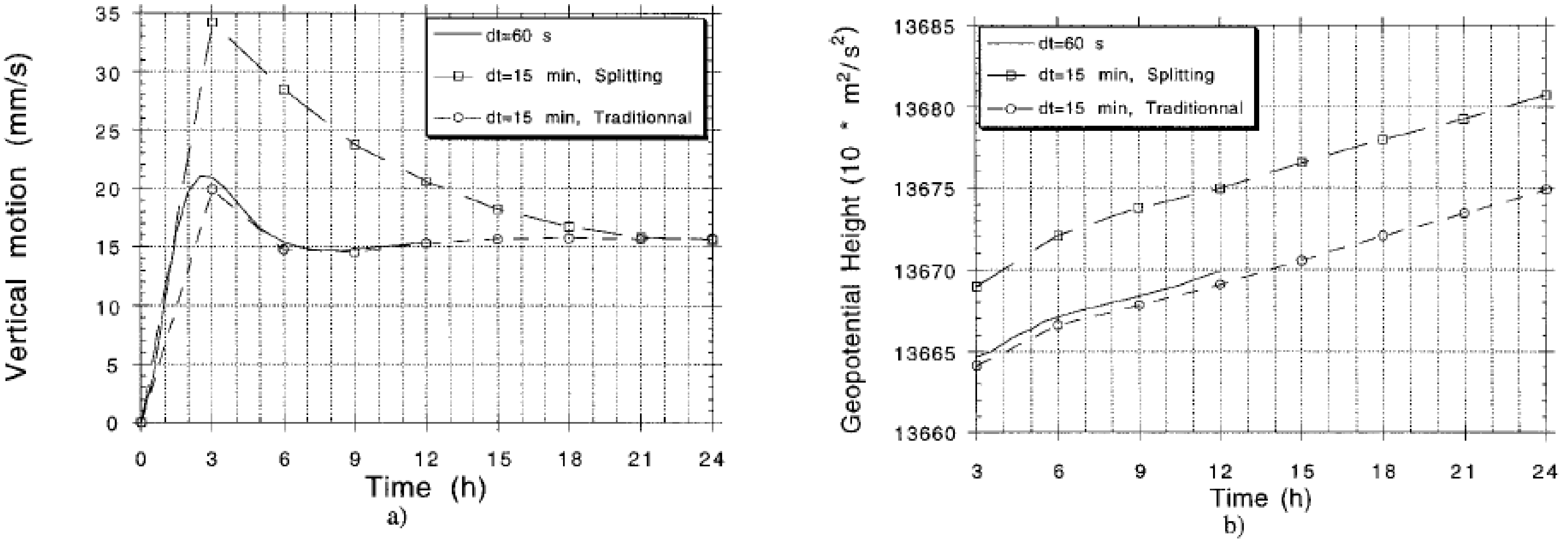


FIG. 3. Time series through 24 h in the center of the domain of (a) vertical motion at 550 hPa and (b) geopotential height at 175 hPa for three simulations: time step of 60 s, time step of 15 min with splitting, and time step of 15 min without splitting.

SEAMLESS PREDICTION OF THE EARTH SYSTEM:

FROM MINUTES TO MONTHS

WMO-No. 1156

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CHAPTER 6. NUMERICAL METHODS OF THE ATMOSPERE AND OCEAN

Jean Côté, Christiane Jablonowski, Peter Bauer and Nils Wedi

EQUATIONS SETS AND BUILD-IN PHYSICAL CONSTRAINTS

1. Equation set:
2. Conservation
3. Balance
4. Stability and accuracy

TIME AND SPACE DISCRETIZATIONS

1. Horizontal discretization
2. Vertical discretization
3. Advection
4. Temporal discretization
5. Orography

TREND TOWARDS HIGH-RESOLUTION, VARIABLE-RESOLUTION AND ADAPTATIVE MESH REFINEMENT (AMR) GCMs

1. High-resolution
2. Variable-resolution
3. Adaptive mesh refinement
4. Model adaptivity

PHYSICAL PARAMETERIZATIONS - COMPUTATIONAL ASPECTS

1. **Currently, all subgrid-scale parameterizations only operate in vertical columns. In the future, more horizontal coupling becomes necessary, especially for increasing resolution**

2. Improving the ***representation of deep convection in the so-called "grey zone"*** (with grid spacings between 2-10 km where deep convection becomes partially resolved) as well as an improved ***representation of orographic and turbulent flow interactions***.

3. It will also be possible that multi-dimensional radiation schemes are needed that interact more realistically with cloud properties (today – horizontal slabs -> cannot deal wtih diffuse radiation from individual cumulus clouds or the horizontal displacement of the shade effect).

4. Numerical discretizations in physics routines are often of low-order and not consistent with the numerical discretization in the dynamical core.

5. Typically, the physics packages and dynamical cores are coupled in a first-order operator-split way. Within the physics package a time-Split approach is used which makes the results dependent on the order of the operations.

