Science Spotlight On Hierarchical System Development for Earth System Models

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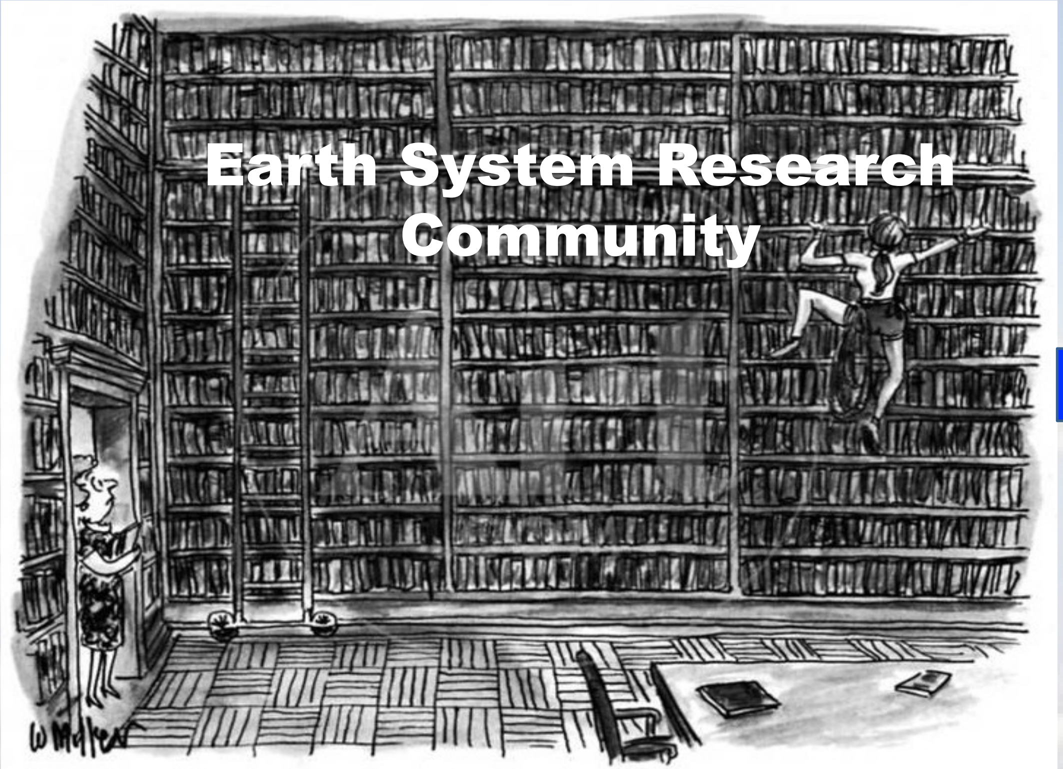
DTC Developmental Testbed Center

UFS workshop (Unifying Innovations in Forecasting Capabilities Workshop)
NCAR, Boulder, Colorado · 24-28 July 2023

Earth System Model Development Process

Previous (or Current?!) Paradigm



A lot of great research!

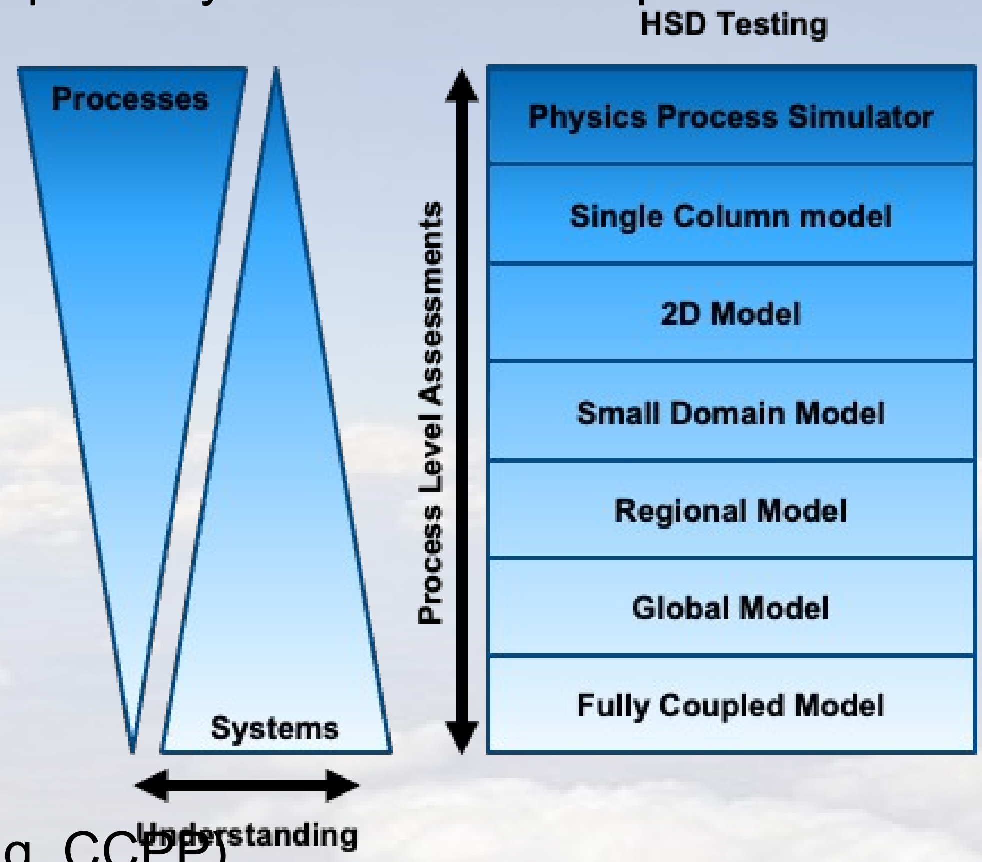
...that needs to be identified and transitioned somehow.

"Toss it over the fence" ?!

But how to improve this process?

Hierarchical System Development: What is it?

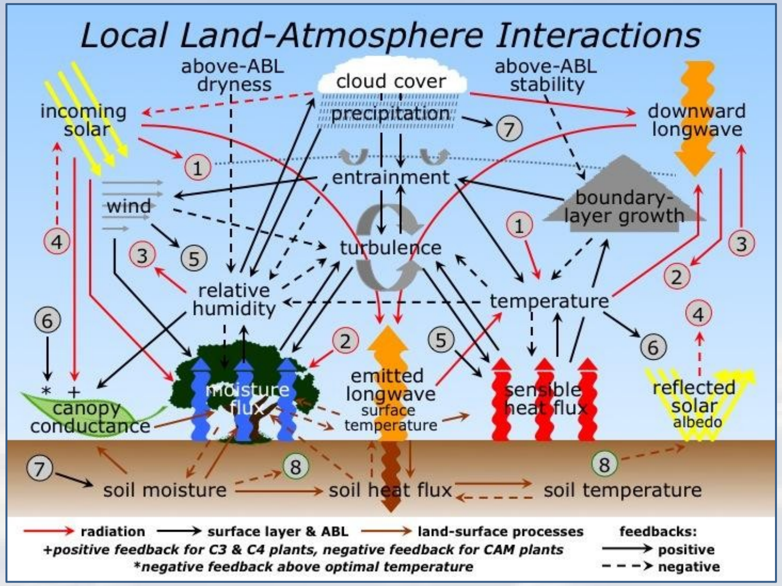
- Hierarchical System Development (HSD) is an efficient pathway for model development.
- Enables model development community with multiple entry points for research efforts spanning simple to complex.
- Many unique perspectives of HSD, defined by Model complexity, Model configurations (Jeevanjee et al. 2017), or Principles of large-scale circulation (Maher et al. 2019).
- Serves as an end-to-end system, i.e. data ingest and quality control, data assimilation, modeling, post-processing, and verification, with a corresponding configurable workflow.

