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

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On the factory floor of model development …

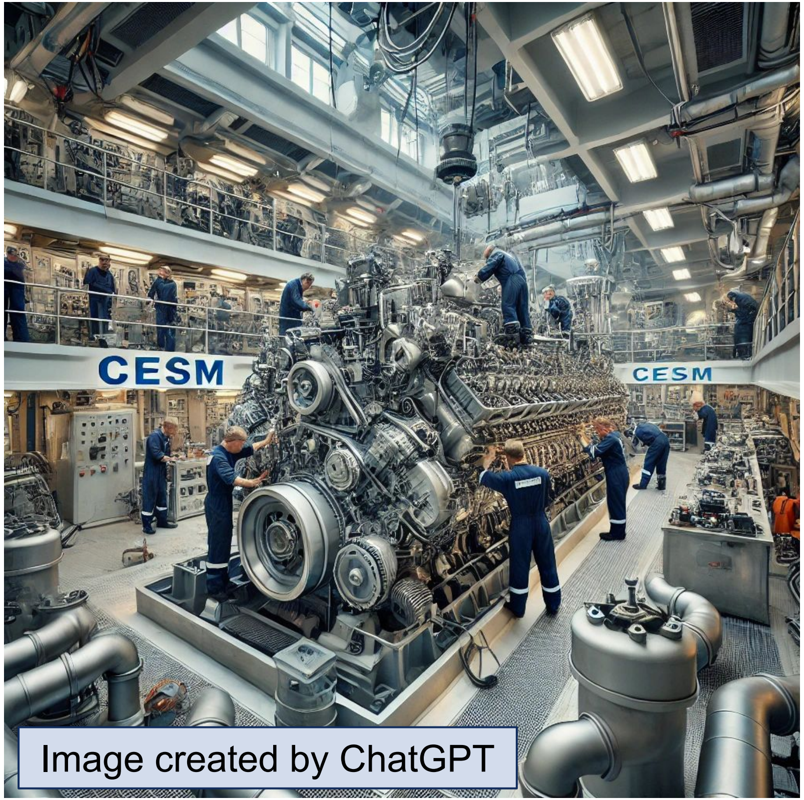

Image created by ChatGPT

We don't want the engine (model) to leak **fluid (mass)** or heat (energy):

Most engines (models) are now constructed so that they don't leak fluid at all (*inherent mass-conservation*) or, if they do leak, the fluid is collected and added back in an 'ad hoc' manner (*mass fixers*)

Inherently mass-conserving atmosphere models: CAM-SE, CAM-MPAS, MPAS-A, GFS-FV3, …

Models using 'ad hoc' mass fixer: ECMWF-IFS, …

On the factory floor of model development …

Consistently closing energy budgets is significantly more challenging:

- **Total energy is a function air mass, wind components, water species (water vapor and various condensates such as liquid and frozen precipitation), …**
- **Defining energy is ambiguous, with various approximations and assumptions, which can differ not only between components but sometimes even within the same component.**

No Earth system model (or weather model) consistently closes its total energy budget, so they all rely on 'ad hoc' fixers

It is widely accepted that closed energy budgets are important for climate change applications, but I argue that they are also important on shorter (weather) time scales

