Earth System Modeling Framework

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Talk Layout

- Historical Development and Motivation
- Architecture
- Data Structures, Memory Model and Implementation
- Hello World and A system test
- Capabilities and Features
- Conclusions
- Please don't hesitate to ask questions after each mini section

Historical Development and Motivation

Evolution

Phase 1: 2002-2005
NASA's Earth Science Technology Office ran a solicitation to develop an **Earth System Modeling Framework** (ESMF).
A multi-agency collaboration (NASA/NSF/DOE/NOAA) won the award.
The core development team was located at NCAR.
A prototype ESMF software package (version 2r) demonstrated feasibility.

Phase 2: 2005-2010
New sponsors included Department of Defense and NOAA.
Many new applications and requirements were brought into the project, motivating a complete redesign of framework data structures (version 3r).

Phase 3: 2010-2015
The core development team moved to NOAA/CIRES for closer alignment with federal models.
Basic framework development will be complete with version 5r (ports, bugs, feature requests, user support etc. still require resources).
The focus is on increasing adoption and creating a community of interoperable codes.

Motivation

In climate research and numerical weather prediction..
increased emphasis on detailed representation of individual physical processes; requires many teams of specialists to contribute components to an overall modeling system

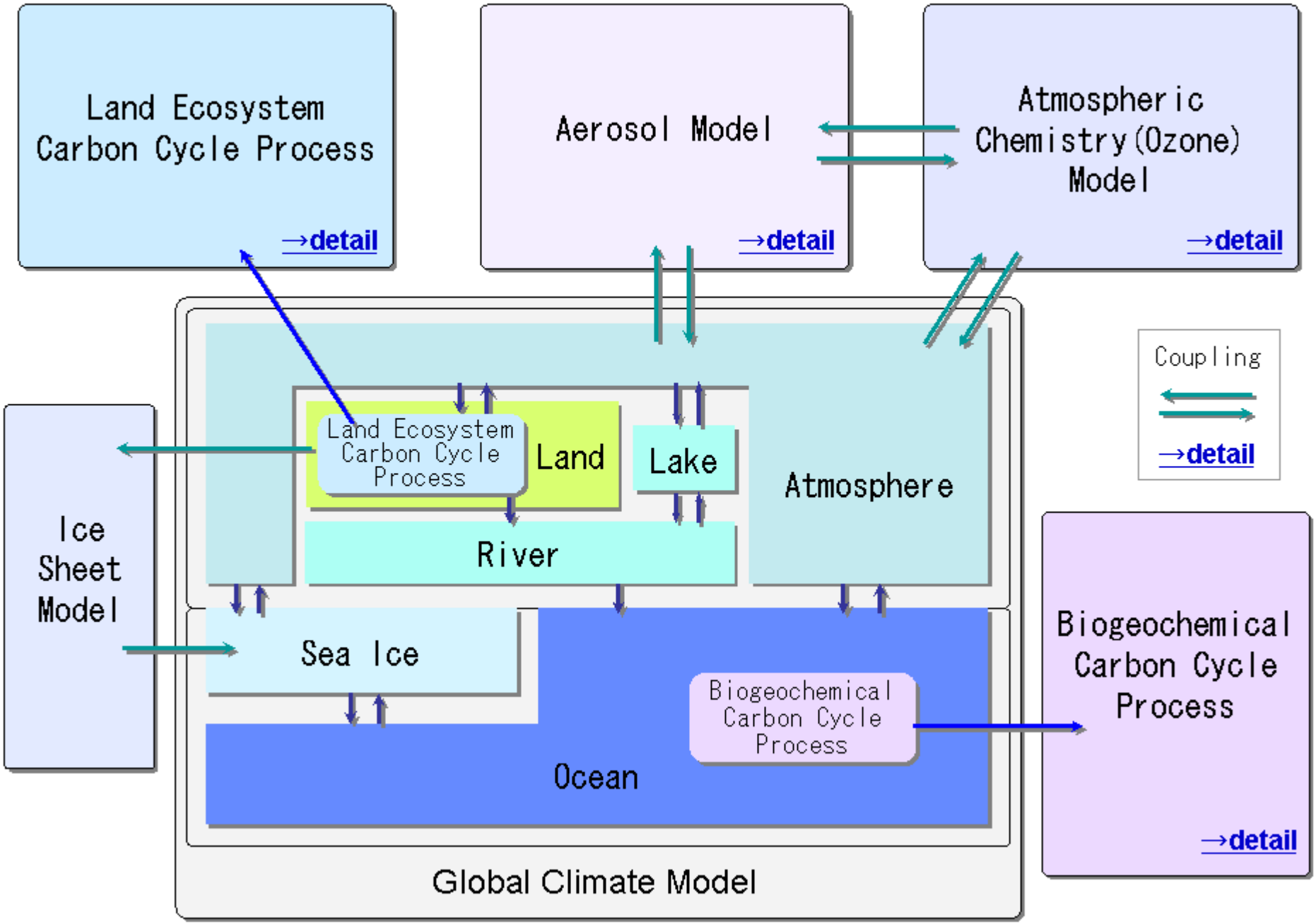
In computing technology...
increase in hardware and software complexity in high-performance computing, as we shift toward the use of scalable computing architectures