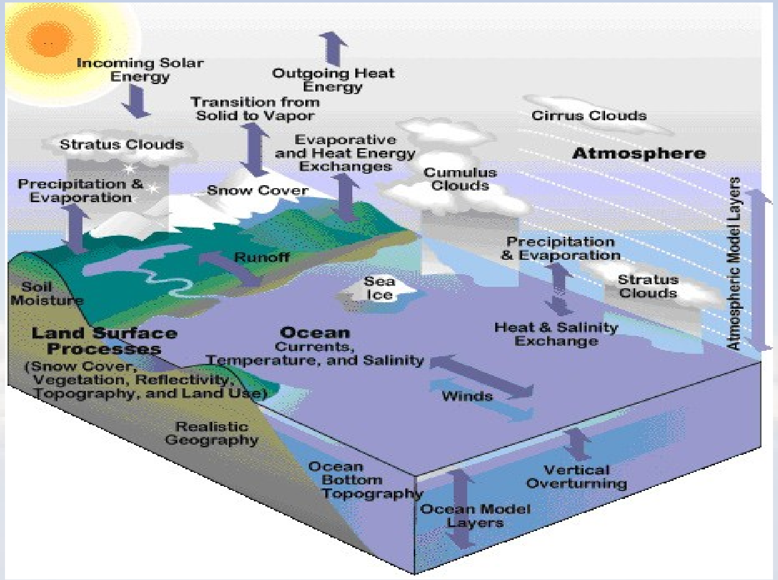


- Infrastructure: necessary to connect the HSD steps (e.g. CCPP).
- Verification: necessary to assess model performance (e.g. METplus).

Hierarchical System Development: Why do we need it?

- **Many 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.

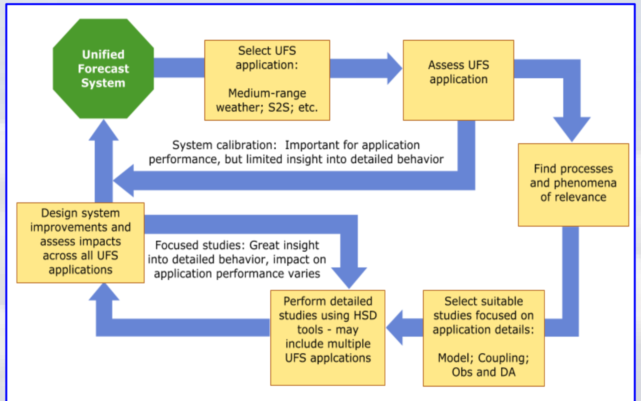
Hierarchical System Development: Brief Background

- ➔ WCRP Climate workshop in 2016: Climate community uses hierarchical approach to understand model components and behavior. Follow-on Aug-Sep 2022: 2nd Model Hierarchies Workshop.

- ➔ 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) 2017 review of WCRP: **Increase focus on process- level understanding for model improvement, and connect weather and climate.**

- ➔ Christian Jakob (Monash U., Australia; AMS BAMS 2010): "…community needs to improve diagnosis of processes contributing to model errors, with **more model developers needed!** *Not just model* ***users!***"



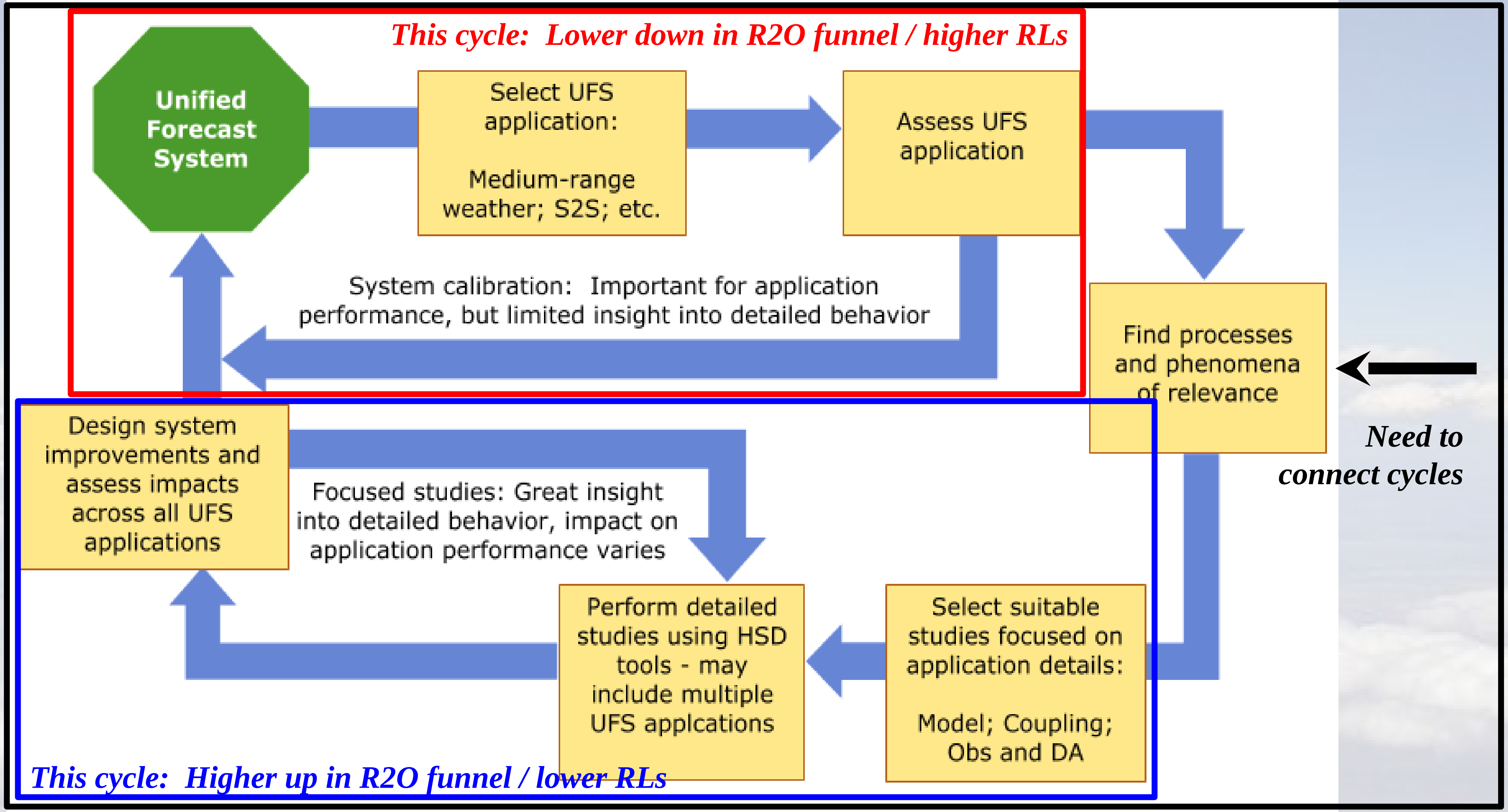
HSD in the UFS Development Process (Figure adapted from Christian Jakob, BAMS 2010)

HSD R2O cycles

- ➔ See the HSD-focused article that leverages Jakob (2010):

www.ufscommunity.org/articles/hierarchical-system-development-for-the-ufs

Hierarchical System Development: R2O cycles



HSD in the UFS Development Process (Figure adapted from Christian Jakob, BAMS 2010)

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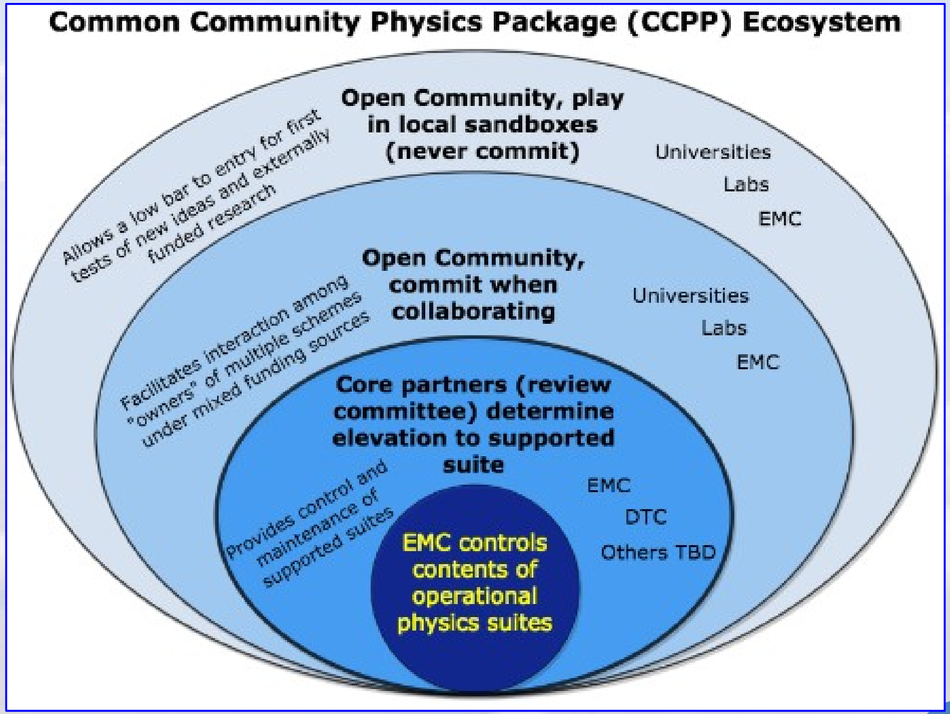
How to connect HSD steps to improve the model development process?