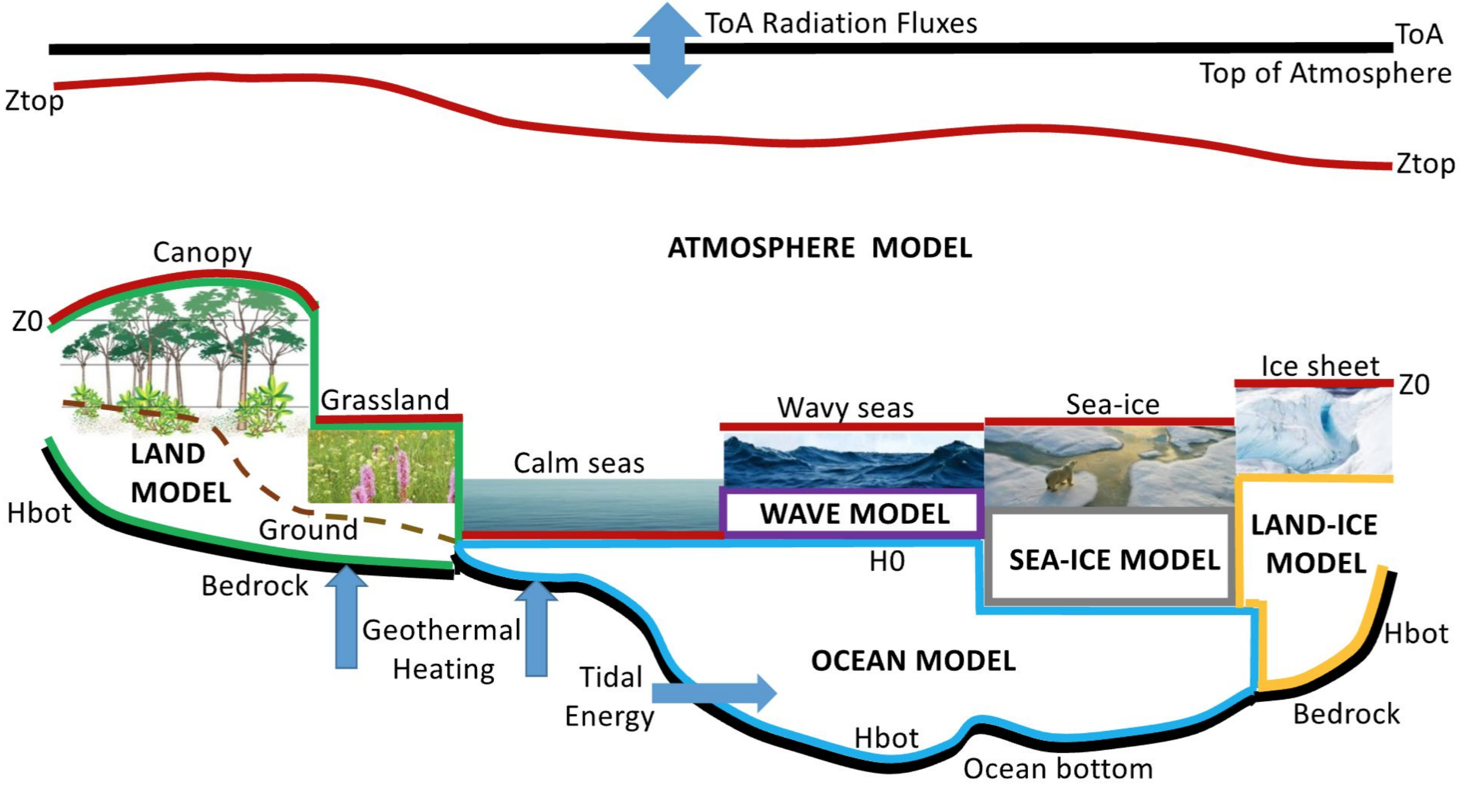

Figure 1. Vertical extents of the modeled Earth System (ToA to Hbot, black); and of its component models of the Atmosphere (Ztop to *Z*0, red); the Ocean (surface, *H*0 to bottom, Hbot, blue); the Land (*Z*0 above ground to bedrock, Hbot); floating Sea-ice (gray); Land-ice (orange) and Surface Waves (purple). The external energy fluxes are Radiation, Geothermal and Tidal.

Closed energy budget? Coupling components

$$\frac{\partial}{\partial t}\iiint \rho\left(E_{atm}\right) dV = -\oiint \mathcal{F}_{atm}^{(top)} d\sigma + \oiint \mathcal{F}_{atm}^{(bottom)} d\sigma,$$

… and similarly for other components, e.g., ocean

$$\frac{\partial}{\partial t}\iiint \rho^{(all)}\left(E_{ocn}\right) dV = -\oiint \mathcal{F}_{ocn}^{(top)} dA + \oiint \mathcal{F}_{ocn}^{(bottom)} dA$$

where the fluxes across components should match

$$\mathcal{F}_{atm}^{(bottom)} = \mathcal{F}_{ocn}^{(top)}$$

Enthalpy flux terms and coupling with MOM6 (= CESM3 ocean model)

