WGNE initiative on Physics-Dynamics Coupling and Energy Budgets in Earth System Models

Peter Hjort Lauritzen (NCAR) and Romain Roehrig (Meteo France)

Working Group on Numerical Experimentation (WGNE) 40, November 3-7, 2025, Beijing, China

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Why this WGNE effort on physics-dynamics coupling and energy budgets?

No coordinated effort to discuss/evaluate how/if Earth System Models close total energy budgets

In 2023, questionnaire to assess current state of the art and interest of the modeling community (cf. synthesis last year)

It is a very technical subject and model development is not always published/presented at conferences -> therefore we chose this informal format of bimonthly(ish) 1-hour Zoom meetings

Meeting frequency (approximately)

Every meeting has a focus area

WGNE Bimonthly Discussion on Physics-Dynamics Coupling and Energy Budgets: Focus on Mass Conservation

Facilitators: Peter Lauritzen (NCAR) and Romain Roehrig (Meteo France)

December 16, 2024

Google drive with presentations, recordings, etc.
https://drive.google.com/drive/folders/1U5lkJP54fPGH70mXhcOyLO2ShT2dadSd

#meetings: one in late 2024 and four (thus far) in 2025

Attendance

Typical attendance: 9–13 participants

Core recurring institutions:
NCAR, Météo-France/CNRM, ECMWF, NASA GISS, DOE Sandia National Labs, IPSL/LMD

Occasional participation from NOAA/NCEP, ECCC Canada, University of Hohenheim, and IITM India.

Should we try to expand? ICON group, UK Met Office, ...

Overview

2024-12-16

Topic: mass-conservation

- ECMWF (Diamantakis)
- CNRM-CM (Roehrig)
- DOE E3SM (Guba)
- GISS ModelE3+
- Atmospheric Mass Conservation in IPSL-CM (LMDZ) (Dubos)
- [NCAR's CESM (Lauritzen)]

- Next meeting date and topic?

Overview

2025-03-24

- GISS ModelE3+
- Atmospheric Mass Conservation in IPSL-CM (LMDZ) (Dubos)
- [NCAR's CESM (Laurizen)]
- E3SM's semi-Lagrangian transport (Andrew Bradley, SNL)

- Next meeting date and topic?

Topic: mass-conservation

WORLD METEOROLOGICAL ORGANIZATION Weather · Climate · Water
Working Group on Numerical Experimentation

Agenda

- Quick DCMIP 2025 overview
- Mass-conservation presentations (wrap-up)

Topic: mass-conservation

2025-06-25

WORLD METEOROLOGICAL ORGANIZATION Weather · Climate · Water
Working Group on Numerical Experimentation

Agenda

- ECMWF
- E3SM
- FV3
- Météo-France
- CESM/CAM

2025-10-01 & 2025-10-22

Topic: physics-dynamics coupling

WORLD METEOROLOGICAL ORGANIZATION Weather · Climate · Water
Working Group on Numerical Experimentation

Overview

2024-12-16

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- [N... CESM (Lauritzen)]
- ...emi-Lagrangian transport (Andrew Bradley, SNL)

- ...topic?

Topic: mass-conservation

During each meeting we have plenty discussions (and often must postpone presentations since we run out of time)

Agenda

- Quick DCMIP 2025 ...
- Mass-conservation presentations (wrap-...

Topic: mass-conservation

2025-06...

...-10-01 & 2025-10-22

To...: physics-dynamics coupling

- ...France
- ...CAM

Mass conservation through mass fixers (meeting 1)

Why mass-fixers?

Traditional interpolating semi-Lagrangian schemes are valued for computational efficiency — they allow long time steps, and interpolation weights can be reused for many tracers.

Used in: ECMWF IFS, Météo-France/CNRM, DOE E3SM, and others.

However, these schemes do not inherently conserve mass, so explicit mass-fixers are required.

Subtleties:

- Fixing total (moist) air mass and applying separate tracer fixers does not guarantee dry-air mass conservation (even though moist mass and tracer mass are individually conserved).
- Fixers can distort tracer correlations and are not always shape-preserving, though most enforce positivity. Also, is a constant dry air mixing ratio conserved? (important for chemistry)

Mass conservation through mass fixers (meeting 1)

Presentation by IFS group (Michail Diamantakis):

This group uses Bermejo-Conde–style global optimization fixers with local weighting (based on Lagrange multipliers).