- **Infrastructure to connect the HSD steps: the Common Community Physics Package (CCPP)** provides a method for testing atmospheric physics (and land).
- CCPP consists of a **library of physical parameterizations** (which can be grouped as physics suites) and an **infrastructure to connect physics with host models.**
- **CCPP is designed to lower the bar** for community involvement in physics testing and development through increased interoperability, improved documentation, and continuous support to developers and users.
- The **CCPP** and CCPP Single Column Model (SCM) provide a s**oftware infrastructure that is an enabling tool that helps to more efficiently connect Hierarchical System Development steps.**
- CCPP has been integrated into the NOAA Unified Forecast System (UFS) for global and regional NWP, and is currently being integrated into NCAR & Naval Research Lab models, and leverages the NOAA-NCAR MOA on sharing modeling infrastructure, e.g. CCPP.



https://dtcenter.org/ccpp

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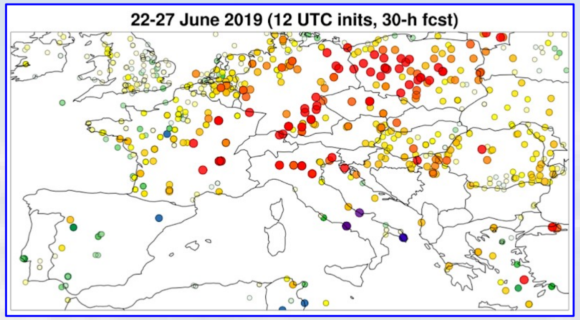
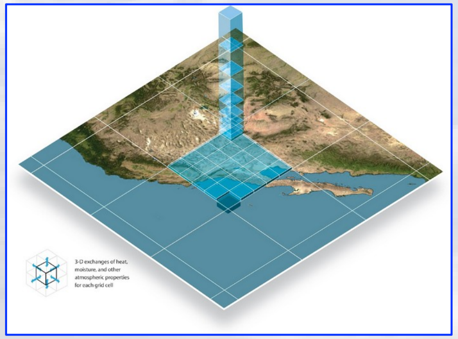
How to connect HSD steps to improve the model development process?

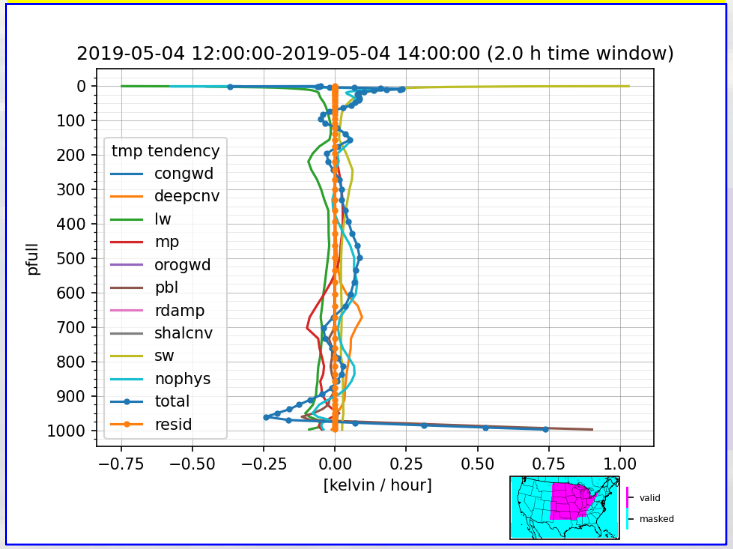
- ➔ **METplus <u>verification</u> software for NWP and other Earth system models for the HSD steps.**
- ➔ **METplus includes metrics at the <u>process level</u>.**

https://dtcenter.org/community-code/metplus

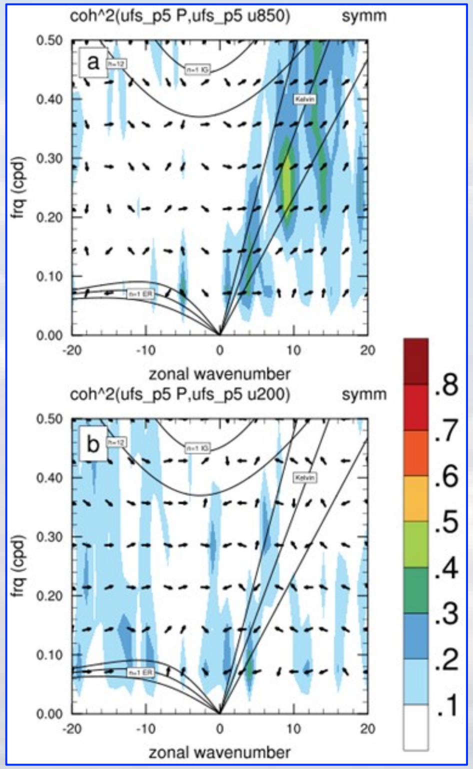




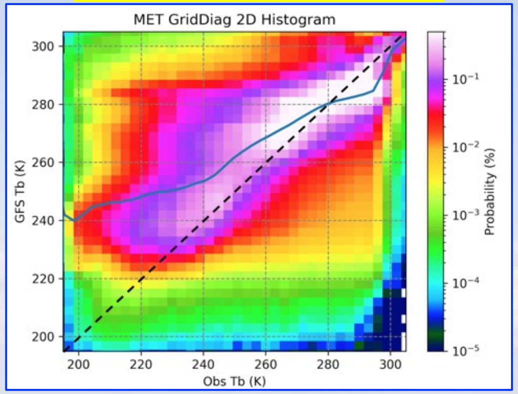
Errors and Tendencies within a columns, soundings, or profiles.

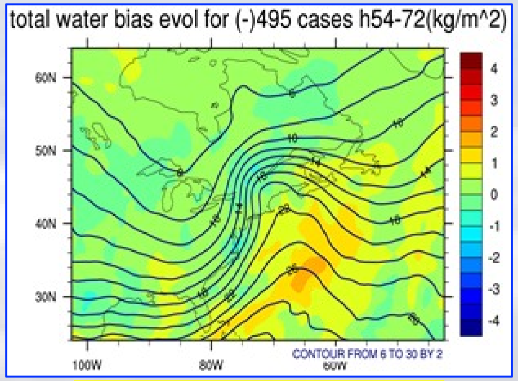


S2S Diagnostics including planetary waves.



Multivariate Relationships.





Systematic Biases.

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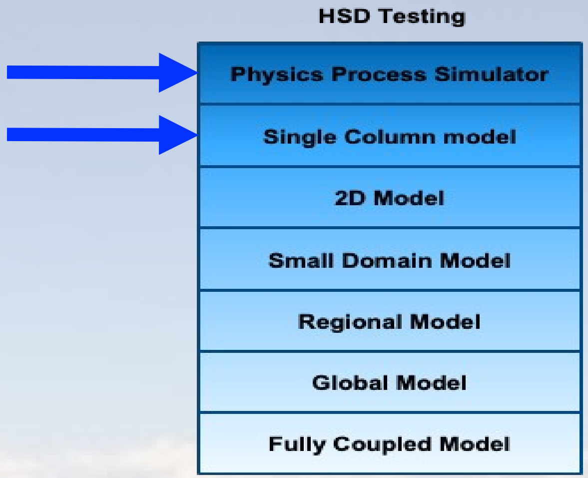
How to connect HSD steps to improve the model development process?

- Corresponding software development for the CCPP Suite Simulator via "on/off" switches in **Single Column Model (CCPP SCM)**.