In software …
emergence of frameworks to promote code reuse and interoperability

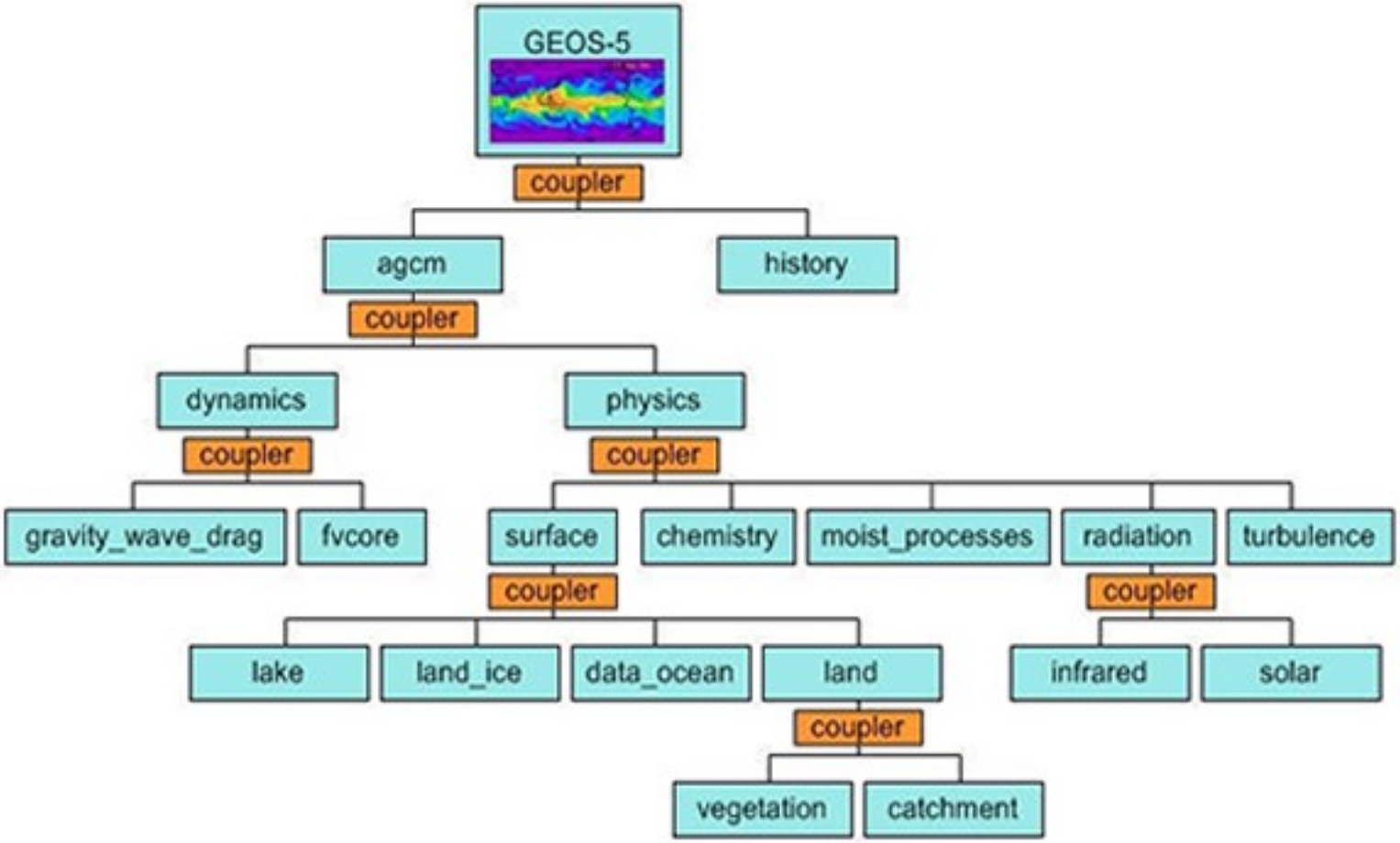
The ESMF is a focused community effort to tame the complexity of models and the computing environment. It leverages, unifies and extends existing software frameworks, creating new opportunities for scientific contribution and collaboration.

