Coupled Modeling Infrastructure for the Unified Forecast System

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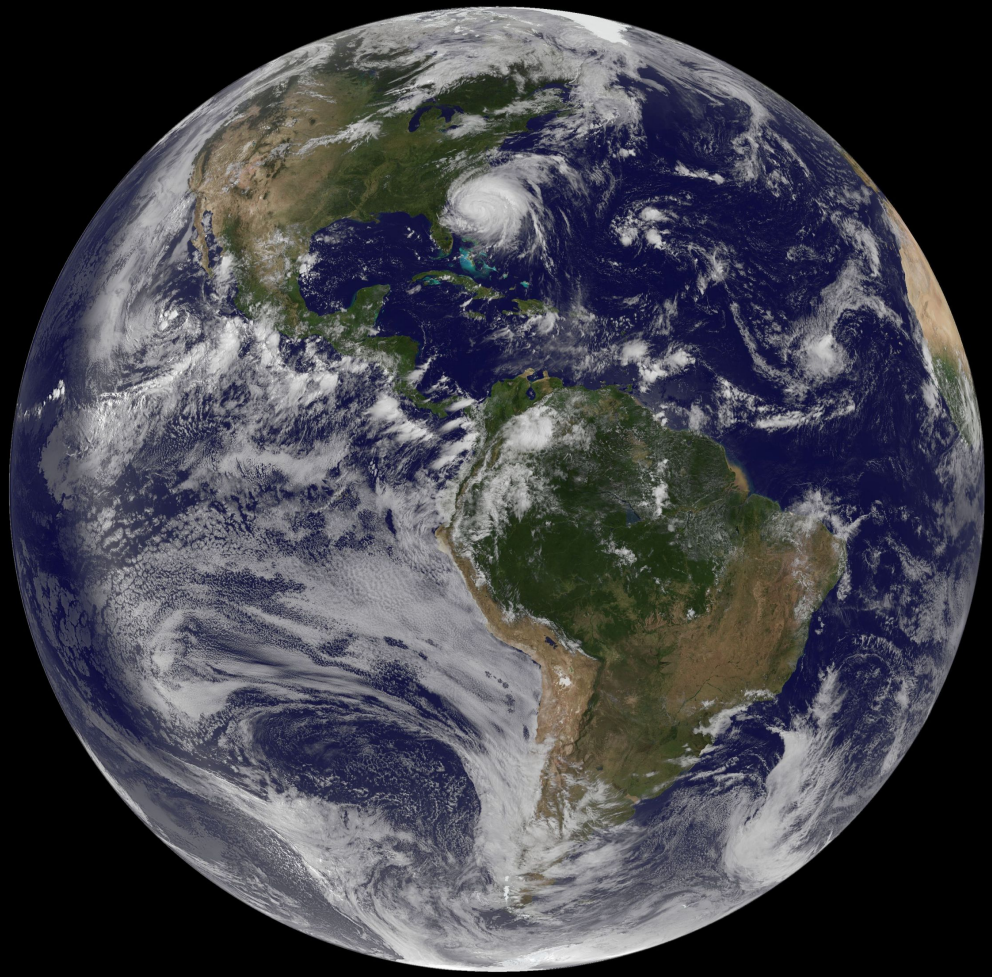
UFS Users' Workshop



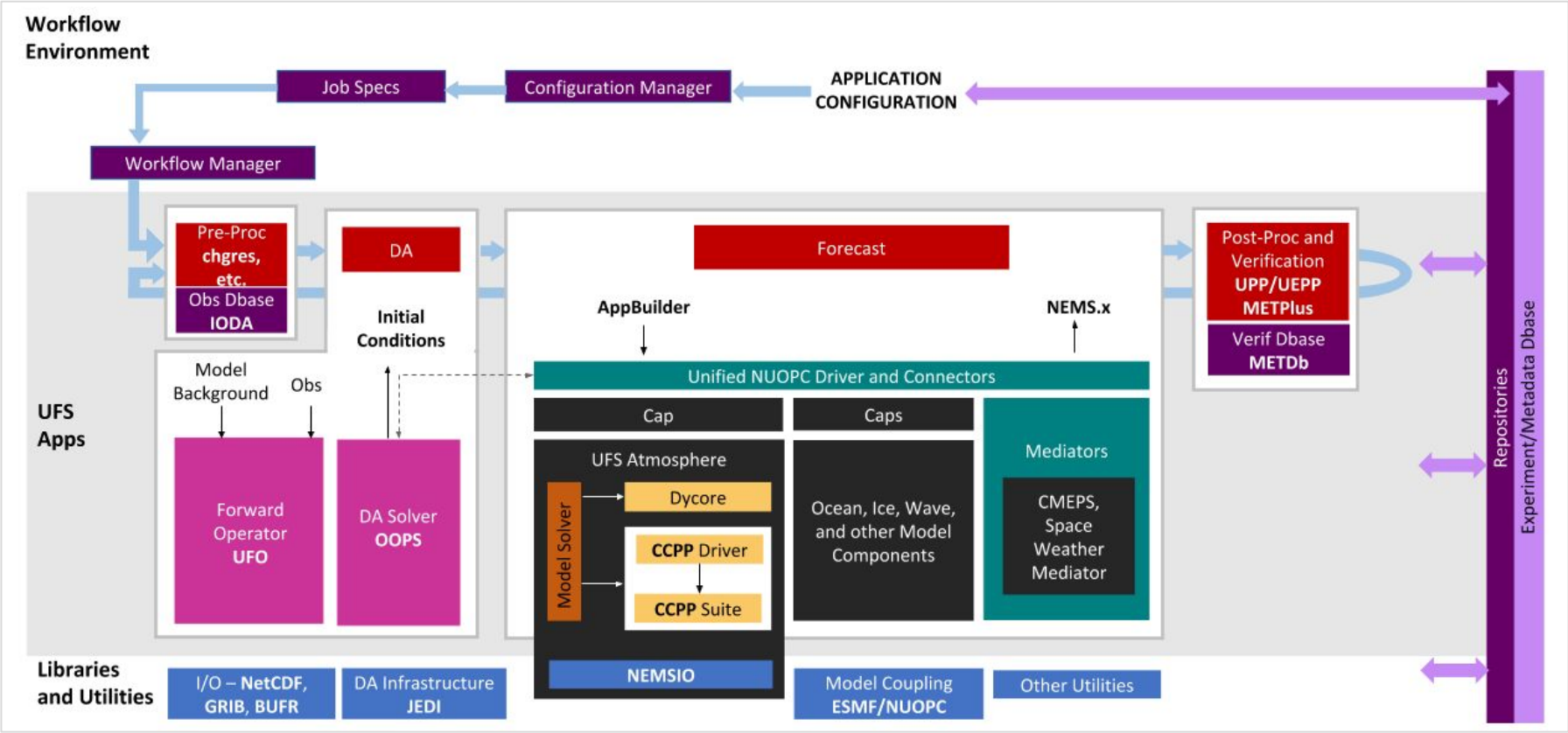
Hurricane Irene/NASA GOES-13 satellite image/August 26, 2011