Within the physics step, the model-state (S) is updated after each physics scheme is called:

Scheme	All active physics	Only one active scheme
Radiation	$\frac{\partial S_{RAD}}{\partial t}$ +	D_{RAD} +
Surface	$\frac{\partial S_{SFC}}{\partial t}$ +	D_{SFC} +
Land-surface	$\frac{\partial S_{LSM}}{\partial t}$ +	$\frac{dS_{LSM}}{dt}$ +
Planetary Boundary Layer	$\frac{\partial S_{PBL}}{\partial t}$ +	D_{PBL} +
Gravity Wave Drag	$\frac{\partial S_{GWD}}{\partial t}$ +	D_{GWD} +
Ozone Photochemistry	$\frac{\partial S_{Ozone}}{\partial t}$ +	D_{Ozone} +
Upper-Atm H_20	$\frac{\partial S_{h2o}}{\partial t}$ +	D_{h2o} +
Deep Convection	$\frac{\partial S_{CNVD}}{\partial t}$ +	D_{CNVD} +
Shallow Convection	$\frac{\partial S_{CNVS}}{\partial t}$ +	D_{CNVS} +
Cloud Microphysics	$\frac{\partial S_{MP}}{\partial t}$ =	D_{MP} =
	$\frac{dS}{dt}$	$\frac{dS}{dt}$

To isolate the impacts of changes in individual physics schemes, we can replace the active physics schemes with **data-driven physics tendencies.**

For example, here all of the physics schemes, *except the land surface model*, have been **"turned off"** and data-driven physics tendencies have been **"turned on"**.

Feature: Test physics coupling scheme-by-scheme

Advance model state w/ **all active** physics schemes.

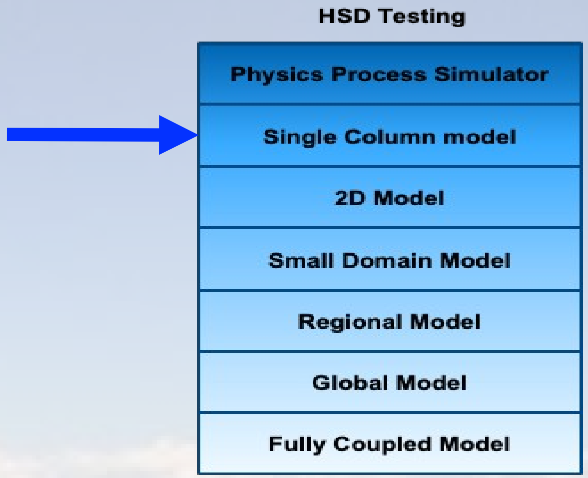
$$S_{t+1} = S_{t0} + \frac{dS}{dt}dt$$

Advance model state w/ only **one active** physics scheme.

CLIM 670 Earth System Modeling Prof. C. Stan, GMU

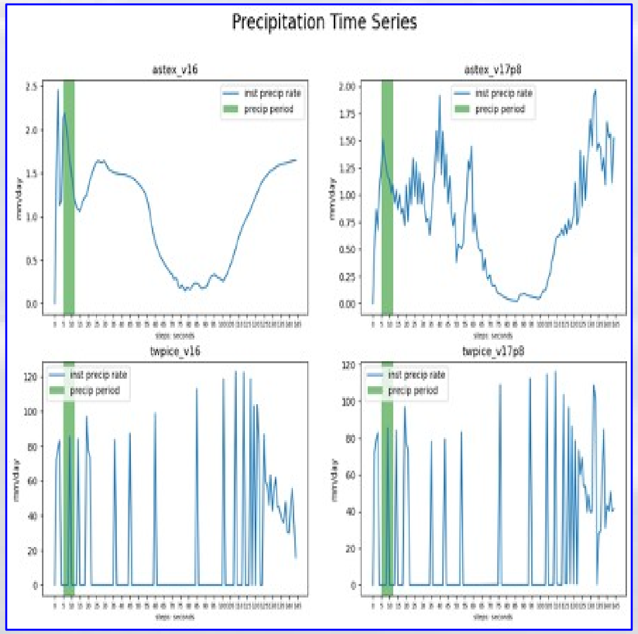
Using the CCPP SCM as a Teaching Tool

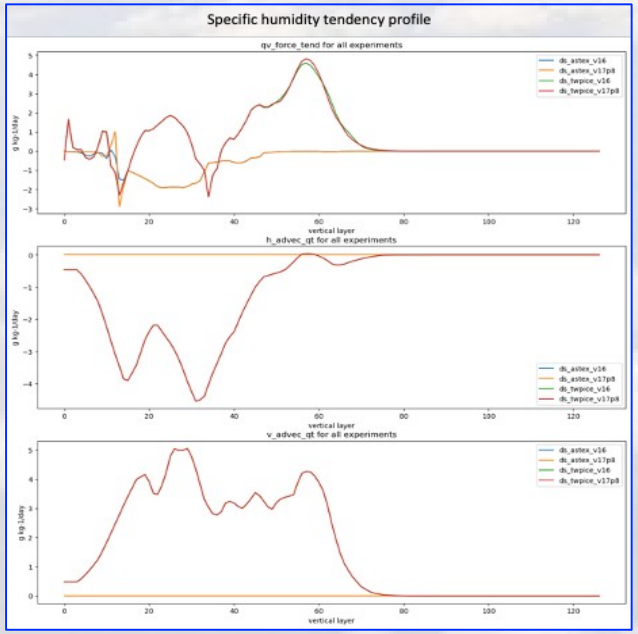
- Easy process of porting and compiling the code.
- Attractive elements as teaching tool: (1) offers relatively large library of physical suites, (2) provides variety of pre-processed forcing data.
- Allows students to design experiments to understand behavior of physical parameterizations in different environments, and explore limitations of the approach.



Assignment

Simulation of active or suppressed convection by two physics suites (e.g., GFS v16, GFS v17P8) in two different environmental conditions (ASTEX, TWICE).

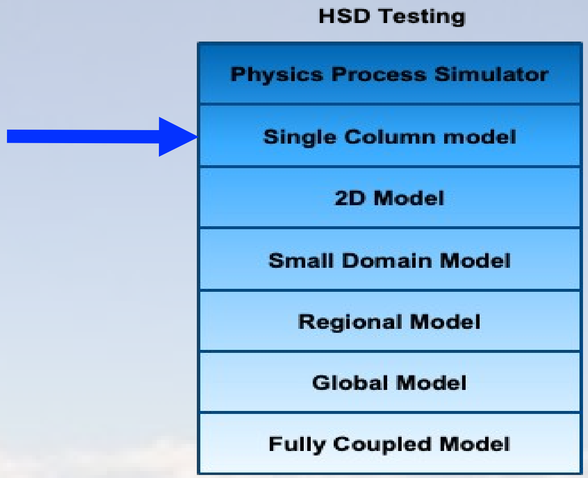




"My decision to select the CCPP SCM, developed by DTC, was influenced by my current work with the NOAA UFS which uses CCPP for majority of physics parameterizations in the atmospheric component, and further motivated by the detailed user and technical guide that accompanies the public release of CCPP SCM code."