In words: Find the smallest possible change to the advected tracer field—weighted toward problematic regions—so that total mass equals its pre-advection value. A more advanced fixer is used for water vapor, aerosols and GHG.

Properties:

- Global mass-conservation
- Preserves tracer positivity (with limiter)
- Maintains inter-hemispheric gradients for greenhouse-gas tracers.

Mass conservation through mass fixers (meeting 1)

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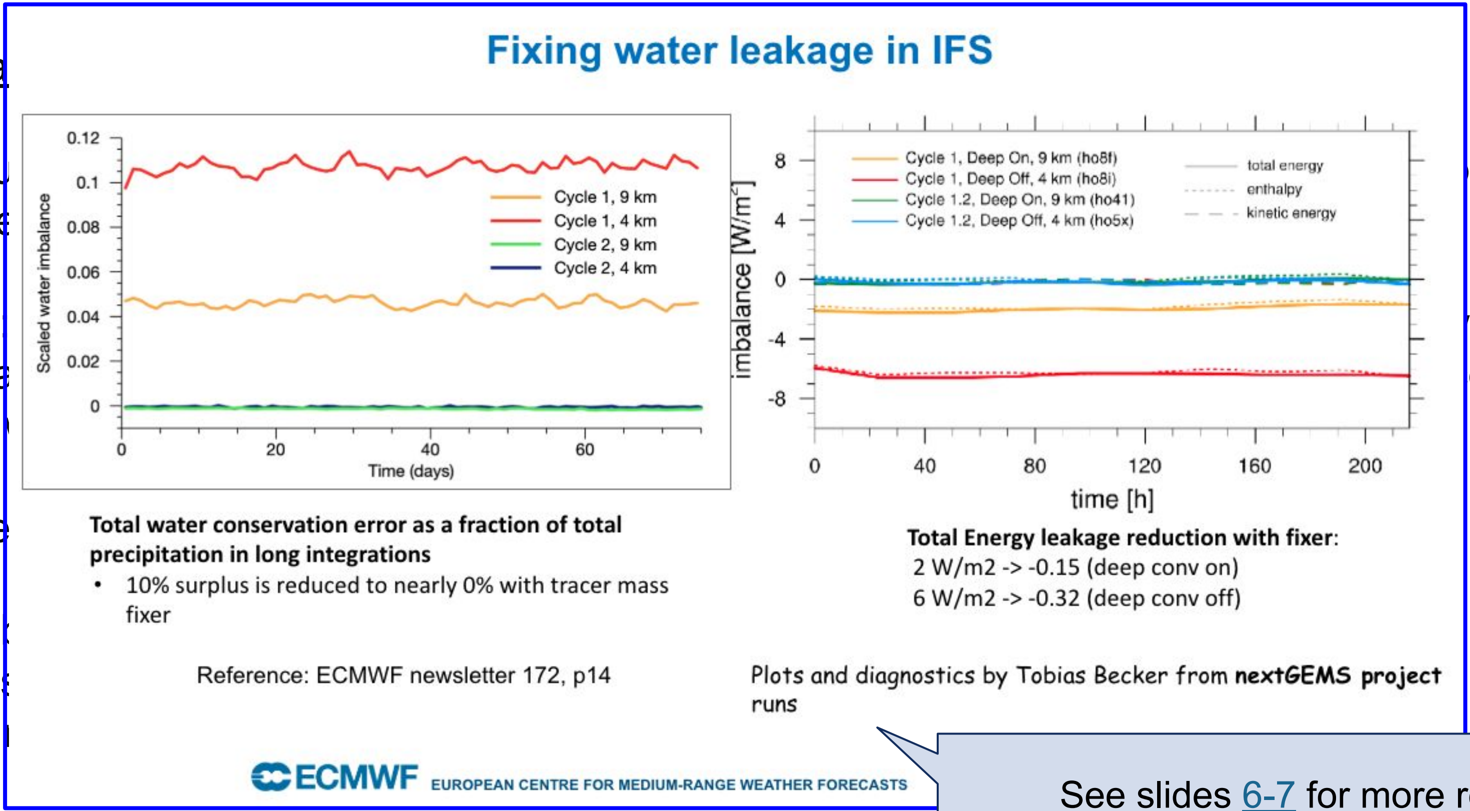

See slides 6-7 for more results

Mass ... ng 1)

Presentatio

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In words: F... ted toward problemati... advanced fixer is used for w...

