C-Coupler3: an integrated coupler infrastructure for Earth system modeling

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Outline

- **Background**

- C-Coupler3

- Summary

C-Coupler (Chinese Community Coupler)?

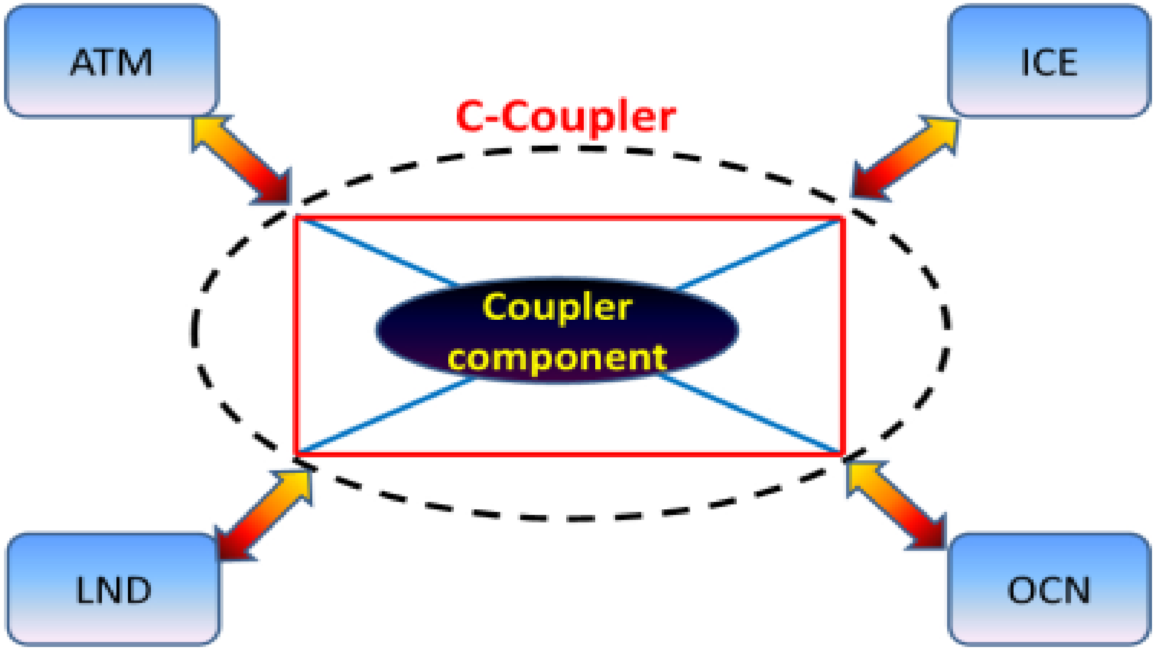
- No coupler team in China before 2010, while there are a lot of coupled models developed in China
- Coupler teams outside of China are generally inconvenient to directly serve Chinese models
- New requirements regarding couplers from Chinese model development

C-Coupler should be able to serve various models developed in China, especially address new requirements

