DART-X: Software Infrastructure for Prototyping in-memory Data Transfer between Ensemble Data Assimilation and Coupled Earth Systems Models

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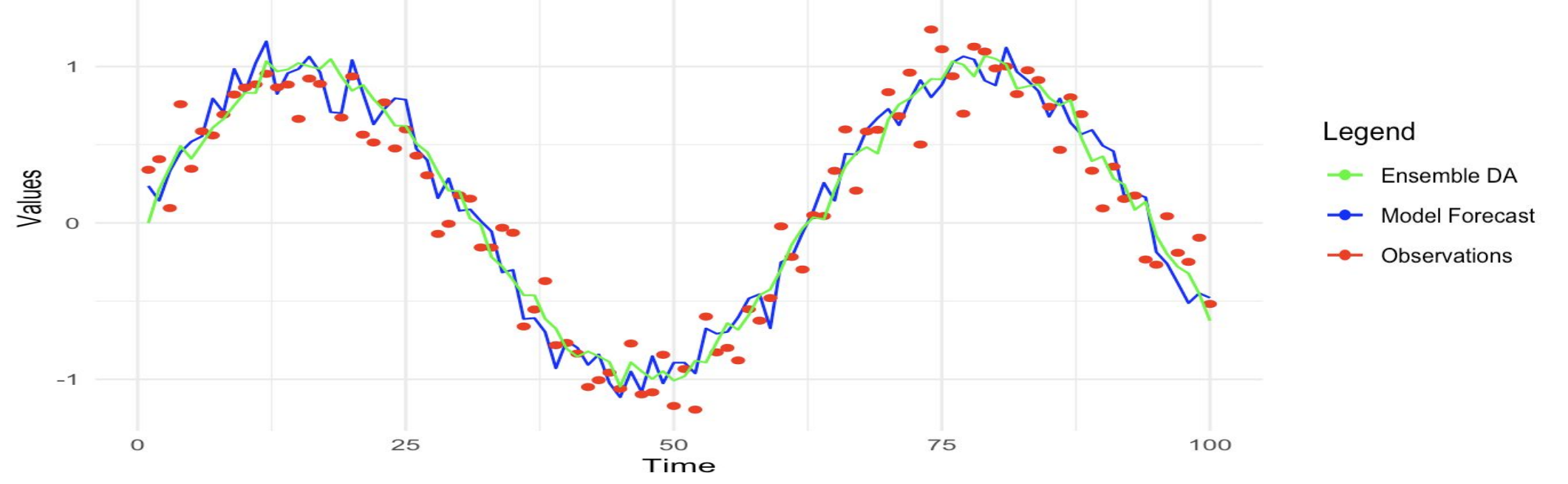
1. BACKGROUND

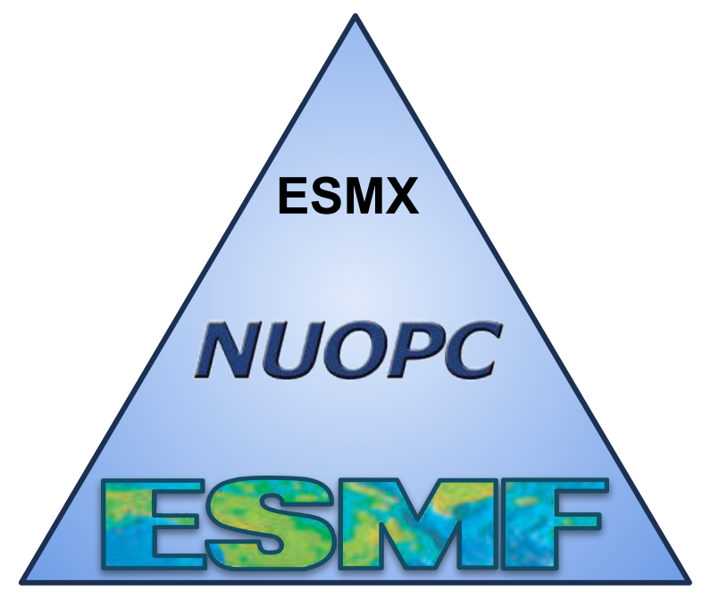
Data Assimilation, DART & CESM

Data assimilation (DA) integrates real-world data into climate models to capture the complexity of the Earth system and enhance prediction accuracy.

NCAR's **DART**, an ensemble DA software used with **CESM** (Community Earth System Model), balances model predictions and real-world observations to minimize uncertainties and represent a more accurate climate state.



