Improving the Land Component in Earth System Models (ESMs) via a Hierarchical System Development (HSD) Approach

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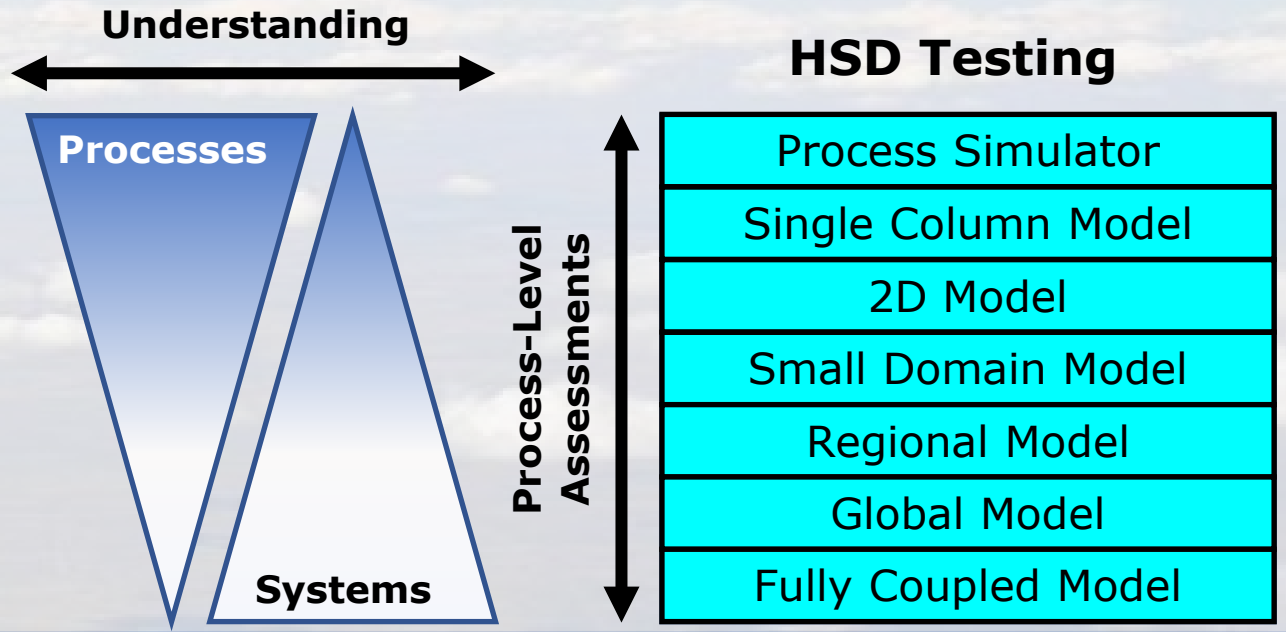
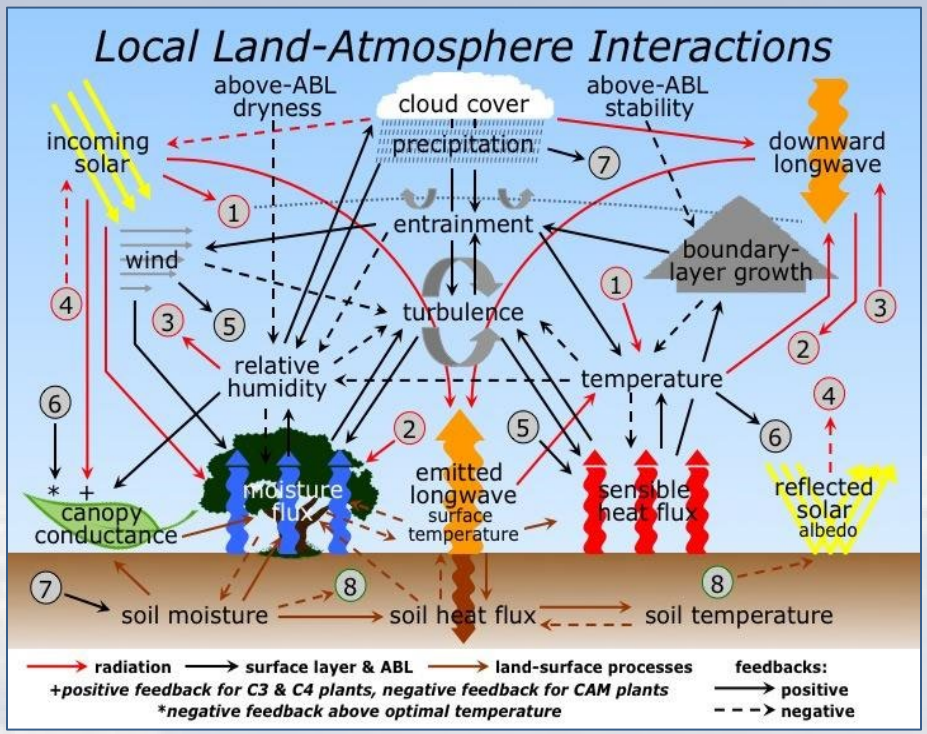
What is Hierarchical System Development (HSD)?