Milestones of C-Coupler development

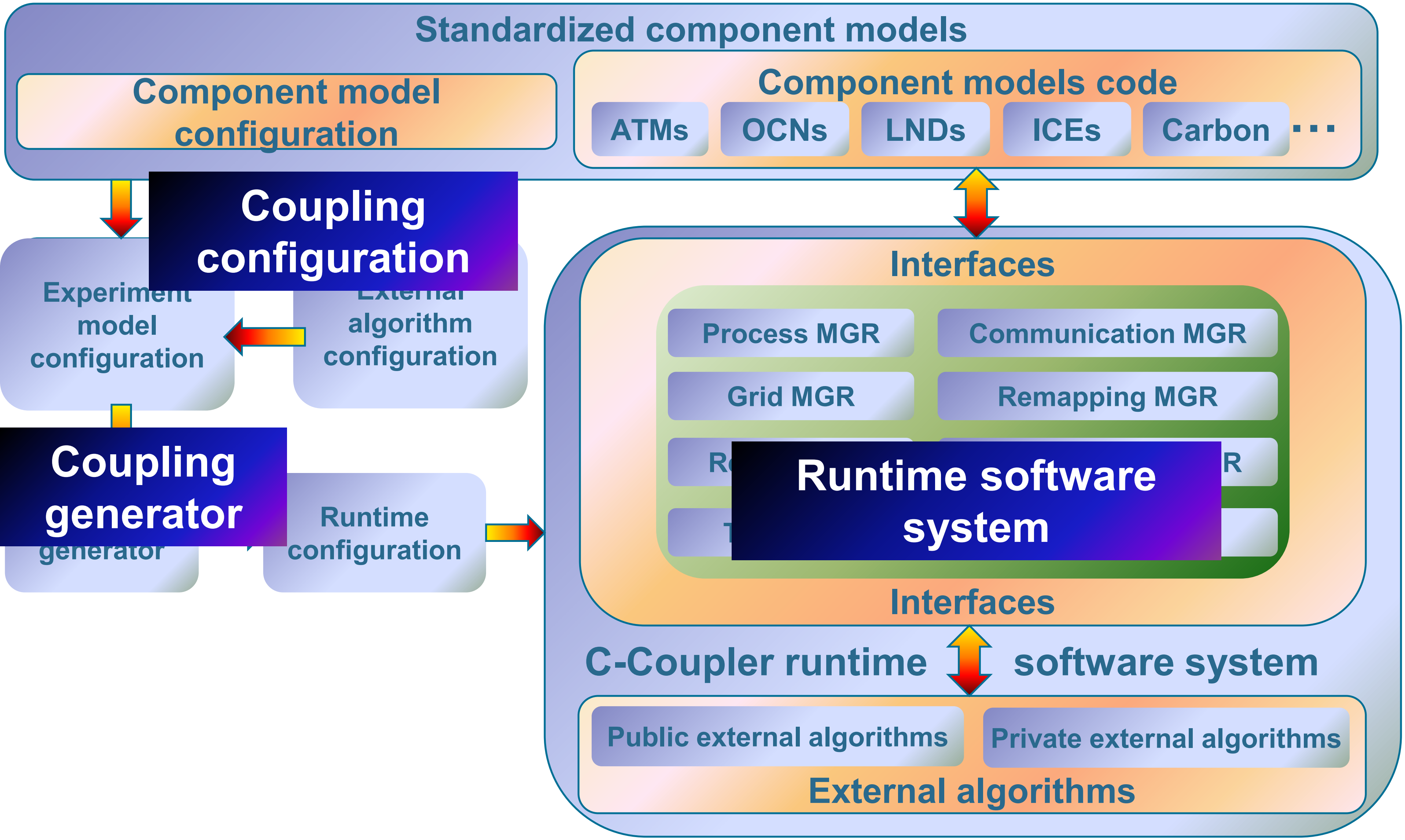
Milestones	**Time**
Initiation of C-Coupler development	2010.01
Main design of C-Coupler	2010.11
Common multi-dimensional remapping software (CoR)	2012.07
C-Coupler1 finished	2014.06
Initiation of C-Coupler2 development	2016.07
C-Coupler2 finished	2018.05
Initiation of C-Coupler3 development	2018.06
C-Coupler3 finished	2022

General architecture of coupled models with C-Coupler



- C-Coupler can serve various coupling configurations in different coupled models
- A component model can have an identical code version in different coupling configurations

General software structure of C-Coupler



Achievements in C-Coupler1 and C-Coupler2

C-Coupler1

- **First Chinese coupler**
- Static **3-D coupling** capability
- **Feasibility** of new coupling architecture and the overall design of C-Coupler

(Liu et al, 2014, GMD)

C-Coupler2

- **Flexible and automatic coupling generation**
- **Dynamic 3-D coupling capability**
- **Facilitation for incremental coupling and model nesting**
- **A common, flexible, and user-friendly coupling configuration interface**
- **Non-blocking data transfer**
- **Adaptive restart capability**
- **Flexible configuration of coupling lags**
- **Parallel online remapping weight generation**
- **Debugging capability**
- **Model coupling within one executable or the same component model**

(Liu et al, 2018, GMD)

Existing applications of C-Coupler2

- Coupled models for Chinese institutions
  - First Institute of Oceanography, Ministry of Natural Resources: **FIO-AOW**
  - National Climate Centre: **parallel coupler version of BCC-CSM**
  - National Marine Environmental Forecasting Center: **MPAS-Wavewatch, WRF-MITgcm, CFS-WaveWatch3**
  - First Institute of Oceanography and National Meteorological Center: **GRAPES-FIOCOM**
  - Institute of Atmospheric Physics, Chinese Academy of Sciences: **a version of CAS-FGOALS-g3**
  - Tsinghua University: **CIESM**
- Coupled models for at least 4 key research projects of China