ESMF, NUOPC, ESMX

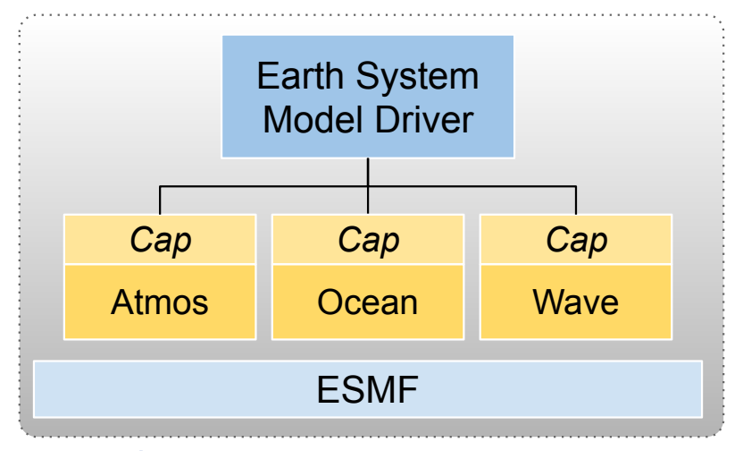


Software Stack

CESM uses **ESMF** (Earth System Modeling Framework) to couple climate models, simulating interactions between Earth components.

NUOPC (National Unified Operational Prediction Capability) **cap** is a software layer that standardizes data sharing within ESMF.

ESMX (Earth System Model eXecutable) is a layer built on top of ESMF and NUOPC APIs to simplify building, running, and testing NUOPC-based systems.

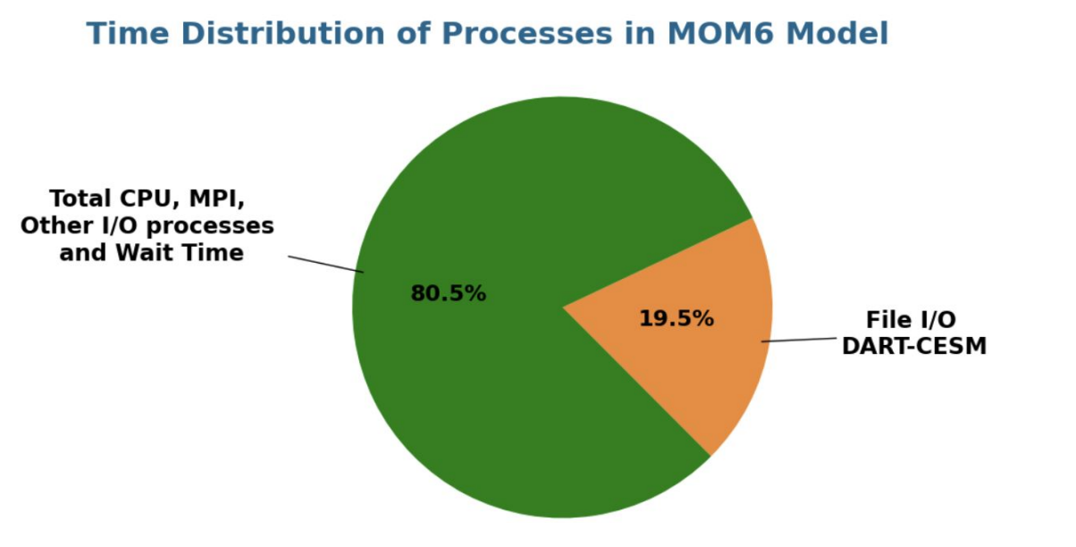


Coupling infrastructure
(includes the NUOPC Cap)