Architecture

Earth System Model of MRI



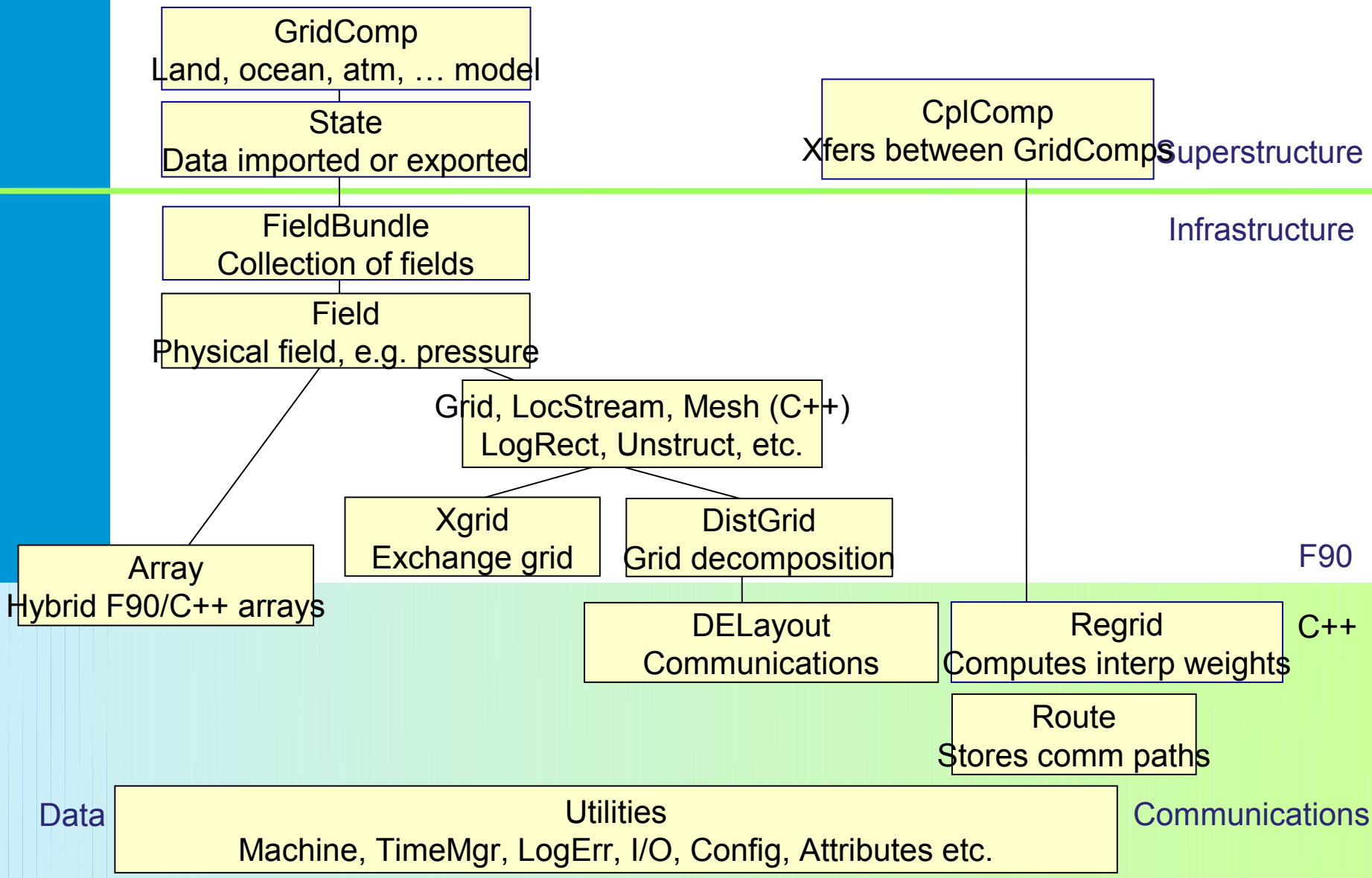
Hierarchical structure of GEOS-5 AGCM



Mathematical Abstraction

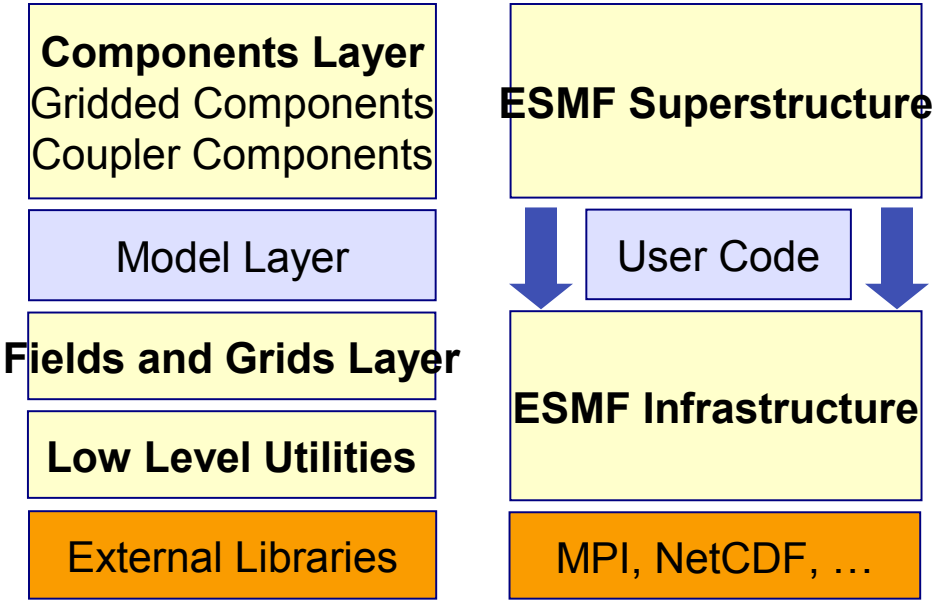
- The power of ESMF lies in the fact that most of the composite structures of the world can be mathematically abstracted into a hierarchical (tree) representation. ESMF is especially tailored towards ESM applications but can also be in other parallel and high performance computing projects.
- The support of ESMF extends from the lowest level of data representation, parallelism, to higher level model abstraction, geophysical constructions, and Earth System Modeling in general.
- The idea of hierarchical structure also extends into the design of ESMF classes and how they relate to each other.