Properties:

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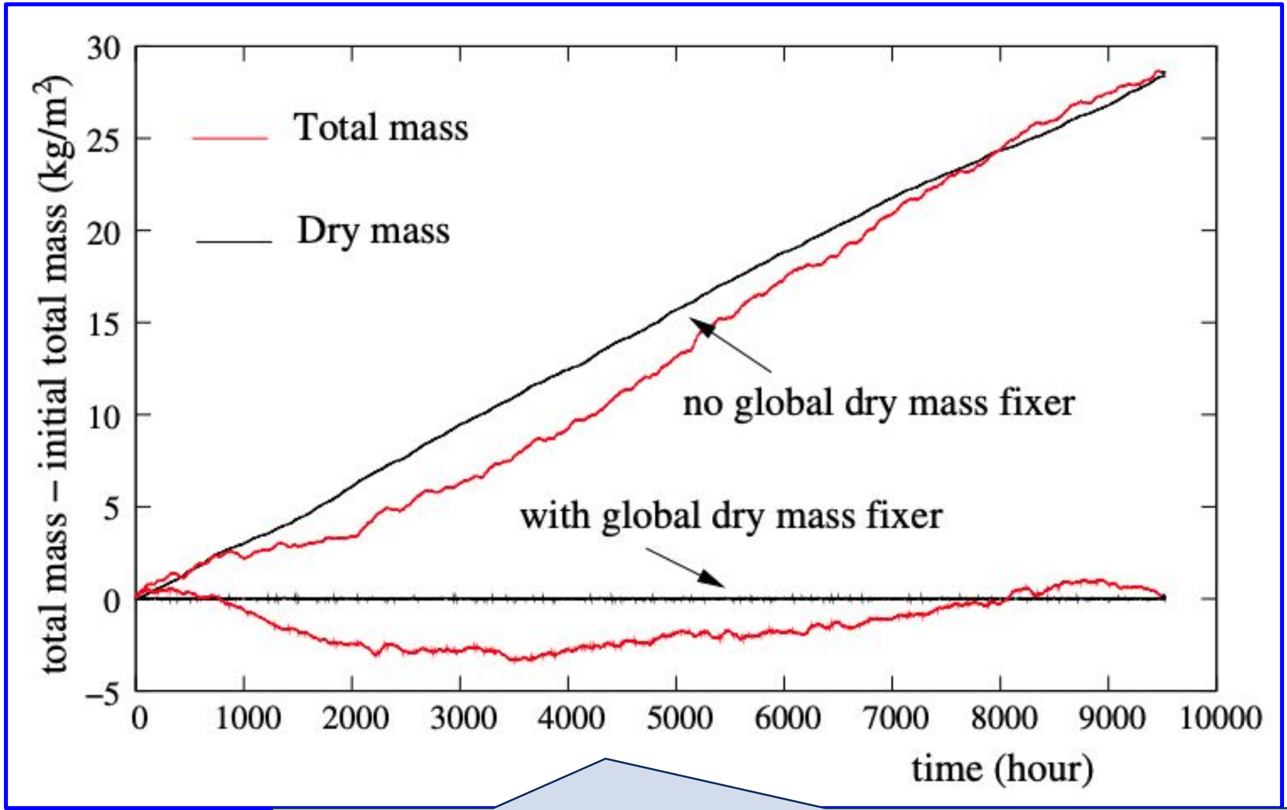


Dry mass versus moist mass fixing issue discussed in detail in IFS (Technical Memorandum No. 849)

Mass conservation through mass fixers (meeting 1)

Presentation by Météo-France/CNRM group (Romain Roehrig, Sylvie Malardel, Claire Laurent):

Closely related to the IFS system

Properties:

- Conserves total air mass (surface-pressure fixer applied each time step).
- Uses semi-Lagrangian tracer fixer for water and other species (Bermejo-Conde form).
- Applies surface precipitation correction to ensure full water closure.
- Dry-air mass not conserved — water-mass changes implicitly compensated by dry-air sources.

Ongoing work:

- Redefining prognostic variables and continuity equations to conserve dry mass explicitly (tested in 1-D RCE).
- Revising physics–dynamics coupling and vertical velocity formulation accordingly.

Mass conservation through mass fixers (meeting 1&2)

<u>Presentation by Météo-France/CNRM group (Romain Roehrig, Sylvie Malardel, Claire Laurent):</u>

Closely related to t

Properties:

- Conserves to
- Uses semi-La
- Applies precip
- Dry-air mass sources.

