2024 CESM SEWG
March 4, 2024

Earth System Modeling Framework

Q&A During Presentation:
https://tinyurl.com/esmf-2024March4

ESMF team: Robert Oehmke, Dan Rosen, Bill Sacks, Gerhard Theurich, Ann Tsay, and Ufuk Turuncoglu,

Topics

- Overview of the Earth System Modeling Framework and applications
- ESMF and NUOPC Capabilities overview
- Recent Releases
  Future Features Considerations

Questions/Comments during presentation?
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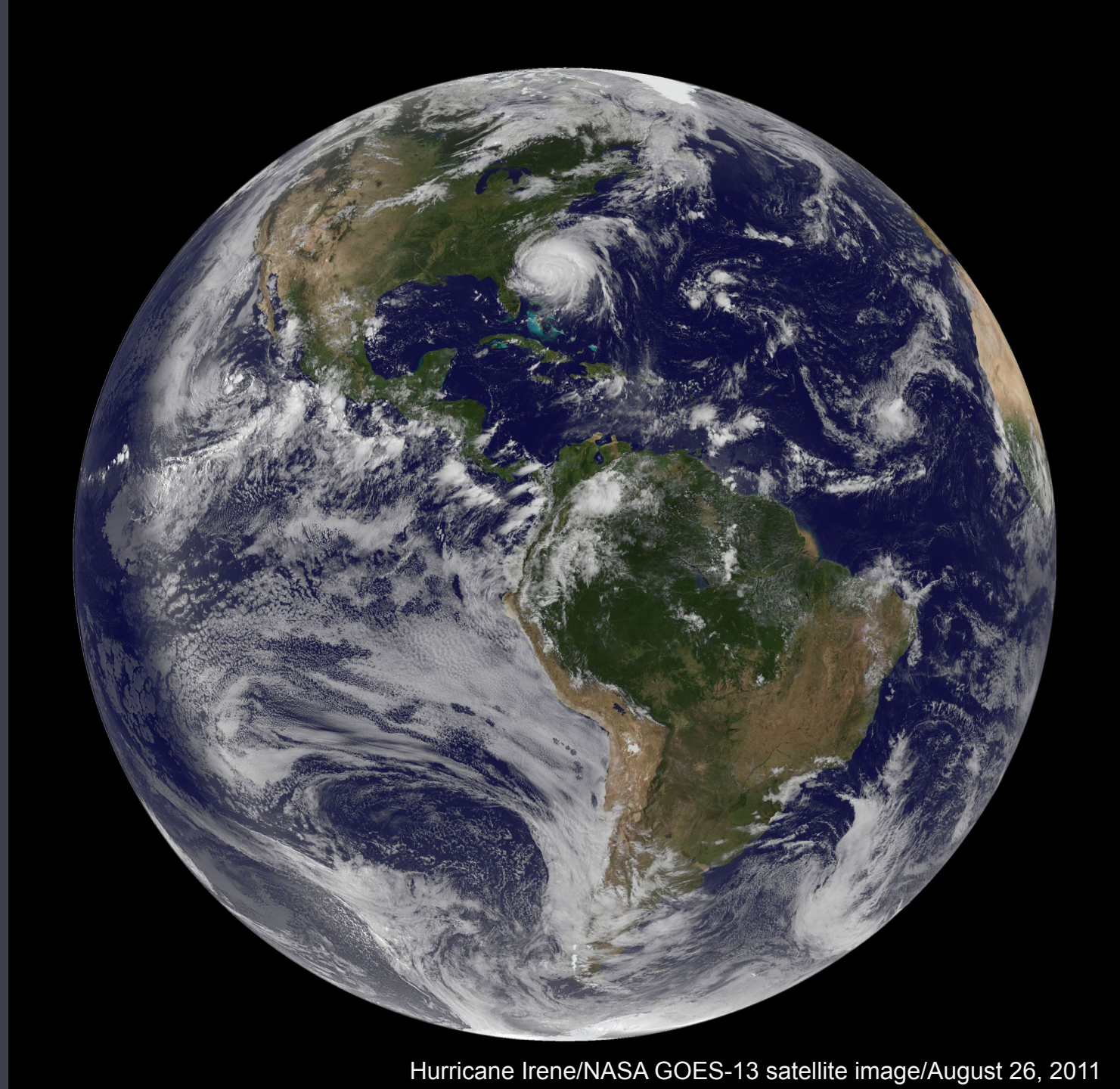
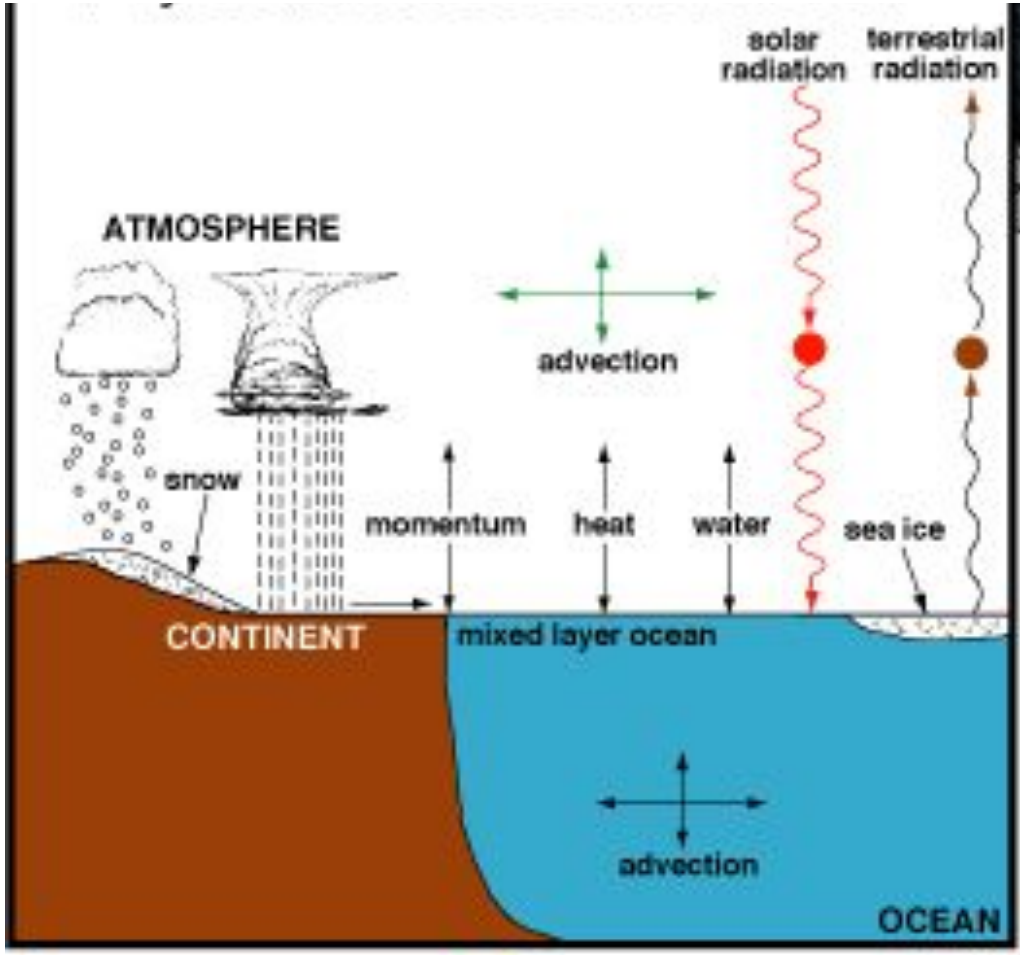


Hurricane Irene/NASA GOES-13 satellite image/August 26, 2011

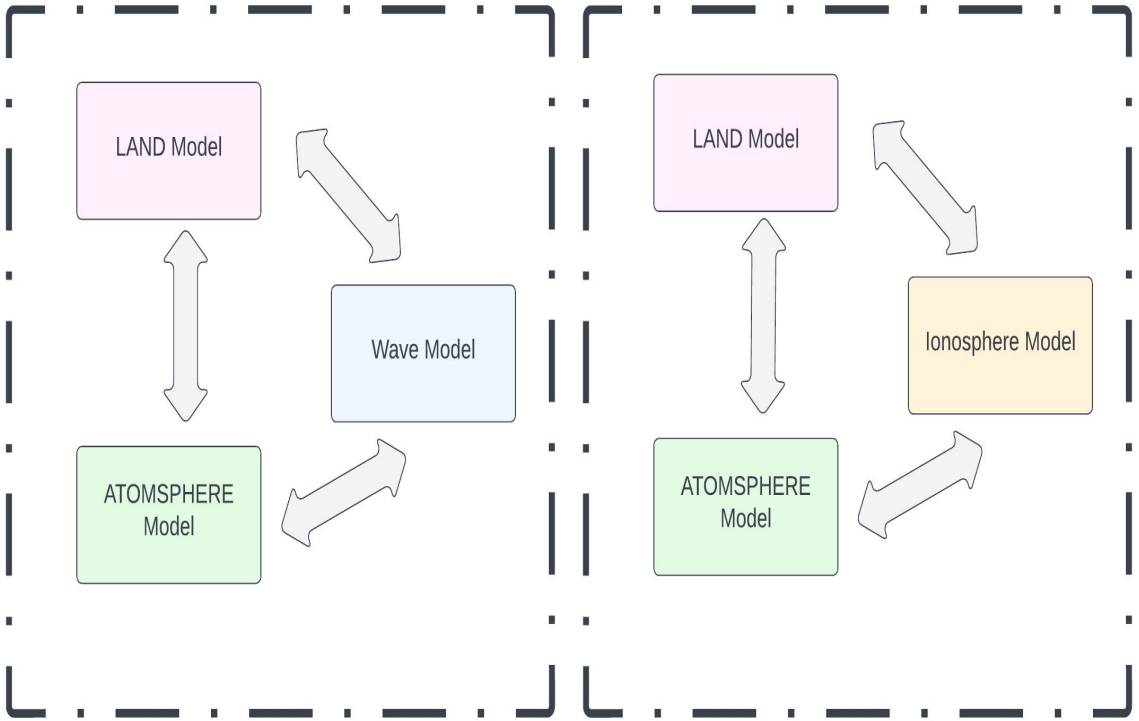
Simulating a Complex Dynamic System



Source: https://www.climate.gov/media/10042

Problems to solve:

- Standardized Model coupling
- Regridding
- Performance
- Simple way to drive Models

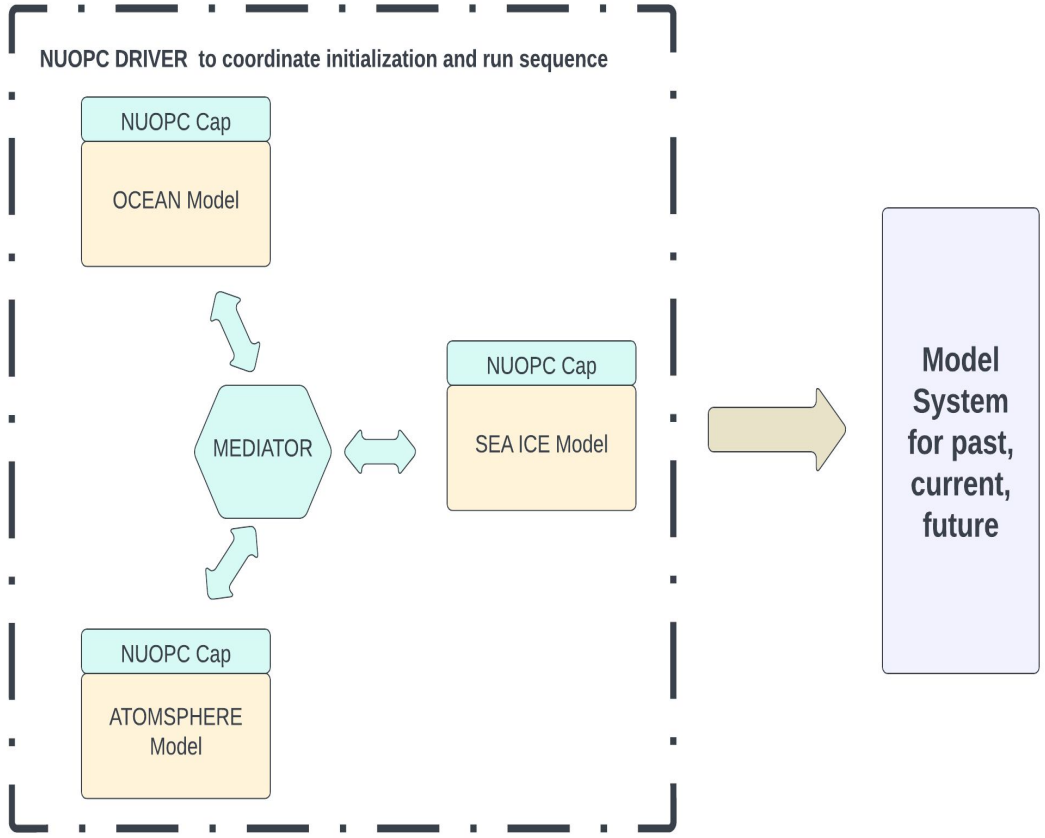


Solution: ESMF and NUOPC

Overview

The Earth System Modeling Framework (**ESMF**) is high-performance software infrastructure used in coupled Earth science applications.

National Unified Operational Prediction Capability (**NUOPC**) is a software layer on top of ESMF that provides **technical interoperability** of model components so they can be **shared across coupled systems**.

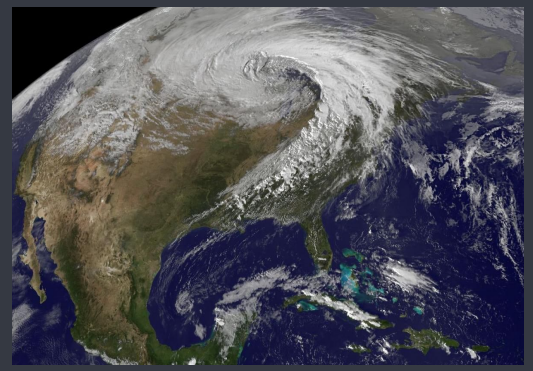


Modeling Systems using ESMF/NUOPC - Some examples in US

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 infrastructure 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 are using ESMF/NUOPC interfaces.

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

GEOS-5 & Model E

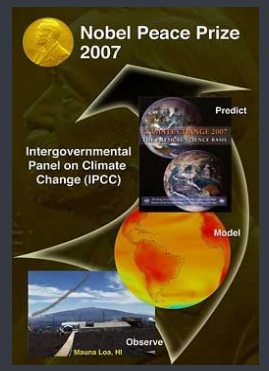
NASA Modeling and Data Assimilation

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

GEOS-5 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

CESM2 is based on ESMF/NUOPC.

Topics

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- **ESMF And NUOPC capabilities overview**
- Version 8.6 Release (Nov, 2023) Future Features Considerations

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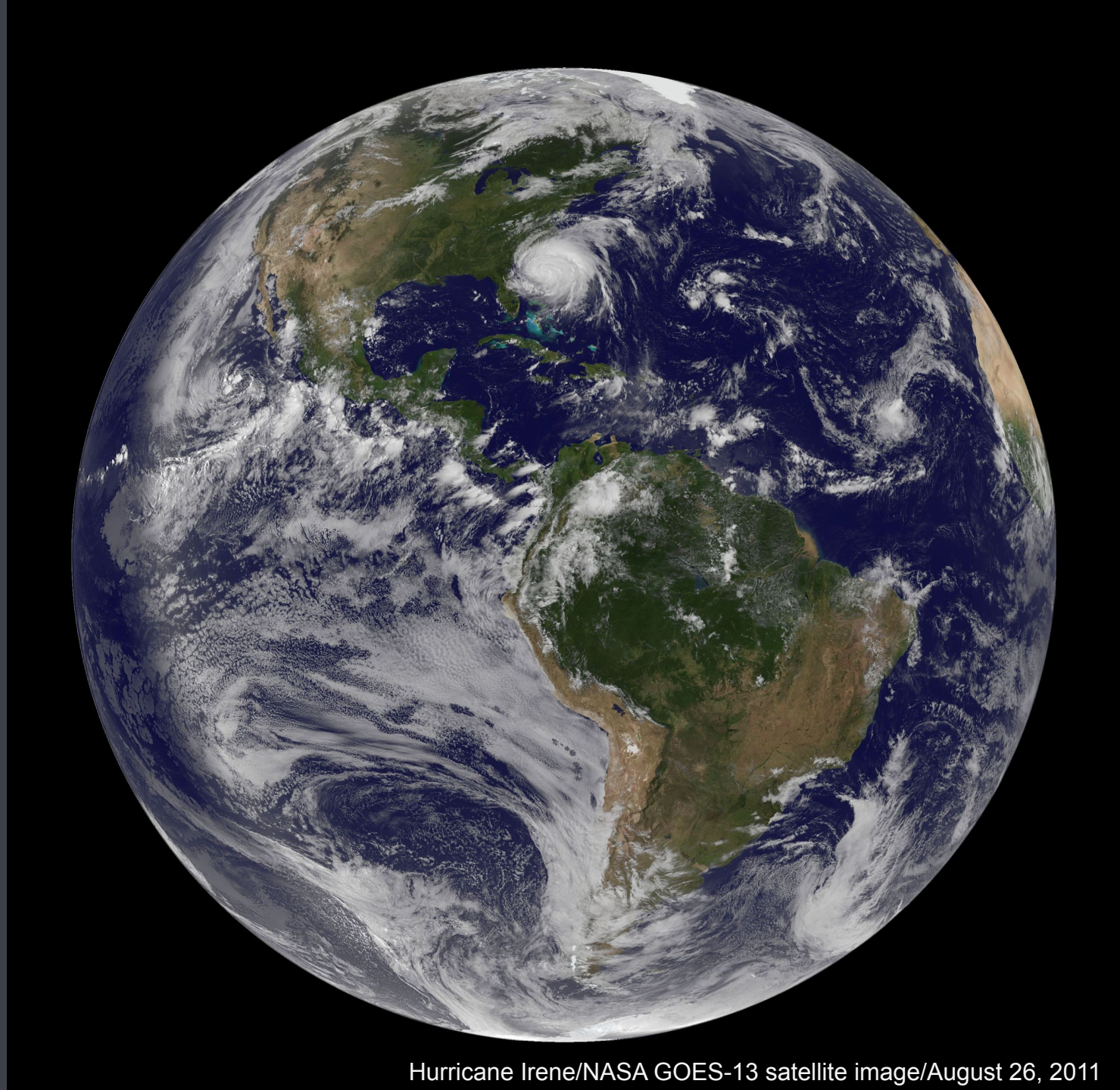