The Hierarchy of ESMF



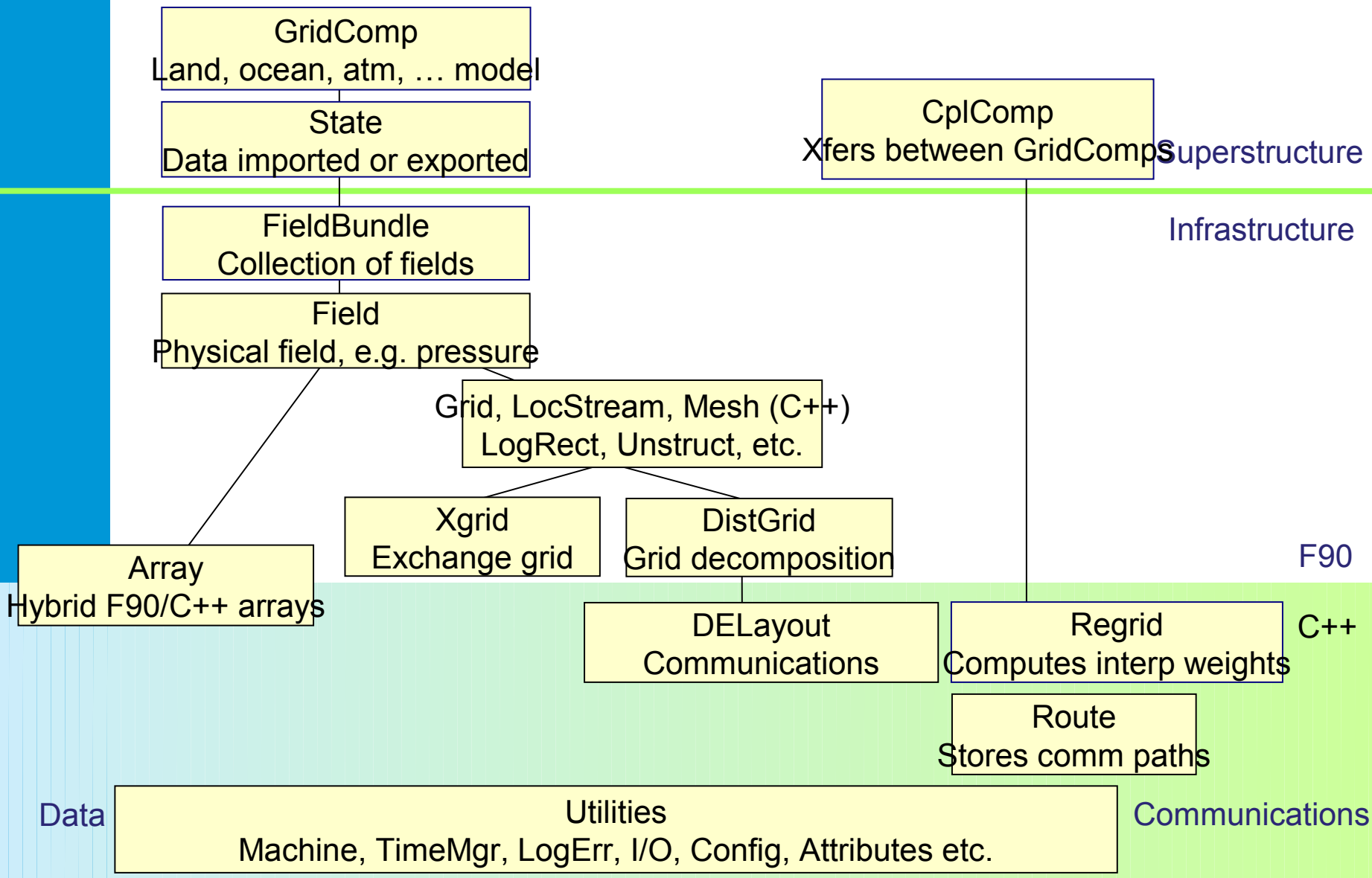
Architecture

- ESMF provides a **superstructure** for assembling geophysical components into applications.
- ESMF provides an **infrastructure** that modelers use to
  - Generate and apply interpolation weights
  - Handle metadata, time management, data I/O and communications, and other functions
  - Access third party libraries



Data Structures, Memory Model and Implementation

The Hierarchy of ESMF



Memory Model and Implementation

- ESMF classes are design in an object oriented manner using features of F90 and C++
- Class APIs take a class object as its first argument by design convention
- There are 2 kinds of ESMF objects : shallow and deep, deep objects must be created and destroyed
- Most ESMF classes are implemented with both Fortran 90 and C++ within different layers.
- Objects are implemented as a common pointer that points to a memory storage shared by both Fortran and C++ pointers
- Array storage follows Fortran convention, that's column major indexed

Hello World, An ESMF System Test

Features and Capabilities

Coupling options in ESMF

- Fortran or C components
- Single executable
- Multiple executable
  - Web service option (loose coupling)
  - Top level MPMD
- Coupling communications can be called either from within a coupler or directly from a gridded component – useful when it is inconvenient to return from a component in order to perform a coupling operation
- Recursive components for nesting higher resolution regions
- Ensemble management with either concurrent or sequential execution of ensemble members

Grid Remapping

- Fast parallel computation of interpolation weights
- Weight generation is separate from weight application (sparse matrix multiply) for flexibility
- Supports grids that can be represented as combinations of triangular or rectangular elements, in 2D or 3D
- Bilinear, higher order finite element patch recovery (see below), or conservative interpolation options
- Pole options: n-point pole, full circle average, no pole

Higher order method:

- Khoei S.A., Gharehbaghi A. R. The superconvergent patch recovery technique and data transfer operators in 3d plasticity problems. *Finite Elements in Analysis and Design*, 43(8), 2007.
- Hung K.C, Gu H., Zong Z. A modified superconvergent patch recovery method and its application to large deformation problems. *Finite Elements in Analysis and Design*, 40(5-6), 2004.