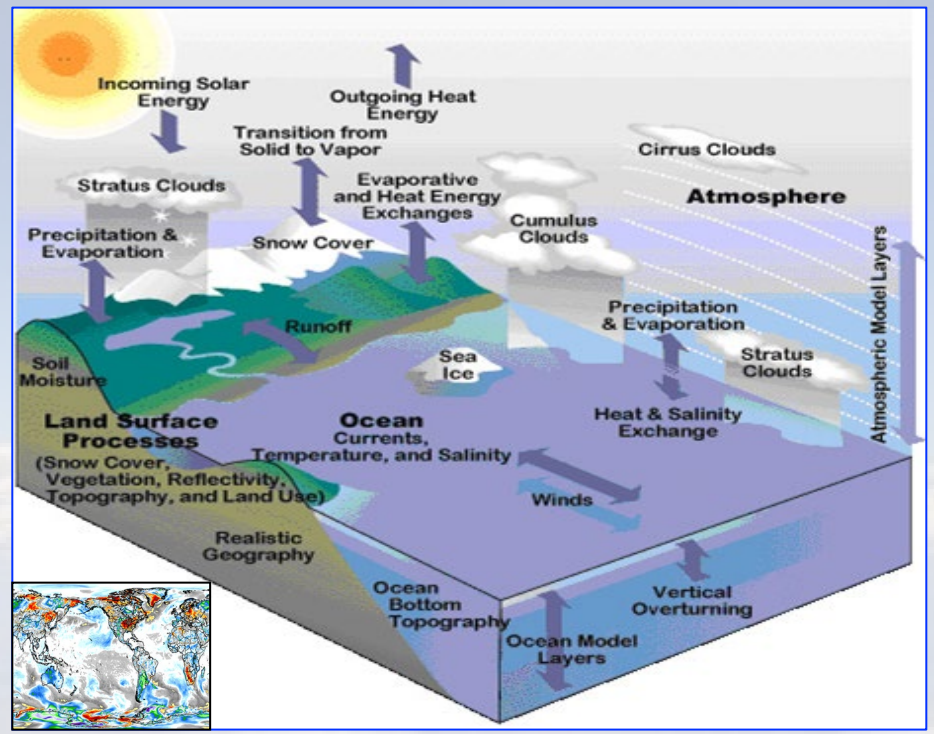
- **HSD**: an efficient model development approach, spanning **simple to complex**, with multiple "entry points" in order to work more easily with the broad Earth system research and modeling community.
- **HSD leverages model development tools:**
  - **Common Community Physics Package (CCPP)** enables HSD via a framework to connect physics to models via CCPP and the CCPP Single Column Model (SCM).
  - **METplus** supports HSD diagnostics & verification, including at the process level.
  - **CCPP & METplus** supported by the Developmental Testbed Center (DTC).
- **HSD provides:**
  - **Simpler versions** of a more complex system, so easier to work with and understand.
  - **Testing pathways** for updates and new innovations, e.g. from research community.
  - **More efficient use of compute resources.**



Why do we need Hierarchical System Development?

- **<u>Many</u> Earth System processes** to model, from local to regional & global.

