Introduction to Earth System Modeling Framework (ESMF): An Atmosphere-Ocean Modeling Application Example

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for Theoretical Physics

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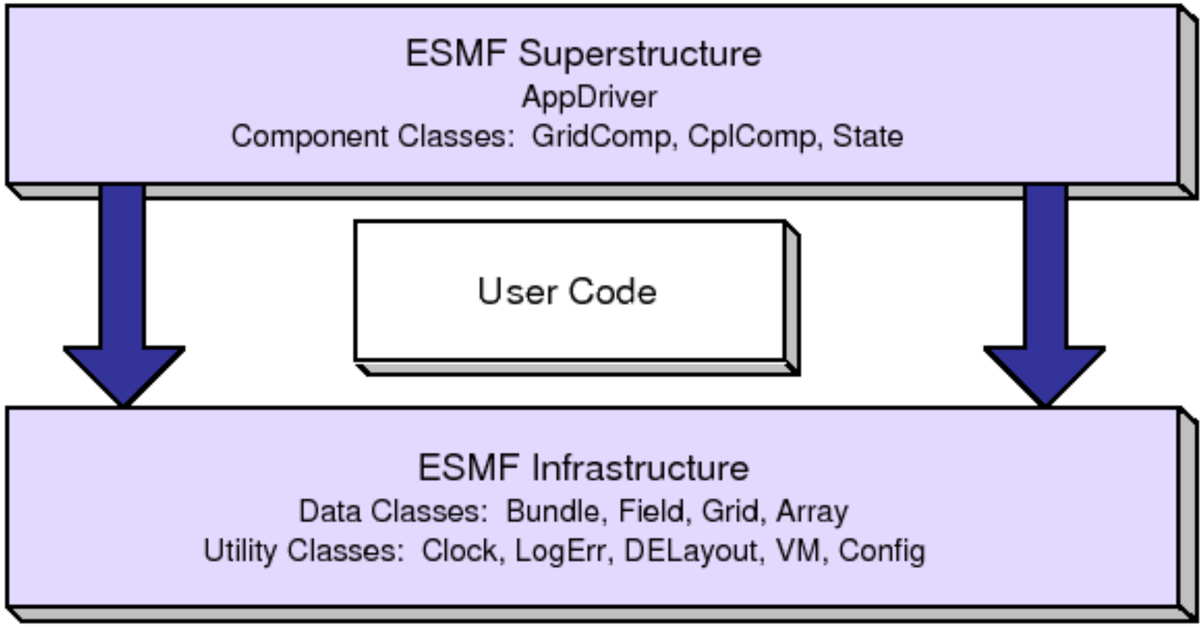
Earth System Modeling Framework (ESMF)

- Complete set of Fortran interface and some C/C++ interfaces
- Open source project:
  http://www.earthsystemmodeling.org
  http://sourceforge.net/projects/esmf
  http://sourceforge.net/projects/esmfcontrib
- Well documented and support
- Well tested (nightly builds on different OS, Architecture, Compiler and MPI versions) and very portable
- Interpolation capability also available via Python (ESMP) and NCL (NCAR Command Language)
- New layer to simplify model coupling: The National Unified Operational Prediction Capability (NUOPC)
  https://www.earthsystemcog.org/projects/nuopc/

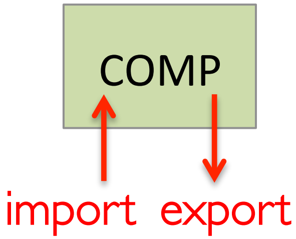
ESMF Architecture

- There are two main type of classes
  - Superstructure
    - Components (gridded and coupler) + States
  - Infrastructure
    - Data Structures (Array, Field, Grid, Bundle)
    - Utilities (Clock, VM, Config etc.)

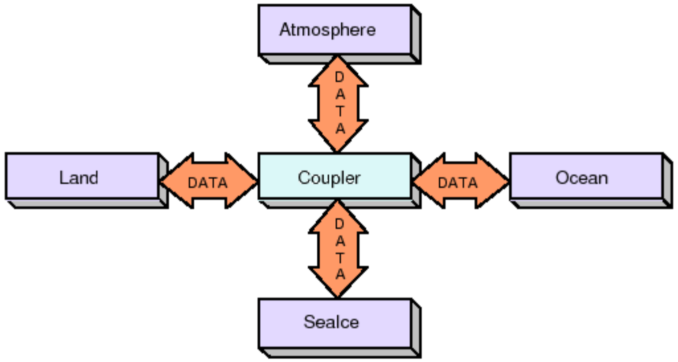

ESMF Superstructure
AppDriver
Component Classes: GridComp, CplComp, State
User Code
ESMF Infrastructure
Data Classes: Bundle, Field, Grid, Array
Utility Classes: Clock, LogErr, DELayout, VM, Config

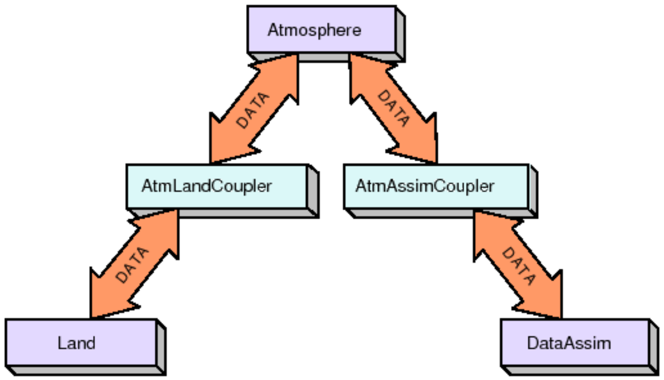
ESMF "sandwich" architecture

Superstructure



- Components
  - Gridded – describes a user component (atm, ocn, etc.) that takes one import and one export State.
    In general, the fields within import and export State will use same discrete grid.
  - Coupler – it takes one or more import States as input and applies spatial/temporal interpolation and/or extrapolation onto one or more output export States.
    In general, import and export States are in different discrete grid.
- Different combination of gridded and coupler components:





Superstructure

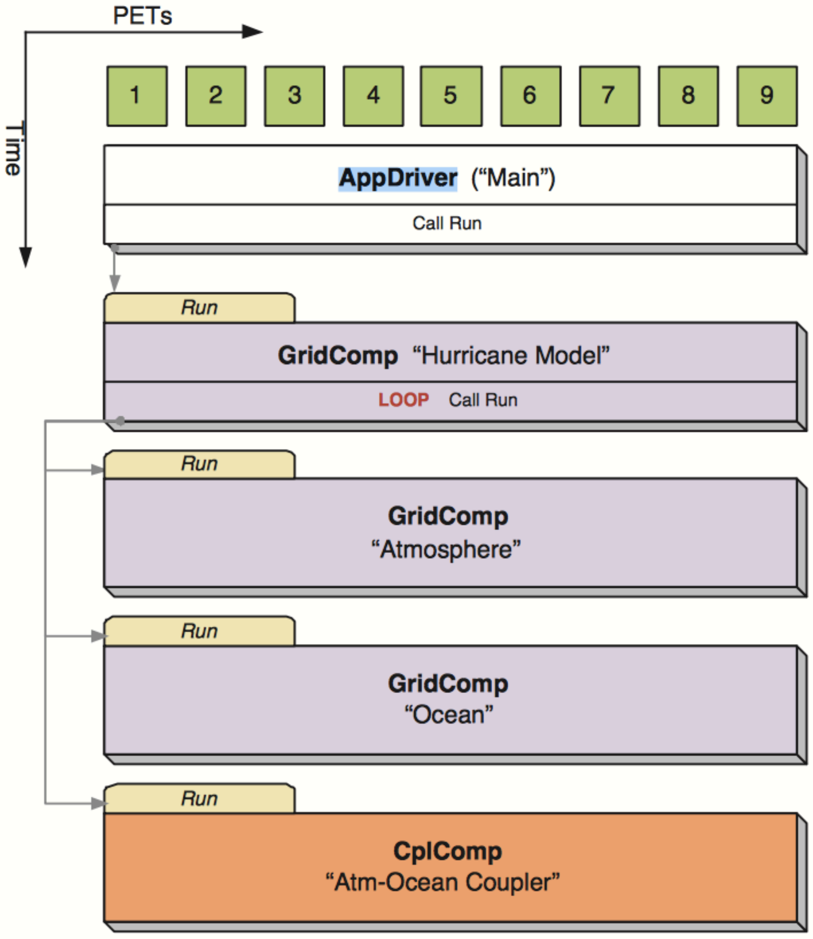
- It also contains methods related with
  - State
  - Web services
- States
  - It contains the data and metadata to be transferred between ESMF Components.
  - There are two types of States, import and export.
  - An import State contains data that is necessary for a Gridded Component or Coupler Component to execute,
  - and an export State contains the data that a Gridded Component or Coupler Component can make available.
  - States can contain Arrays, ArrayBundles, Fields, FieldBundles, and other States (in a specific VM).

Infrastructure

- Fields and Grids
  - Array and Field are used to store data
  - Array contains a data pointer along with information about data type, precision and dimension
  - Field holds model and/or observational data with its underlying grid or set of spatial locations
  - Bundles are the collections of Arrays (ArrayBundle) or Fields (FieldBundle)
  - Grid definition (Grid, Mesh and XGrid)
- Utilities
  - They are a set of tools for quickly assembling modeling applications
    - Attribute, Time Management (+Clock), Config, LogErr, DELayout, VM and I/O Utilities

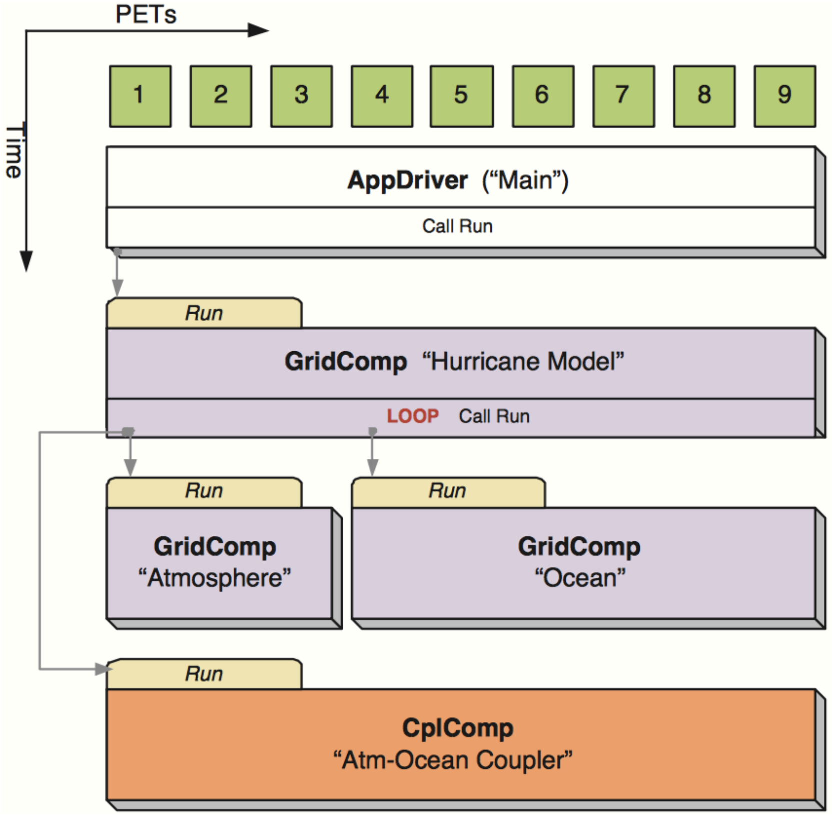
Parallelization

- Sequential (Consecutive) vs. Concurrent



PETs
Time
1 2 3 4 5 6 7 8 9
AppDriver ("Main")
Call Run
Run
GridComp "Hurricane Model"
LOOP Call Run
Run
GridComp "Atmosphere"
Run
GridComp "Ocean"
Run
CplComp "Atm-Ocean Coupler"

Sequential



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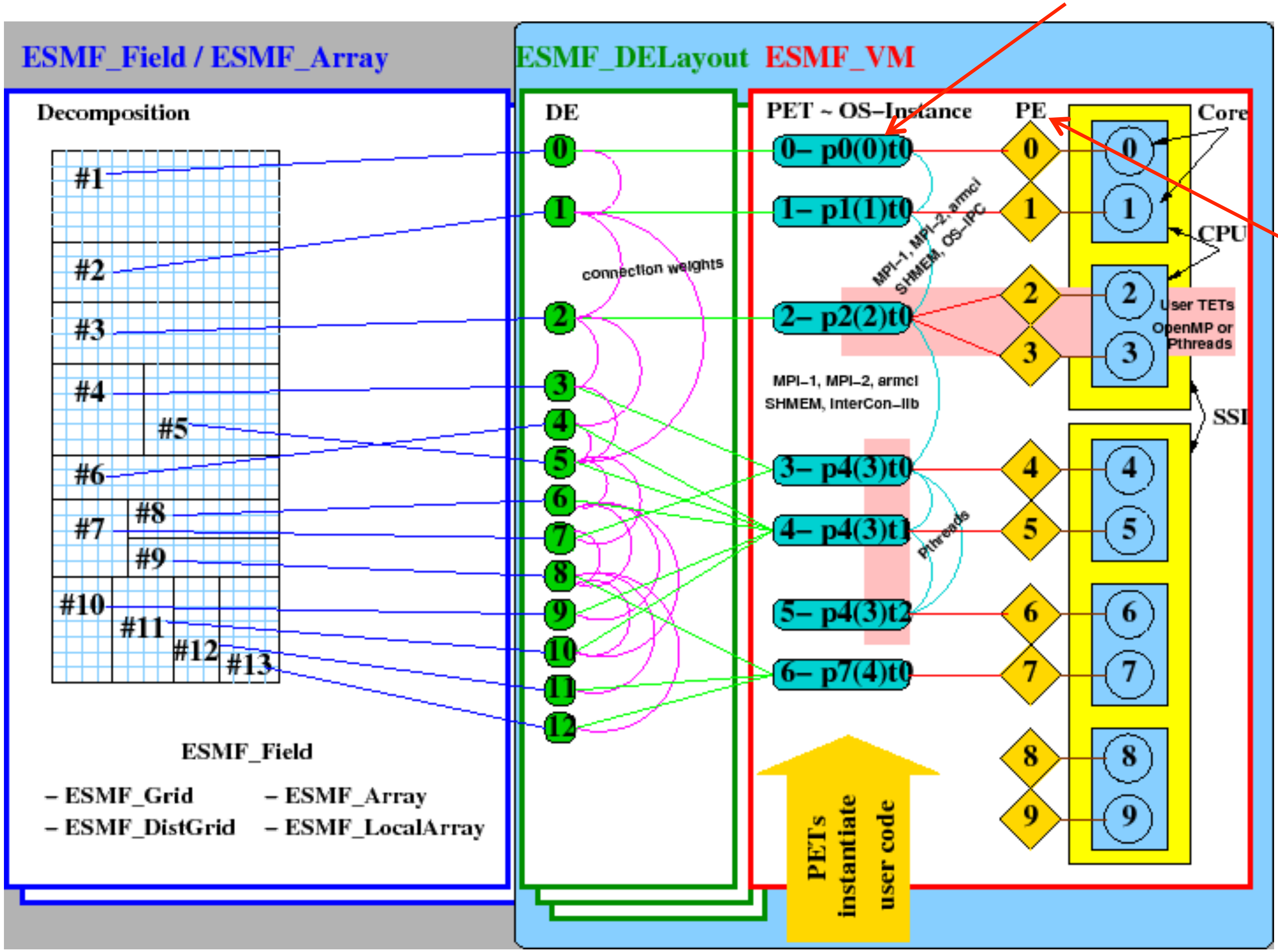
Concurrent