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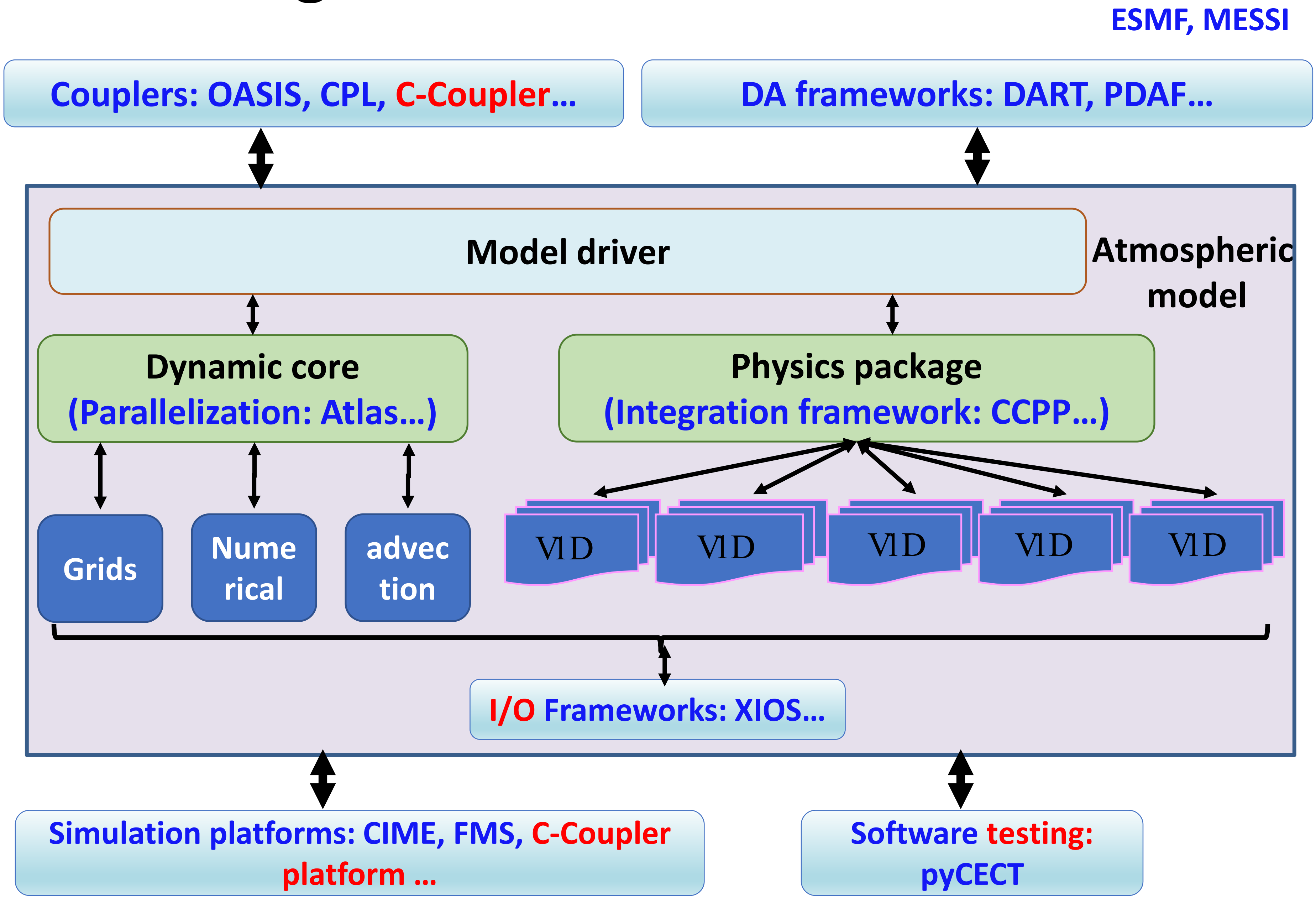
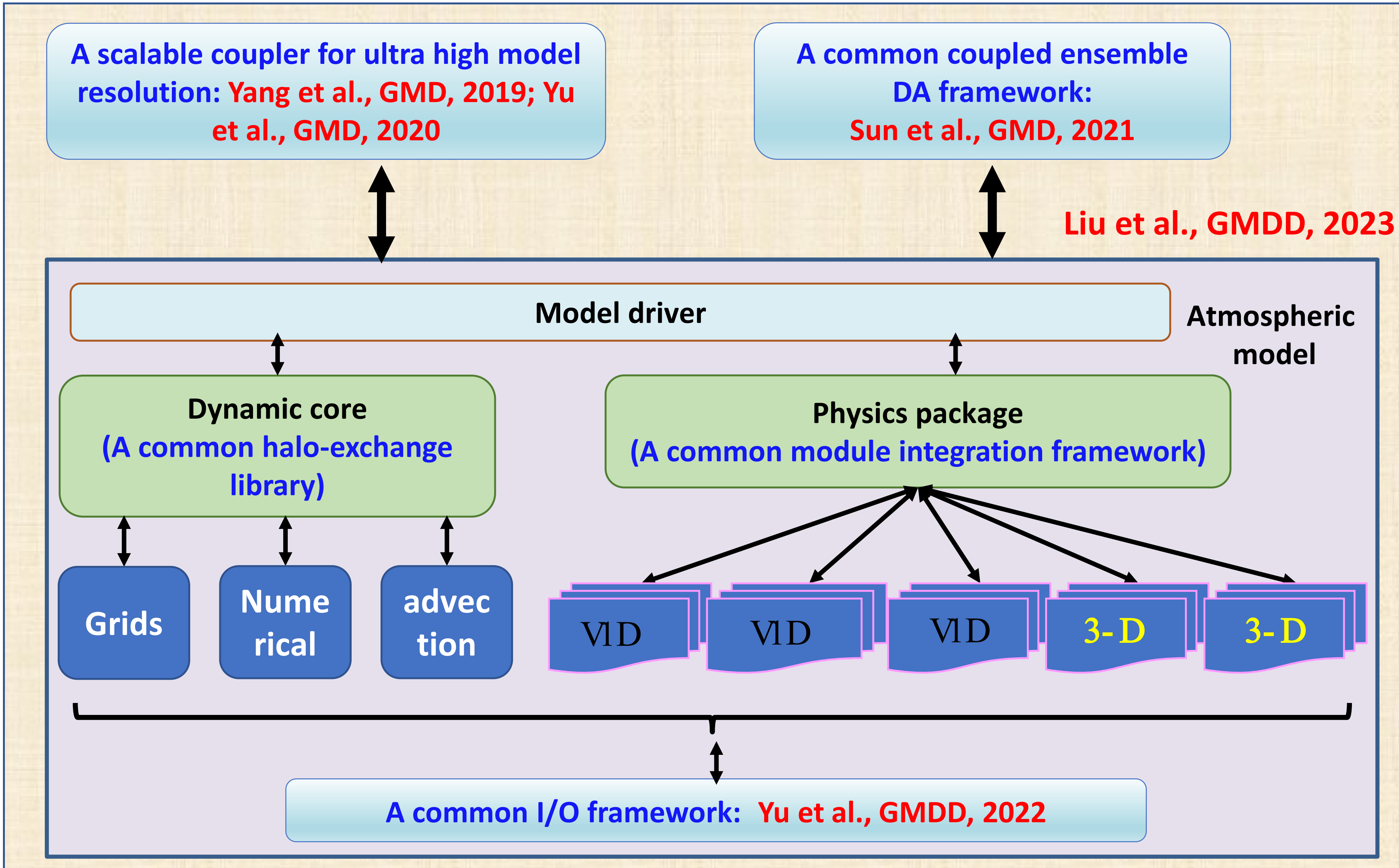
Existing Software infrastructures