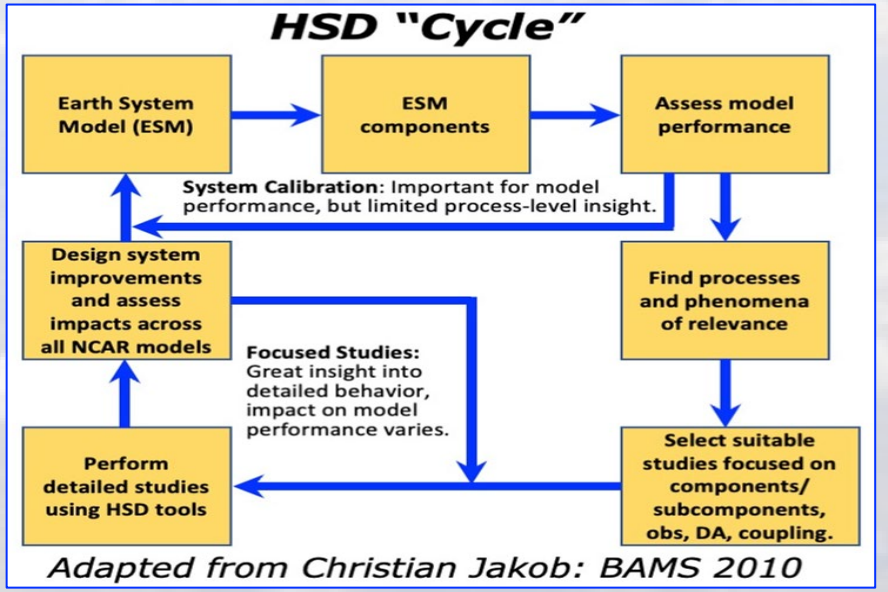




- **To understand model biases**, we often need to start by simplifying the atmosphere/earth system down to a few key processes and interactions.
- **For efficient use of compute resources**, need to identify/fix bugs early in the testing process… before making longer model runs.

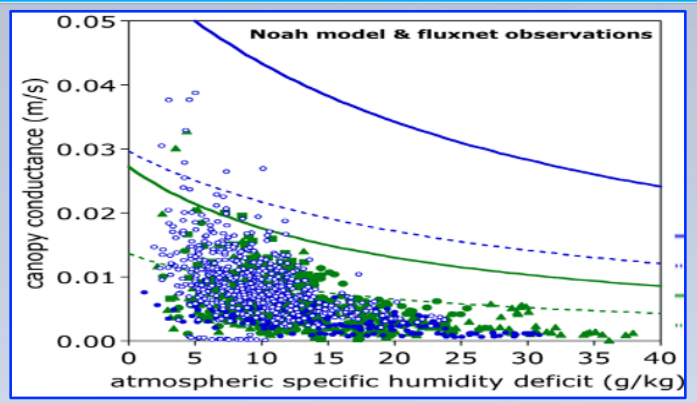
Hierarchical System Development: Brief Background

- WCRP Climate 2016 & 2022 workshops: Climate community uses hierarchical approach to understand model behavior.
- Tim Palmer (Univ. Oxford, UK MetOffice, ECMWF): ***"Hierarchical thinking should be second nature for all weather/climate scientists (of course)."***
- Julia Slingo's (UK Met Office, ret.; 2017 WCRP review): ***"Increase focus on process-level understanding in making model improvements, and connect weather & climate research and modeling."***
- Christian Jakob (Monash U., Australia; AMS BAMS 2010): ***"…our community needs to improve diagnosis of processes contributing to model errors. We need more model developers, not just model users!"***
- Tom Hamill (weather.com; NOAA SAB 2021 "PWR" report author): ***"We need to become more systematic in addressing systematic errors in Earth system models."***
- See the HSD-focused article that leverages Jakob (2010): www.ufscommunity.org/articles/hierarchical-system-development-for-the-ufs.