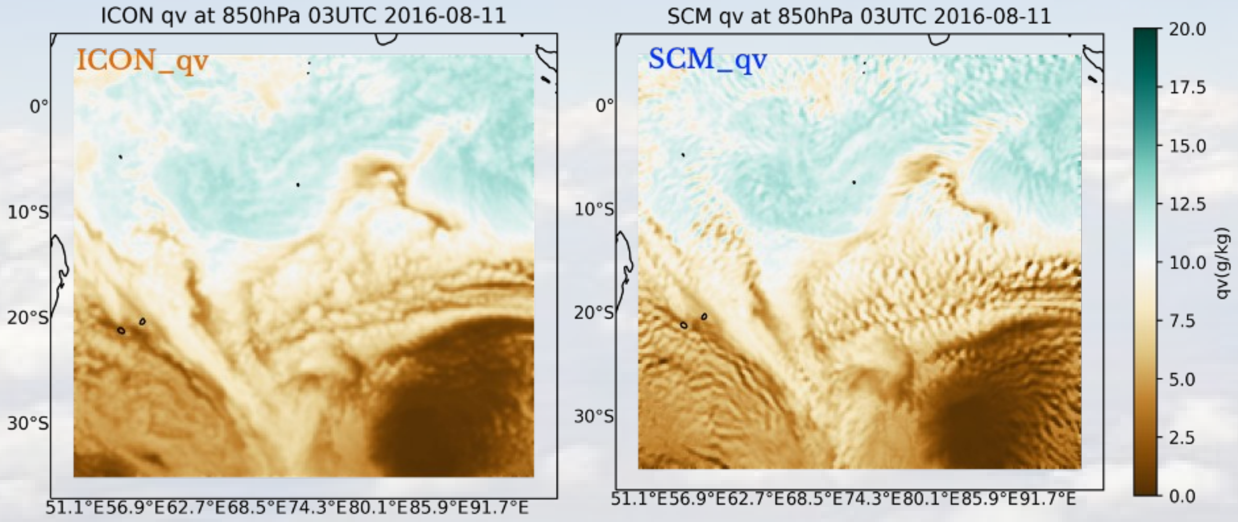
DTC WWRP project

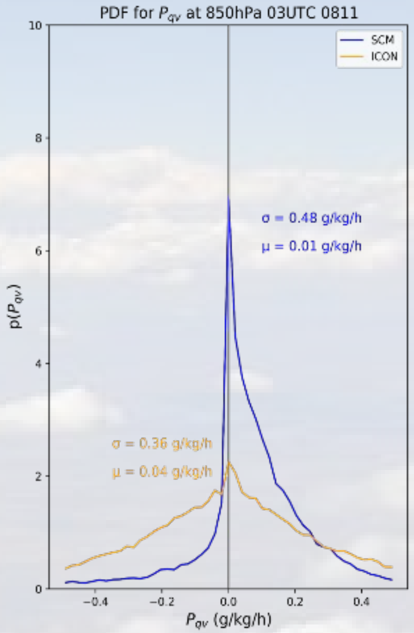
Hierarchical System Development: Example
Model Uncertainty – Model Intercomparison Project (MU-MIP)



Hierarchical testing for improvement of stochastic and deterministic physical parameterizations.

Key Method: Compare state variables and tendencies in a convection-permitting high-resolution simulation against a lower-resolution parameterized-convection simulation.





SCM: Computationally cost-effective way to characterize model uncertainty to inform model development.

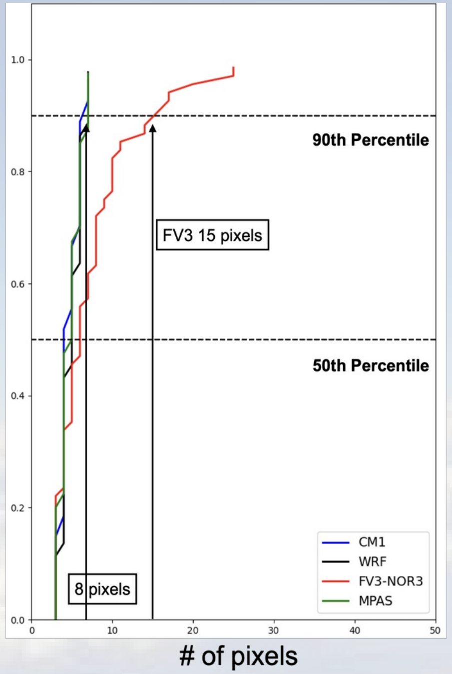
- An array of CCPP SCM runs at 44,000 grids over Indian Ocean for 40-days (reinitialized every 3 hrs for 6 hr forecast), driven by ICON coarse-grained forcing.
- CCPP SCM reproduces the spatial distributions of meteorological variables.
- PDFs show **SCM** has larger probability for positive physics tendencies of *qv* than **ICON,** indicating missing or misrepresenting physical processes in low resolution SCM runs.

NOAA NSSL research

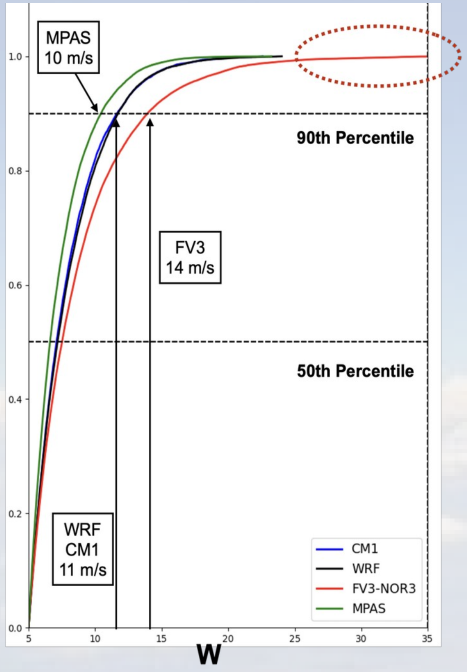
Hierarchical System Development: Example

Evaluation of Convective Storm Characteristics/Biases Across Model Cores

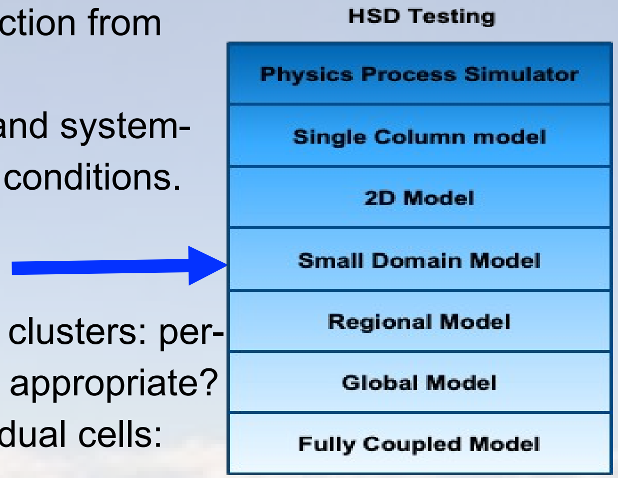
Size (# of pixels) for storm objects Squall Line simulation 0-2 hours



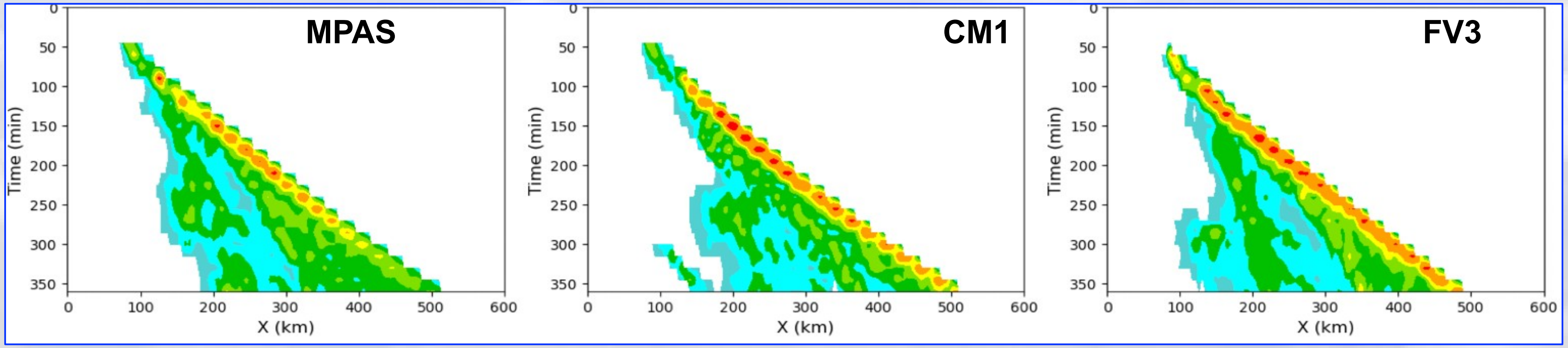
Squall Line W's Cumulative Frequency over 6hr simulations



- Understanding the characteristics of convection from full physics simulations is difficult.
- Less complex framework to better understand systematic biases: 3D simulations using idealized conditions.
- NGGPS and DCMIP2016:
  Only looked at single supercell.
- Most CONUS convection occurs in lines or clusters: perhaps idealized squall line simulations more appropriate?
- Squall lines generate a large number individual cells: Better sample size?
- Can specify CAPE (instability) and vertical wind profile: generating a wide variety of convective lines, intensities, precipitations, etc.
- Controlled comparison of various systems for surface precipitation, vertical velocity, cloud top depth, etc.
- NCAR is in the process of making all physics packages CCCP compliant.