Outline

- Overall UFS System Architecture
- Role of ESMF and the NUOPC Layer within the UFS
  - Unified Driver
  - Model Interfaces - NUOPC “caps”
  - Communication and Regridding between Models
  - Multi-model Interactions
  - Asynchronous I/O
  - Systematic testing with “data models”
- Download, User Support, and Training

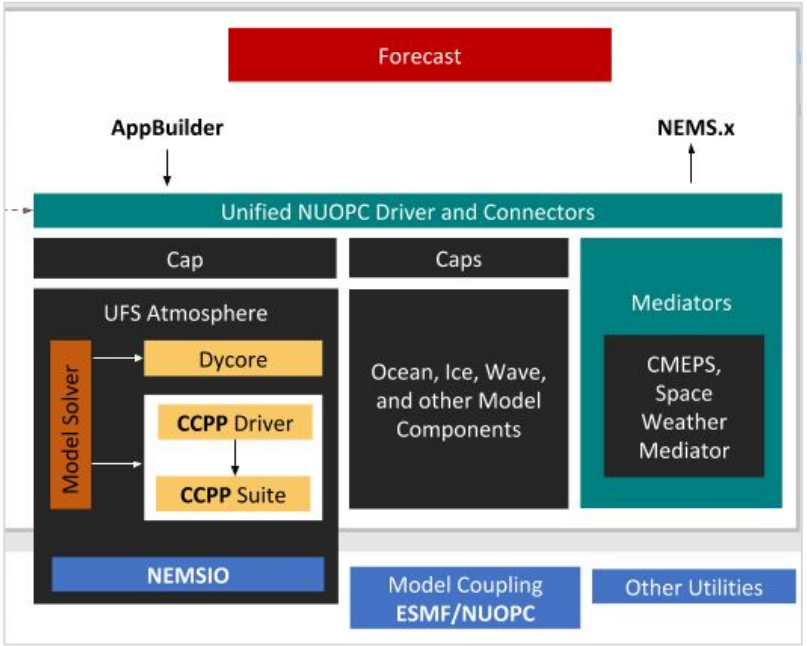
The UFS has a Unified System Architecture

All UFS applications share a common architecture with shared components for pre-processing, data assimilation, model coupling and forecast, post-processing, and verification.



ESMF/NUOPC in the UFS Architecture

- ESMF/NUOPC is central to the UFS Architecture.
- ESMF/NUOPC is the infrastructure within UFS that provides model interfaces and integrates them into a unified Earth System Model.
- ESMF/NUOPC ensures a high degree of *architectural consistency* among the seven UFS applications.
  - eliminates duplication of effort across UFS Application Teams
  - developers move easily between Applications
  - significant code reuse
  - promotes a consistent architecture across UFS Application releases



Forecast model portion of the UFS System Architecture

ESMF/NUOPC

The **Earth System Model Framework (ESMF)** is community-developed, community-governed software for building numerical weather prediction, climate, and other Earth system modeling applications.

- standard model component interfaces
- high-performance capabilities for connecting models, such as grid remapping and parallel communication

The **National Unified Operational Prediction Capability (NUOPC) Layer** simplifies the technical interoperability of ESMF components by standardizing coupling protocols.

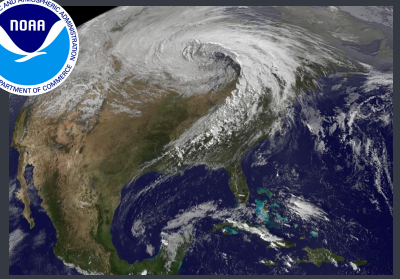
- includes four generic, extensible components with built-in capabilities
- Driver, Connector, Model, Mediator

Modeling Systems using ESMF/NUOPC

ESMF supports a wide range of scientific coupling requirements

UFS

NOAA's Unified Forecast System



Next-generation operational prediction for weather through seasonal time scale

UFS architecture is based on ESMF/NUOPC and supports **multiple coupled modeling applications** with different model components and different coupling configurations.