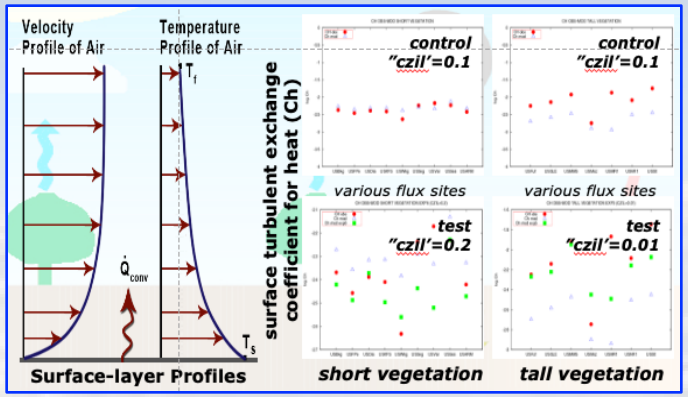
HSD Example: evaluation of land physics using process simulators

(a)



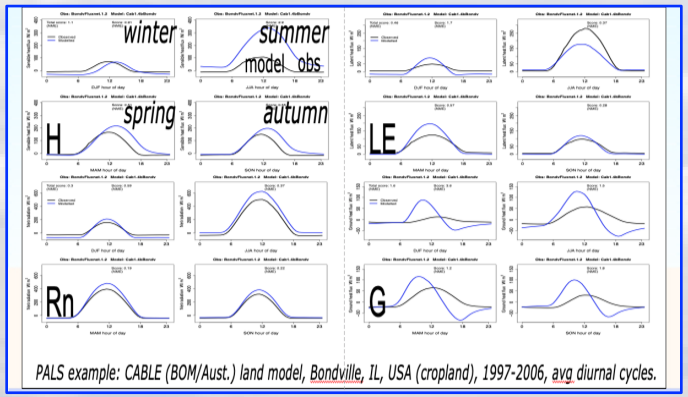
Land model subcomponent:
Canopy conductance and effect on transpiration calculation.
Finding: adjust effect of specific humidity deficit on canopy conductance.

(b)



Land model subcomponent:
Surface-layer turbulent exchange coefficient (Ch).
Finding: adjust Ch as a function of vegetation height following Chen & Zhang (2008, GRL).

(c)



Land model:
Focus on surface fluxes for different seasons/regions/veg types, noting systematic biases.
Finding: revisit various land model subcomponents.

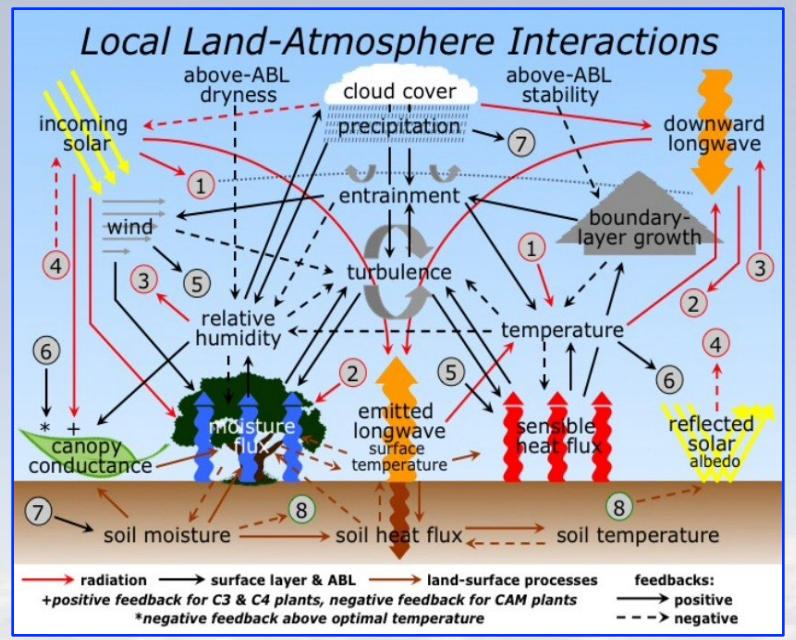
HSD Testing

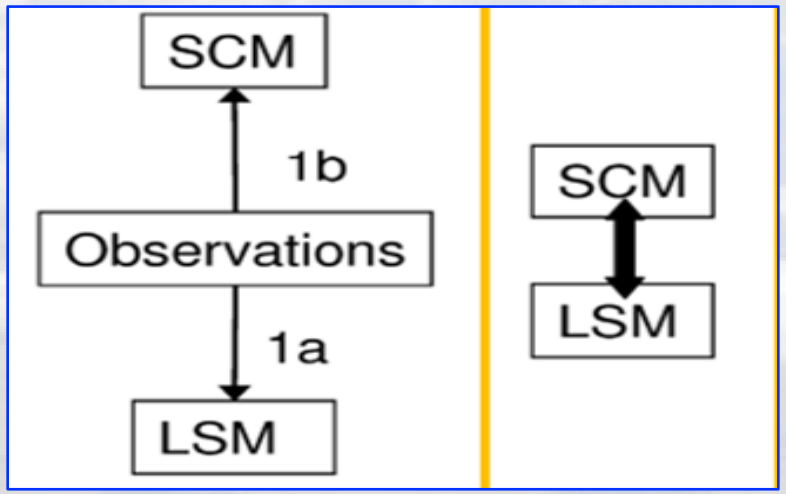
- Process Simulator
- Single Column Model
- 2D Model
- Small Domain Model
- Regional Model
- Global Model
- Fully Coupled Model