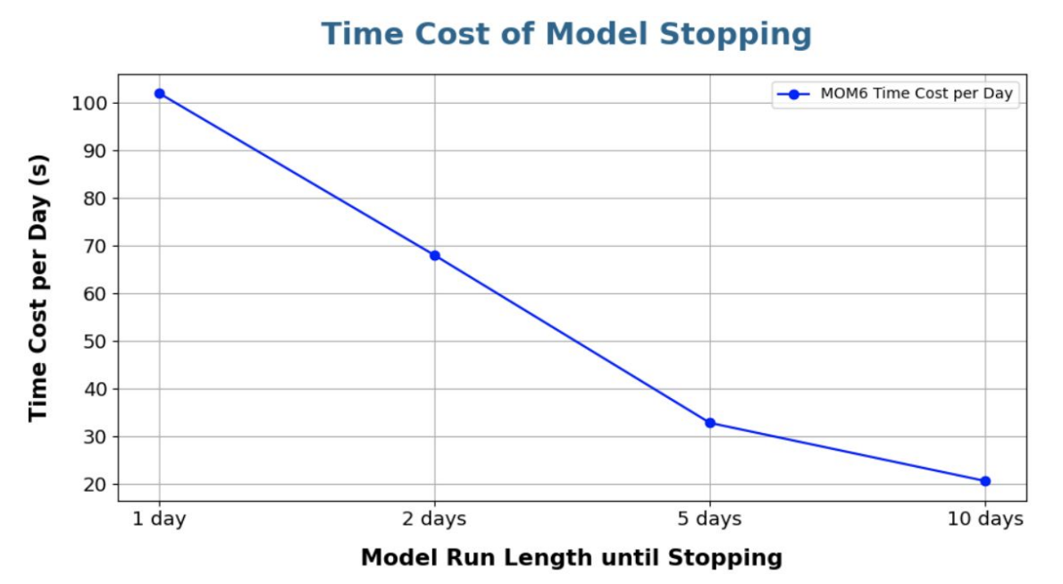
2. MOTIVATION

DART-CESM I/O Bottleneck

DART traditionally modifies "restart" files written into disk to update model states, requiring CESM models to stop for data assimilation and then restart. This process causes significant I/O bottleneck, leading to high computational costs, even on large supercomputers, especially for high-resolution models.



Benchmark profiling shows read/write operations consume significant runtime, even at relatively low-resolution (⅔ deg).

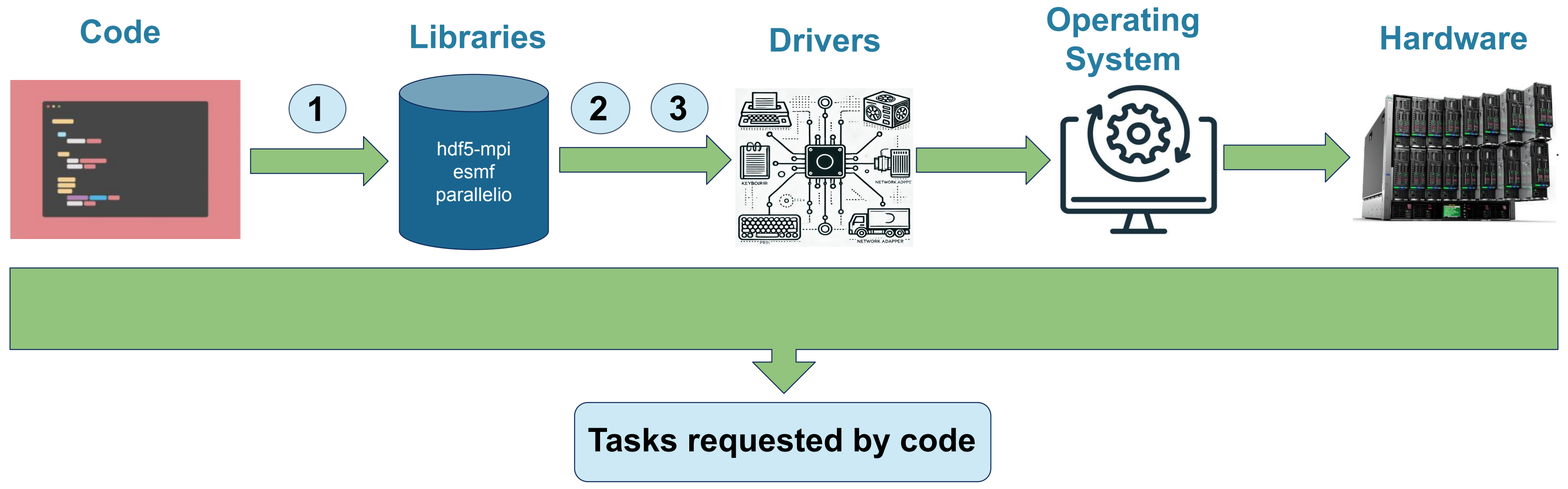


The more frequently we stop the model, the higher the fractional time cost. DA typically stops at least once per day.

3. OBJECTIVES

- Build infrastructure to develop and test a **DART-NUOPC cap** to allow DART to access CESM model states **directly in memory**, avoiding an I/O bottleneck from traditional file system data transfer and reducing resource waste.
- Validate the cap's functionality by passing 2D fields (data) in memory.