COAMPS & NavGEM

Navy Regional and Global Forecasting

Research and operational weather forecasting in support of military operations and national security

Regional and global systems use ESMF/NUOPC interfaces.

Support for specialized coupling requirements with telescoping **nested domains and nest-to-nest coupling**.

GEOS & Model E

NASA Modeling and Data Assimilation

Data assimilation, utilization of satellite measurements, seasonal to climate forecasting, creation of reanalysis datasets

GEOS features a large number of ESMF components, each handling different physics, **organized into a deep hierarchy**.

CESM

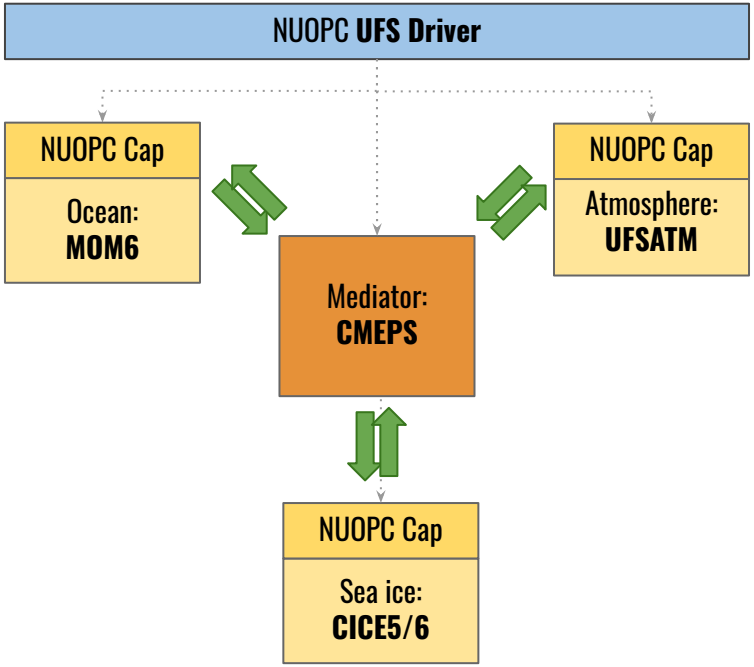
Community Earth System Model

Research into all aspects of the climate system, including participation in the Intergovernmental Panel on Climate Change assessment reports

CESM's next generation coupler is based on ESMF/NUOPC, including a shared, community-developed NUOPC-compliant Mediator (CMEPS).

UFS Unified Driver

- ESMF/NUOPC provides a *single Driver for all UFS applications*
  - no duplication of driver code for each forecast configuration (MRW, SRW, HAFS, etc.)
  - run sequences specified in small, user-friendly text file (no code!); this can be modified without recompiling
  - model components are optionally included/excluded during initialization, allowing different configurations without code changes
  - the Driver is easily extended with new components, and supports multiple models of the same type (e.g., MOM6 and HYCOM ocean models)

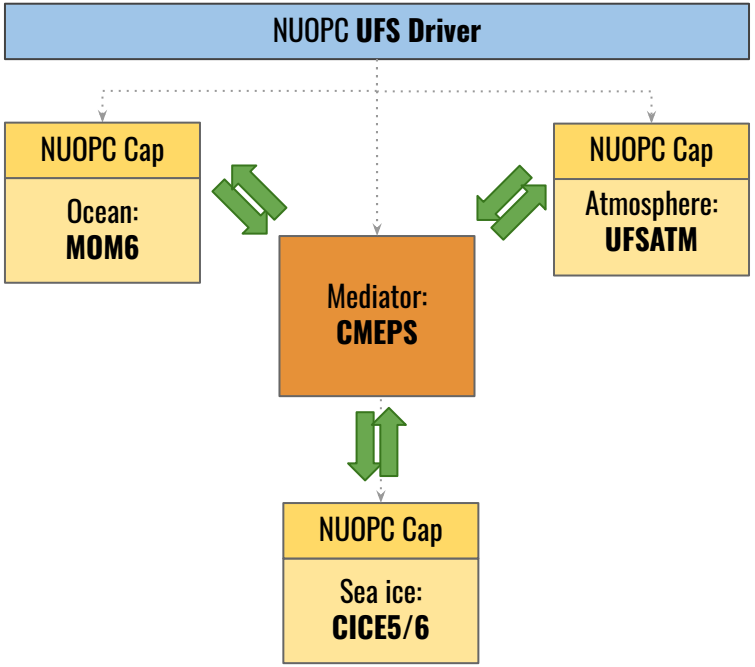


A configuration of the UFS S2S Application

User-friendly Run Sequence

```
runSeq::
@1800
  MED med_phases_prep_ocn_accum_avg
  MED -> OCN :remapMethod=redist
  OCN
  @600
    MED med_phases_prep_atm
    MED med_phases_prep_ice
    MED -> ATM :remapMethod=redist
    MED -> ICE :remapMethod=redist
    ATM
    ICE
    ATM -> MED :remapMethod=redist
    ICE -> MED :remapMethod=redist
    MED med_fraction_set
    MED med_phases_prep_ocn_map
    MED med_phases_prep_ocn_merge
    MED med_phases_prep_ocn_accum_fast
    MED med_phases_profile
  @
  OCN -> MED :remapMethod=redist
@
::
```