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  - **Standardized Model Coupling**
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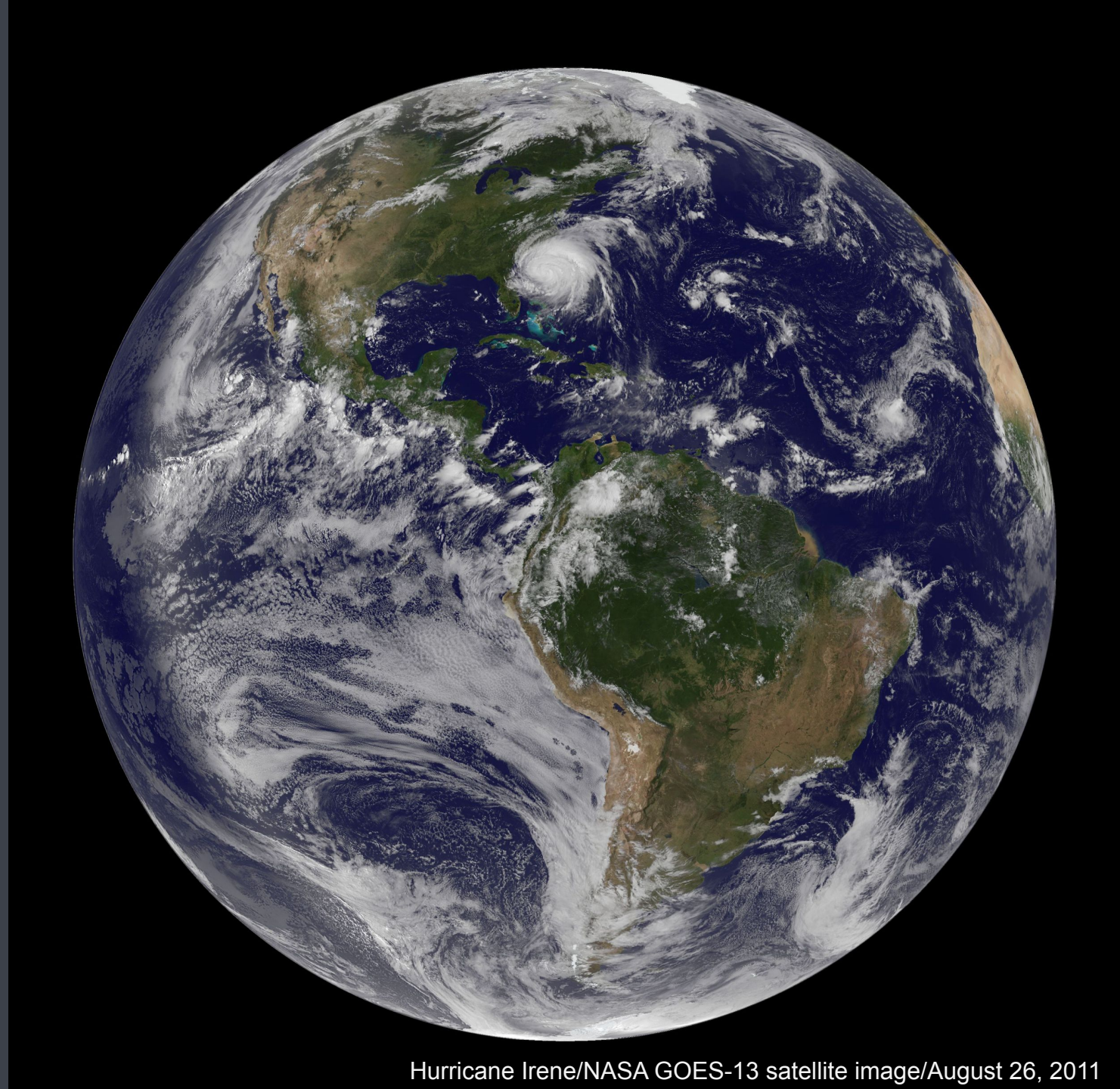

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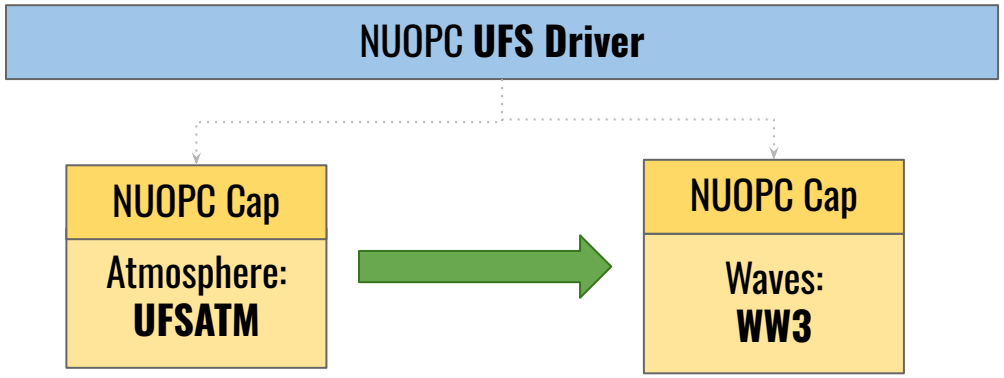
Standardized Model Interfaces

Model Components Coupling

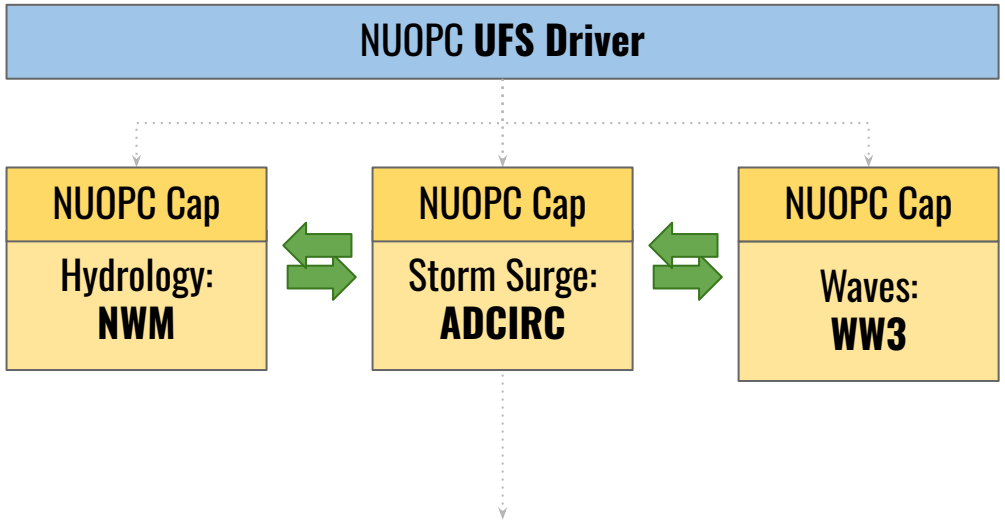


UFS Medium-Range Application
(GFSv16 configuration)

- ESMF/NUOPC provides unified model interfaces to all models across 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