Ocean (liquid reference state + constant latent heats)

$$F_{net}^{(h)} \approx F_{net}^{(H_2O)} \left[c_p^{(liq)} \left(\tilde{T}_s - T_{00}\right) + h_{00}^{(liq)}\right] + F_{net}^{(wv)} L_v \left(\tilde{T}_s\right) - F_{net}^{(ice)} L_f \left(\tilde{T}_s\right)$$

Atmosphere (ice reference state + dry heat capacity + constant latent heat)

$$F_{net}^{(h)} \approx \overline{F}_{net}^{(H_2O)} \left[c_p^{(d)} \left(\tilde{\overline{T}}_s - T_{00}\right) \right. + \overline{F}_{net}^{(wv)} L_{s,00} + \overline{F}_{net}^{(liq)} L_{f,00}.$$

Inconsistent … I don't see how this can be made consistent!

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022MS003117

Current CESM3: MOM6 passes its enthalpy flux to atmosphere through global fixer in the coupler and atmosphere fixes its enthalpy flux using global energy fixer.

Loosely speaking: each components does it’s own thing and fixes its own thing independently of each other ...

$$F_{net}^{(h)} \approx F_{net}^{(H_2O)} \left[c_p^{(liq)} \left(\tilde{T}_s - T_{00}\right) + h_{00}^{(liq)}\right] + F_{net}^{(wv)} L_v \cancel{\left(\tilde{T}_s\right)} - F_{net}^{(ice)} L_f \cancel{\left(\tilde{T}_s\right)}$$

Atmosphere (ice reference state + dry heat capacity + constant latent heat)

$$F_{net}^{(h)} \approx \overline{F}_{net}^{(H_2O)} \left[c_p^{(d)} \left(\overline{\tilde{T}}_s - T_{00}\right) \; + \overline{F}_{net}^{(wv)} L_{s,00} + \overline{F}_{net}^{(liq)} L_{f,00}\right.$$

Inconsistent … I don’t see how this can be made consistent!

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Closed energy budget? Within components

$$\frac{\partial}{\partial t}\iiint \rho\left(E_{atm}\right) dV = -\oiint \mathcal{F}_{atm}^{(top)} d\sigma + \oiint \mathcal{F}_{atm}^{(bottom)} d\sigma,$$

… and similarly for other components, e.g., ocean

$$\frac{\partial}{\partial t}\iiint \rho^{(all)}\left(E_{ocn}\right) dV = -\oiint \mathcal{F}_{ocn}^{(top)} dA + \oiint \mathcal{F}_{ocn}^{(bottom)} dA$$

where the fluxes across components should match

$$\mathcal{F}_{atm}^{(bottom)} = \mathcal{F}_{ocn}^{(top)}$$

What are the total energy fixers fixing?

Note: Many of these errors will NOT decrease with higher resolution — in fact, they may even worsen!

- Total (spurious) energy dissipation in the fluid flow solver (a.k.a. dynamical core)
- Energy discrepancies between dynamical core and parameterizations

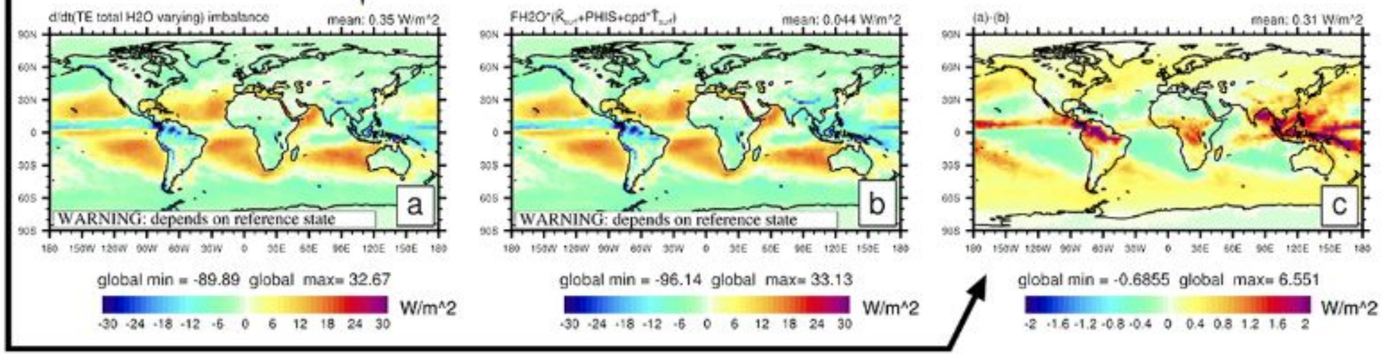
  In CESM we generalized our energy fixer so that it accommodates MPAS dynamical core and introduced generalized thermodynamic infrastructure in support of that.
- The energy loss/gain associated with precipitation/evaporation (e.g., enthalpy flux)