Remapping Performance

- All ESMF interpolation weights are generated using unstructured mesh
- Increases flexibility with 2D and 3D grids
- Adds overhead to bilinear interpolation
- Greatly improved performance over existing conservative methods

ESMF parallel conservative remapping is scalable and accurate

- Platform: Cray XT4, jaguar, at ORNL
- Versions: ESMF_5_2_0_beta_snapshot_07 and SCRIP 1.4
- Resolution:

- fv0.47x0.63: CAM Finite Volume grid, 576x384
- ne60np4: 0.5 degree cubed sphere grid, 180x180x6

Weight Generation Options

- Ways to generate interpolation weights:
  - Online
    - Subroutine calls which calculate weights during run
    - Can get weights or feed directly into ESMF sparse matrix multiply
  - Offline
    - Application which generates a netCDF weight file from two netCDF grid files

Summary of grid remapping options is posted at:
http://www.earthsystemmodeling.org/esmf_releases/non_public/ESMF_5_1_0/esmf_5_1_0_regridding_status.html

Parallel I/O

- I/O is increasingly a bottleneck in high resolution simulations
- ESMF parallel I/O based on the PIO library developed by NCAR/DOE
- Integrated so that the user only sees ESMF data types:
  - ESMF_ArrayRead(), ESMF_ArrayWrite()
  - ESMF_FieldRead(), ESMF_FieldWrite()
- NetCDF and binary formats

See: PIO User's Guide, http://web.ncar.teragrid.org/~dennis/pio_doc/html/

Timekeeping

- Clocks
  - startTime, stopTime, runDuration, timeStep, many other properties
  - Forward and reverse modes for running clocks

- Alarms
  - Unsticky (turn themselves off after ringing) or sticky alarms

- TimeInterval and Time data types with many operators (+,-,/,==, more)

Supported Calendars:

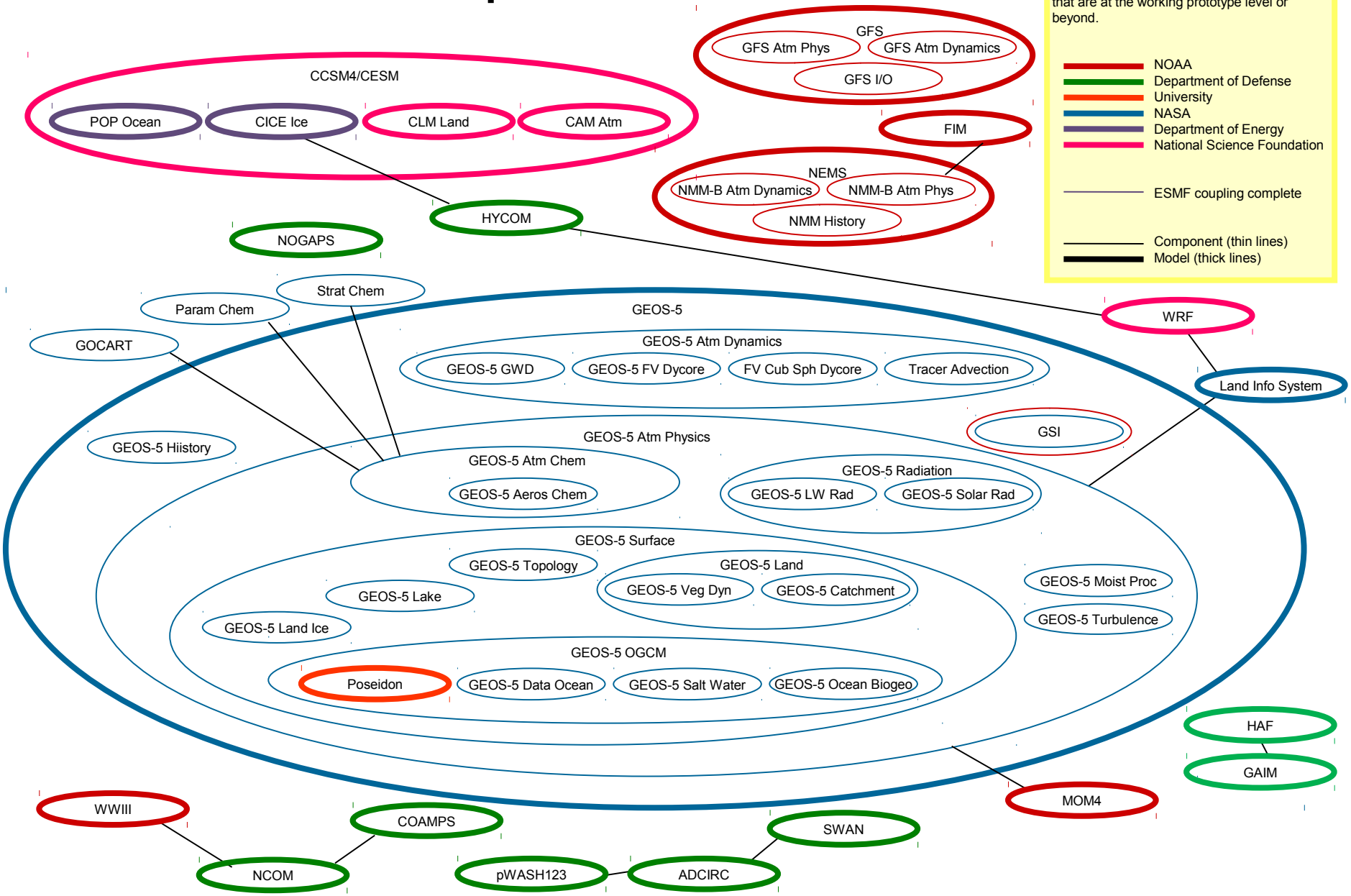
- 360 day
- No leap
- Gregorian
- Julian
- Julian Day
- Modified Julian Day
- No calendar
- custom