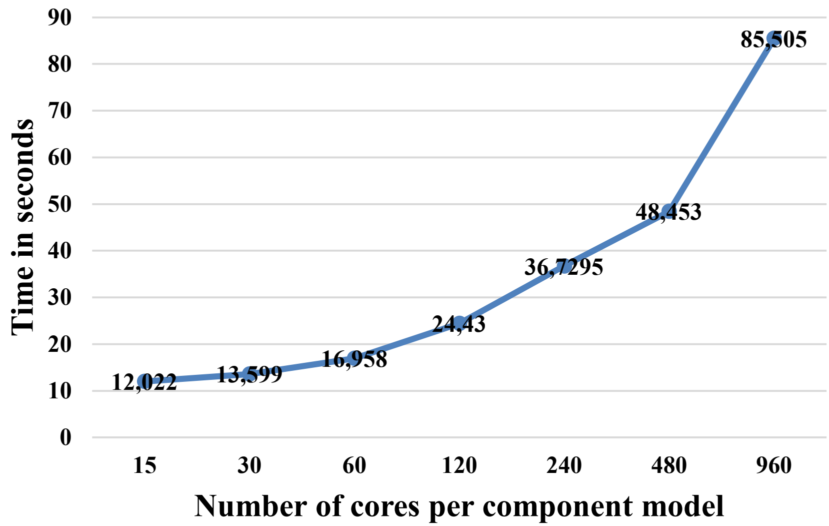
C-Coupler3



A scalable coupler for ultra high model resolution: Yang et al., GMD, 2019; Yu et al., GMD, 2020
A common coupled ensemble DA framework: Sun et al., GMD, 2021
Liu et al., GMDD, 2023
Model driver
Atmospheric model
Dynamic core (A common halo-exchange library)
Physics package (A common module integration framework)
Grids
Numerical
advection
1D
1D
1D
3-D
3-D
A common I/O framework: Yu et al., GMDD, 2022

- **New parallel optimization technologies**
- Common halo-exchange library
- Common module-integration framework
- Common I/O framework
- Common coupled ensemble DA framework

High initialization cost of C-Coupler2



Initialization cost

Between two toy component models with a regular longitude–latitude grid of 1440×720 grid points and a tripolar grid of 1440×1021 grid points respectively

Technologies for faster initialization and lower memory usage

- A distributed parallel triangulation algorithm (GMD, 2019)

- Distributed routing network generation (GMD, 2019; CN202010127096.3)

- Distributed management of horizontal grids
  – Distributed generation of remapping weights