4. SOFTWARE INFRASTRUCTURE



- A code extension that provides a platform to coordinate, optimize and integrate distinct software components.
- 1, 2, 3 indicates the corresponding steps in the build process in section 6.

5. INFRASTRUCTURE CHALLENGES

- The sophisticated ESMF infrastructure, with 2 million lines of code, requires extensive communication with external labs, exceeding time and resource constraints.
- Building the interface requires integrating DART and CESM with minimal disruption to their core structure and existing functionalities.
- Integrating systems with varying object forms, infrastructures, and data formats is complex.

6. THE BUILD PROCESS (DART-X)

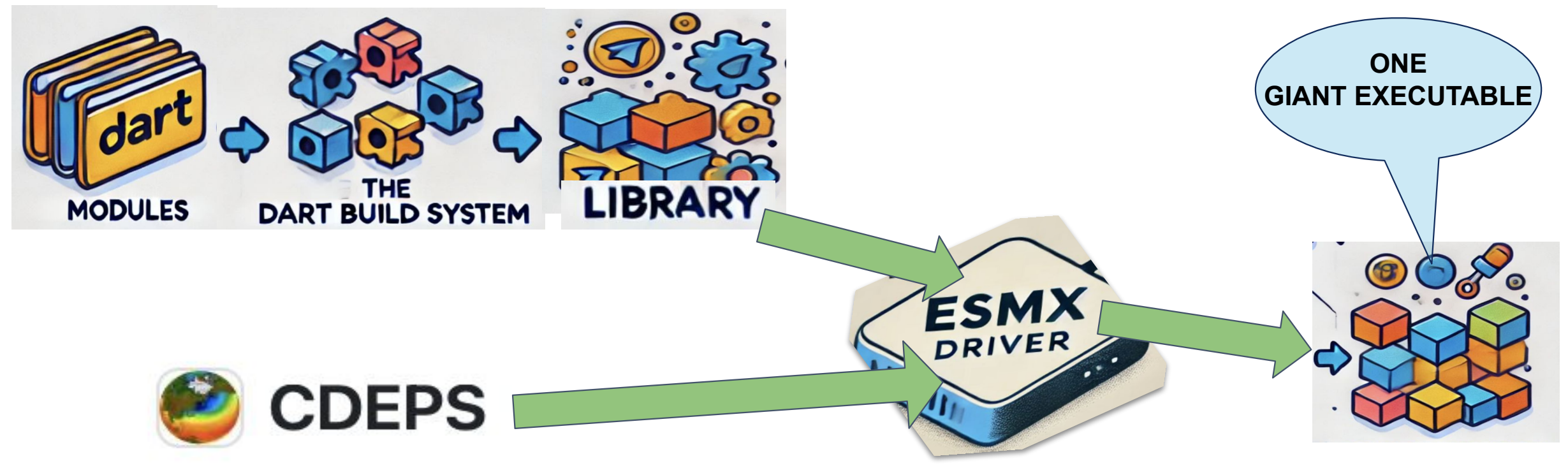
DART-X Build Process

1. Select environments and frameworks

- ➢ Build the cap on NCAR's Derecho supercomputer for its robust ESMF and NUOPC support.
- ➢ Utilize **ESMX** to simplify NUOPC-based development, handle orchestration, and isolate cap testing.
- ➢ Use **CDEPS** for targeted testing without a fully coupled system model to speed up development.
- ➢ Ensure build dependency compatibility for High Performance Computing (HPC) with build templates.

2. Transform and Unify Objects

- ➢ ESMX expects input components to be compiled as modules or libraries for a unified executable.
- ➢ However, DART outputs executables by default.
- ➢ DART-ESMX integration (DART-X): Modify DART to function as a library to incorporate into ESMX.



3. Build Configuration

- ➢ ESMX helps avoid extensive Fortran coding, streamlining compilation and linking via the human-readable YAML language.
- ➢ In the esmxBuild.yaml configuration file, locate DART in memory by pointing to its address and include the cap code as a module.