Summary of Features

- Fast parallel remapping: unstructured or logically rectangular grids, 2D and 3D, using bilinear, higher order, or conservative methods, integrated (during runtime) or offline (from files)
- Core methods are scalable to tens of thousands of processors
- Supports hybrid (threaded/distributed) programming for optimal performance on many computer architectures
- Multiple coupling and execution modes for flexibility
- Time management utility with many calendars, forward/reverse time operations, alarms, and other features
- Metadata utility that enables comprehensive metadata to be written out in standard formats include XML format
- Runs on 24+ platform/compiler combinations, exhaustive test suite and documentation
- Couples Fortran or C-based model components

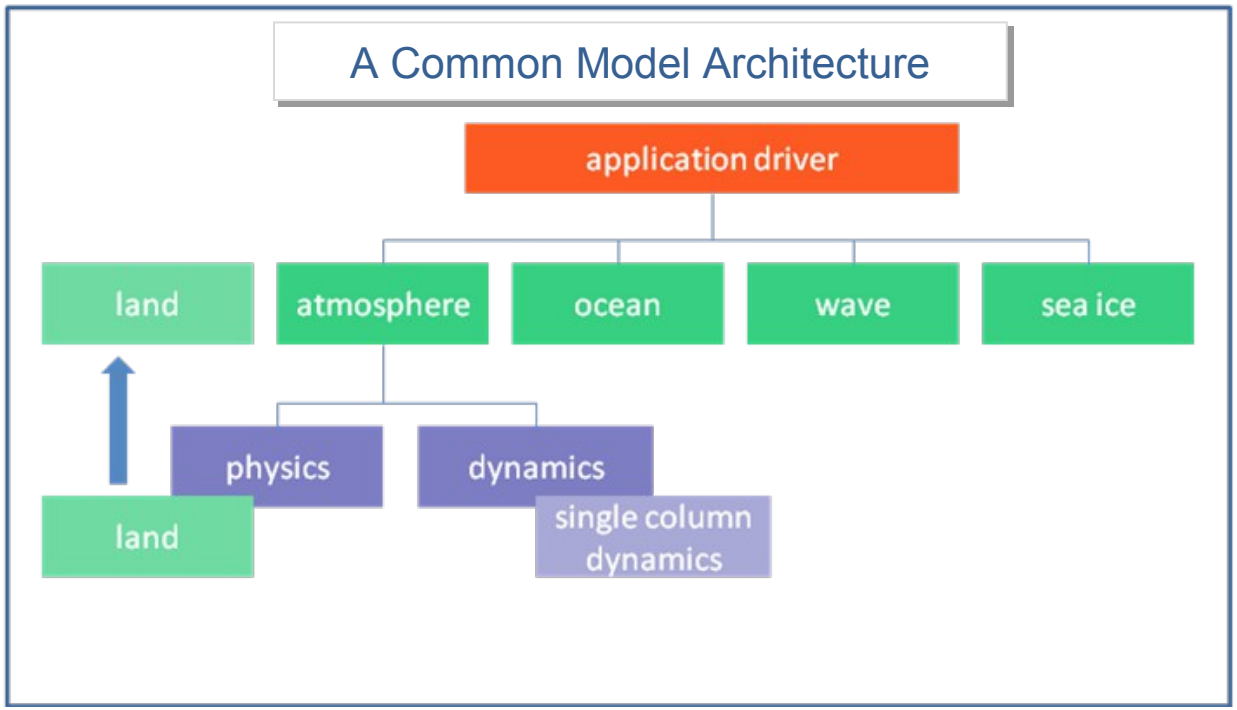
ESMF applications

ESMF Model Map 2010



A Common Model Architecture

- The U.S. Earth system modeling community is converging on a common modeling architecture
- Atmosphere, ocean, sea ice, land, wave, and other models are ESMF or ESMF-like components called by a top-level driver or coupler
- Some models are modularizing further with nested components

