**Improving the Earth System Model Development process via a Hierarchical System Development approach and use of the Common Community Physics Package**

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Hierarchical System Development (HSD) is an efficient approach to effectively connect the “Research-to-Operations” and “Operations-to-Research” (R2O2R) process, with the ability to test small elements (e.g., atmospheric physics subroutines) of an Earth System Model (ESM) first in isolation, then progressively connecting those elements with increased coupling between ESM components and HSD steps. *System* in the HSD is end-to-end in that it includes data ingest and quality control, data assimilation, modeling, post-processing, and verification. The HSD includes Single Column Models (SCMs; including individual physics elements within the SCM), small-domain atmosphere-only models, all the way up to complex fully-coupled ESMs with components for atmosphere/chemistry/aerosols, ocean/waves/sea-ice, land-hydrology/snow/land-ice, and biogeochemical cycles/ecosystems. Figure 1 illustrates the HSD approach and the different tiers in the HSD Testing “Harness”.

Although an ESM subset (i.e. atmosphere-land and specified ocean conditions) has traditionally addressed Numerical Weather Prediction (NWP) needs, we assert that the R2O2R process may be improved by further utilizing the complexity spectrum inherent with the HSD approach. Datasets for use in the different tiers of the HSD are obtained from measurements (e.g. field programs and observational networks), ESM output, or idealized conditions (e.g. a constant background flow to simplify physics interactions, or extreme winds, or instability to “stress-test” system components across the HSD steps, among other options). The requirements for advancing from one HSD step to the next are appropriate evaluation metrics/benchmarks of ESM performance, many of which are at the physical process level.

It is important to note that this process is concurrent and iterative such that more complex HSD steps can provide information to be used at simpler HSD steps, and vice versa. The HSD approach can also help increase understanding of spatial and temporal dependencies in model physics where there is a need for consistencies in model solutions between higher-resolution/limited-area short-range, global medium/extended-range and subseasonal-to-seasonal, as well as longer term climate time scales.

An effective “enabler” of a physics-focused HSD approach is the Common Community Physics Package (CCPP), which 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 is a collection of atmospheric physical parameterizations and a framework that couples the physics for use in ESMs. The CCPP Framework was developed by the U.S. Developmental Testbed Center (DTC) and is now an integral part of the Unified Forecast System (UFS), where the UFS is being used by the National Oceanic and Atmospheric Administration (NOAA) for their operational NWP models as well as by the NWP community for research. The CCPP is also being experimented with in the U.S. Navy Research Laboratory NEPTUNE model (NEPTUNE: Navy Environmental Prediction System Using the NUMA Core; NUMA: Nonhydrostatic Unified Model of the Atmosphere), and at the National Center for Atmospheric Research (NCAR) for the WRF, MPAS, and CAM/CESM models (WRF: Weather Research and Forecasting; MPAS: Model for Prediction Across Scales; CAM: Community Atmosphere Model; CESM: Community Earth System Model).

A primary goal for the CCPP is to facilitate research and development of physical parameterizations, while simultaneously offering capabilities for use in operational models. The CCPP Framework supports configurations ranging from process studies to operational NWP as it enables host models to assemble the parameterizations in suites. Framework capabilities include flexibility with respect to the order in which schemes are called, ability to group parameterizations for calls in different parts of the host model (including the dynamical core), and ability to call some parameterizations more often than others with a reduced time step or in an iterative process. Furthermore, the CCPP is distributed with a SCM to test innovations and conduct HSD studies in which physics and dynamics are decoupled, in order to isolate processes and more easily identify systematic errors or biases.

The CCPP is developed as open-source code and has received contributions from the broad community in the form of new schemes and innovations within existing schemes. Today, there are more than 30 primary parameterizations in the CCPP, representing a wide range of meteorological and surface processes. Physics schemes are typically used by the host models in suites, and classified as operational or experimental. The CCPP is scheduled for all upcoming operational implementations of the UFS Weather Model, and the CCPP v6 release (planned for June 2022) is publicly supported for use with the CCPP SCM and the UFS Medium- and Short-Range Weather Applications. For existing CCPP resources for users and developers, which includes information on public releases, documentation, tutorials and forums, see: https://dtcenter.org/community-code/common-community-physics-package-ccpp.

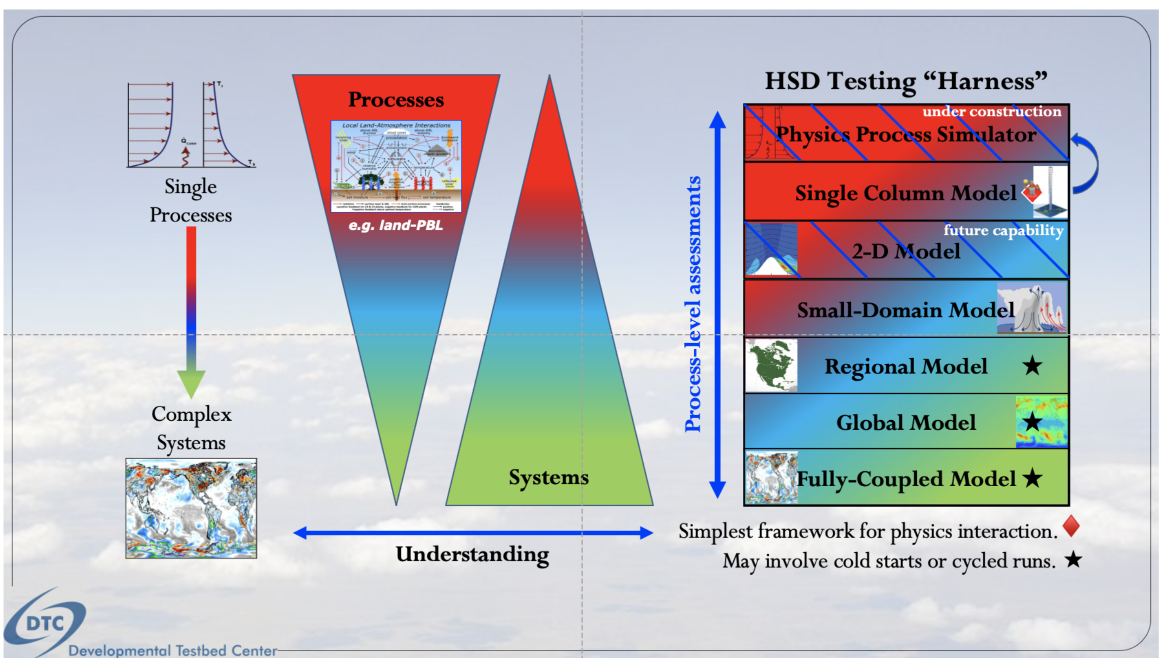

*Figure 1. Hierarchical System Development (HSD): A simple-to-more-complex comprehensive approach to identify systematic errors or biases and improve Earth System Models (ESMs) for weather and climate. Important understanding about a single process does not yield corresponding understanding about a complex system of which it is a part, and conversely, important understanding about a complex system does not necessarily yield corresponding understanding about a single process. The HSD Testing "Harness" allows examination of processes and modeling systems across different tiers of the HSD. Datasets to drive and validate models for different HSD steps come from measurements, model output, or idealized conditions, with "cumulative" performance benchmarks, including process-level assessments, at all HSD steps.*