Hovmoller Diagrams for 3 Models Strongly Shear Squall Line 0-6 hour 15 min Accum. Precip

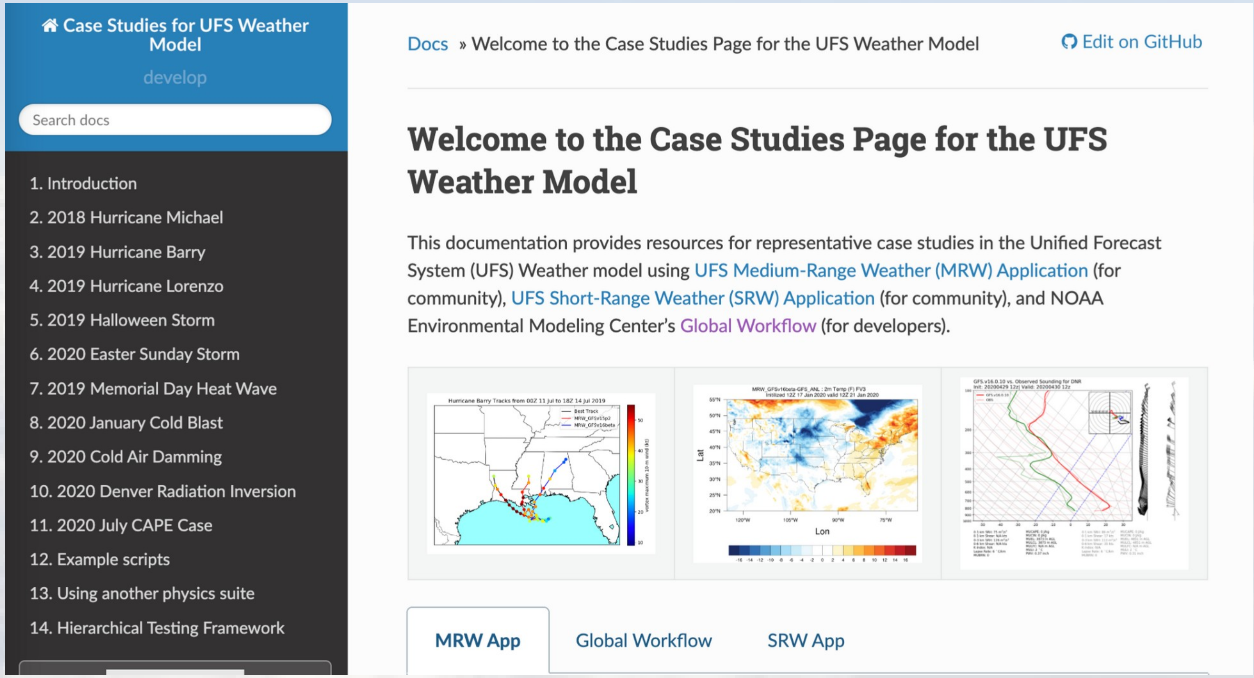


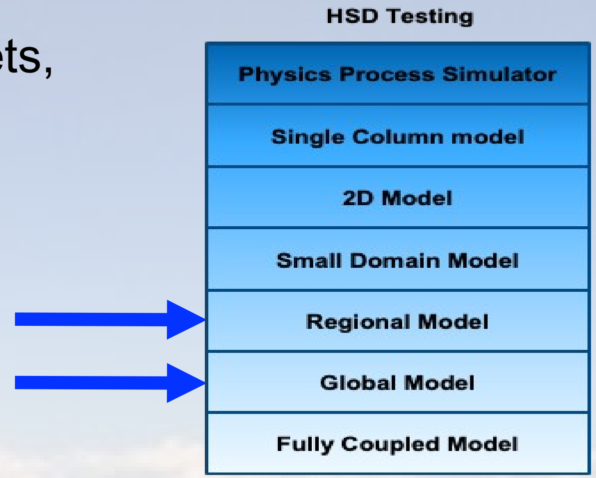
Developmental Testbed Center

HSUP project

Hierarchical System Development: Example
UFS Case Studies

- A platform to share UFS model representative case study configurations, datasets, results, and example visualization scripts.
- ufs-case-studies have recently been integrated into SRW apps.
- DTC and EPIC teams are collaborating to update repository & instructions.





UFS Case Studies: An entry point for UFS HSD

Read the Docs: https://ufs-case-studies.readthedocs.io/en/develop/index.html
GitHub: dtcenter/ufs-case-studies

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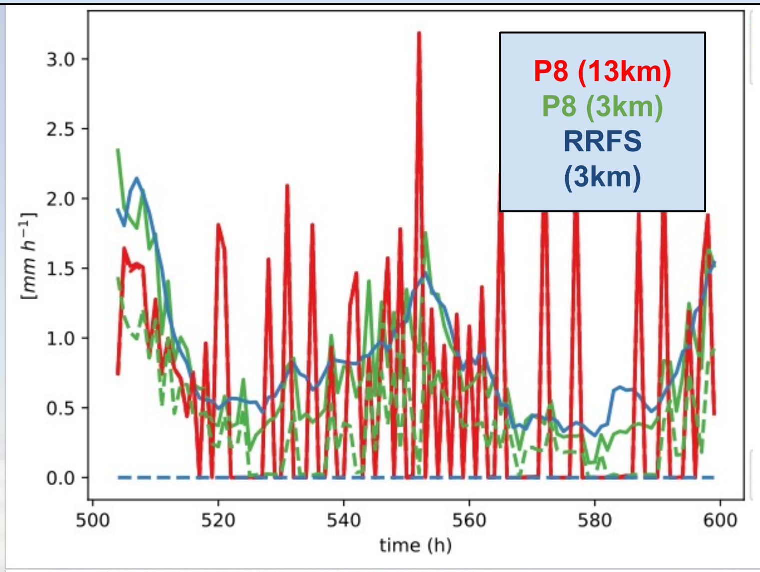
DTC UniPhy project

Hierarchical System Development: Example

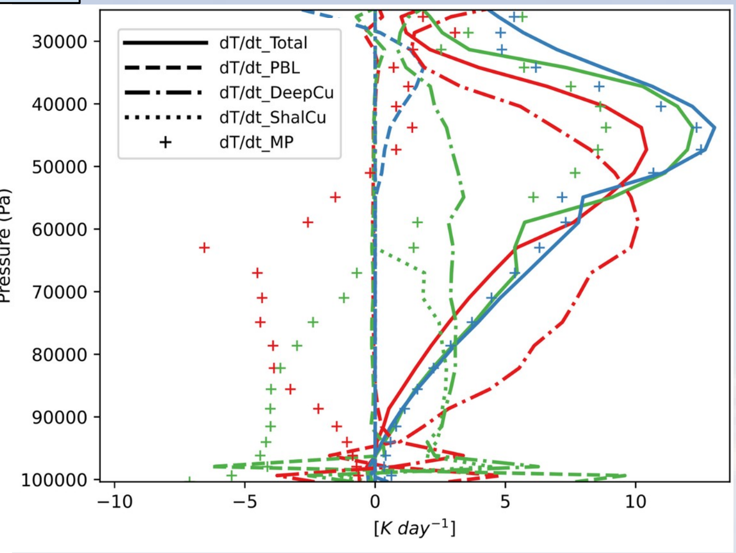
Physics Testing and Evaluation towards Physics Unification

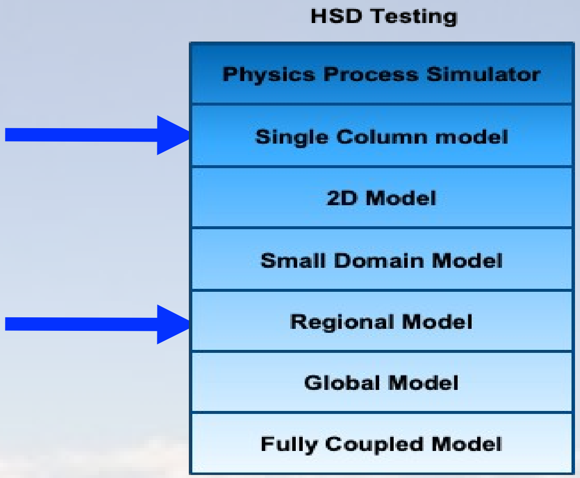
SCM

Total (solid) vs Parameterized (dashed) Precip Rate [mm/hour]

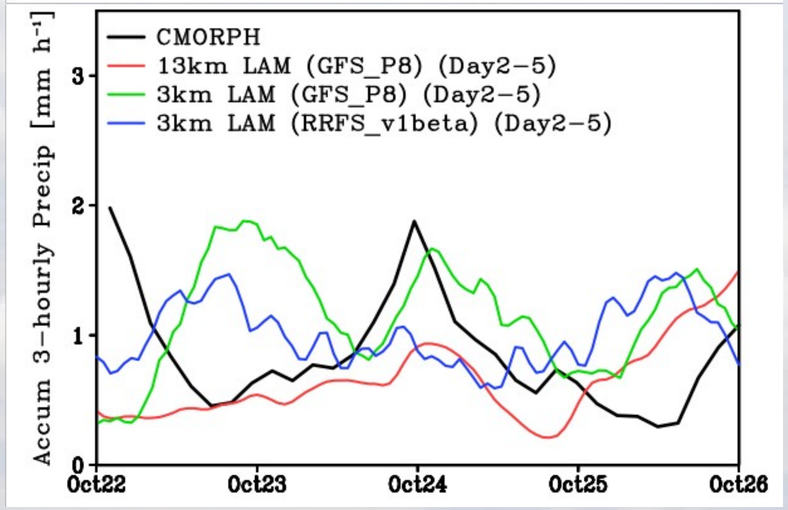


dT/dt by model physics





LAM



- SCM better than LAM *wrt* rainfall amount & variations.
- Large-scale env critical for simulating MJO-induced rainfall.
- Physics (3 km *vs* 13 km): higher res → more realistic.
- deep_cu may be activated too frequently.
- Tendency analysis: reality is somewhere b/t 13- & 3-km runs.