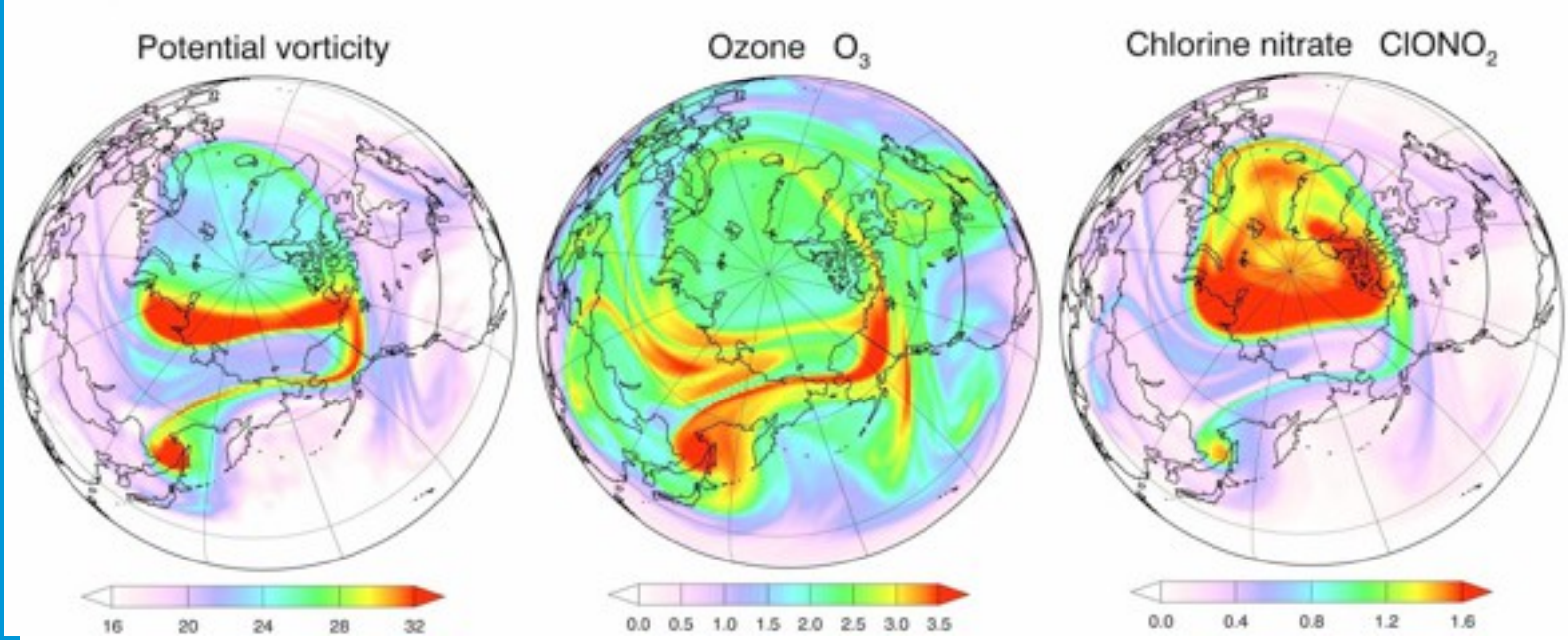


ESMF 的广泛应用

- ESMF 的美国欧洲用户包括： NCAR CCSM4 ／ CESM1， NASA GEOS － 5 (Goddard Earth Observing System Model version 5)， NOAA FIM (Flow-following Finite Element Isosahedral Model)， DOE NEMS (National Energy Modeling System)， GFDL MOM4 (Modular Ocean Model)， DOD COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System)，河床和海岸模型，等。

- 从我们的 SUPPORT 电子邮件地址来看，国内至少有 5 个以上的研究所联系并从我们获得有关过非常初步的有关 ESMF 的技术支持。

NASA‘s Global Modeling and Assimilation Office (GMAO) 发展的 GEOS-5 数据整合系统是完全使用 ESMF 建立起来的。这个系统的 ESMF 格点模▪个数超▪ 24 。这些模块可以耦合起来构造各▪气象和气候研究的▪用模型，比如大气分析，气象▪▪，到耦合气候模型。