(a) NCEP/EMC study.
(b) NCEP/EMC study.
(c) GEWEX/GLASS land model "benchmarking" project.

Note: these studies/projects did not use CCPP SCM, but should be repeated with CCPP SCM.

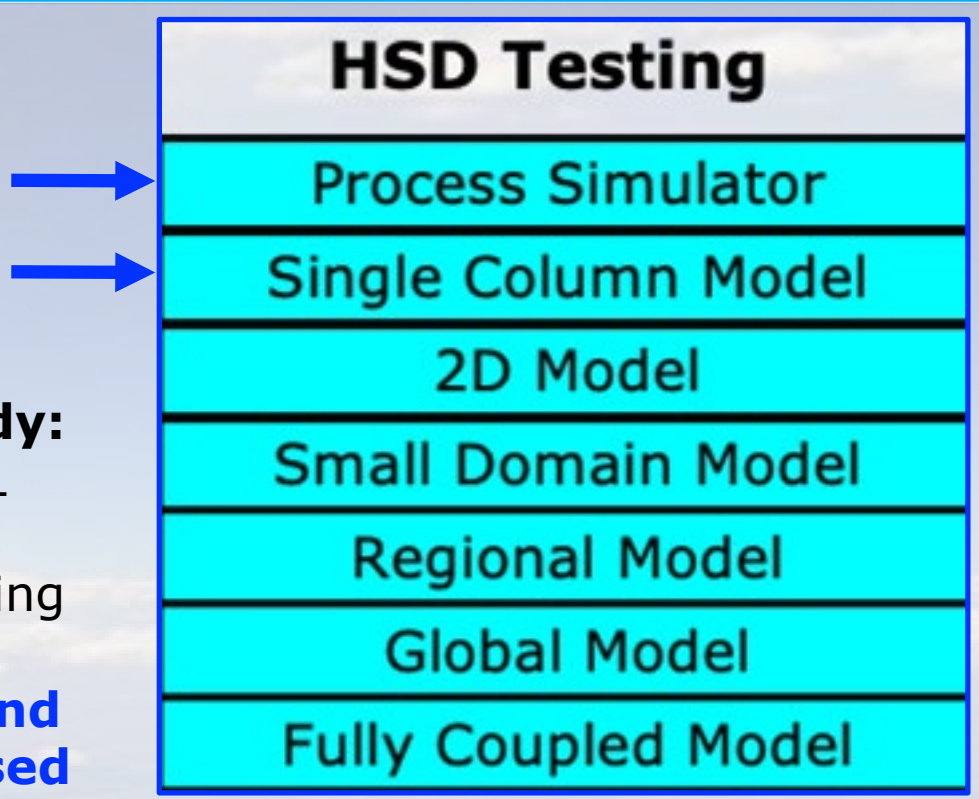
HSD Example: evaluation of interacting land-PBL physics using SCM





Single column model study: Focus on surface fluxes, PBL characteristics and land-atmosphere interaction, noting systematic biases.

Finding: review/refine land model subcomponents used for surface flux calculations.



GEWEX Atmospheric Boundary Layer Study (GABLS): DIurnal land-atmosphere Coupling Experiment (DICE) project.

Note: this study/project also did not use CCPP SCM, but should be repeated with CCPP SCM.