Ongoing work:

- Redefining pr (tested in 1-D
- Revising phys

Funded by the European Union

EU project CATRINE

(evaluate and improve the numerical schemes for tracer transport in the new Copernicus anthropogenic CO2 emissions Monitoring and Verification Support capacity (CO2MVS) and more widely in the Copernicus Atmosphere Monitoring Service (CAMS))

CATRINE
Carbon Atmospheric Tracer Research to Improve Numerics and Evaluation

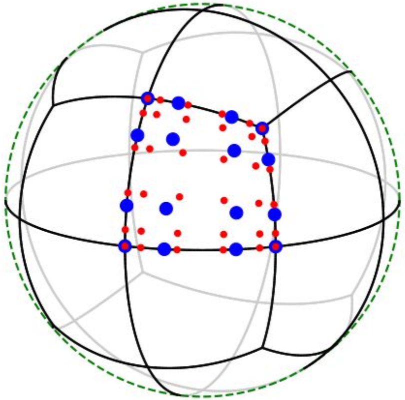
- WP1 and WP2 : Improve the conservation properties of the SL scheme without losing its accuracy and efficiency
- MF in WP1 : working with COMAD method
  - Extension of COMAD method for linear interpolations
  - Implementation of idealized test cases for Arpege-IFS,
  - A lot of testing with COMAD (COMAD along vertical, along SL trajectory, new formulation, boundary condition at the surface)
- MF at very beginning of WP2 : revisiting the multi-fluid atmospheric equations
  - Re-establishing the equations for the atmosphere from the general multi-fluid framework
  - Choice for the advection velocity: gas velocity vs barycentric velocity (mean mass velocity)

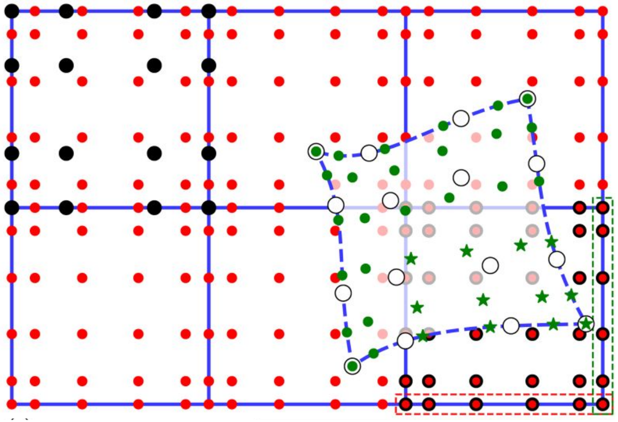
Mass conservation through mass fixers (meeting 1)

Presentation by DOE E3SM group (Andrew Bradley, Oksana Guba):

ISLET (Interpolation Semi-Lagrangian Element-based Transport) and mass conservation

In words: Trace each element backward along trajectories and interpolate within the distorted upstream element using specially modified basis functions to ensure unconditional stability. A communication-efficient global fixer (CEDAR) enforces exact mass conservation and local bounds.





Mass conservation through mass fixers (meeting 2)

Presentation by DOE E3SM group (Andrew Bradley, Oksana Guba):

ISLET (Interpolation Semi-Lagrangian Element-based Transport) and mass conservation

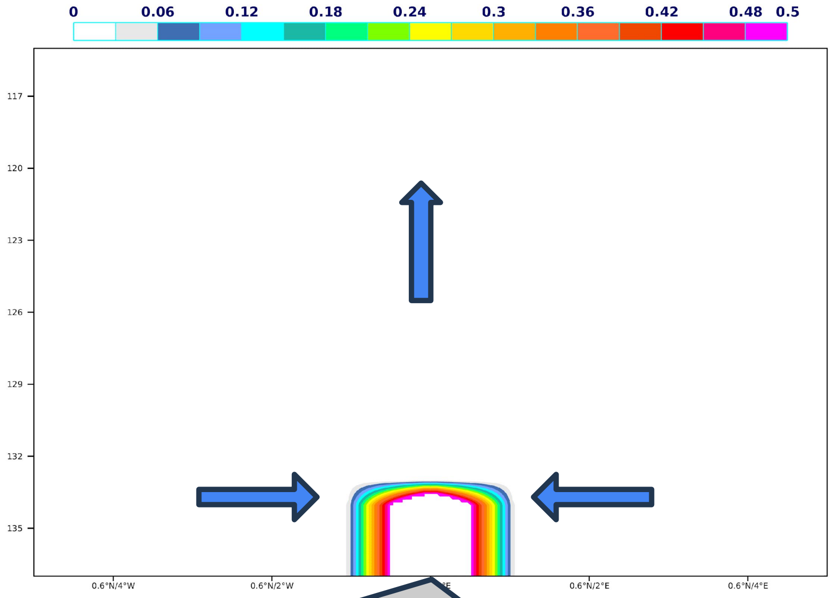
In words: Trace each element backward along trajectories and interpolate within the distorted upstream element using specially modified basis functions to ensure unconditional stability. A communication-efficient global fixer (CEDAR) enforces exact mass conservation and local bounds.