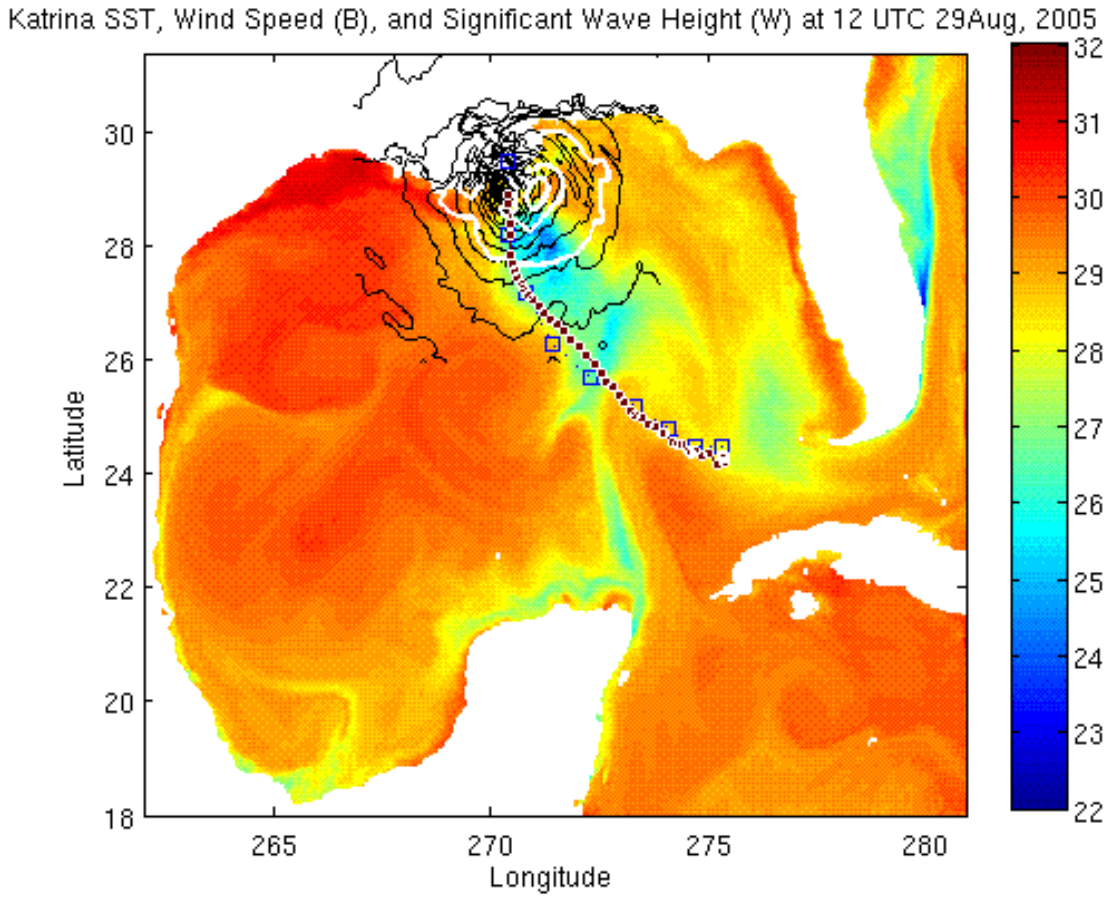


使用 **GEOS-5** 的高分辨率化学 – 气候模拟

图例显示的是 GEOS-5 大气模式耦合复杂的平流层化学模式（STRAT-CHEM）在超高分辨率（2／3 经度，1／2 纬度）化学 – 气候耦合的模拟结果。 ESMF 的耦合作用允许模型进行各种交互模式的计算，比如化学过程和大气辐射，大尺度动力学，和次网格格点的参数化。

The Naval Research Laboratory (NRL) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) 是第一个采用 ESMF 解决大气海洋耦合问题的局部区域模型。

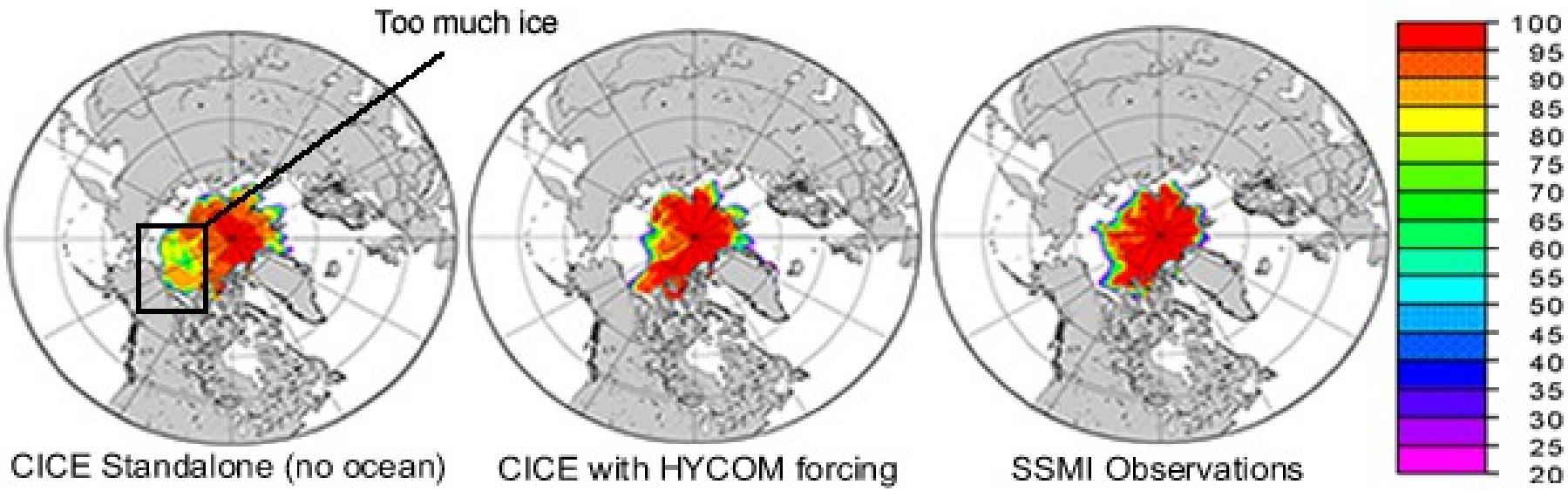
在 COAMPS, the Navy Coastal Ocean Model (NCOM), and the Simulating WAves Nearshore (SWAN) model 中的三相耦合▪▪是通▪ ESMF 解决的。



图例是 COAMPS 对 Katrina 飓风 48 小时的模拟结果。

ESMF 海冰模型中的海洋和冰层耦合

ESMF 通过耦合 Los Alamos National Laboratory （LANL） Community Ice Code (CICE) 和 the HYCOM Consortium Hybrid Coordinate Ocean Model 提高了 CICE 中的冰覆盖模拟结果 .



Concluding Remarks

ESMF highlights

- Sound architecture for earth system modeling (why do we want to bother to learn ESMF?)
- Multitudes of features and capabilities help modelers build model components that are reusable and interoperable.
- Comprehensive documentation and reliable customer support.
- Practices that predate the community and improves the robustness of the framework.
- Expanding influence and community adaptation

Portability and Testing

- ESMF is comprehensively tested and extremely portable!
- Many tests and examples bundled with the software
  - About 4000 unit tests
  - An additional, automated test harness to cover the many options related to grids and distributions
  - Dozens of examples
  - Dozens of system tests
  - External demonstrations, showing ESMF linked to applications
- Users can separately download use test cases, with more realistic problem and data sizes
- Regression tests run nightly on 24+ platform/compiler combinations

Where to Get Help

Documentation and training materials

- Users Guide, comprehensive Reference Manuals
- Many examples and system tests
- Coming with public release 5r
  - Updated demonstration program
  - New web-based, user-friendly tutorial format

If you're stuck

- Write the support line, esmf_support@list.woc.noaa.gov