Results based on UFS SRW v2.0 and CCPP SCM v6.0

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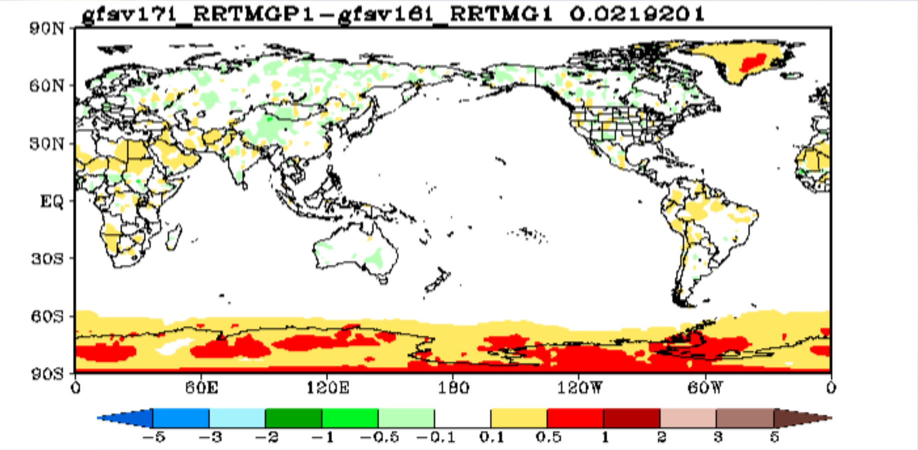
DTC UFS
R2O project

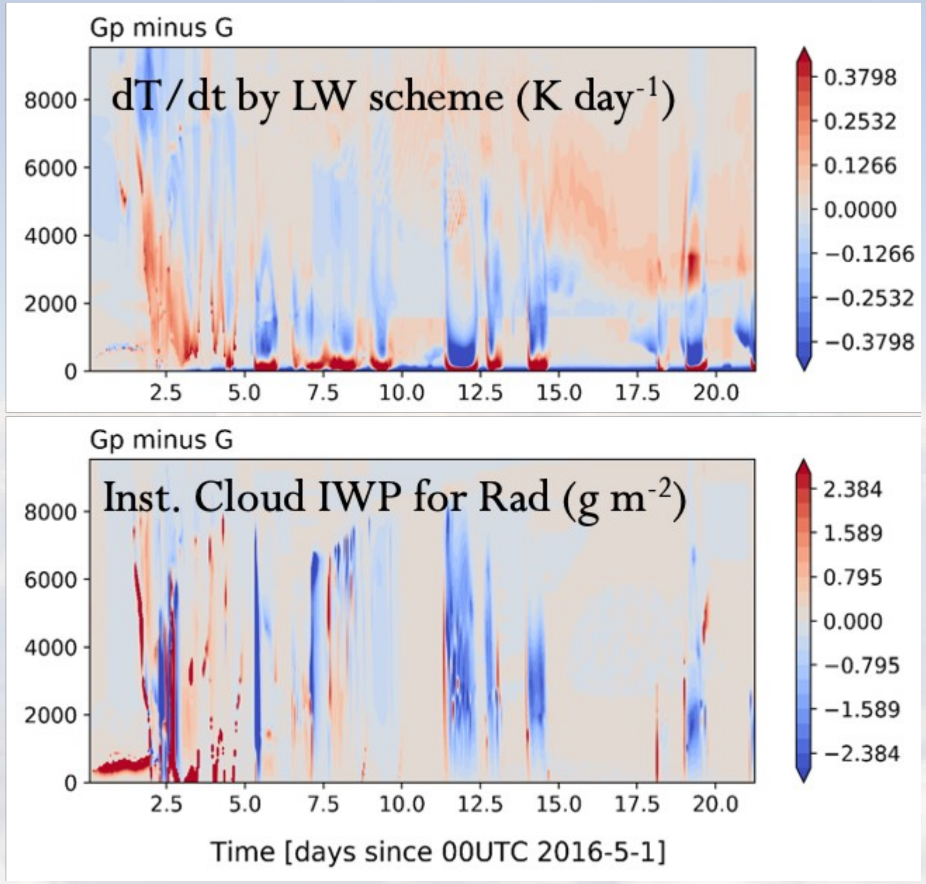
Hierarchical System Development: Example

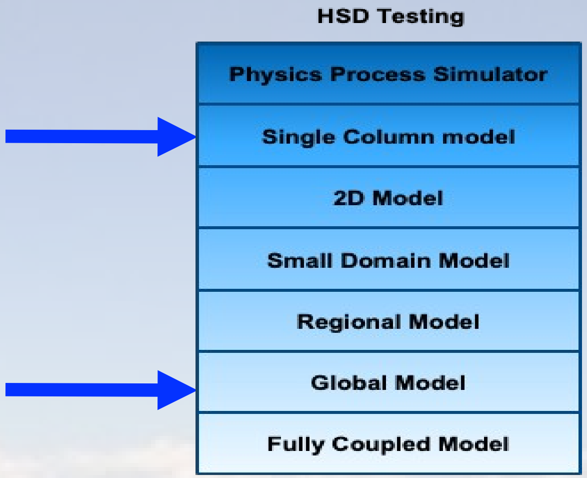
Physics Testing and Evaluation for the UFS MRW and S2S Applications

SCM T&E of warmer Antarctic in RRTMGP for prototype-8 physics using ARM AWARE case - Informed possible <u>cloud-radiation interaction</u> issues in addition to land-atmosphere interactions; assisted decision making for exclusion of RRTMGP in public release of P8.