- Parallel I/O of remapping weight files

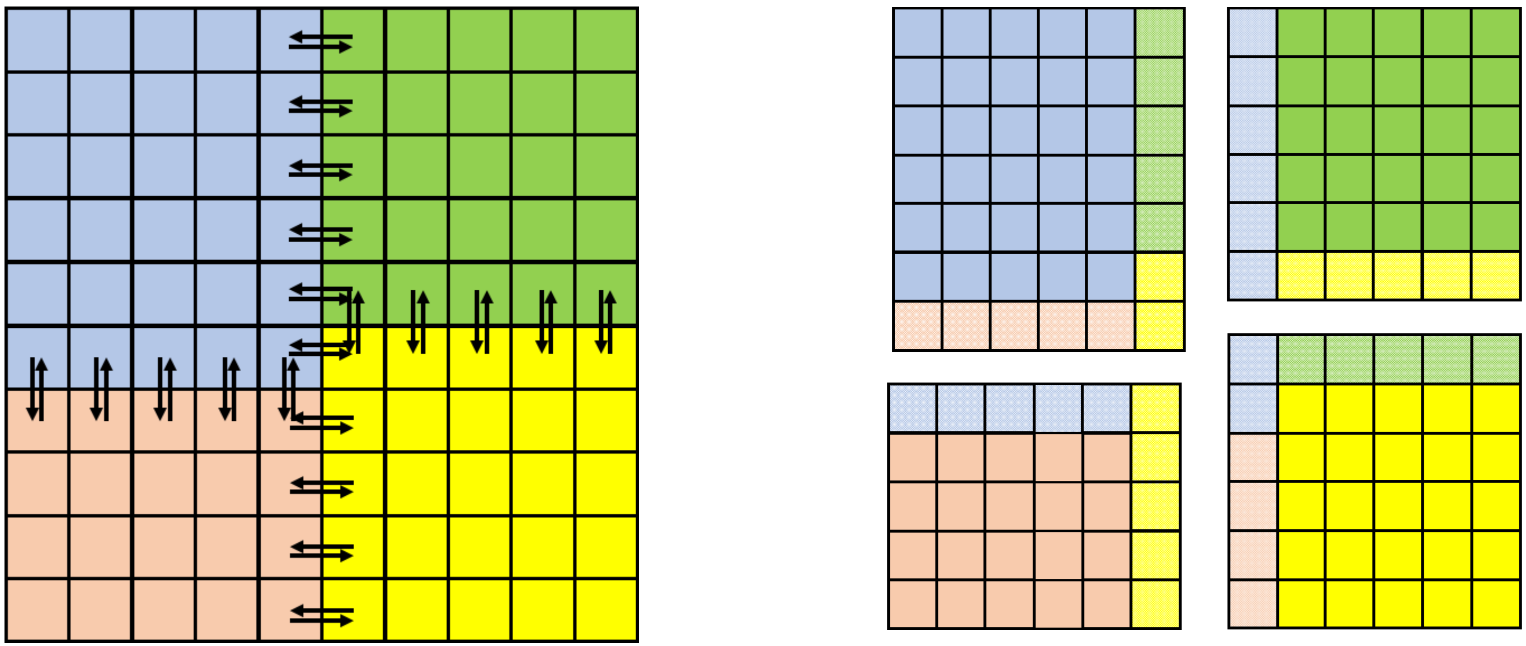
Each technology does not change bitwise results

Performance of initialization

Resolution of toy comp1 (grid size)	Resolution of toy comp2 (grid size)	Procs of comp1	Procs of comp2	Time (s) of coupling initialization	Average memory usage (MB)	Time (s) of remapping weight generation	Size (GB) of remapping weight files
0.0375° (34588806)	0.075° (8654406)	1920	1920	7.92	601	99.91	2.5
		3840	3840	7.27	624	65.31	
		7680	7680	8.50	649	65.21	0.96
0.0375° (34588806)	0.05° (19461606)	1920	1920	12.19	594	127.12	3.0
		3840	3840	10.71	617	86.71	
		7680	7680	14.15	640	93.23	2.1
0.025° (77803206)	0.075° (8654406)	1920	1920	18.85	629	179.67	5.6
		3840	3840	15.58	649	150.31	
		7680	7680	15.81	658	130.31	1.8
0.015° (175024806)	0.0375° (34588806)	7680	7680	40.41	683	556.89	15.0
		15360	15360	56.50	729	592.44	
		23040	7680	56.74	791	645.56	5.9

- New parallel optimization technologies
- **Common halo-exchange library**
- Common module-integration framework
- Common I/O framework
- Common coupled ensemble DA framework

Halo-exchange: fundamental to model parallelization



- Operations
  - Data packing, MPI communications, data unpacking

Common halo-exchange library

- Commonality: supports any grid structures, any parallel decomposition, any halo region, any dimension order of fields
- Usability: automatically finishing all operations for halo exchanges via simple APIs
- Efficiency: parallel communication, asynchronous communication, exchanging multiple fields at the same time

APIs for halo exchanges

APIs	Descriptions
CCPL_register_halo_region	Registering a halo region
CCPL_register_halo_exchange_interface	Registering a halo exchange interface for multiple fields
CCPL_execute_halo_exchange_using_id CCPL_execute_halo_exchange_using_name	Run a halo exchange interface
CCPL_finish_halo_exchange_using_id CCPL_finish_halo_exchange_using_name	Finish a halo exchange in asynchronous mode