Parallelization

- Abstraction

Persistent Execution Threads (PETs)



Processing Element

smallest physical processing unit

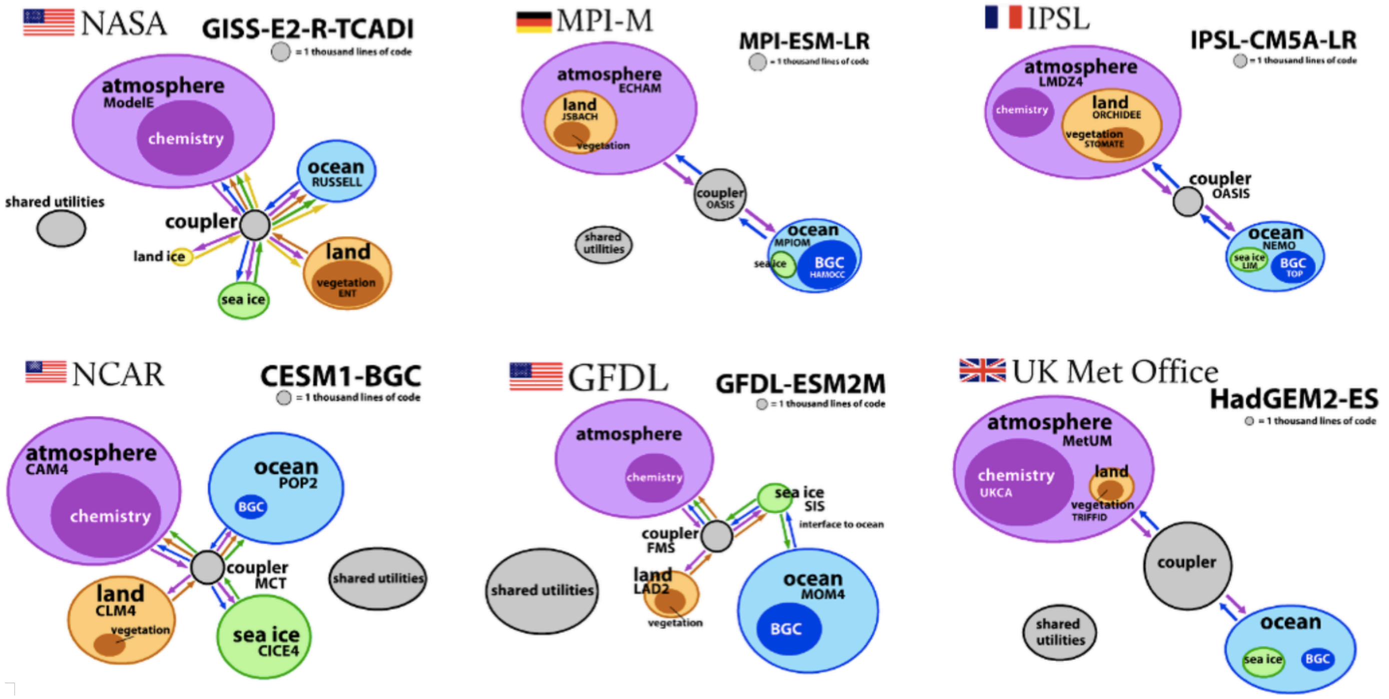
Code Adaptation

PARSE

Prepare
Adapt
Register
Schedule
Execute

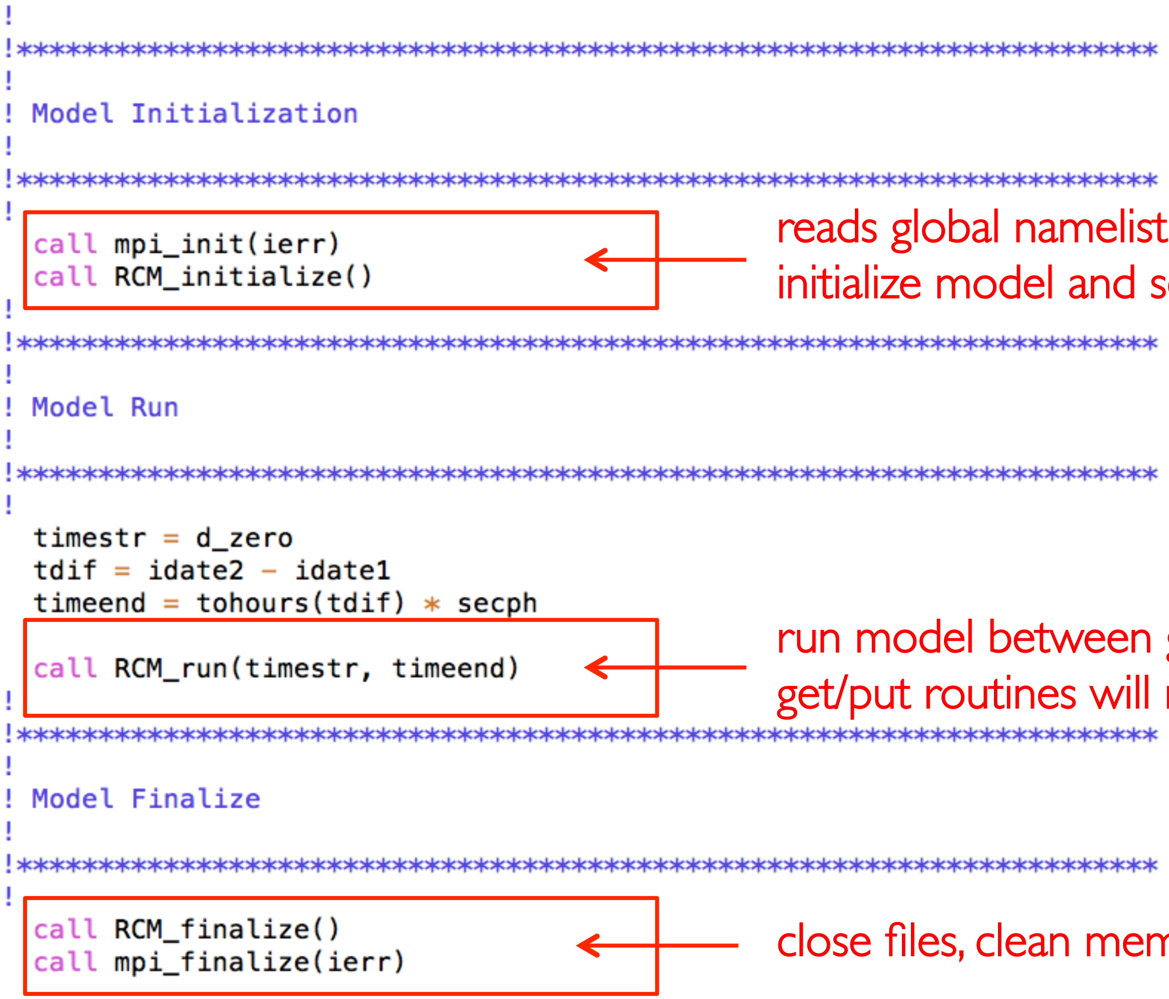
Preparing

1. Prepare user code
   - Decide on components and model design
   - Decide on coupling (or exchange) fields
   - Decide on control flow (order of the execution of components)
   - Split component code into initialize, run and finalize sections