Properties:

- Unconditionally stable element-based semi-Lagrangian interpolation.
- **6–8× faster tracer transport** than the original scheme (40 tracers benchmark).
- Globally mass-conserving via one-reduction CEDAR fixer (Lagrange-multiplier formulation).
- Locally bounds-preserving and consistent with dynamics (mass–tracer consistency).
- Vertically Lagrangian coordinate; horizontal advection 2-D, vertical remap PPM.

Mass conservation through mass fixers (meeting 1)

In addition to the dry mass conservation problem, the IFS group points out the “infinite fountain problem” (Boundary-condition effects!)



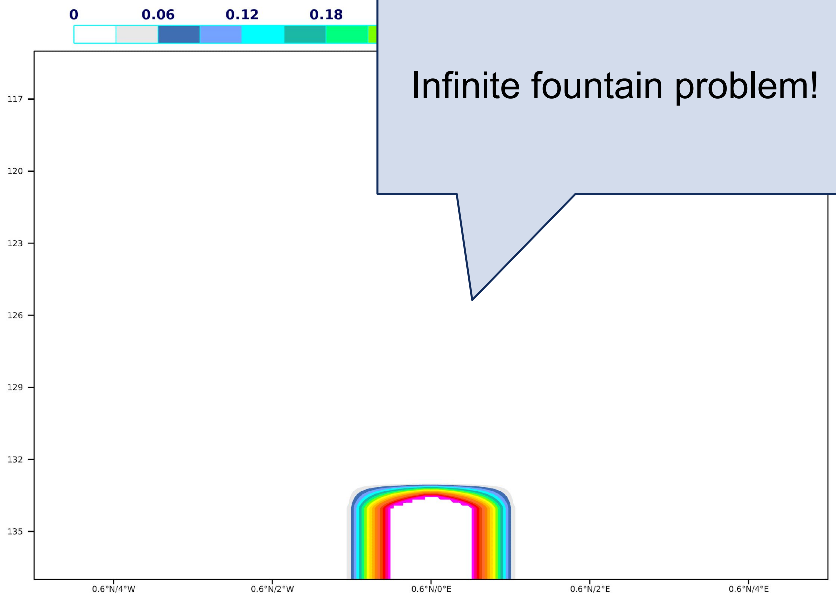
Warm bubble at the surface in the initial state, evolving in a stratified atmosphere

Idealized case from [Malardel and Ricard (2014)]

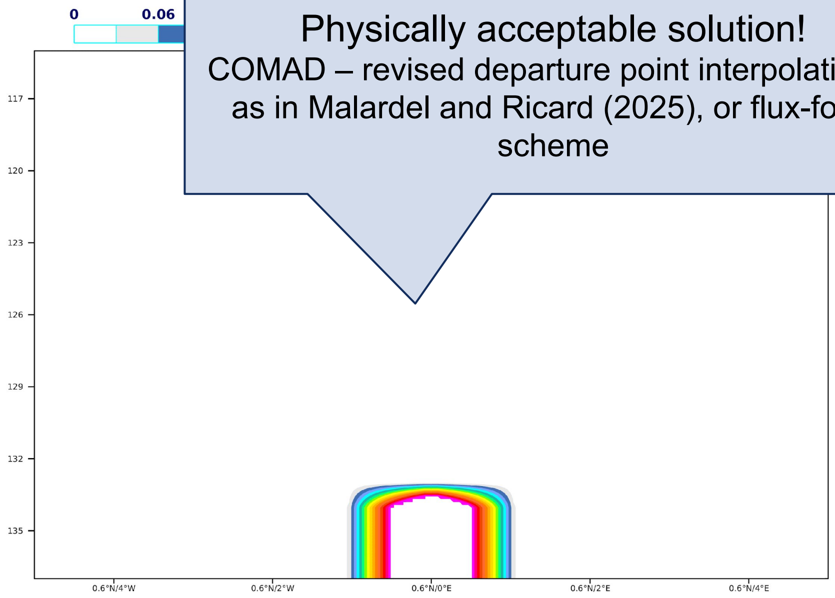
- Evolution of warm bubble initially near the surface, with a passive tracer within it.
- Converging horizontal winds at a point of no horizontal wind, which struggle conventional semi-Lagrangian scheme, given the boundary condition of the tracer when extrapolation below the surface is needed