Performance of the halo-exchange library

Horizontal grid size	Number of processes	Size (MB) of data transferred by each process	Performance (MB/s) of halo exchange per process			
			Each field separately	2-D separately, all 3-D together	All 2-D together, 3-D separately	All fields together
1000×1000	20×25	0.70	14.4	54.2	57.8	109.6
	40×50	0.37	8.9	24.8	22.3	66.0
2000×2000	40×50	0.71	9.3	25.1	25.5	70.3
	80×100	0.38	4.9	13.4	12.8	38.7
4000×4000	80×100	0.72	8.0	22.0	20.0	60.4
	160×200	0.37	3.0	9.6	9.9	35.2

- New parallel optimization technologies
- Common halo-exchange library
- Common module-integration framework
- **Common I/O framework**
- Common coupled ensemble DA framework

Functionalities of common I/O framework

- Parallel I/O
- Automatic input of fields from time-series dataset under specified time mapping rules
- Automatic output of fields under any time series
- Automatic data interpolation between different model grid and file grid

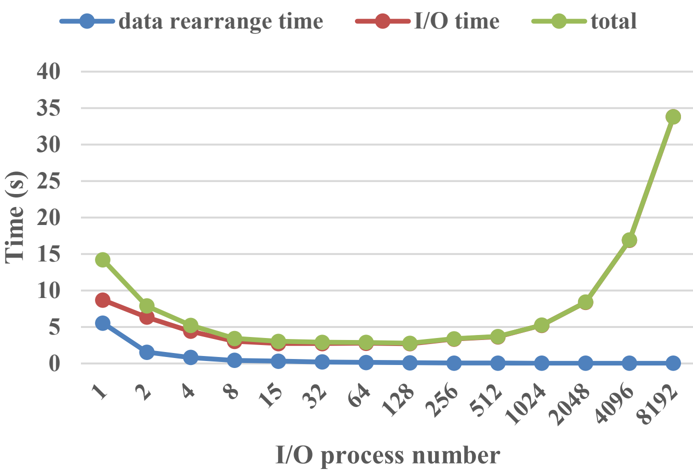
https://gmd.copernicus.org/preprints/gmd-2022-77/

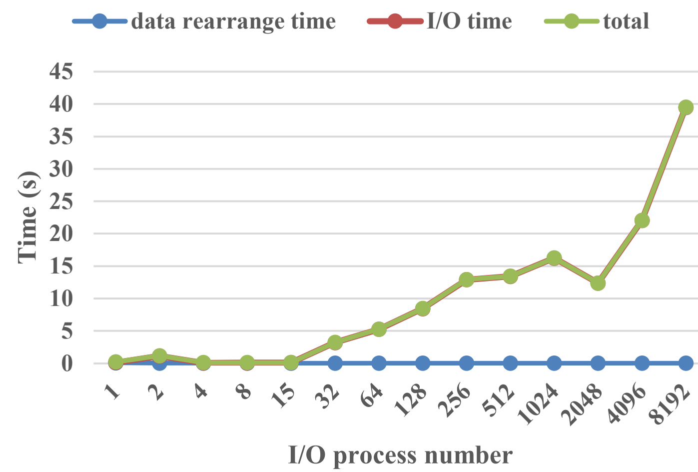
APIs of common I/O framework

APIs	Description
CCPL_register_configurable_output_handler	Register an output handler whose I/O settings are specified in an XML configuration file
CCPL_handle_normal_explicit_output	Register an output handler whose I/O settings are specified via the API arguments
CCPL_register_normal _output_handler	Explicitly execute an output handler
CCPL_get_io_proc_num	Input a field from a specific data file
CCPL_readin_field_from_dataFile	Registering an input handler whose I/O settings are specified in an XML configuration file. It works for a set of fields and can input data values from a time-series dataset
CCPL_register_ input_handler	Execute an input handler
CCPL_execute_input_handler	Register an output handler whose I/O settings are specified in an XML configuration file
CCPL_set_3D_grid_3D_vertical_coord_field	Set the field of 3-D vertical coordinate values for a 3-D grid