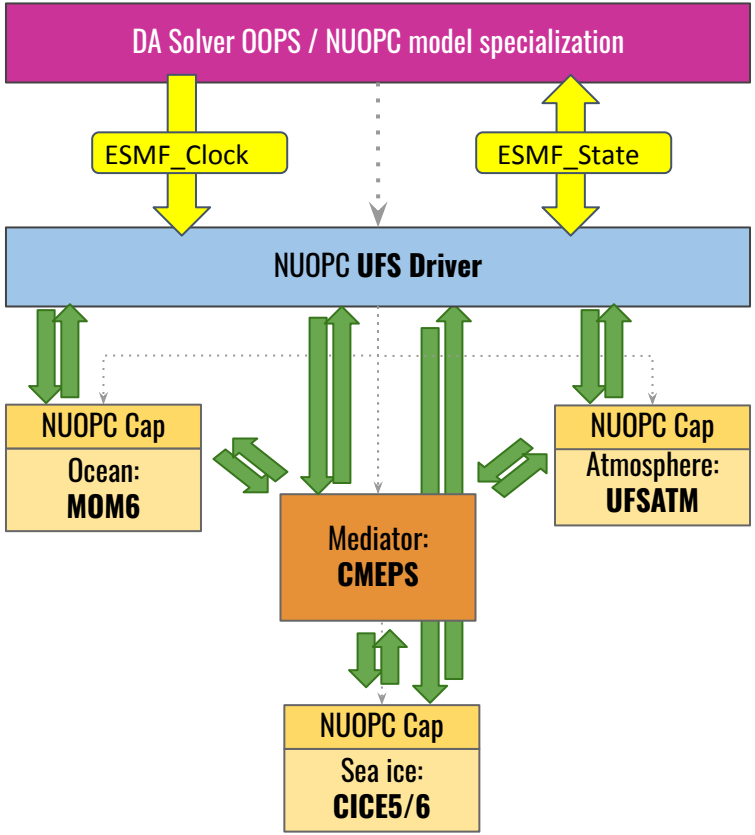
Run sequence syntax replaces hundreds of lines of Fortran code



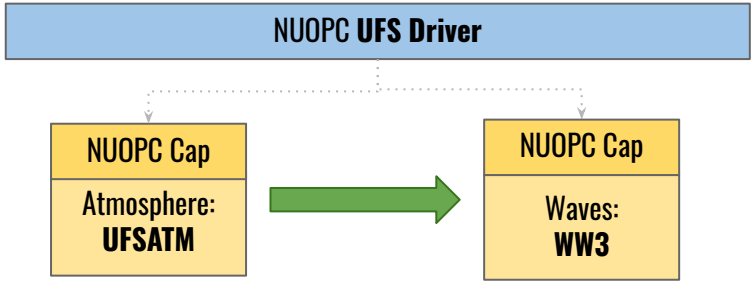
A configuration of the UFS S2S Application

UFS Unified Driver Connection to DA

- The NUOPC UFS Driver provides full range of access to the complete forecast model
  - Access to individual component states
  - Access to the combined coupled model state
  - ESMF regridding methods to interpolate between model grid and observation location
  - ESMF redistribution methods to move data from model memory layout to JEDI memory layout
  - ESMF reference sharing for efficient high volume data access
  - The mediator provides a place for temporal interpolation or aggregation to support different DA windows (e.g. fast ATM and slow OCN)
  - Mechanism for sending modified states back to the individual components and/or the combined coupled state to the mediator



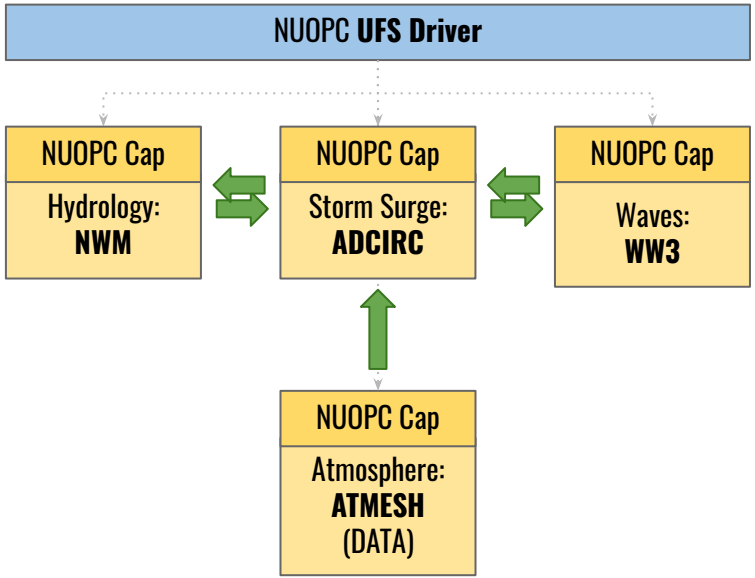
Unified Model Interfaces



UFS Medium-Range Application
(GFSv16 configuration)