Model Components Coupling -> performance

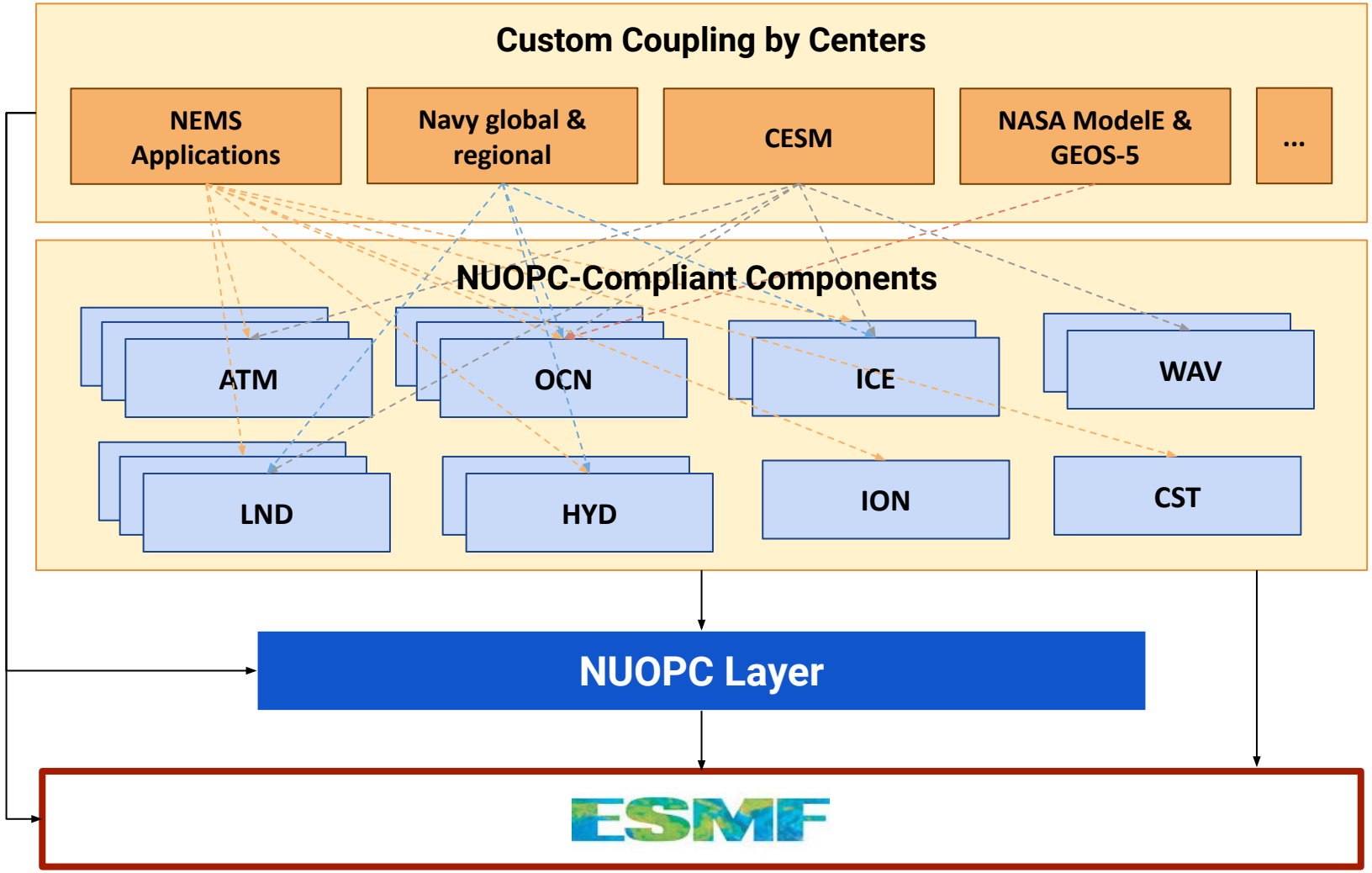


- ESMF/NUOPC provides optimized communication between model components
  - NUOPC “Connectors” are generated automatically by the Driver - no user code!
  - Connectors determine at runtime which coupling fields need to be exchanged, removing hard-coded field mappings
  - Connectors provide fast parallel communication options, including online generation and applications of interpolation weights
  - Connectors negotiate the most optimized connection possible, allowing tight coupling (shared memory) to loose coupling (grid remapping)

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

Component Reuse across Coupled Systems

Model Components Coupling



Custom Coupling
Each coupled system includes a set of components and specific technical and scientific choices; includes custom drivers and mediators

NUOPC-Compliant Components
Each component has a standard interface so that it can technically connect to any NUOPC-based coupled system

NUOPC Layer
Provides generic components and technical rules to enable sharing of components across coupled systems

ESMF
Provides generic utilities and data structures

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  - **Regridding**
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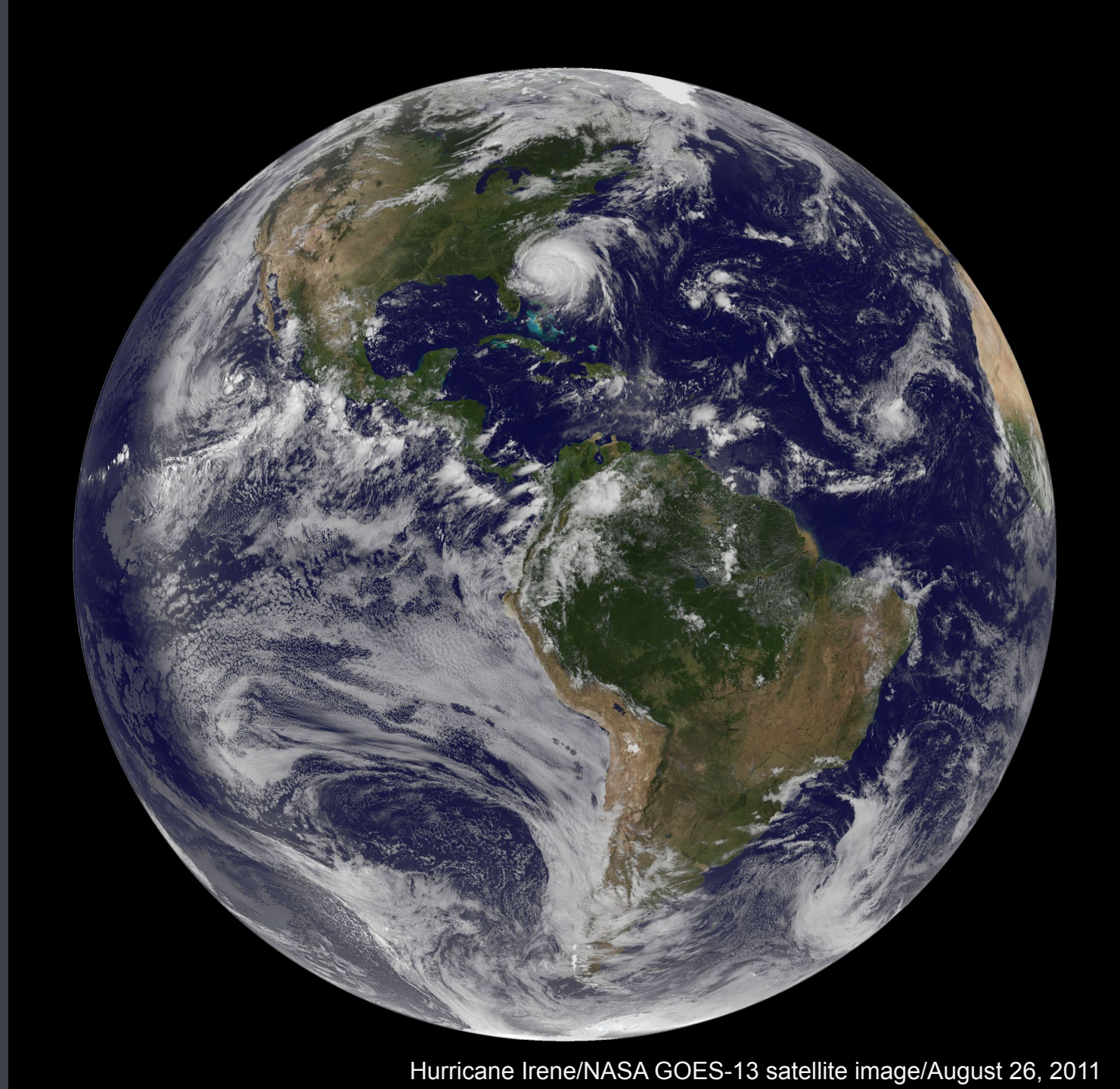

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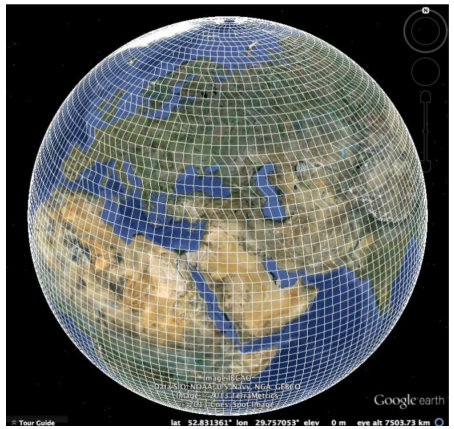
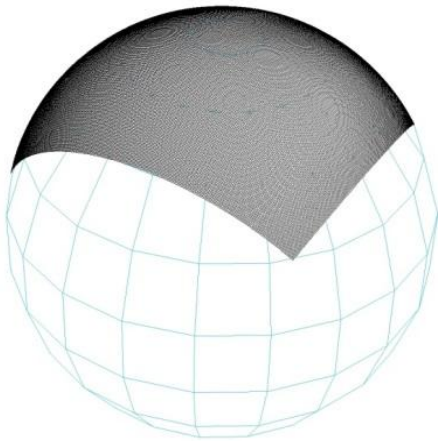