Preparing

- Split model code: initialization, run and finalize (i.e. RegCM)



```
!
!**********************************************************************
!
! Model Initialization
!
!**********************************************************************
!
  call mpi_init(ierr)
  call RCM_initialize()
!
!**********************************************************************
!
! Model Run
!
!**********************************************************************
!
  timestr = d_zero
  tdif = idate2 - idate1
  timeend = tohours(tdif) * secph

  call RCM_run(timestr, timeend)
!
!**********************************************************************
!
! Model Finalize
!
!**********************************************************************
!
  call RCM_finalize()
  call mpi_finalize(ierr)
```

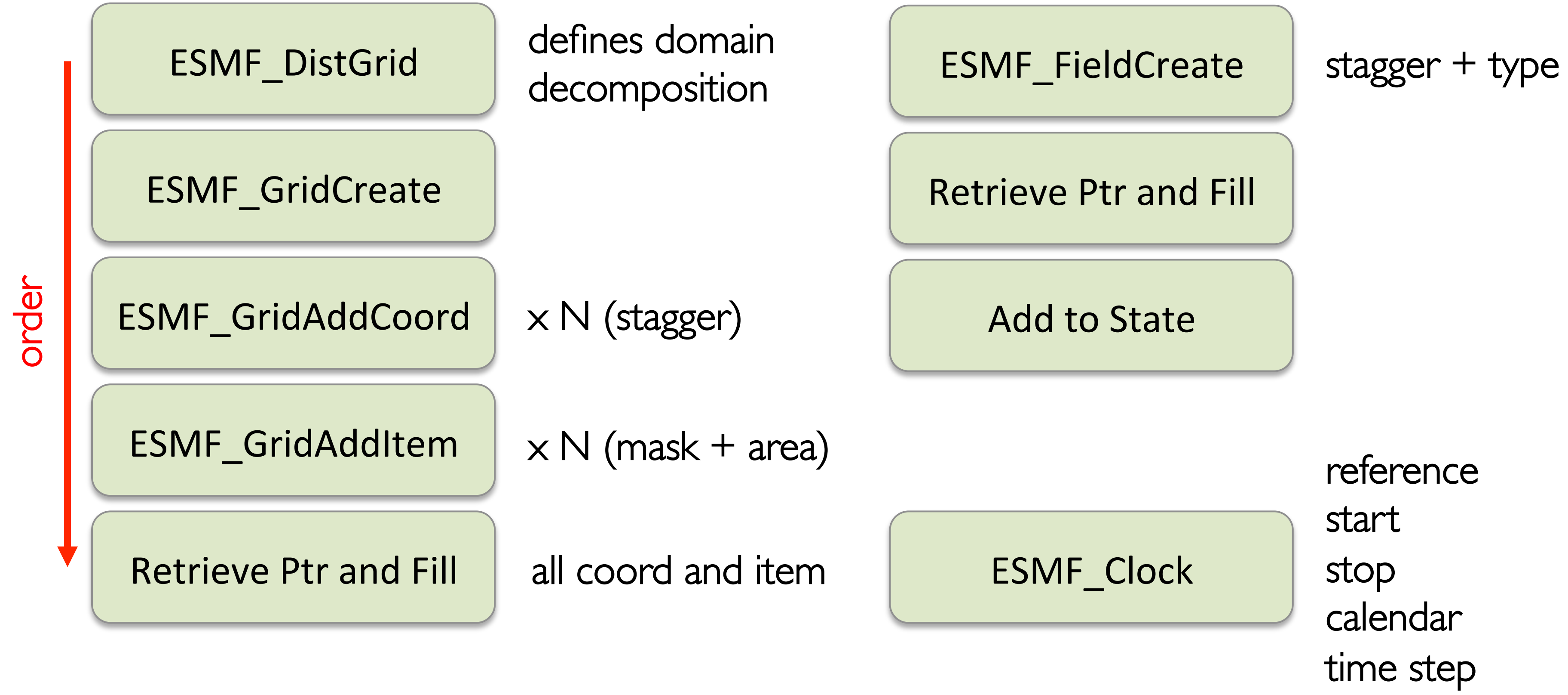
reads global namelist, read ICBC, initialize model and setup output files

run model between given interval get/put routines will retrieve/send data

close files, clean memory and kill processes

Adapting

2. Adapt data structures
   - Wrap component grid in Grid or Xgrid object
   - Wrap data structures in Array and/or Field objects
   - Wrap time information in Clock object



order

ESMF_DistGrid — defines domain decomposition

ESMF_GridCreate

ESMF_GridAddCoord — x N (stagger)

ESMF_GridAddItem — x N (mask + area)

Retrieve Ptr and Fill — all coord and item

ESMF_FieldCreate — stagger + type

Retrieve Ptr and Fill

Add to State

ESMF_Clock — reference
start
stop
calendar
time step

Adapting

- Arrays vs. Fields
  - Arrays represent user data in index space. They don't have coordinate information. So, Arrays can not be used to calculate interpolation weights.
  - To do interpolation, user need to supply interpolation weights externally and SMM can be applied to Array.
  - Field object includes coordinates. So, it represents user data in physical space.
- Grid Definition
  - The most important part of the model adaptation.
  - Be careful about the definition of halo or ghost regions
  - ESMF uses right-hand-coordinate system and smallest stride to the first dimension. The order of dimension can be reversed some times.
  - The actual grid definition might be check by ESMF_GridWriteVTK. It creates a set of VTK files (separated for each PET and read by Visit)