Mass conservation through mass fixers (meeting 1)

In addition to the dry mass conservation problem, the IFS group points out the “infinite fountain problem”



Infinite fountain problem!



Physically acceptable solution!
COMAD – revised departure point interpolation – as in Malardel and Ricard (2025), or flux-form scheme

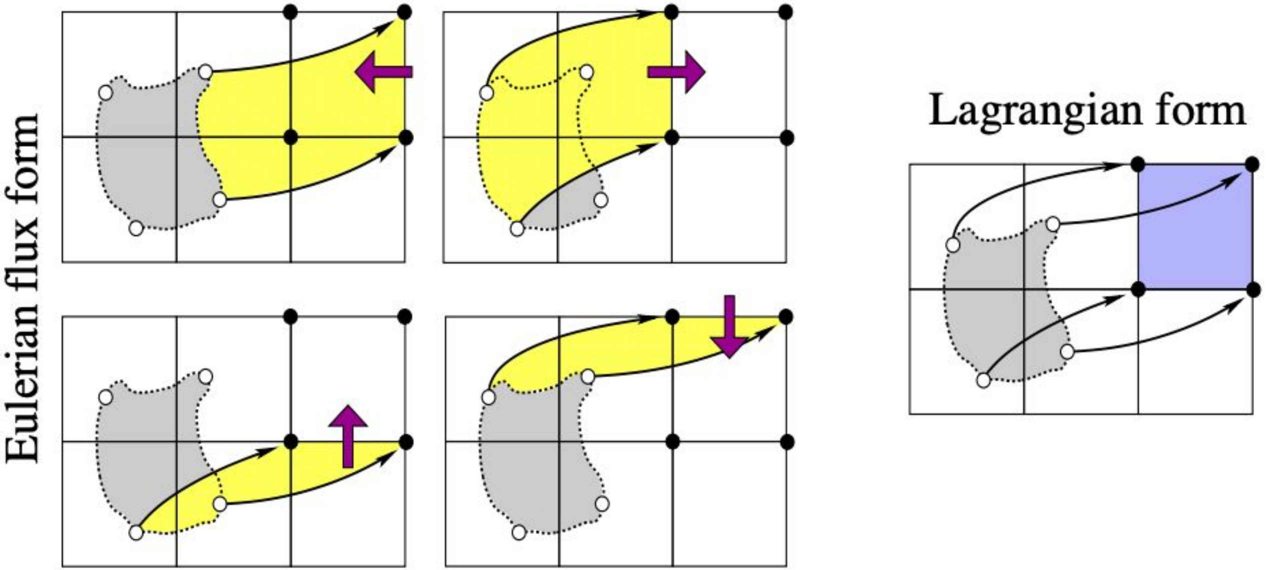
This situation is not part of standard idealized test case!

Inherent mass conservation (meeting 1 & 2)

Flux-form semi-Lagrangian:

These schemes are more expensive and usually cannot accommodate long time-steps (CFL>1) but they are inherently conserve mass!

Dry-mass conservation only inherent if continuity equation for dry-mass is used!



- **FV3 (GFDL, NOAA):** Lin & Rood dimensionally split (most accurate for CFL<1)
- **CESM/CAM with CSLAM (Conservative semi-Lagrangian multi-tracer) scheme:** (allows for CFL>1 but current implementation is CFL<1)
- **IPSL-CM (LMD):** ????

Other mass-conservation remarks (meeting 2)

Even with perfect dynamics conservation, physics parameterizations can break mass balance if tendencies are applied inconsistently in time or with outdated layer thicknesses.