- ESMF/NUOPC provides unified model interfaces to all models across all UFS applications
  - NUOPC “caps” are non-intrusive - a small translation layer; usually a single source code file
  - provided and required coupling fields are identified by standard names; model internal names do not have to change
  - supports 1D, 2D, and 3D coupling fields and a wide variety of structured grids and unstructured meshes; global and regional
  - adapts to native memory layouts already used by the underlying model
  - A NUOPC “cap” lives in a model component’s authoritative repository and is shared across different community modeling systems -- i.e., only one NUOPC “cap” per model

Optimized Inter-model Communication

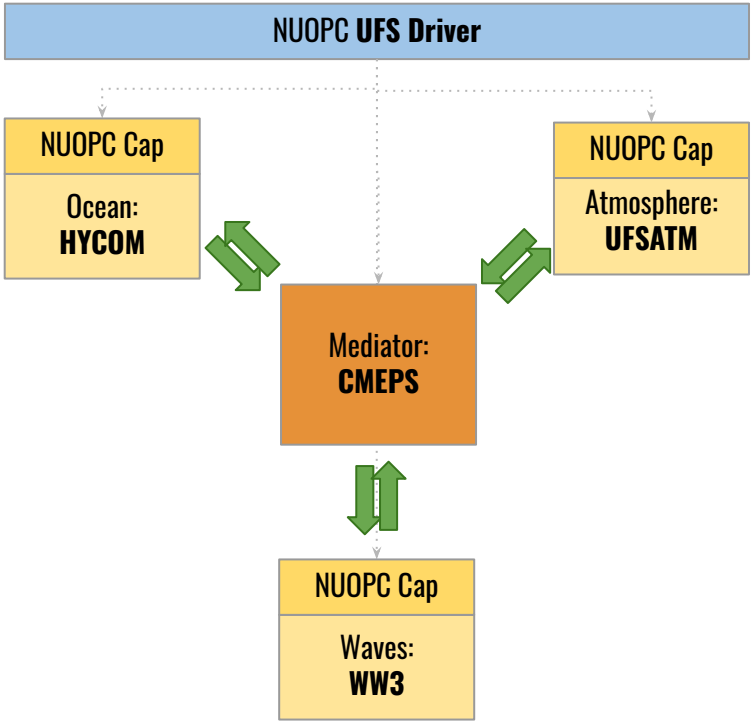


Named Storm Event Model (NSEM) configuration of the UFS Coastal Application

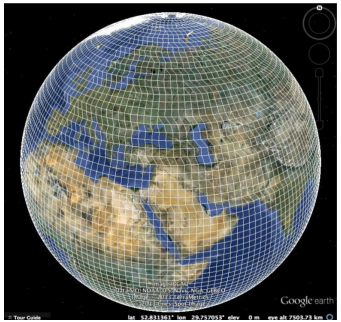
- ESMF/NUOPC provides optimized communication between model components
  - NUOPC "Connectors" are generated automatically by the Driver - no user code!
  - Connectors determine at runtime which coupling fields need to be exchanged, removing hard-coded field mappings
  - Connectors provide fast parallel communication options, including online generation and applications of interpolation weights
  - Large number of interpolation options: bilinear, patch, conservative (1st and 2nd order), nearest neighbor; extrapolation
  - Connectors negotiate the most optimized connection possible, allowing tight coupling (shared memory) to loose coupling (grid remapping)

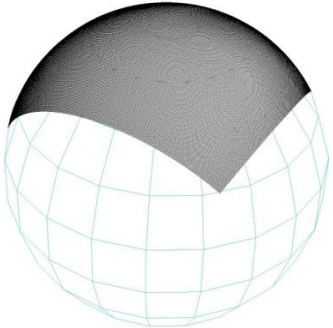
Multi-Model Coupling Interactions

- ESMF/NUOPC manages complex interactions involving several models
  - NUOPC “Mediators” manage coupling field exchanges between two or more model components
  - each model component tells the Mediator what fields it requires and sends
  - two Mediators in UFS: CMEPS and Space Weather Mediator
  - Mediators leverage the full power of ESMF parallel communication and online regridding
  - Mediators organize code and promote “separation of concerns”