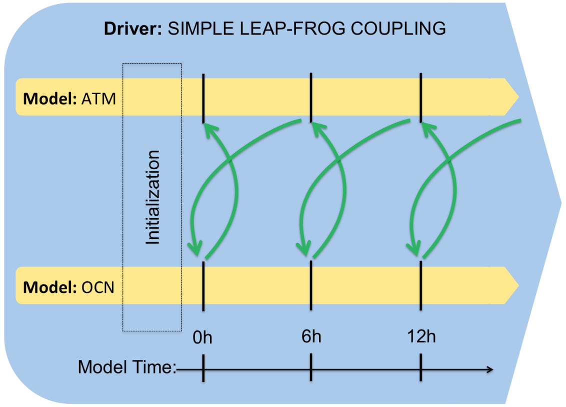
Registering

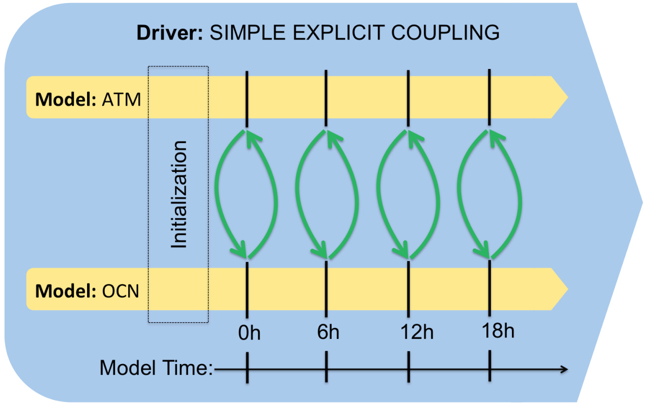
3. Register user methods
   - Attach user code methods to the framework through registration calls
   - Create register routine for each component (gridded or coupler)
   - The register routine attaches initialization, run and finalize routines. By this way, ESMF know the routines to control ESMF_[Grid | Cpl]CompSetEntryPoint
   - Then register routines called in main application to allow ESMF take control of the model components.
     ESMF_[Grid | Cpl]CompSetServices

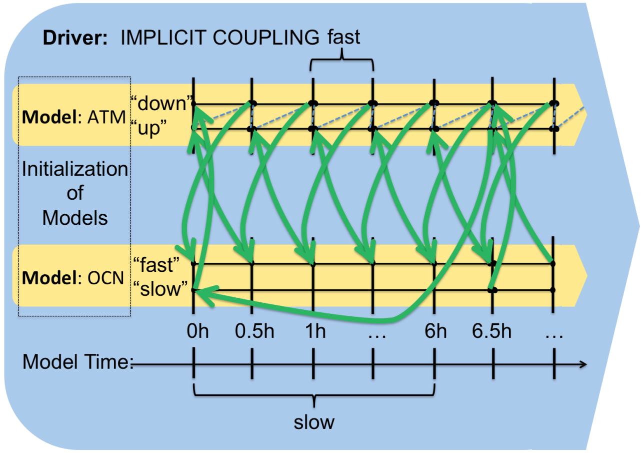
- Then, the registered model components can be initialized
  - Definition of grids
  - States (import and export)
  - Clocks

Scheduling

4. Schedule, synchronize and send the data
   - The scheduling, synchronization and data exchange can be controlled via coupler (optional)
   - In this case, all the data redirected by coupler / driver. There is no direct interaction among the components.
   - Regridding, SMM, data redistribution
   - Different scheduling options exists
     - Explicit
     - Semi-implicit
     - Implicit

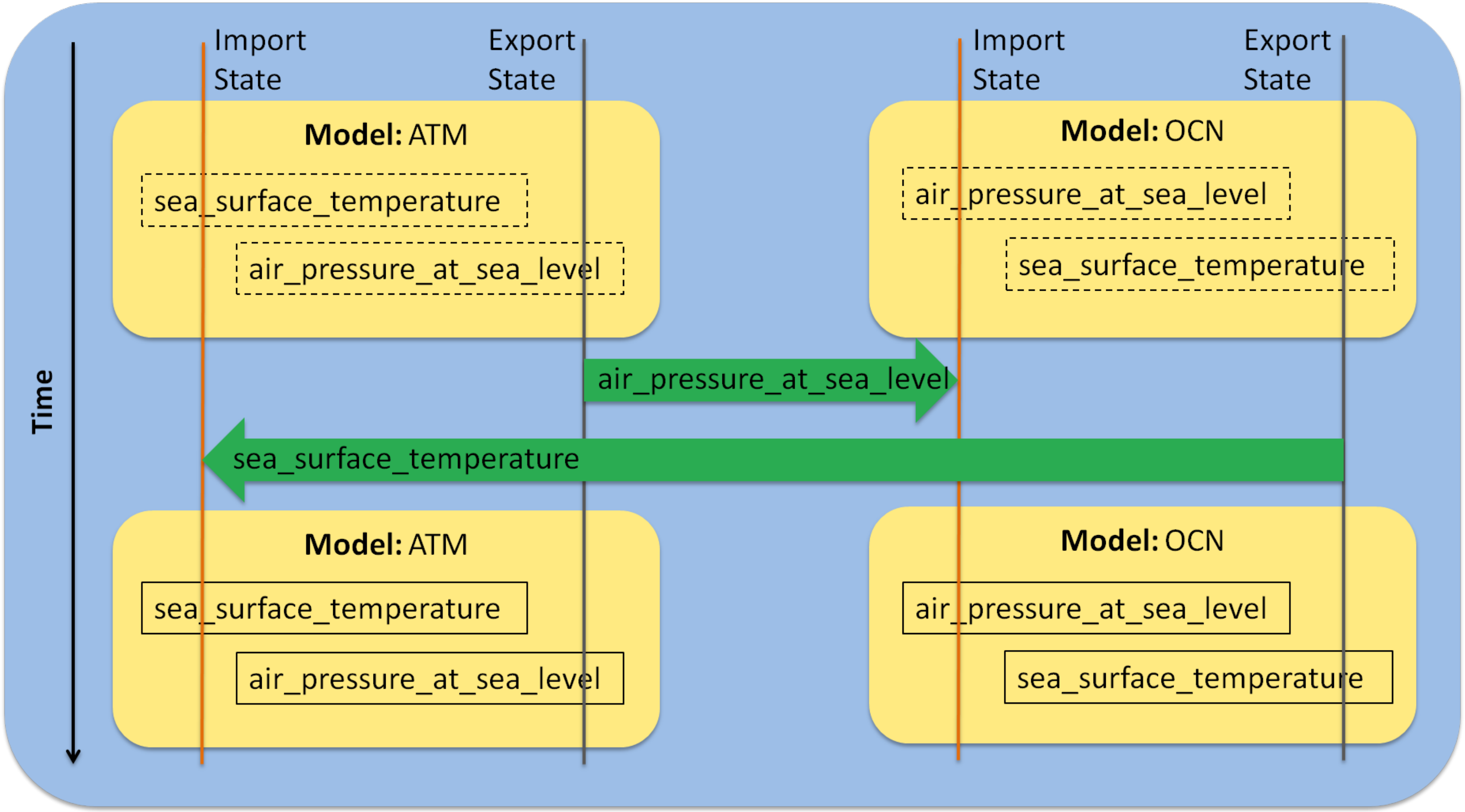






Executing

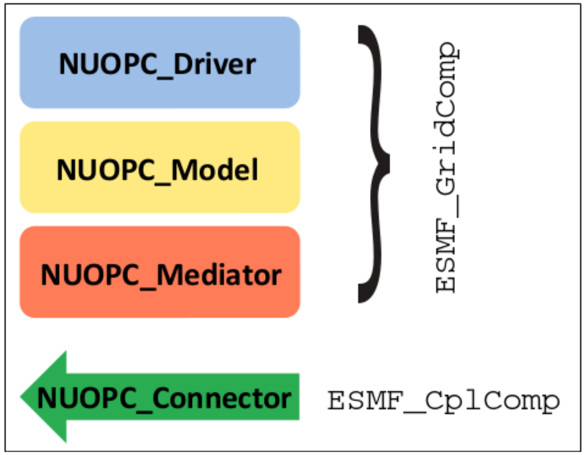
5. Execute
   - Run components using ESMF driver