Examples: Physics Testing & Evaluation using CCPP SCM

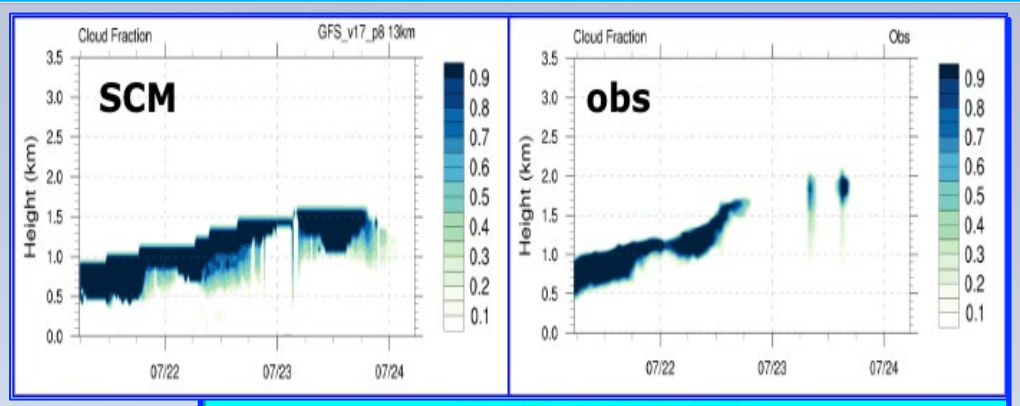
Marine stratus. Case study for MAGIC (Marine ARM GPCI* Investigation of Clouds). Uses CCPP SCM tests to examine the representation of Sc-to-Cu transition. ***Finding: Physics FAILS to capture shallow cumulus transition in Sc-to-Cu transition regime on day 3.***

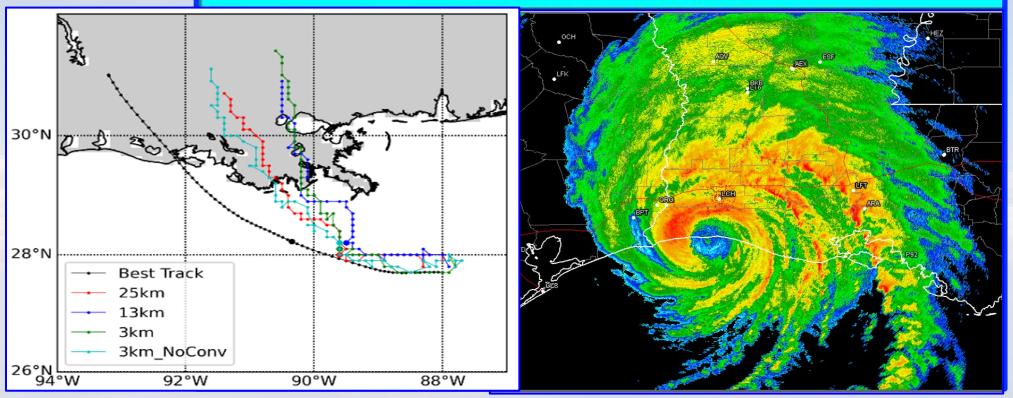
*GPCI: GCSS Pacific Cross-section Intercomparison, GCSS: GEWEX Cloud System Study, GEWEX: Global Energy and Water Exchanges project, GEWEX a core project in the World Climate Research Programme (WCRP).

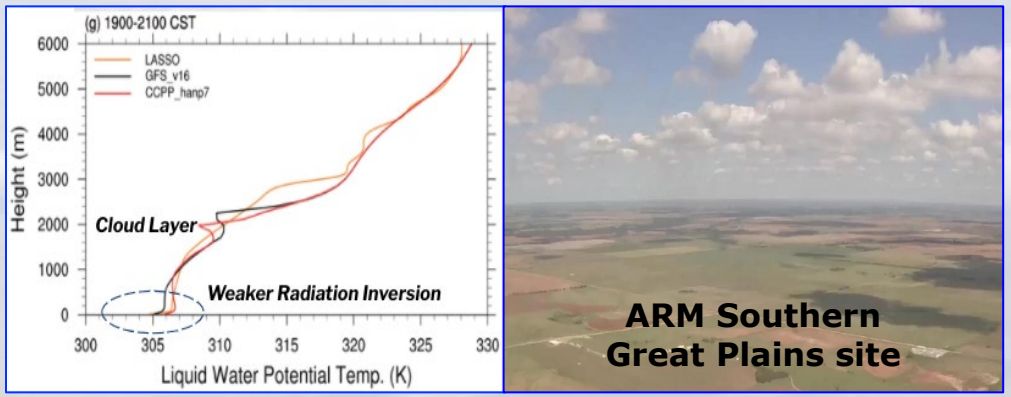
CCPP physics suites evaluation across scales. 3km (CAM+), 13km (Global medium-range), 25km (S2S#) resolution, and CCPP SCM. ***Finding: Physics suites DID NOT produce scale-invariant results for forecasts of temperature, cloud cover, precipitation or TC track.***

+Convection-Allowing Models. #Subseasonal-to-Seasonal.