UFS Hurricane Application





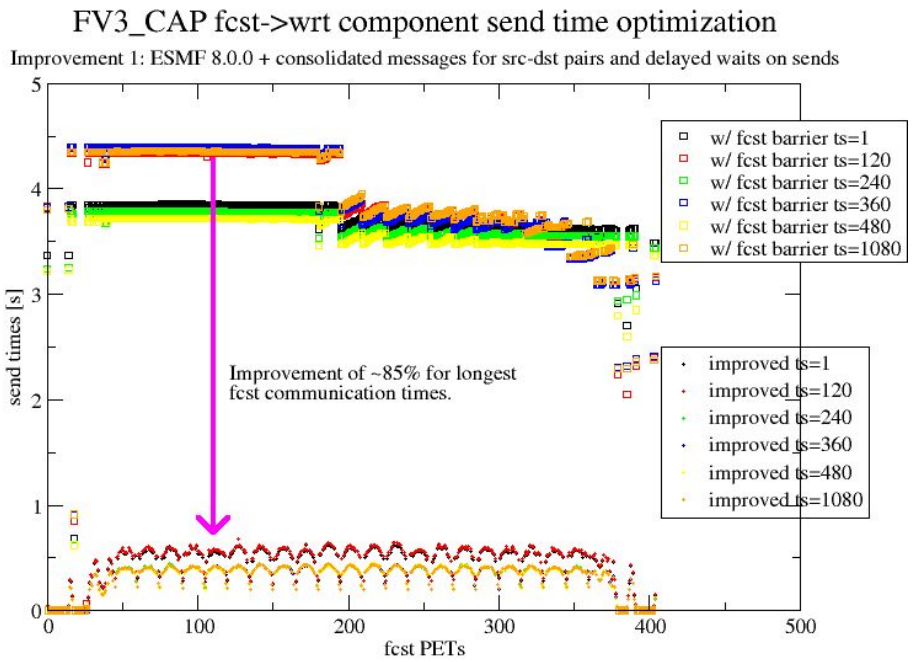
ESMF Regridding

Fast, flexible interpolation of gridded data

- ❖ High-performance
  - ➢ Interpolation weight matrix is generated in parallel in 3D space and applied in parallel
- ❖ Wide range of supported grids
  - ➢ Logically rectangular and unstructured grids in 2D and 3D, observational data streams (point cloud), global and regional grids, Cartesian and spherical coordinates
- ❖ Multiple interpolation methods
  - ➢ Bilinear, higher-order patch recovery, nearest neighbor, first order conservative, second order conservative
- ❖ Options
  - ➢ Masking, multiple pole treatments, straight or great circle distance measure
- ❖ Multiple interfaces
  - ➢ **Fortran API** - generate and apply weights during a model run
  - ➢ **Python API** - generate and apply weights using ESMPy
  - ➢ **File-based** - generate and apply weights from grid files using ESMF command line utilities

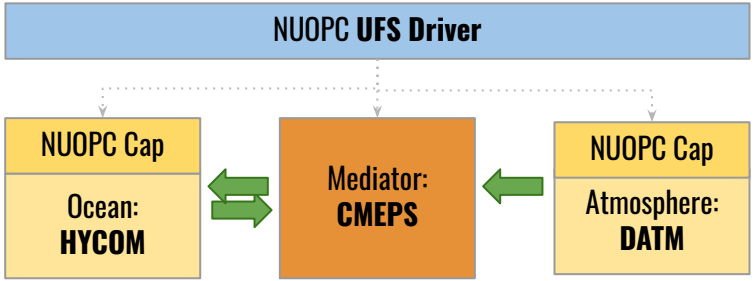
Asynchronous I/O

- ESMF/NUOPC provides asynchronous I/O in the UFS Atmosphere
  - Hides time to write model output by overlapping disk access with model forecast
  - UFS Atmosphere divided into two sub-components: *forecast* and *write*
  - Treat as a coupling problem, and leverage ESMF regridding to send data
  - Recent optimizations in ESMF 8.0.1 reduce communication time for asynchronous I/O and other communication methods with a disproportionate number of sending/receiving processes



Reduction in send times from UFSATM forecast component to write component were required for GFSv16 to meet operational 8min/day requirement. ESMF 8.0.0 vs. 8.0.1.

Incremental Building and Testing of Coupled Configurations



Configuration of the UFS Hurricane Application with a “Data Atmosphere”

- ESMF/NUOPC supports incremental building and testing of coupled configurations
  - the NUOPC “cap” approach simplifies the process of substituting a “data” component for an active model
  - enables “hierarchical model development” by isolating coupling feedbacks
  - Mediator interfaces do not change when connecting data models
  - “data” models are typically less expensive to run than active models, speeding up the development process

Download, User Support, and Training

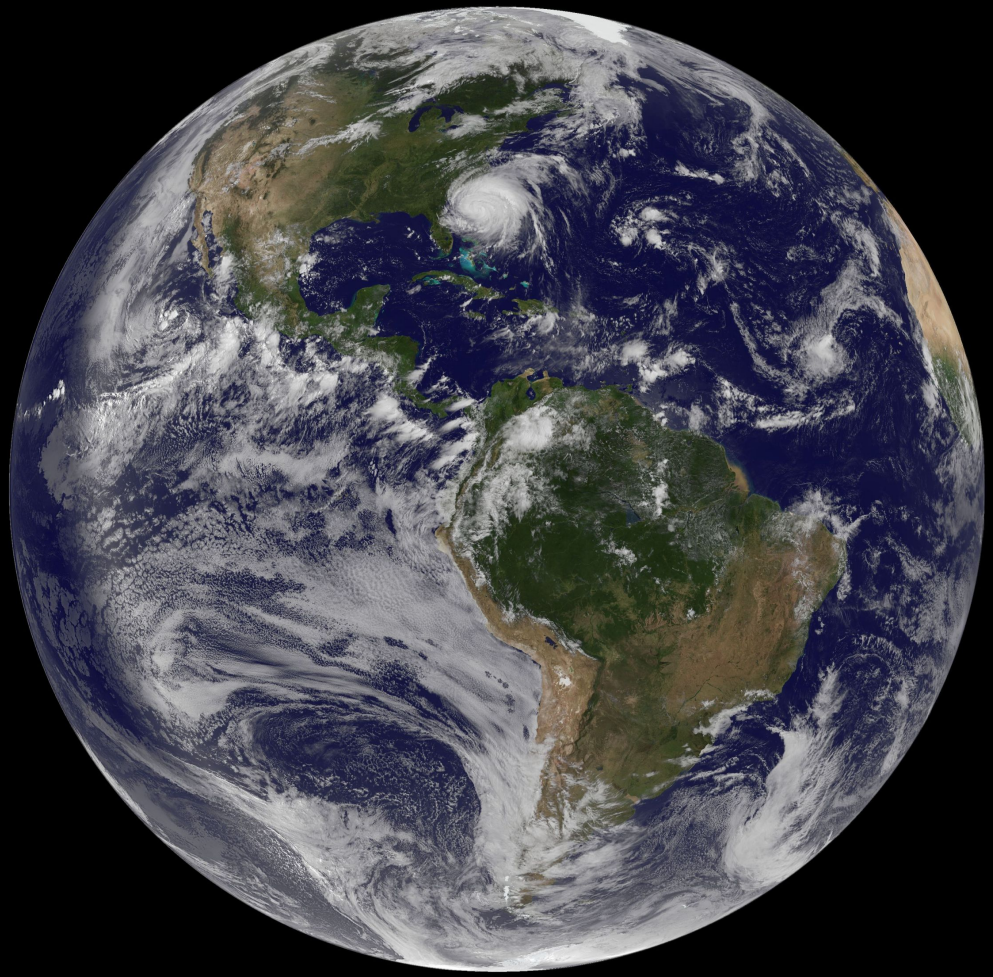
- **Download/Install** Options
  - With the UFS Medium-Range Application release, ESMF is installed automatically with the NCEPLIBS-external repository
  - Separate download available from GitHub: https://github.com/esmf-org/esmf