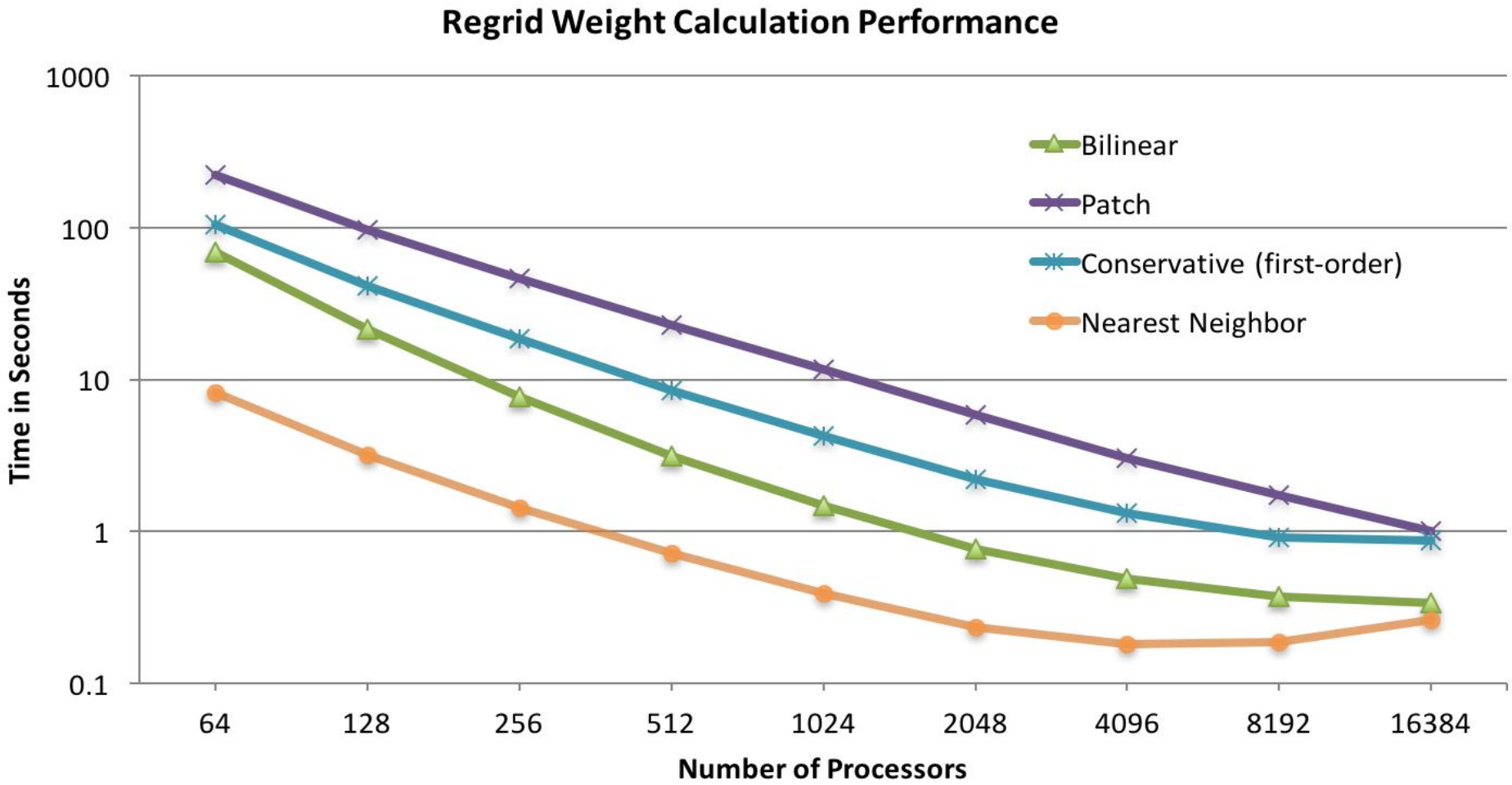
Fast, flexible interpolation of gridded data

Regridding

- **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 available in ESMF 8.0+
- **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

Regridding Performance

Strong scaling of different regrid methods



Source: cubed sphere grid (~25 million cells)

Destination: uniform latitude longitude grid (~17 million cells)

Platform: IBM iDataPlex cluster (Yellowstone at NCAR)

Results from ESMF 7.1.0 beta snapshot 25

Regridding in Python with ESMPy

ESMPy is a Python interface to ESMF functionality

- **A Python API to ESMF regridding and related classes**

  Transforms data from one grid to another by generating and applying remapping weights.

  Supports structured and unstructured, global and regional, 2D and 3D grids, created from file or in memory, with many options.

  Fully parallel and highly scalable.

  Visit the ESMPy home page for user documentation and installation instructions.

```
In [1]: import ESMF
        import numpy

In [2]: import os
        DD = os.path.join(os.getcwd(), "ESMPy-data")

        Create a uniform global latlon grid from a GRIDSPEC formatted file

In [3]: grid = ESMF.Grid(filename=os.path.join(DD, "tas_day_CanCM4_decadal2000_r2i1p1_20010101-20101231.nc"),
                         filetype=ESMF.FileFormat.GRIDSPEC, add_corner_stagger=True)

        Create Fields on the centers of the Grid cells

In [4]: srcfield = ESMF.Field(grid)

        Read Field data from "tas" variable in the file.

In [5]: srcfield.read(filename=os.path.join(DD, "tas_day_CanCM4_decadal2000_r2i1p1_20010101-20101231.nc"), variable="tas")

        Create a destination grid from a SCRIP formatted file

In [6]: dstgrid = ESMF.Grid(filename=os.path.join(DD, "T42_grid.nc"), filetype=ESMF.FileFormat.SCRIP, add_corner_stagger=Tru

        Create a destination Field on the centers of the Grid cells

In [7]: dstfield = ESMF.Field(dstgrid)

        Create an object to regrid data from the source to the destination Field using conservative regridding

In [8]: regridS2D = ESMF.Regrid(srcfield, dstfield, regrid_method=ESMF.RegridMethod.CONSERVE,
                                unmapped_action=ESMF.UnmappedAction.IGNORE)

In [9]: dstfield = regridS2D(srcfield, dstfield, zero_region=ESMF.Region.SELECT)
```

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  - **Regridding**
  - **Performance**
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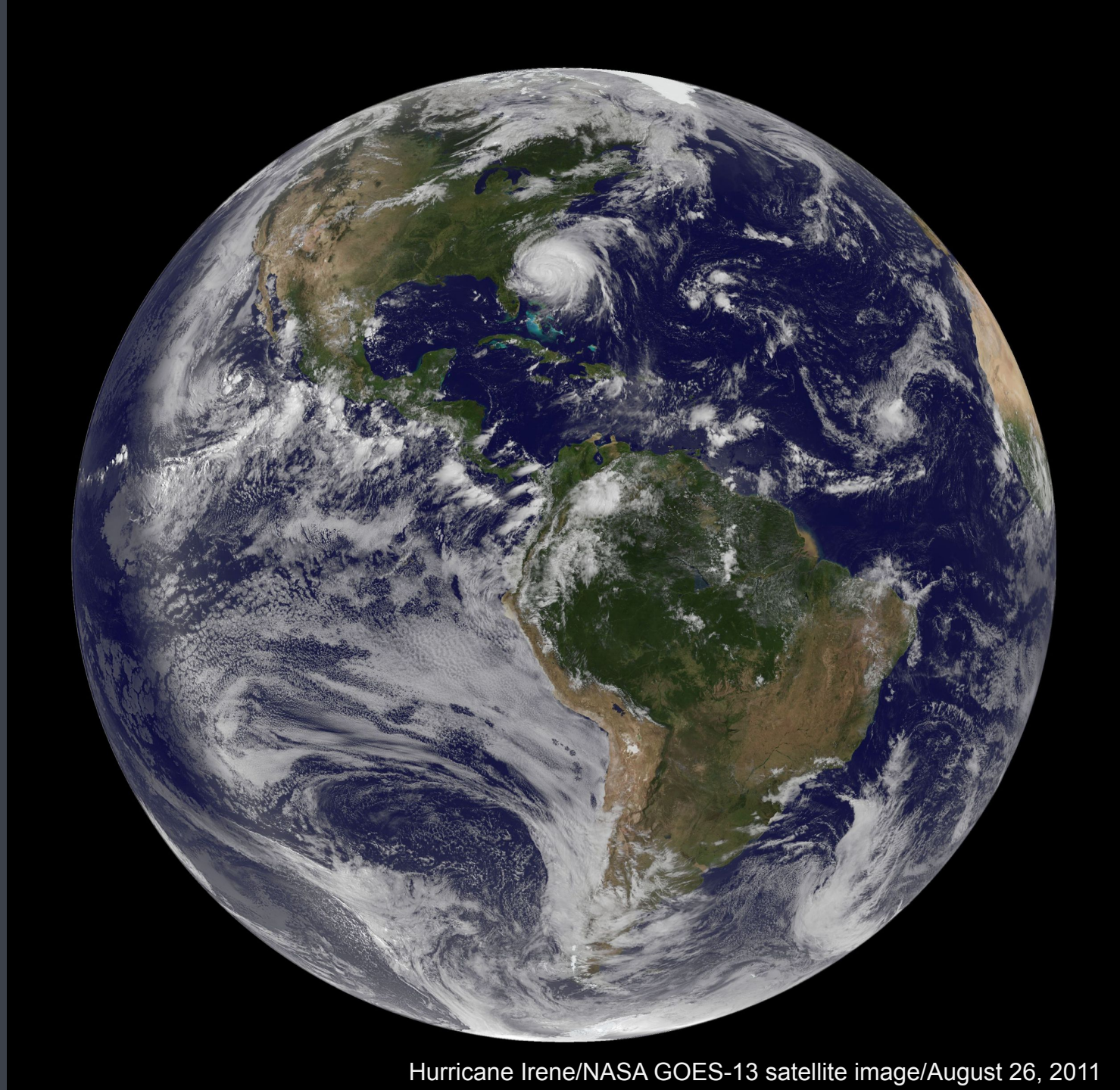