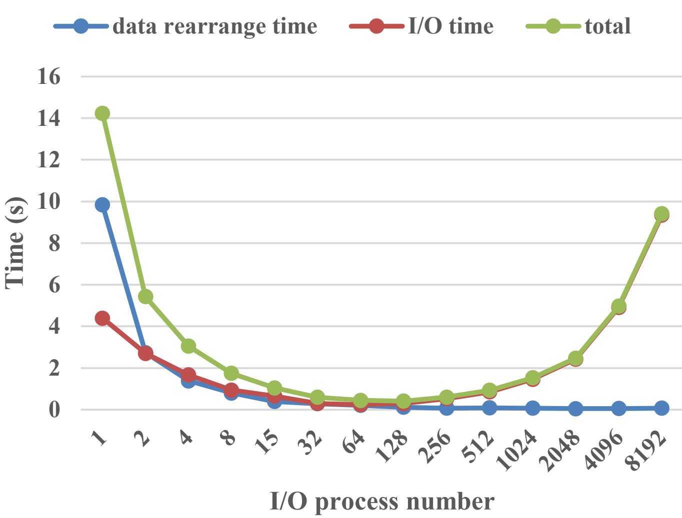
Performance of common I/O framework

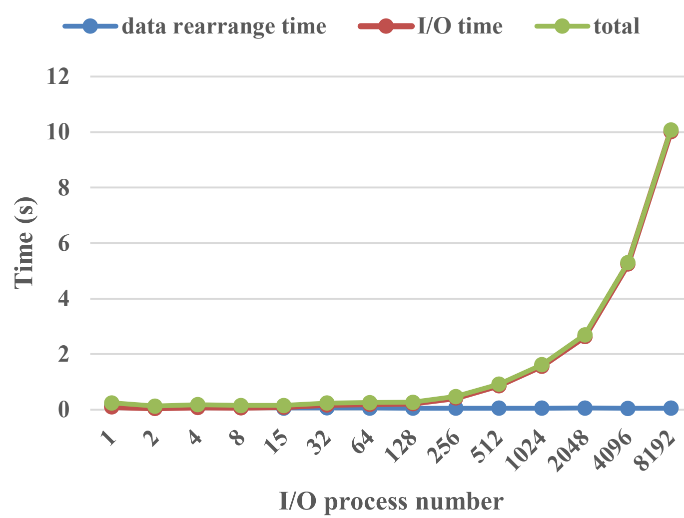
Output





Input





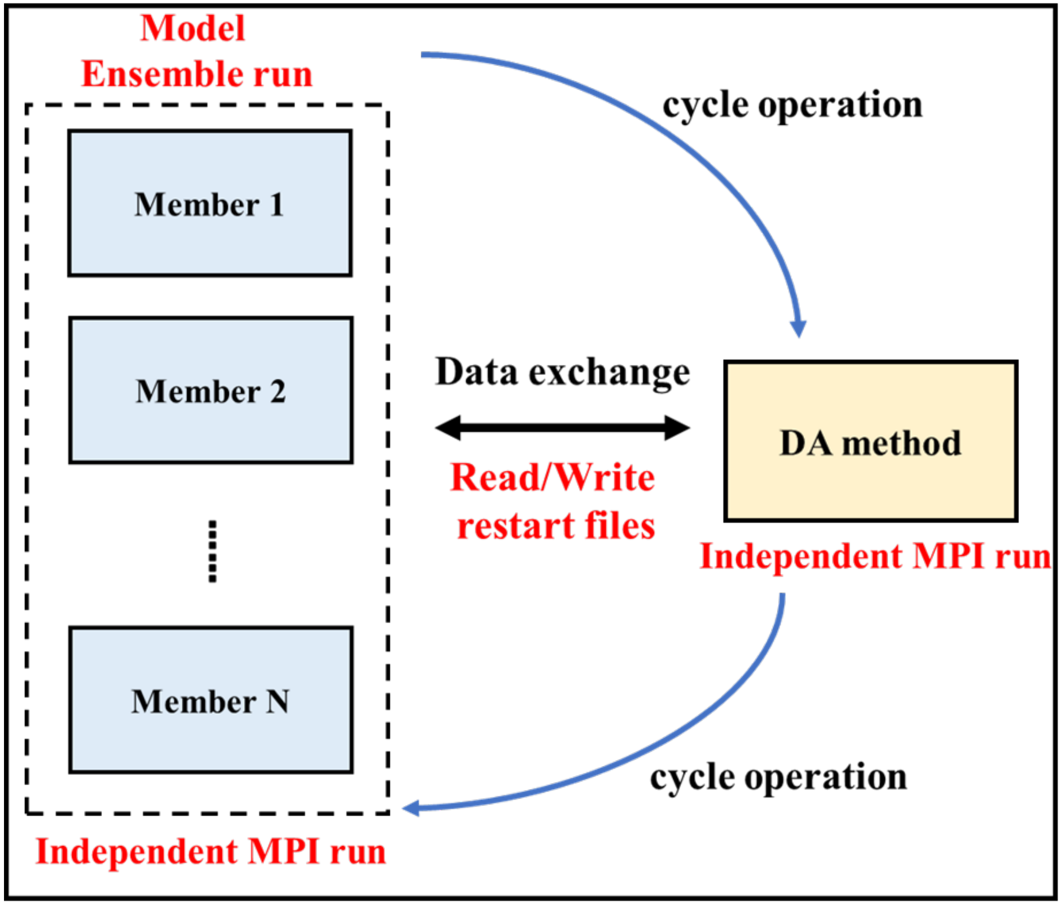
Global 0.1 degrees, 80 vertical levels, single precision

- New parallel optimization technologies
- Common halo-exchange library
- Common module-integration framework
- Common I/O framework
- **Common coupled ensemble DA framework**

Coupled ensemble DA

- Data assimilation (DA) methods provide initial states of model runs by combining observational information and models
- Seamless prediction based on Earth system models is in urgent need of upgrading data assimilation (DA) from a single model to a coupled model.
- Ensemble-based DA methods such as EnKF or hybrid DA that require an ensemble run of members, have been widely used in weather forecasting and climate prediction.