Lauritzen et al. (2022)

Modified CAM total energy equation incl. missing flux terms

$$\frac{\partial}{\partial t}\int \overline{\rho}^{(d)}\left\{\left(1+\overline{m}^{(H_2O)}\right)\left[\overline{K}+\overline{\Phi}_s+c_p^{(d)}\left(\overline{T}-T_{00}\right)\right]+\overline{m}^{(wv)}L_{s,00}+\overline{m}^{(liq)}L_{f,00}\right\}dz$$

$$-\Delta\hat{\mathcal{I}}_{\partial m^{(H_2O)}/\partial t}-\Delta\mathcal{I}_{m_{tn}^{(H_2O)}} = \overline{F}_{net}^{(H_2O)}\left[c_p^{(d)}\left(\tilde{\overline{T}}_s-T_{00}\right)+\tilde{\overline{K}}_s+\overline{\Phi}_s\right]+\overline{F}_{net}^{(wv)}L_{s,00}+\overline{F}_{net}^{(liq)}L_{f,00}+\overline{F}_{net}^{(turb,rad)}$$



Panel a shows the discrepancy in the column-integrated energy budget of a typical Earth System Model that results from a common approximation: neglecting the energy loss associated with precipitation of frozen and liquid water. Panel b shows the discrepancy in the surface energy flux that results from another common approximation: neglecting the energy carried by precipitation reaching the surface. Both fields are large but are almost equal (panel c shows a minus b). A more consistent treatment of the energy budget would relax both approximations at the same time. Credit: Lauritzen et al. [2022], Figure 6

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 (yet climate change is an energy imbalance!)

It is a very technical subject and model development is not always published

Why WGNE?

The Working Group on Numerical Experimentation (WGNE) has responsibility for the development of Earth system models for use in weather, climate, water and environmental prediction on all time scales, and diagnosing and resolving shortcomings.

Questionnaire sent out to WGNE members, CMIP7 groups, etc. (April 2023)

https://docs.google.com/document/d/1cztvWzraYX4oD_Vv8tJpUo3Af_kyG21hr1PDc9knu_4/edit?usp=sharing

Modeling groups who responded *(received many in-depth responses)*

- NCEP GFS/UFS (USA)
- GFDL (USA)
- NASA GISS (USA)
- CNRM-CM (France)
- CMC (Canada)
- ECMWF IFS (Europe)
- DOE E3SM (USA)
- NCAR CESM3/CAM7 (USA)

National Center for Atmospheric Research is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977

Next steps

Challenges?

- Very technical subject
- Energy budgets can **not** be computed from standard (CMIP) datasets - needs tailored diagnostics computed inline in the model (time consuming!)
- Not all model developers attend the same conferences so hard to organize well-attended sessions ("bar to entry too high" in terms of funding/effort!)
- No funding! Have to rely on the will/interest from modeling groups

ADVANCING EARTH AND SPACE SCIENCE

JAMES Journal of Advances in Modeling Earth Systems®

Reconciling and Improving Formulations for Thermodynamics and Conservation Principles in Earth System Models (ESMs)