Hurricane Irene/NASA GOES-13 satellite image/August 26, 2011

Parallel Programming Model

Performance

Component resources

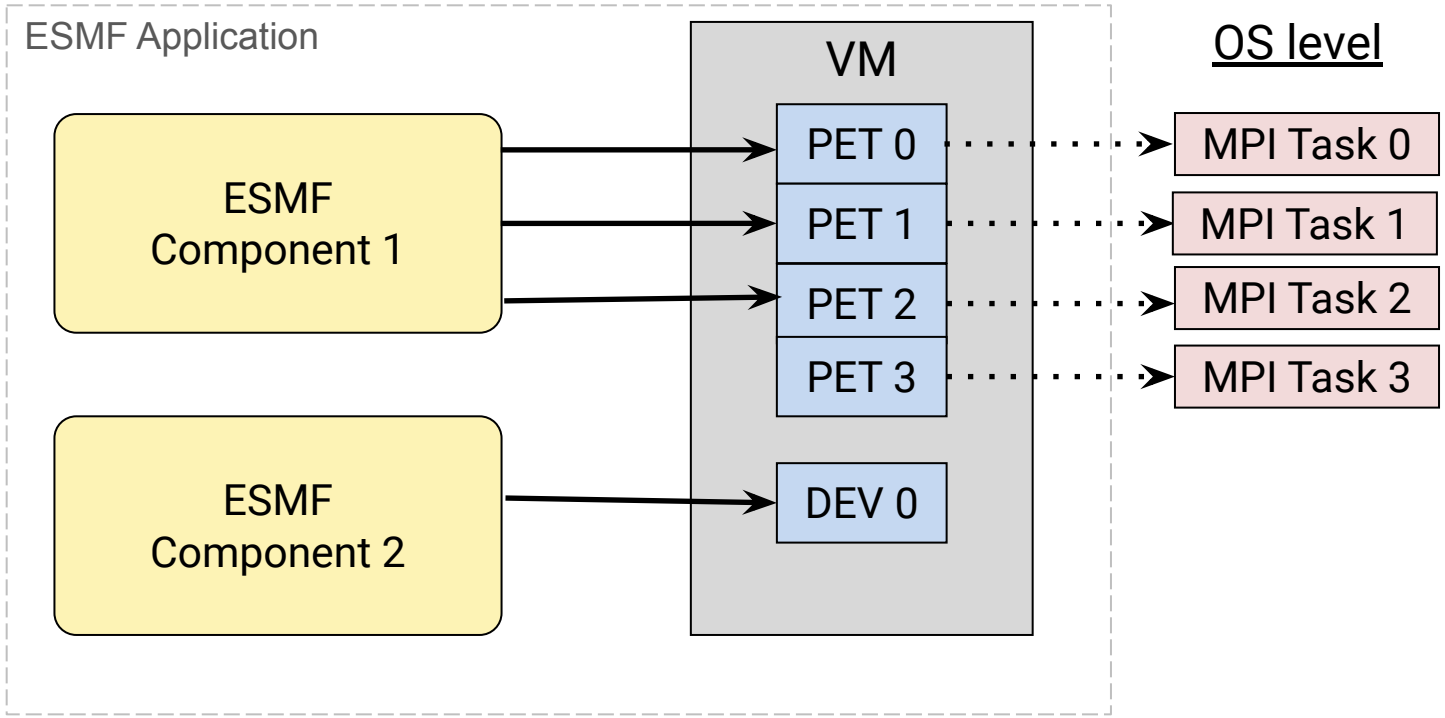
The Virtual Machine (VM) class manages a component's computational resources.

The basic elements contained in a VM are **Persistent Execution Threads (PETs)**. A PET typically maps to an **MPI process (task)**, but may also map to a **Pthread**.

Flexible mapping to resources

PETs can be assigned to components flexibly, allowing **concurrent** or **sequential execution**. The ESMF VM has recently been extended to allow **heterogeneous resources** (e.g. CPU and GPU devices)

In this example, each PET is mapped to an MPI task.



Parallel Communication Operations

Performance: Inter-model and intra-model communication

Sparse Matrix Multiply

- Apply coefficients (weights) in parallel to distributed data
- Auto-tunes for optimal performance
- Underlies most of ESMF distributed data operations

Redistribution

- Move data between parallel distributions without changing values; e.g., same global field moves from M PETs (processes) to N

Scatter/Gather

- Distribute data from one PET to multiple PETs or vice versa

Halo

- Most numerical algorithms require values of neighboring cells, but they may not be available on the local process
- Fills surrounding “halo” cells (or “ghost” cells) with data from another processor

Regrid

- Move a physical field from a source model grid/mesh to a destination model grid/mesh
- Unlike other operations, requires physical coordinates for source and destination

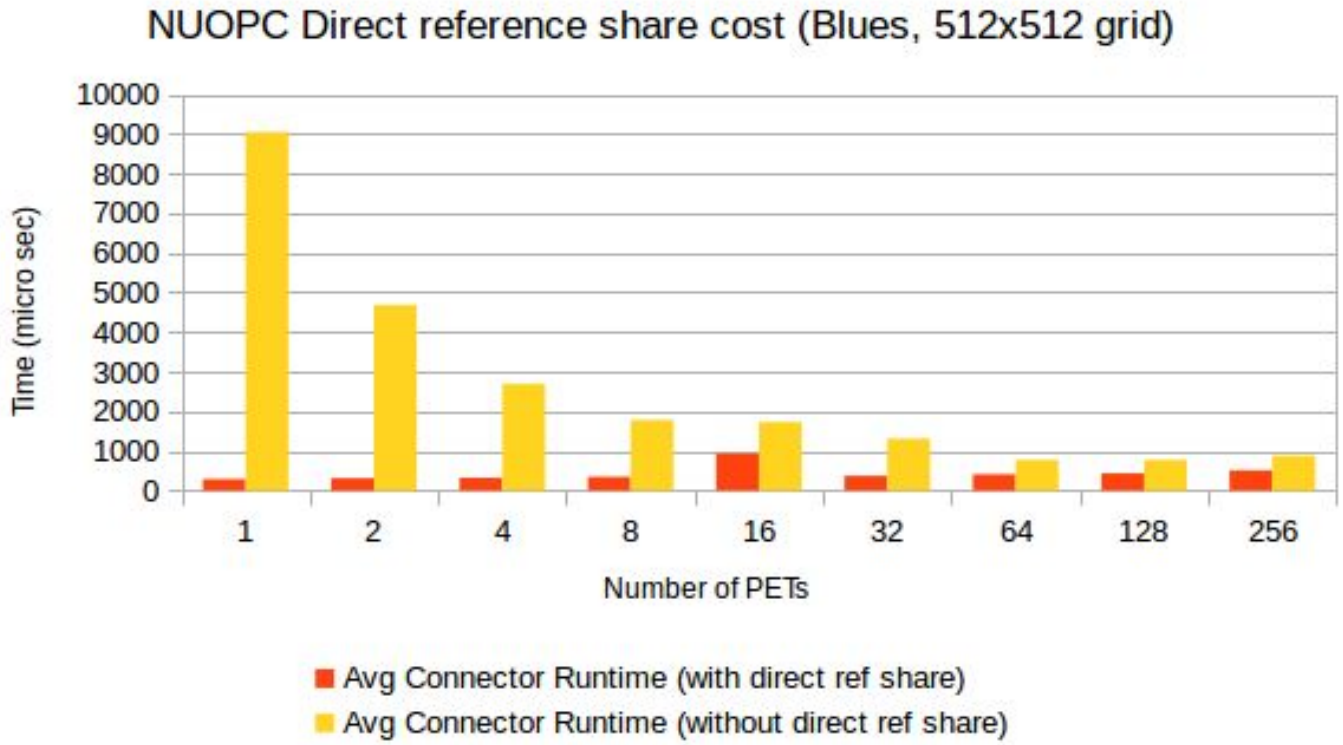
Measurement associated with ESMF/NUOPC

Performance

Overhead of ESMF/NUOPC Coponent interface is small (foor ESMF, ~55 us)

Direct reference sharing

Direct reference sharing is a feature in NUOPC where components that share the same grid and decomposition pass data as a reference (instead of a memory copy or MPI communication). **Measurements compare the runtime of a Connector with direct reference sharing (red) vs. an ESMF redistribution operation (yellow).**