DART as a component

```
dart:
  build_type: script
  build_script: quickbuild.sh
  source_dir: /glade/u/home/sumansh/Altrun/DART/models/cdeps/work
  install_prefix: /glade/u/home/sumansh/Altrun/DART/models/cdeps/work
  fort_module: dart_comp_nuopc.mod
```

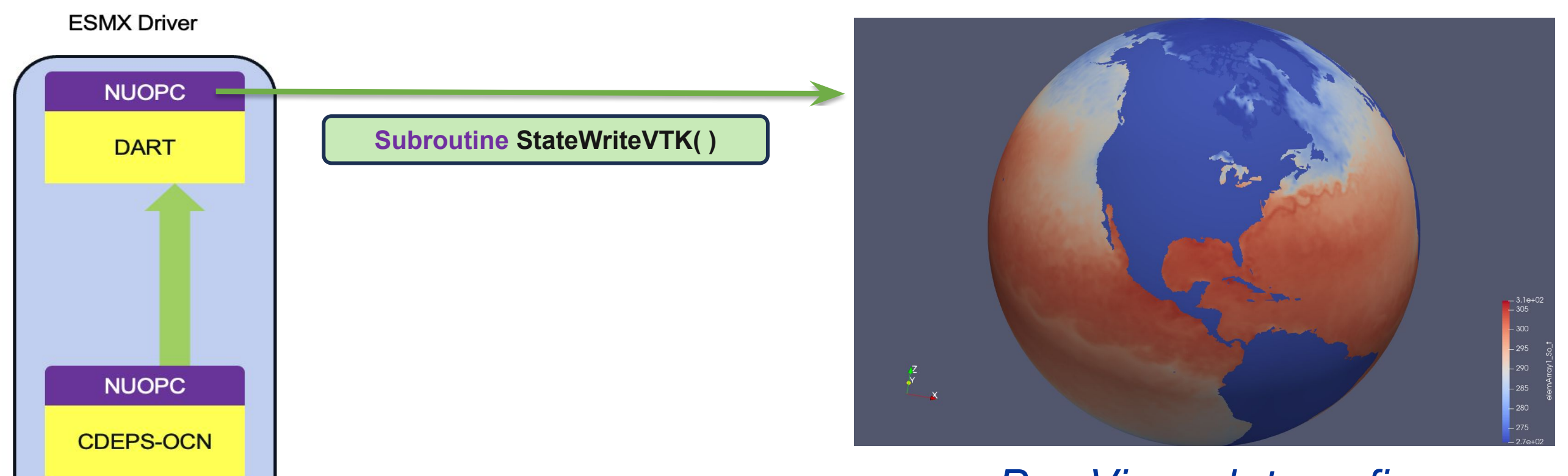
DART-NUOPC cap

7. RESULTS

First in-memory DART ⟺ CESM

Using DART-X, the DART-NUOPC cap successfully transfers 2D field Sea Surface Temperature (SST) from the ocean model (OCN) to DART.

The Model Advance subroutine in the DART-NUOPC cap writes the SST field to a VTK file, validating in-memory transfer.



ParaView plot confirms DART receives the 2D field

With the DART-NUOPC Cap integrated, DART advances in time like a model component.

8. CONCLUSIONS

- Developing robust software infrastructure minimizes disruptions and enables new feature development and testing. DART-X supports the DART-NUOPC Cap, the first in-memory data transfer prototype between DART and CESM.
- The first DART-NUOPC cap prototype paves the way to explore direct memory sharing, potentially reducing disk I/O bottlenecks. This enables DART to act as a model component, speeding up data assimilation and reducing computational costs.

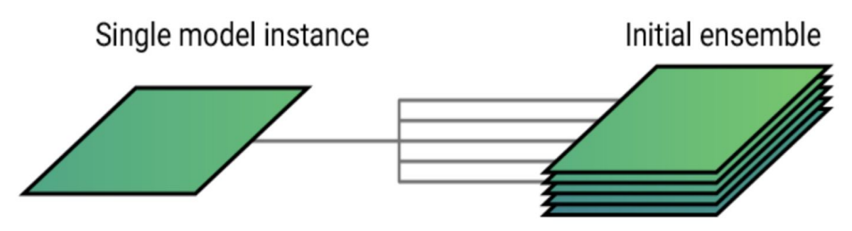
9. FUTURE WORKS

Full DART-ESMF integration

Advance from a successful ESMX prototype, DART-X, to a full DART-CESM cap using ESMF driver.

Ensemble Field Transfers

Continue testing DART as a model component for ensemble models to transfer ensemble fields.



Profiling: Memory vs. Disk Improvement

Profile: quantify performance improvement for DA-model with in-memory data transfer versus traditional disk transfer.

Handling Missing Fields In Memory

The cap currently exchanges fields; future work will address missing data in DART-CESM communication.

Generalizing in-memory data passing

In-memory data passing techniques in this prototype may extend to other data systems and ML frameworks.

REFERENCES AND ACKNOWLEDGEMENT

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DART ESMF