ESMF / NUOPC Layer

- National Unified Operational Prediction Capability
  - Consortium of U.S. operational weather and water prediction centers
  - NOAA, Navy, Air Force, NASA, and other associated modeling groups
  - http://earthsystemcog.org/projects/nuopc/
- It is a software layer implemented on top of ESMF
- It defines generic components (Model, Mediator, Connector and Driver). The generic components can be customized by attachable methods.
- It contains utility methods for common tasks
- It contains Field dictionary (standard names and units)
- It is distributed with ESMF

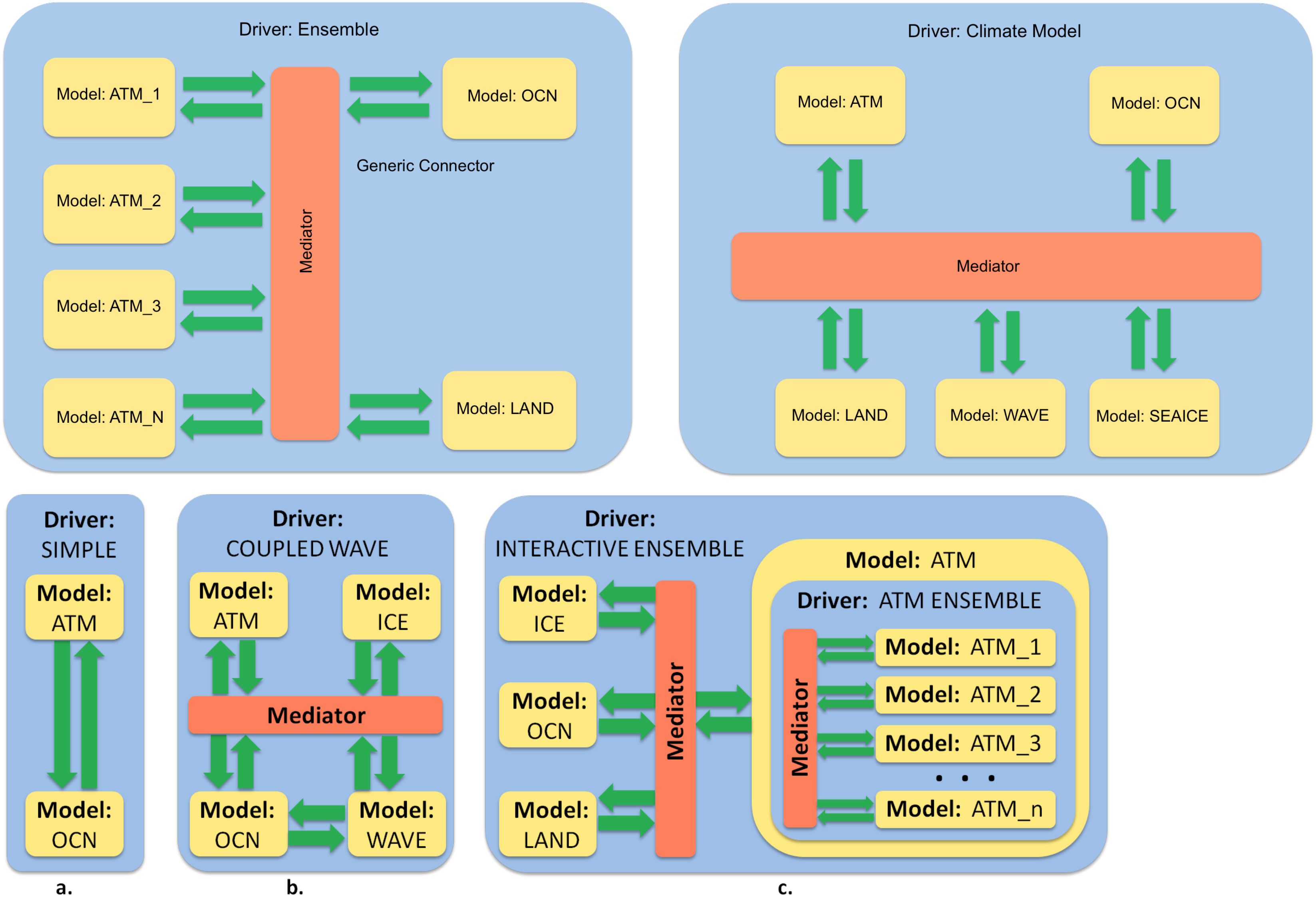
ESMF / NUOPC Layer



- Building Blocks
- Model
  - Typically implements a specific physical domain (i.e. atmosphere, ocean and ice)
- Connector
  - Connects pairs of components in one direction, e.g. Model to/from Model, or Model to/from Mediator
  - Executes simple transforms (Regrid or Redist)
- Mediator
  - Used for custom coupling code (flux calculations, averaging, etc.) between Models
- Driver
  - Provides a harness for Models, Mediators, and Connectors.
  - Coordinates initialize and run sequences.