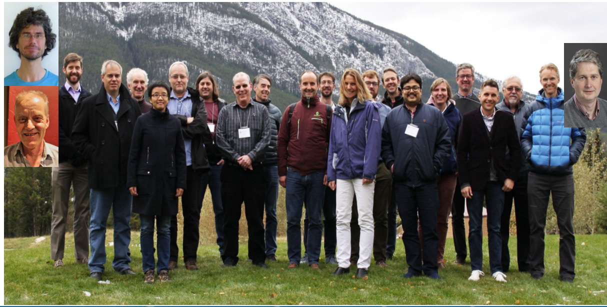
P. H. Lauritzen[1], N. K.-R. Kevlahan[2], T. Toniazzo[3,4], C. Eldred[5], T. Dubos[6], A. Gassmann[7], V. E. Larson[8,9], C. Jablonowski[10], O. Guba[5], B. Shipway[11], B. E. Harrop[9], F. Lemarié[12], R. Tailleux[13], A. R. Herrington[1], W. Large[1], P. J. Rasch[9], A. S. Donahue[14], H. Wan[9], A. Conley[1], and J. T. Bacmeister[1]

Paper link: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022MS003117
(warning: 83 pages; 166 equations excluding equations in the Appendices)

I was surprised that co-authors kept calling in to meetings (probably a total of 15-20 over 2 years) to discuss and some contributed large sections of the manuscript …

Banff International Research Station for Mathematical Innovation and Discovery

The paper was the result of a BIRS workshop held in 2019



Next steps

Organized Zoom meeting October 17, 2024; all modeling groups who responded to survey were invited (some modeling groups invited more people)

Spreadsheet with contacts:
https://docs.google.com/spreadsheets/d/1XStreXONlaxT4fai1-OR9rfEl6HHn9NI3JC0jIOTKMk/edit?gid=0#gid=0

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Purpose of this meeting

- Connect with all of you (virtually) rather than via Email!
- Introduce this effort (why?)
- Present results from questionnaire
- Discuss next steps

Next steps

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*"The goal of these discussions is to shed light on the inner workings of our modeling systems, share insights on what works well and what doesn't, assess the impact of certain errors, and work towards compiling a **WGNE table for physics-dynamics coupling and energy budgets**. For certain topics, we'll also invite experts from other fields (e.g., convection specialists when discussing the heat content of falling precipitation)."*

- > Based on discussions from previous WGNE meetings and recent Zoom meeting with modeling groups that compiled survey, we decided on:

WGNE Bimonthly Discussion on Physics-Dynamics Coupling and Energy Budgets

Each discussion will be centered around a specific theme (VERY INFORMAL!)

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

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

December 16, 2024

Overview

- Intro (Lauritzen)
- ?
- NCAR's CESM (Laurizen)

ç

- DOE E3SM (Guba)

Bla bla

- **Bla bla bla**

Please use this slide as template

Closing remarks

- Here is link to Google drive with presentations, spreadsheets, questionnaire responses, etc.

  https://drive.google.com/drive/folders/1U5lkJP54fPGH70mXhcOyLO2ShT2dadSd

- Still need to advertise

  WGNE Bimonthly Discussion on Physics-Dynamics Coupling and Energy Budgets

  more broadly

- Nils asked about possible publication

Recommendations for future directions and priorities

Inclusion of Neglected Physical Processes

Incorporating processes such as frictional heating caused by falling precipitation and surface heating/cooling from precipitation.

Consistent Thermodynamic Treatment

Using more self-consistent thermodynamic methods (thermodynamic potentials).

Energy-Conserving Numerical Methods

Employing/deriving numerical methods that inherently conserve energy and/or careful accounting of kinetic energy loss by the dynamical core

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Featured as Editor's Highlight in Eos:
https://eos.org/editor-highlights/consistently-closing-the-energy-budget-in-earth-system-models

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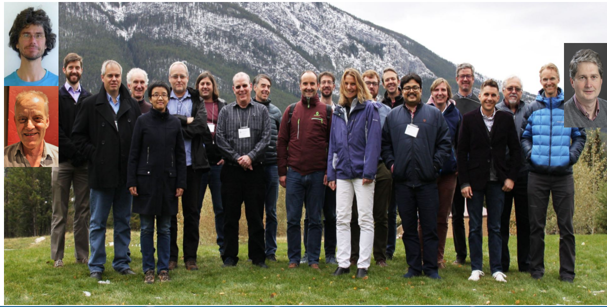

It is unusual for a model development paper to receive this kind of attention. Model developers are usually 'hidden in the engine room!'