Numerical precision and drift: Single precision can accumulate small pressure or tracer errors, requiring regular mass re-scaling.

Oxidation of methane in the stratosphere converts CH_4 into water vapor, adding real mass to the atmospheric water budget. (small but will show up above round-off errors in budgets)

Tracer transport is expensive so computational performance is paramount!

It is interesting that some emulators use global mass-fixers (e.g. CAMulator, Ai2 Climate Emulator, …); is there something to be learned from existing mass-fixers in traditional models that can be used in emulators?

Physics-dynamics coupling (meeting 3-4)

Two meetings thus far but still ongoing! Will be summarized in future WGNE meeting …

Next steps

Publication?

WGNE bluebook summary (but should we also consider something longer?)

Please encourage your model group to participate in discussions?

E.g. ICON, NICAM, UK Met Office etc. is missing …

DCMIP & WGNE?

DCMIP-2025
The Dynamical Core Model Intercomparison Project and Summer School

National Center for Atmospheric Research (NCAR), Mesa Lab, Boulder, CO, USA

June/2-6/2025

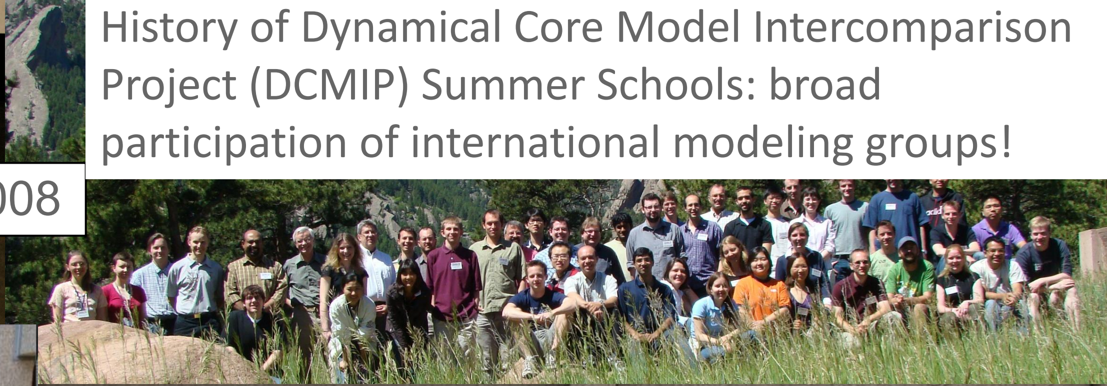
The DCMIP-2025 Vision

The DCMIP-2025 summer school surveys the design decisions in atmospheric General Circulation Models (GCMs) with a focus on their dynamical cores and takes a unique look at Machine Learning emulators for GCMs. DCMIP is built upon lectures, hands-on dynamical core & ML modeling projects, shared cyberinfrastructure, and computational tools that utilize the Community Earth System Model (CESM) from NCAR.

https://sites.google.com/umich.edu/dcmip-2025/home

History of Dynamical Core Model Intercomparison Project (DCMIP) Summer Schools: broad participation of international modeling groups!

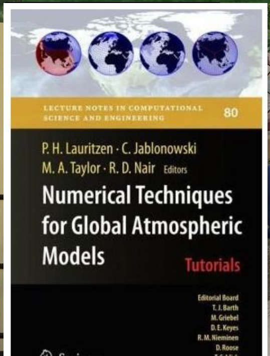
2008



2012

2016

Slides from Christiane Jablonowski



2016

What is DCMIP-2025?

- Hands-on summer school (June 2-6, 2025) that highlighted the characteristics of the dynamical cores: **CAM-Spectral Element** and **CAM-FV3 (both non-hydrostatic/hydrostatic), CAM-MPAS,** upcoming **LFRIC-Gungho (U.K. Met Office),** plus **ML emulators for GCMs**
- DCMIP-2025 focused on the impact of topography on the flow field, physics-dynamics coupling aspects with a simple warm-rain Kessler physics scheme and idealized assessments of existing Machine Learning (ML) emulators

Group of about 60 students/postdocs & early career scientists plus model mentors, NCAR Mesa Lab

Supported by the University of Michigan via the:

- NSF StormSPEED project (main sponsor)
- NOAA UFS-R2O project

Slides from Christiane Jablonowski

DCMIP Participants (50 Total)

Countries with representation at DCMIP-2025

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We are starting to raise money for DCMIP 2027(ish) … WGNE involvement?

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