EMCVSDB



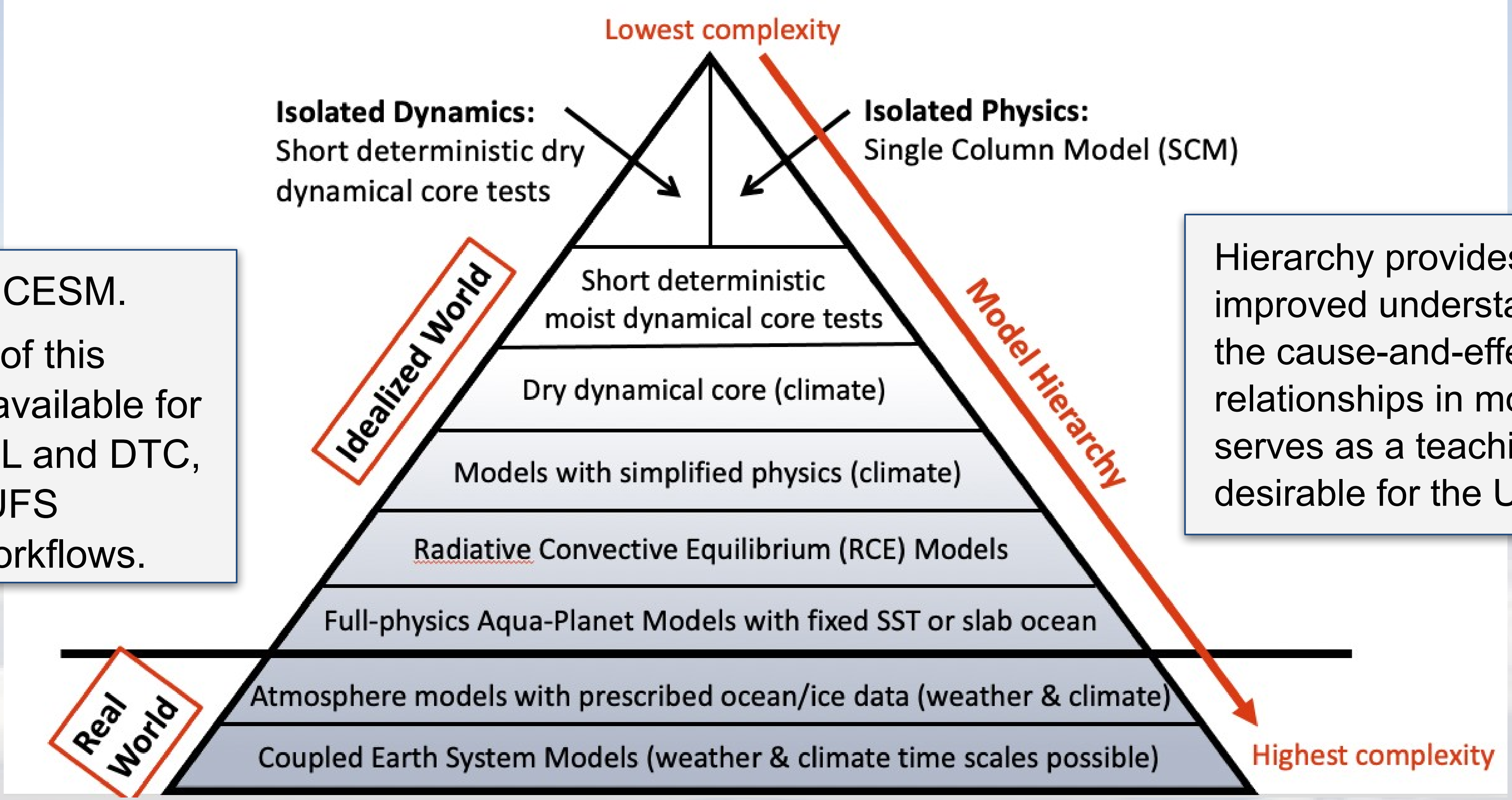


Excessive near-surface LW heating in GP but no corresponding cloud differences

Example of an Existing Model Hierarchy: CESM's "Simpler Models"

Purpose: HSD approach for the climate community: NCAR's CESM 'Simpler Models' framework.

- Many CESM 'Simpler Models' elements (see below) for the **Global Model** domain + **SCM** are similar to what we are trying to build for the UFS.



FV3 is an option in CESM.

Selected elements of this hierarchy are also available for FV3 at GFDL, NSSL and DTC, but not via official UFS distributions and workflows.

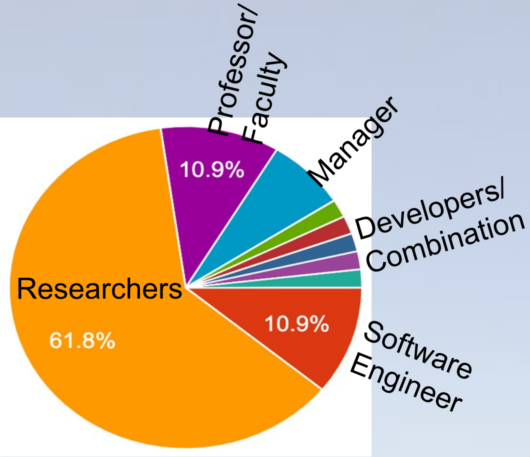
Hierarchy provides an improved understanding of the cause-and-effect relationships in models & serves as a teaching tool: desirable for the UFS

Adapted from a talk by Christiane Jablonowski (Univ. Michigan) at a EPIC-UFS workshop in 2022.

HSD Community Survey and DTC-EPIC White Paper on HSD

Purpose: To gather insights & feedback from broader community to help shape future direction of HSD.

- 55 participants from a broad spectrum of disciplines and organizations.
- Questions pertained to the necessity to develop HSD capabilities such as nesting/idealized/LES/CRM/etc.



Pie chart of survey respondents' roles

Hierarchical System Development for the Unified Forecast System

-long-term vision and plan for its progressive implementation

Xia Sun[a,b,d], Tracy Hertneky[c,d], Ligia Bernardet[b,d] (Co-lead), Tara Jensen[c,d] (Co-lead), Yi-Cheng Teng[e,f], Stelios Flampouris[e,f], Lulin Xue[c,d], Weiwei Li[c,d], Louisa Nance[c,d], Mike Ek[c,d]

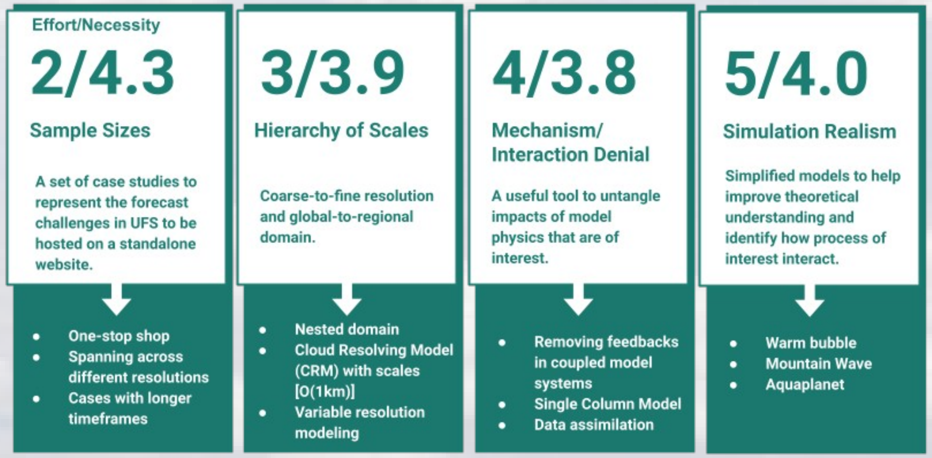
a. *Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO*
b. *NOAA Global Systems Laboratory, Boulder, CO*
c. *NCAR Research Applications Laboratory, Boulder, CO*
d. *Developmental Testbed Center, Boulder, CO*
e. *Tomorrow.io, Boston, MA*
f. *Earth Prediction Innovation Center, Riverdale, MD*

June 2023

Developmental Testbed Center is a distributed facility where the NWP community can test and evaluate new models and techniques for use in research and operations.

Emerging themes:

- Importance of HSD to span across all Earth system model components and not just land-atmosphere.
- Need for highly configurable and well-documented testing workflows, such as for idealized cases.
- "One-stop-shop" to test relevant case studies using different UFS capabilities, tools, and software, which are readily available and easy to install.
- Capability to initialize a model with a large variety of datasets.



Effort and necessity rankings on the four HSD aspects proposed in the white paper for UFS HSD

Summary – Challenges & Opportunities

→ **Earth System Models (ESMs) for weather and climate are becoming increasingly complex**, with many processes and interactions. We need to get **right answers for the right reasons!**

→ **Hierarchical System Development (HSD) is a systematic "engineering" approach** that tests small elements (e.g. physics schemes/subroutines) of an ESM first in isolation, then progressively connects elements with increased coupling between ESM components (e.g. via SCMs, and small-domain and limited-area models), regional and global models, all the way to a fully-coupled global model.

→ **HSD can help improve understanding of spatial and temporal dependencies** in model physics, i.e. consistent solutions between models/applications at different resolutions. Also, **HSD process is concurrent and iterative**, i.e. more complex HSD steps can provide information to be used at simpler HSD steps, and vice versa.

→ The **Common Community Physics Package** (CCPP) provides an **efficient infrastructure** and **set of physics** that connects HSD steps, where **CCPP is under active development** by the community, with new parameterizations and framework capabilities being added.

→ **METplus** provides the necessary **verification** that includes metrics at the **process level**.

→ **DTC and EPIC worked together to develop a HSD White Paper** describing different aspects of the HSD approach for efficient and effective UFS model development and improvement (recently completed and will be posted on the DTC, UFS-community and EPIC websites).

DTC Visitor Program

https://dtcenter.org/visitor-program

Propose a project to work on with us!

Two types of visitor projects:

- Principal Investigator (PI) - Up to 2 months salary, travel and per diem - can be split into multiple visits.
- Graduate Student - Up to 1 year of temporary living per diem and travel expenses for graduate student, plus support for advisor visits.

See Announcement of Opportunity on DTC website for more information on how to apply and guidance on topics of interest.

This is an important mechanism to support HSD-related work that will be of great benefit to the NWP and Earth system research and modeling community!