ESMF / NUOPC Layer

- Architectural Options

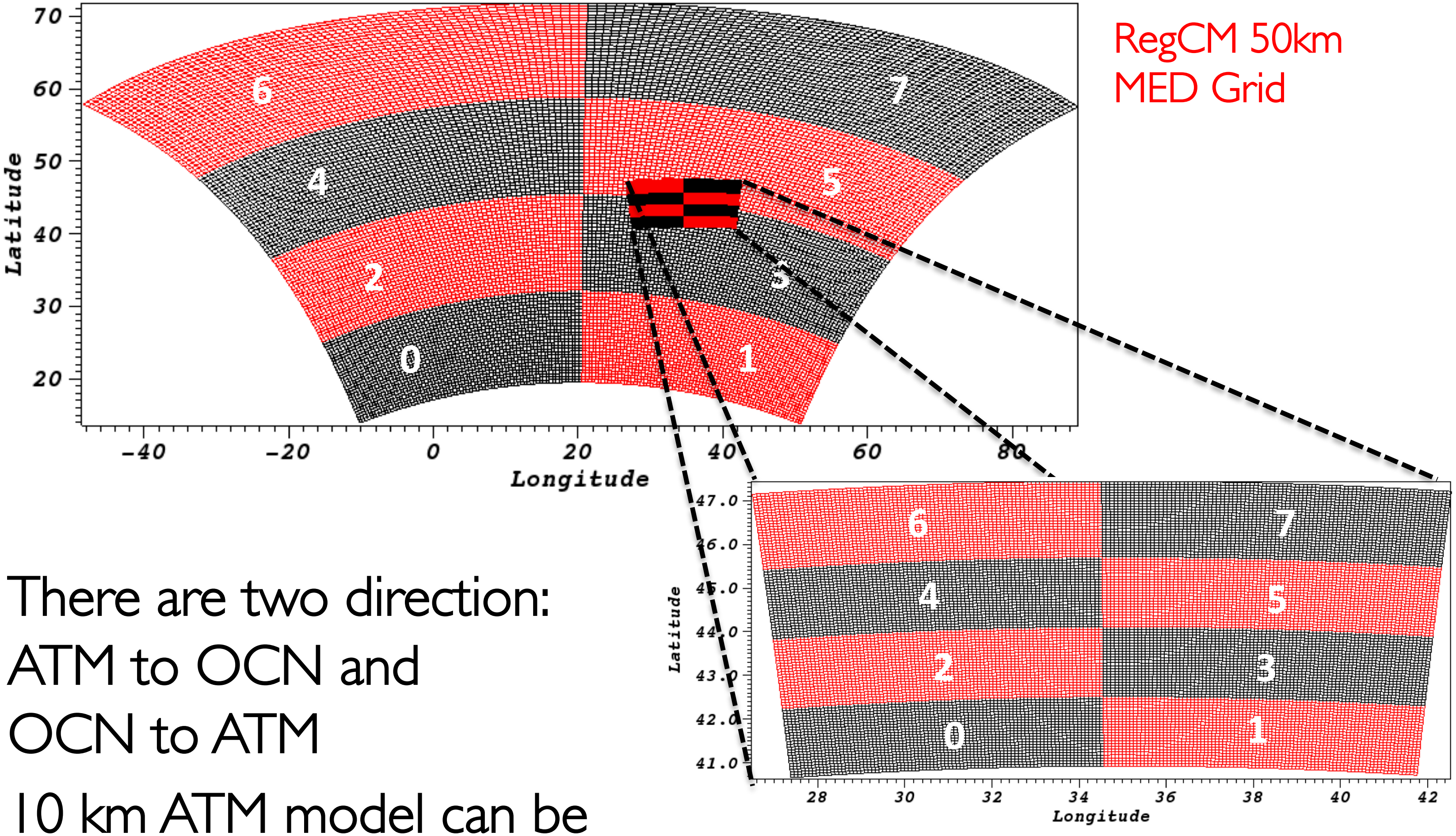


Test Case

- The code that is used in the test case are extracted from RegESM (Regional Earth System Model)
- The component codes are removed to have a independent, easy to use and understand test code
- It demonstrates:
  - Creation and running components (gridded + coupler)
  - Creating grids via SCRIP formatted netCDF files
  - Generation of routehandles (online)
    - Main component of the regridding and stores weight matrices
    - Components need to different routhandle for different grids and interpolation types
  - Regridding using routehandles
    - Two step interpolation to fix land-sea mask mismatch
    - Interpolation (bilinear) + Extrapolation (nearest-neighbor)

Test Case Configuration

- Data exchange between two components



RegCM 50km
MED Grid

ROMS 8km
Black Sea Grid

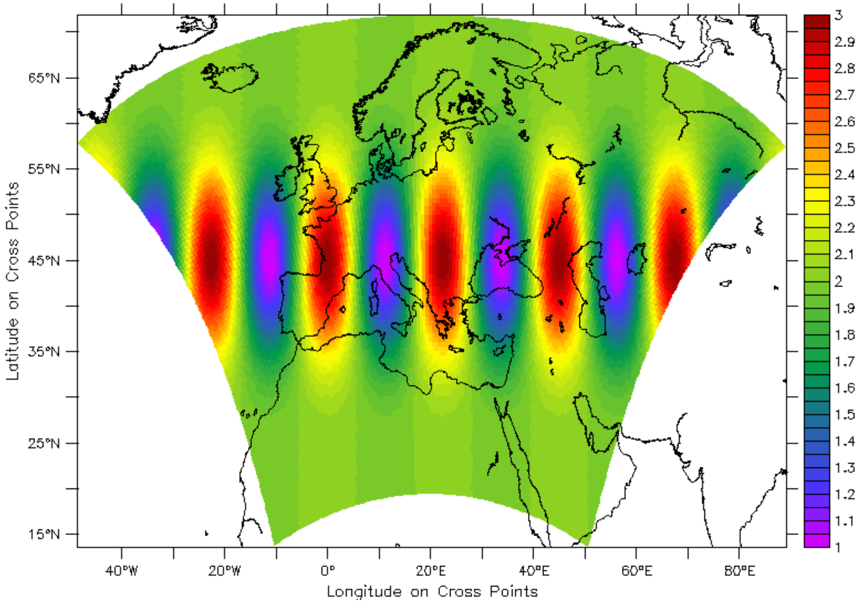
- There are two direction:
  ATM to OCN and
  OCN to ATM
- 10 km ATM model can be used by generating SCRIP formatted files

Exchange Field

- Input field from standard SCRIP tests fields
- Pseudo spherical harmonics (L=32, M=16)

$$f = 2 + \sin^{16}(2\theta)\cos(16\phi) \qquad \theta = lat, \quad \phi = lon$$

- It is good to have a field that has a analytical solution. The interpolation error can be estimated in this case.



- Regridding is performed only over sea
- In this case, ATM component will send masked data

http://oceans11.lanl.gov/trac/SCRIP

Description of Test Code

- Get the code

  https://www.dropbox.com/s/hwfk4b39bxyovll/smr2613.tar.gz?dl=0

- The list of the files

ESMF_netcdf_read.f	Reads components grid information (from netCDF)
Makefile	Compiles test case
fix.sh	Adds coordinate information to output of the test app
main.F90	Main program (creates components and trigger them)
main.job	Job submission script
namelist.rc	Configuration file (decomposition, files etc.)
proc	Directory to create SCRIP definition of grids
user_coupler.F90	Coupler component code (field interpolation)
user_model1.F90 user_model2.F90	Gridded components code (model1: ATM, model2: OCN)

Login and Environment Setup

- Login to Argo cluster
- Load required modules

```
module use-append /opt/smr2613/modules/usermodule
module purge
module load esmf-6.3.0r
module load ncl-6.2.1-gcc-4.4.7
module load pnedcdf-1.3.1
module load zlib-1.2.8
module load hdf5-1.8.11-intel
module load netcdf-4.3.0
module load xerces-3.1.1
```

- Still need to define a set of environment variables

in csh shell

```
setenv ESMF_LIB "${ESMF_INSTALL_PREFIX}/lib/lib${ESMF_BOPT}/${ESMF_OS}.$
{ESMF_COMPILER}.${ESMF_ABI}.${ESMF_COMM}.${ESMF_SITE}"
setenv ESMFMKFILE "${ESMF_LIB}/esmf.mk"
setenv LD_LIBRARY_PATH ${ESMF_LIB}:${LD_LIBRARY_PATH}
setenv PATH ${ESMF_INSTALL_PREFIX}/bin/bin${ESMF_BOPT}/${ESMF_OS}.${ESMF_COMPILER}.$
{ESMF_ABI}.${ESMF_COMM}.${ESMF_SITE}:${PATH}
```