6. In view of the smaller time steps chosen in CFL-limited dynamical cores, much efficiency can be gained by operating different physical parameterizations at different time steps, performing differently in different regions (e.g. stratosphere and troposphere, day and night areas in chemical calculations) and in computing these parameterizations asynchronously or on accelerator-type processors.

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7. Another emerging issue is the question whether the dynamics and physics grids should be different. Numerical noise and grid imprinting signatures in the vertical velocity field when the physical parameterizations were computed on a diferente grid.

8. However, this also raises the interesting question whether the grid spacings of the dynamics and physics grids should be different. The physics tendencies could be e.g. sub-sampled on a finer grid and averaged back onto the coarser dynamics grid scale.

9. This mimics the idea behind the so-called super-parameterization, which has gained popularity in recent years.

10. A contrasting viewpoint is that the effective resolution of the dynamical core is a multiple of the grid spacing. Therefore, it can also be argued that the physics grid should not be refined since the dynamical information at the grid scale is uncertain.

11. One can even claim that the grid point information should even be horizontallyaveraged before calling the physical parameterizations. Such physics-dynamics coupling questions are areas of active research.

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High-resolution : Increasing scientific demand for high-resolution, even cloud-resolving, GCM simulations that can accurately represent processes at regional and local scales

a) **Uniform high-resolution GCM grid spacings, that are currently feasible for multi-year simulations, range from 3.5-14 km;**

b) **finest “ultra-high” resolution to date was employed by Miyamoto et al. (2013) who utilized a sub-km global grid with 870 m grid spacing!**

c) **it is likely that such resolutions will become the new norm in future decades. This “grand challenge” can only be met by a significant boost of the available computing resources.**

d) High-resolution grid spacings under 10 km necessitate non-hydrostatic dynamical core designs.

e) Today, new dynamical core model developments recognize that non-hydrostatic designs are paramount for the future GCM generation.

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f) **Multi-scale GCM design allows the development of unified modelling systems that can be used for both local weather predictions and global climate.**

i. Questions concerning the scale-awareness (or scale sensitivities) of the subgrid-scale physical parameterizations that are not necessarily well suited for a wide range of resolutions.

ii. *This technique has the potential to replace traditional Limited-Area Models (LAMs) that can be nested within a coarse-resolution host GCM and rely on periodic updates of the boundary conditions.*

iii. These boundary data updates can cause inconsistencies, like the violation of mass conservation constraints, and numerical noise, which is often damped via diffusion in “sponge zones” .

iv. some LAMs employ a nudging (relaxation) of the high-resolution solution towards the large-scale flow conditions of the host GCM to prevent the splitting between the LAM and GCM flow fields.

v. *Nudging is equivalent to the introduction of a physical forcing coupled to the dynamics!!!! Not present in the real world!!!*

vi. nudging compromises the versatility of regional climate assessments since the flow is not allowed to freely evolve in the high-resolution domain.

vii. Most often, the LAMs are also onlycoupled to the host model in a one-way interactive way and do not feed back the fine-grid information to the coarse GCMs.

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Temporal discretization

a) splitting between slow and fast waves.

b) A popular Split is HEVI that stands for horizontal explicit and vertical implicit

c) non-traditional time integrators such as semi-implicit predictor corrector schemes or exponential time integration methods for stiff problems.

d) Research also continues into 3D implicit solvers suitable for massively parallel implementation. These typically feature hierarchical, multi-scale designs using multi-grid techniques.

e) “Parallel-in-time” time integrators would exploit untapped parallelism in GCMs, utilize the newest computing architectures more efficiently and thereby reduce the wall-clock execution time of GCMs

    a) New efficient multi-scale time integration algorithms are an active area of research considering the

Variable-resolution

1. Until about 2010, most variabler esolution GCMs used a grid stretching technique.

2. More recently, variable resolution grids are provided as an option in selected GCMs that are built upon unstructured icosahedral, hexagonal or cubed-sphere grid topologies.

Adaptive mesh refinement

1. Dynamic adaptivity of the mesh (AMR) has been a topic of interest for many years: development of global models that can track objects and refine resolution as the objects develop smaller scale (cyclones, mesoscale convective systems etc.).

2. Very few 3D AMR models in spherical geometry have been developed so far, and this research field might become an emerging trend for future-generation GCMs.

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Model adaptivity

1. Another type of model adaptivity, where the model changes locally in a region of the domain, will also play an important role in future computing.

2. Most effective when combined with hierarchical adaptive mesh and algorithm refinement techniques

3. Model adaptivity can potentially exploit different levels of parallelism, asynchrony, and mixed precision and can minimize communication across layers. ***Poses important issues concerning the coupling between physics and dynamics!!!***

Desirable Future Directions

- **Parallel Efficiency: needs careful analysis of physics/dynamics coupling!**
  - **Auto-tuning**
- **Validation**
  - **Theoretical developments + Observations**
- **Single source, multi-scale, multi-model**
  - **Global + regional + environmental**
- **Intersections between the physical, mathematical and computational viewpoints!**
  - Provides pointers to future high performance and energy consistent models and high-resolution GCM research.
- **Increase university and research institutions partnerships**
  - **Plenty of research directions as indicated in this lecture!**