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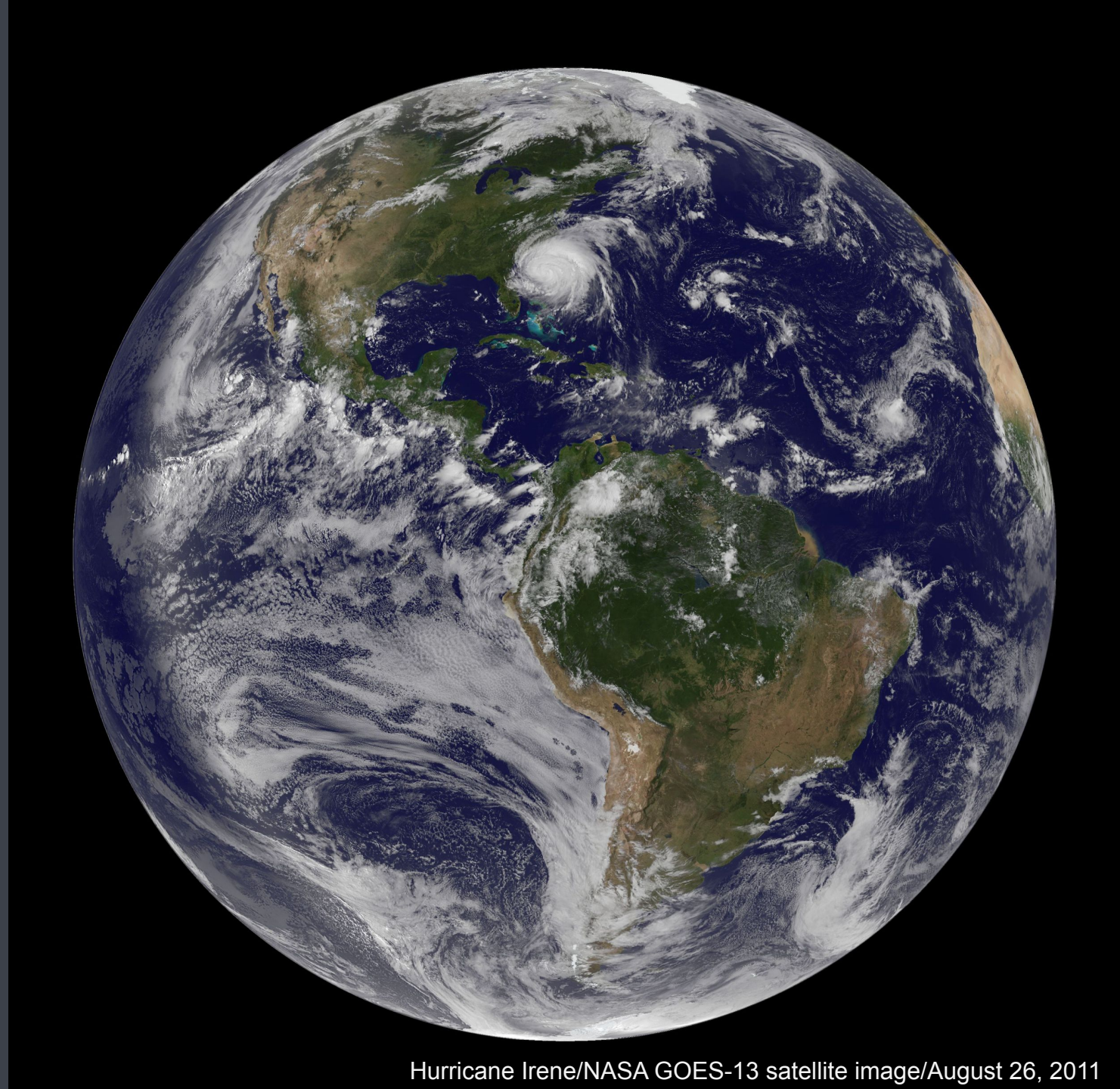
- **ESMF And NUOPC capabilities overview**
  - **Model Component Coupling**
  - **Regridding**
  - **High Performance**
  - **Easy way to drive the models**
- Recent Releases

  Future Features Considerations



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Earth System Modeling eXecutable (ESMX)

Simple way to drive model

- Build components
- Run the system

esmxBuild.yaml

```
application:

  link_packages: OpenMP

components:

  mycompname:

  somecomp:
    source_dir: scdir
    install_prefix: scdir
```

```
>
> ESMX_Builder
```

```
>
> ./install/bin/esmx_app
```

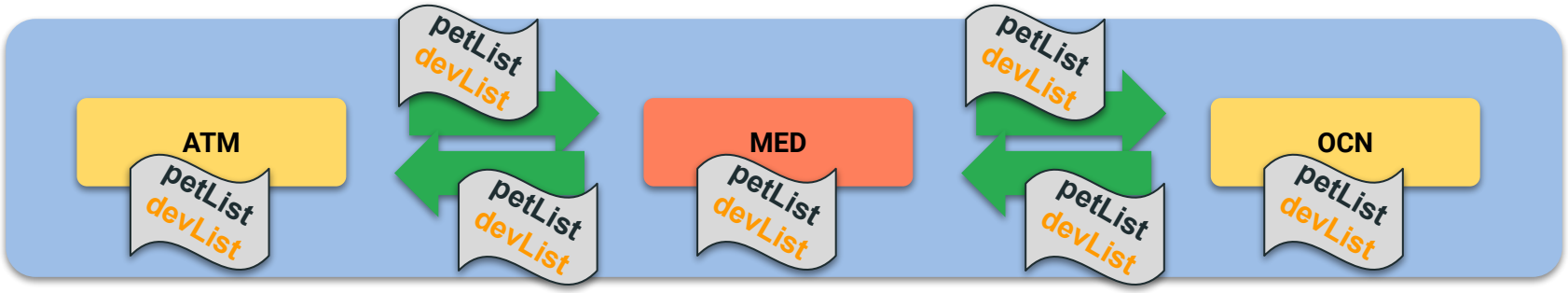
esmxRun.yaml

```
ESMX:

  App:
    logKindFlag:    ESMF_LOGKIND_Multi
    logAppendFlag: false
    logFlush:       true
    startTime:      2012-10-24T18:00:00
    stopTime:       2012-10-24T19:00:00

  Driver:
    componentList: [ATM, OCN]
    attributes:
      Verbosity: low
    runSequence: |
      @900
        ATM -> OCN
        OCN -> ATM
        ATM
        OCN
      @

ATM:
  model:           somecomp
  ompNumThreads:   4
  attributes:
    Verbosity: high
  petList:         0-3

OCN:
  model:           mycompname
  petList:         1,3
```

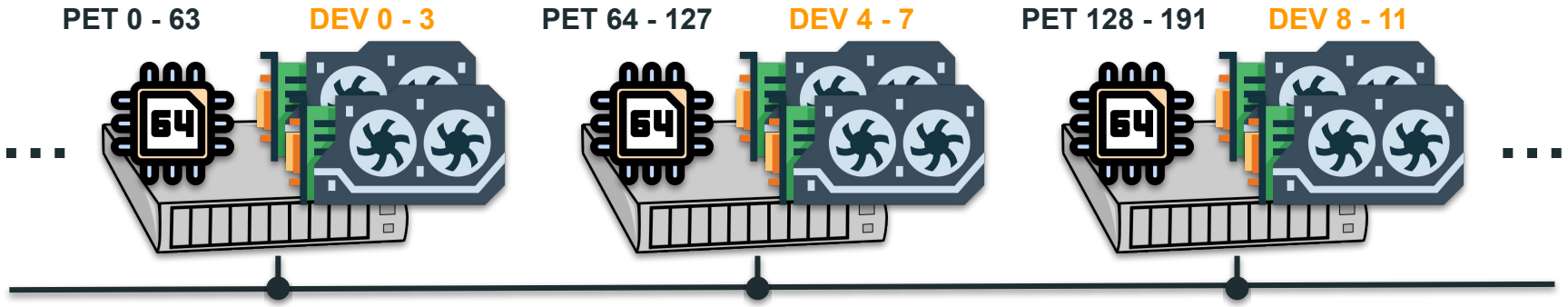
Accelerator Device Management

NEW in Version 8.6.0 (released in Nov, 2023)