PBL, surface layer & cloud processes over land. HSD approach: CCPP SCM runs (test GFS physics with & w/o updated Cu) compared with LASSO LES. ***Finding: SCM produces weaker radiation inversion with stronger entrainment & capping inversion yielding excessive clouds.***







Summary – Challenges & Opportunities

- **Earth System Models for weather and climate are becoming increasingly complex**, with many processes & interactions. Need to get the **right answers for the right reasons!**
- **Hierarchical System Development (HSD) is a "systems engineering" approach** that tests small elements (e.g. physics schemes) of an ESM first in isolation, then progressively connects elements with increased coupling between ESM components (e.g. via **SCMs**, and small-domain & limited-area models), regional, global models, fully-coupled models.
- **HSD can help improve understanding of spatial and temporal dependencies** in model physics, i.e. consistent solutions between models/applications at different resolutions. Also, the **HSD process is concurrent and iterative**, i.e. results from more complex HSD steps can provide information to be used at simpler HSD steps, and vice versa.
- Testing & Evaluation Development tools: **Common Community Physics Package** (CCPP) provides an **efficient infrastructure** and **sets of physics** that connect HSD steps, where CCPP is under active development by DTC & the community, with new parameterizations & framework capabilities being added. "**METplus**" provides **verification/diagnostics** that includes **process-level metrics**; also under active development by DTC & the community.
- NCAR Joint Numerical Testbed and DTC working with the Earth system research and modeling community on the use of HSD for a more effective model improvement process.

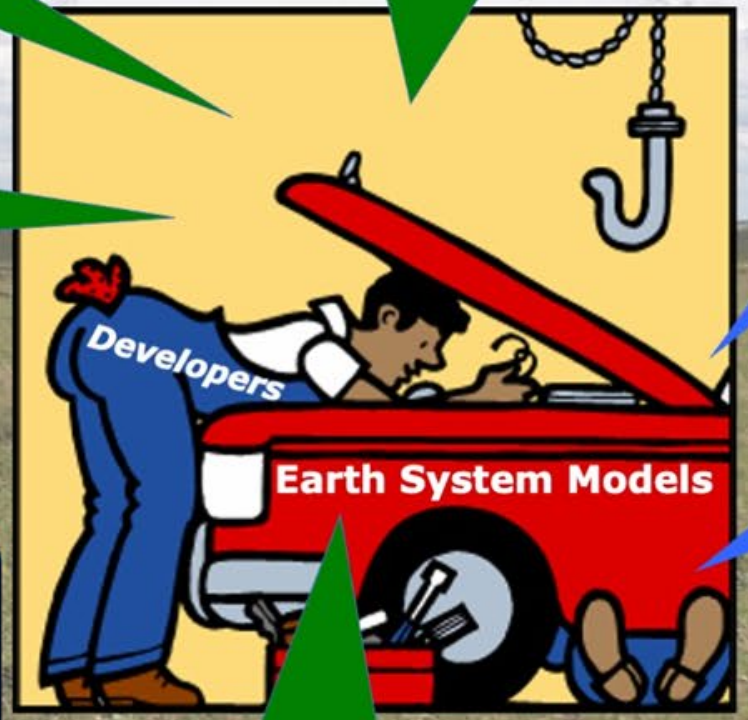
Thank You!

..and you're also going to need an atmospheric alignment to get the interactions right.

Uh oh! These surface fluxes don't look so good.

Ugh! Look at the hydrology in this thing! It's leaking everywhere!

We need to carefully look at all the process-level metrics.



...and its carbon output is way too high...

Earth System Modellers:
But we just want to jump in and DRIVE!? ...and How much will all this COST?!

Well... at least SEVERAL more funding cycles.