- **User support** for bug fixes, technical questions, and features requests: esmf_support@ucar.edu

- Regular **training opportunities** are provided in webinar format. See training page for upcoming dates and materials from previous events: https://earthsystemcog.org/projects/esmf/tutorials

Thank you!

- ESMF on GitHub:
  https://github.com/esmf-org/esmf
- ESMF Home Page:
  https://earthsystemcog.org/projects/esmf
- NUOPC Layer Home Page:
  https://earthsystemcog.org/projects/nuopc/
- Support:
  esmf_support@ucar.edu



Hurricane Irene/NASA GOES-13 satellite image/August 26, 2011

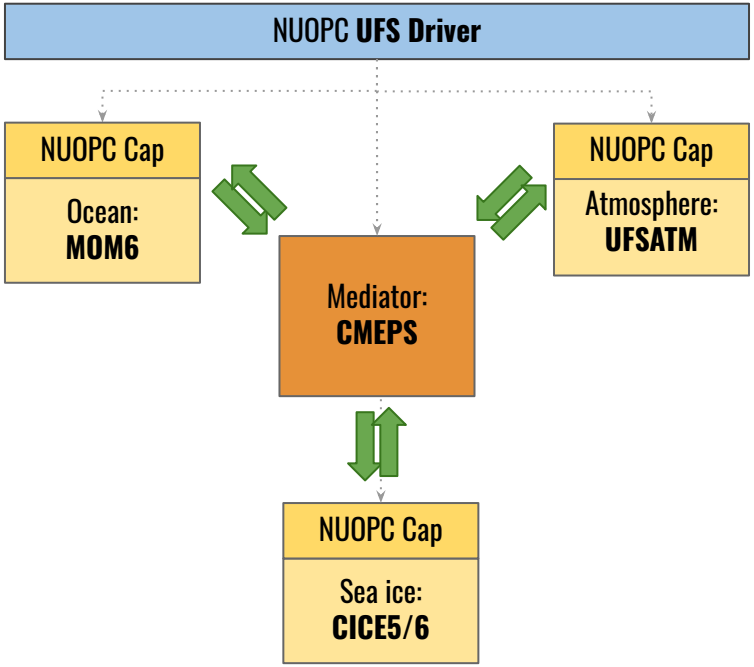
Extra Slides

Cross-Agency Collaboration: Community Mediator (CMEPS)

ESMF/NUOPC provide a **common coupling infrastructure layer** used by NCAR and NOAA. This has enabled substantial **collaboration** between the two organizations on development of a **community coupler**.

CMEPS is the
Community Mediator for Earth Prediction Systems:

- A collaboration between NCAR, NOAA/EMC, and NOAA/GFDL; developed openly on GitHub to allow community code contributions and to encourage collaboration and innovation; *inter-model coupling* is part of NCAR-NOAA MoA
- A NUOPC-compliant Mediator designed to flexibly couple configurations of atmosphere, land, ocean, wave, sea ice, and land ice components using a hub-and-spoke architecture
- Used in NCAR's Community Earth System Model (CESM), NOAA's UFS S2S application, and NOAA's Hurricane Analysis and Forecast System (HAFS)



CMEPS integrated into the UFS S2S Application

Cross-Agency Collaboration: Community Mediator (CMEPS)

CMEPS Features

- Ready to couple combinations of atmosphere, land, ocean, wave, sea ice, and land ice NUOPC components
- Fully conservative 2D coupler
  - computes consistent land/sea mask during initialization
  - supports time-evolving ice fraction
- Data-driven field exchange specification
  - **one file** per application specifies field routing, mapping and merging
- Automatic:
  - interpolation weight generation
  - mapping from source to destination fields
  - merging of source fields to destination field
- Bit reproducible restarts
- Mediator history writes
- Modular design with separate phases that can be turned on/off

Cross-Agency Collaboration: Community Mediator (CMEPS)