ESMF-managed threading



- Globally label all Persistent Execution Threads (**PETs**), i.e. MPI ranks, in sequence.
- Globally label all Accelerator Devices (**DEVs**), in sequence.
- Associate each component with PETs and DEVs via its own **petList** and **devList**.




```
ESMX:

  ...


ATM:
  model:            tawas
  petList:          0-3,64-67
  devList:          0-3,4-7
  attributes:
    Verbosity: high

OCN:
  model:            lumo
  petList:          128-129
  devList:          8-11

MED:
  model:            BestMed
  petList:          4-63,68-127,130-191
  ompNumThreads:    2
```

esmxRun.yaml

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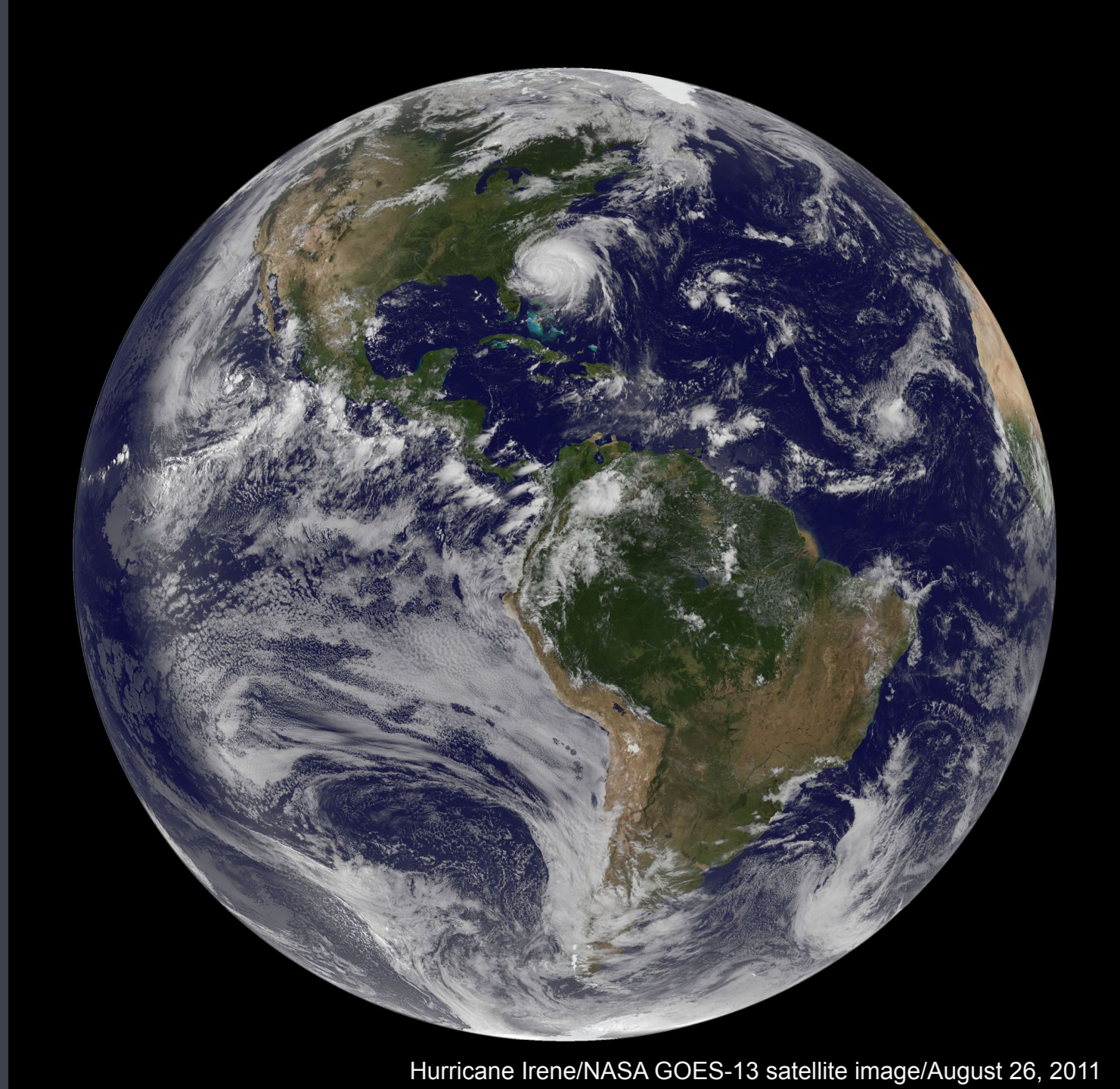

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Most recent releases: 8.4.x, 8.5.x and 8.6.x

8.6.0 is the latest release: November, 2023

See 8.6.0 release notes for full list of release items:
https://earthsystemmodeling.org/docs/release/latest/ESMF_usrdoc/

	Version 8.4.0 (Oct, 2022), 8.4.1, 8.4.2	Version 8.5.0 (July, 2023)	Version 8.6.0 (Nov, 2023)	Version 8.6.1 (planned Early Summer 2024)
Release notes	• I/O with PIO 2.x • Support dynamically changing grid coordinates via transfer • ESMX prototype • Spack Build support	• A hierarchical configuration class implemented (ESMF_HConfig) with Fortran API • A generic geometry class (ESMF_Geom) was added • Creating a Mesh, or adding nodes to an existing Mesh, without specifying the nodeOwners argument • Grids that contain DEs of zero width are now supported in regridding	• Vector regridding option • Accelerator device management • Basic ESMF C API added to provide access to the ESMF tracing and profiling capability from code written in C	• Remove 1024 Character attribute+value limitation • Fix inserting and deleting to config buffer • Fixes support for values enclosed in quotes • Fixes support for blank values • Fixes memory leak in config destroy • Fixes support for blank values • Fix start_index for ESMFMesh file format • Add 'ESMF::ESMF CMake target alias to support unambiguous linking - this may still in the process of being modified until the final version.

Future Feature Considerations

Next Release Planned: 8.6.1 in late Spring 2024.

- **ESMF:**
  - Clock Management
  - Field Merging / Blending
  - StateReconcile Overhead reduction - better to scale with large number of cores
  - Efficient coupling of GPU resident models
  - Regional Coupling Enhancement

- **ESMX**
  - Established testing strategy in ESMXbuild.yaml
  - Support for logical component hierarchies

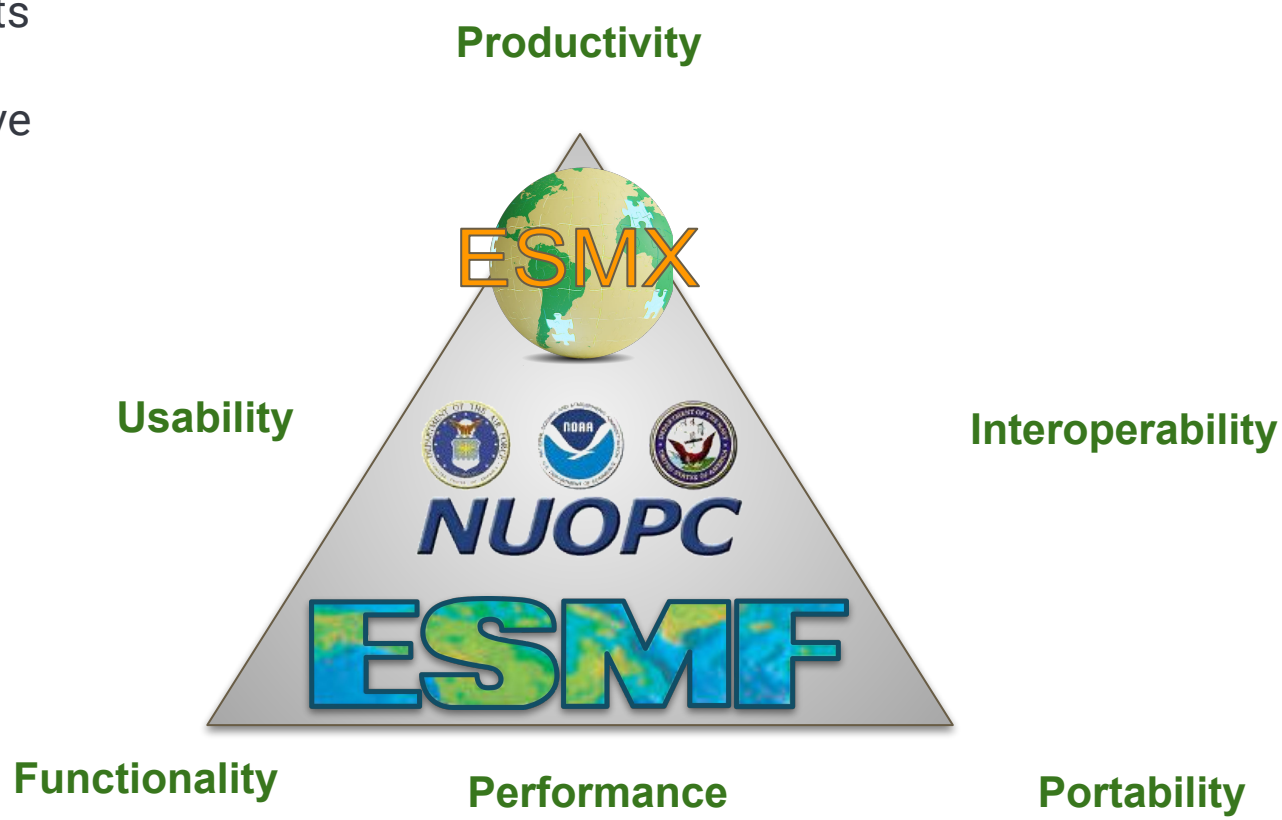
- **NUOPC:**
  - I/O enhancement
  - Full Component hierarchy support

- **Code/Process Modernization**
  - Build system to improve efficiency in development

- **Interoperability**
  - Meta data transfers between components
  - Enhancement in ESMPy
  - Machine Learning (ML) interfacing
  - Interaction with JEDI or DA

Community Feedback

- **Community Outreach and Feedback**
  - General/new features requests
  - More use cases
  - Problem you are trying to solve
  - Training session



Thank You!

Questions welcome!
esmf_support@ucar.edu

We would appreciate your feedback on

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