Running Test Code

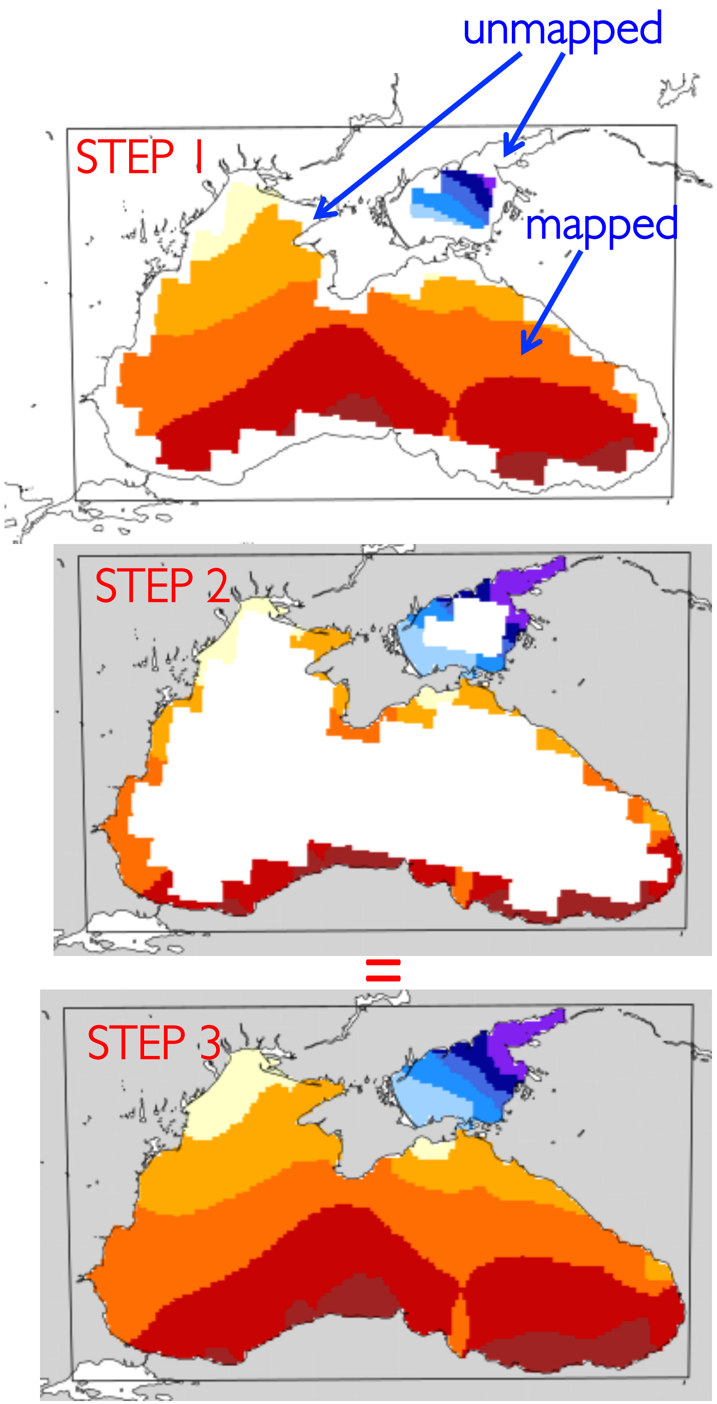
- Run “make” command to install executable
  - Make clean can be used to clean files
- Following variables are used from ESMF configuration
  - $(ESMFMKFILE)
  - $(ESMF_F90COMPILER)
  - $(ESMF_F90LINKPATHS)
  - $(ESMF_F90ESMFLINKLIBS)
- The code is designed to run in parallel
- main.job script can be used to submit job on Argo (queue?)
- Don’t forget to modify the job script
  - Queue which is dedicated to HPC school
  - The working directory (just before “ulimit -s unlimited” command)
- Submit job to cluster: qsub main.job

Analyzing Output

- There are four group of files
  - *.vtk files store information about grid definition for each component (each PET has its own part)
  - gcomp*.nc files have initial data stored by components
  - remap*.nc files are the fields after interpolation
    - 1: interpolation,
    - 2: interpolation + extrapolation
    - forward: ATM to OCN
    - backward: OCN to ATM
  - mask*.nc files store mask information (created by "UTIL_FindUnmapped" subroutine in user_coupler.F90)
    - 0: land
    - 98: mapped grid points (filled just after bilinear interpolation)
    - 99: unmapped grid points (needs extrapolation)

Unmatched Land-sea Masks

- Two step interpolation (i.e. interpolation over ocean)
  1. Interpolate from ATM to OCN using bilinear interpolation. Use only sea grid points
  2. Use result of previous step, interpolate data from OCN to OCN from mapped grid points to unmapped ones using nearest-neighbor type regridding
  3. Merge results of 1 and 2 to create filled field
- Still has problem in some applications (sharp gradient in some cases) but used in RegESM
- Other extrapolation techniques?

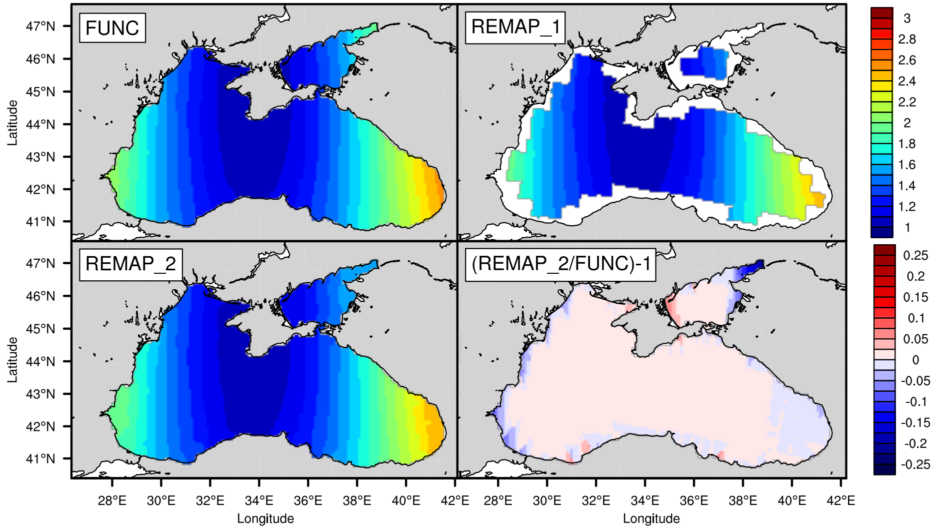


Thanks to ESMF Group (especially to Bob Oehmke) for their support and help

Interpolation Error

- Two step interpolation (ATM to OCN)

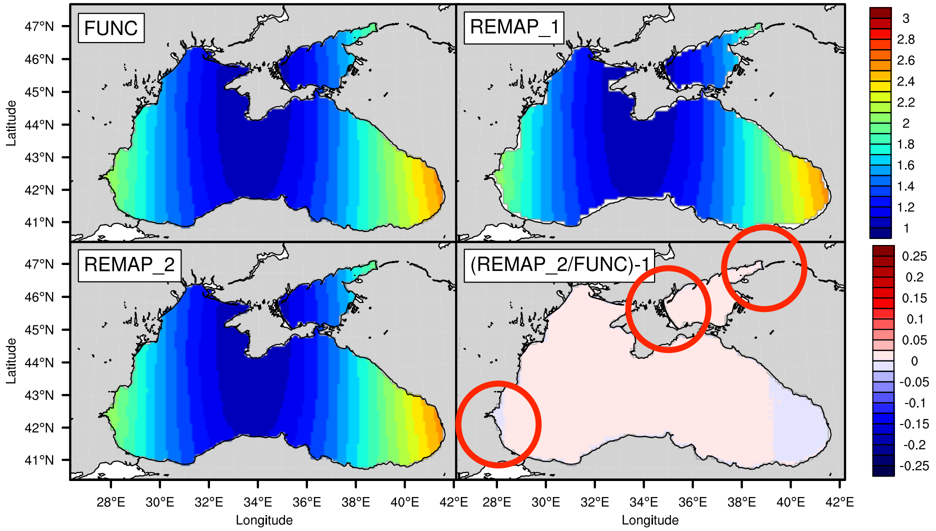
MED 50km



Relative Error = (Mod/Obs)-1

Min: -0.207
Max: 0.071

TR 10km



Min: -0.025
Max: 0.014

- Run code
- Add coordinate data by using ./fix.sh
- Copy plot_err.ncl script from proc/ directory and run

Questions!

Contact:

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