CMEPS Exchange Field Specification

```
! to atm: unmerged from ice
! - zonal surface stress, meridional surface stress
! - surface latent heat flux,
! - surface sensible heat flux
! - surface upward longwave heat flux
! - evaporation water flux from water
! - mean ice volume per unit area
! - mean snow volume per unit area
! - surface temperatures
allocate(flds(9))
flds = (/'Faii_taux', 'Faii_tauy', 'Faii_lat ', &
         'Faii_sen ', 'Faii_lwup', 'Faii_evap', &
         'Si_vice  ', 'Si_vsno  ', 'Si_t     '/)
do n = 1,size(flds)
   fldname = trim(flds(n))
   call addfld(fldListFr(compice)%flds, trim(fldname))
   call addfld(fldListTo(compatm)%flds, trim(fldname))
   call addmap(fldListFr(compice)%flds, trim(fldname), compatm, mapnstod_consf, 'ifrac', 'unset')
   call addmrg(fldListTo(compatm)%flds, trim(fldname), mrg_from1=compice, mrg_fld1=trim(fldname), mrg_type1='copy')
end do
deallocate(flds)
```

https://github.com/ESCOMP/CMEPS/blob/master/mediator/esmFldsExchange_nems_mod.F90

Example shows specification of mapping ice fields to the atmosphere.

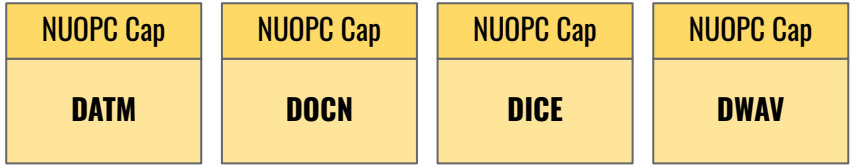
The specification includes interpolation method, normalization by surface fraction, and how to merge multiple source files into a single destination field.

Only a few basic calls are needed and 11 lines of code.

Cross-Agency Collaboration: Community Data Components (CDEPS)

- Open source, NUOPC-compliant components that provide data streams
  - data model versions of atmosphere, ocean, sea ice, land, runoff, and wave
- Easily add new input streams
  - plus out of box reanalysis/forcings (e.g., CORE, ERA5)
- Automatic regridding
  - Online regridding between input streams and model mesh
  - Multiple regridding options including conservative regridding
  - Support for 3D regridding

- Modular design for science specific data model functionality
- Compatible with CMEPS
- Data model share code has interface that can be called directly from prognostic component code base
- https://github.com/ESCOMP/CDEPS

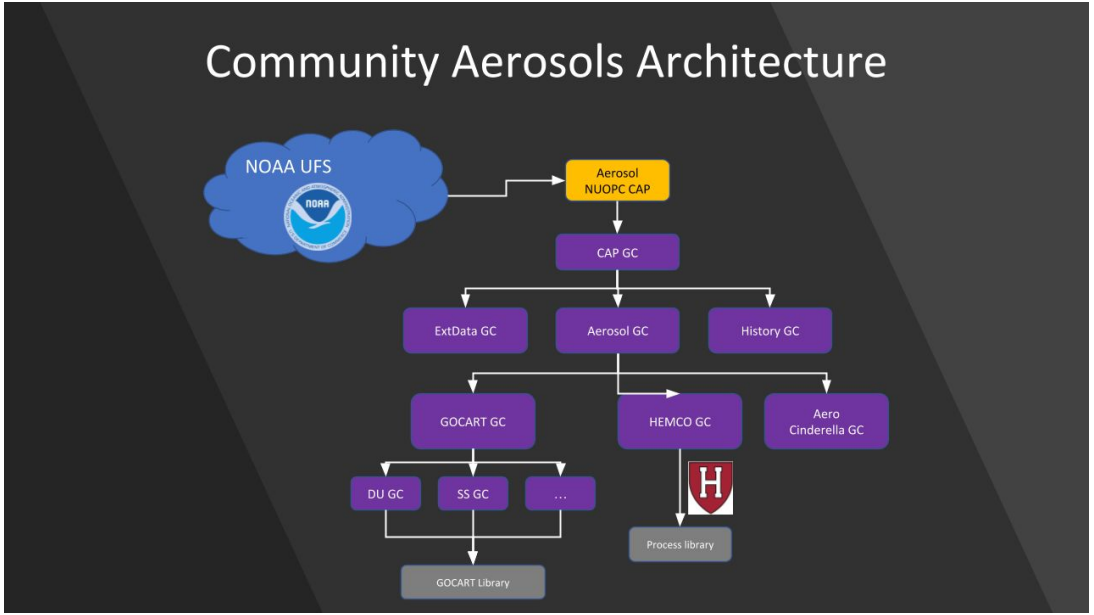


Cross-Agency Collaboration: Aerosol Modeling

NOAA and NASA are engaging in a collaborative project for joint development of the GOCART aerosol model.

ESMF provides **technical interoperability** between the MAPL and NUOPC layers, allowing GOCART to be used in multiple modeling systems.

Ability to **leverage prior work** between ESMF team and NASA/GMAO to create a MAPL-NUOPC "wrapper."



NASA's GOCART aerosol model uses MAPL interfaces when run in the GEOS model. A wrapper layer developed in collaboration with ESMF and NASA/GMAO provides allows MAPL components to be used in NUOPC-compliant systems. *Image courtesy Tom Clune/NASA/GMAO.*

Full Set of Active Components in UFS