Offline DA system



Script control integration

- **Easy to implement**
- **Good independence** of model and DA method

Low computational efficiency:

- **I/O based data exchange**
- **Program restart**
- **Higher overhead under larger ensemble number or finer resolution**

DAFCC: Common coupled ensemble DA framework

- Enables to conveniently integrate a DA method into a model as a procedure that can be directly called by the model ensemble, based on DLL technologies

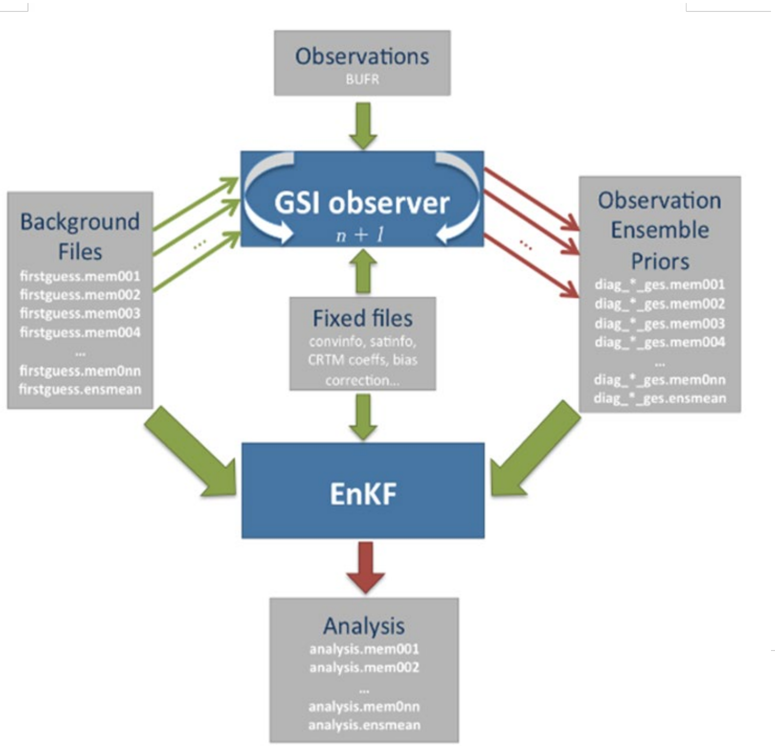
- DAFCC1 automatically and efficiently handles data exchanges between the model ensemble members and the DA method without global communications

Common module-integration framework

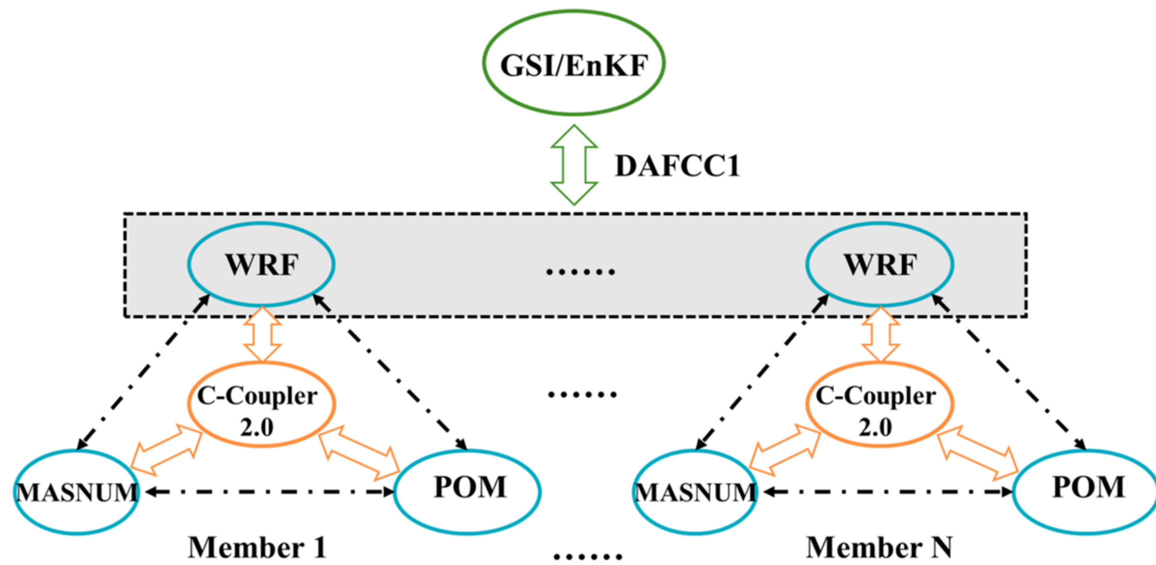
- Enables to conveniently specify statistical processing among ensemble members via XML configuration files

https://gmd.copernicus.org/preprints/gmd-2020-75/gmd-2020-75.pdf

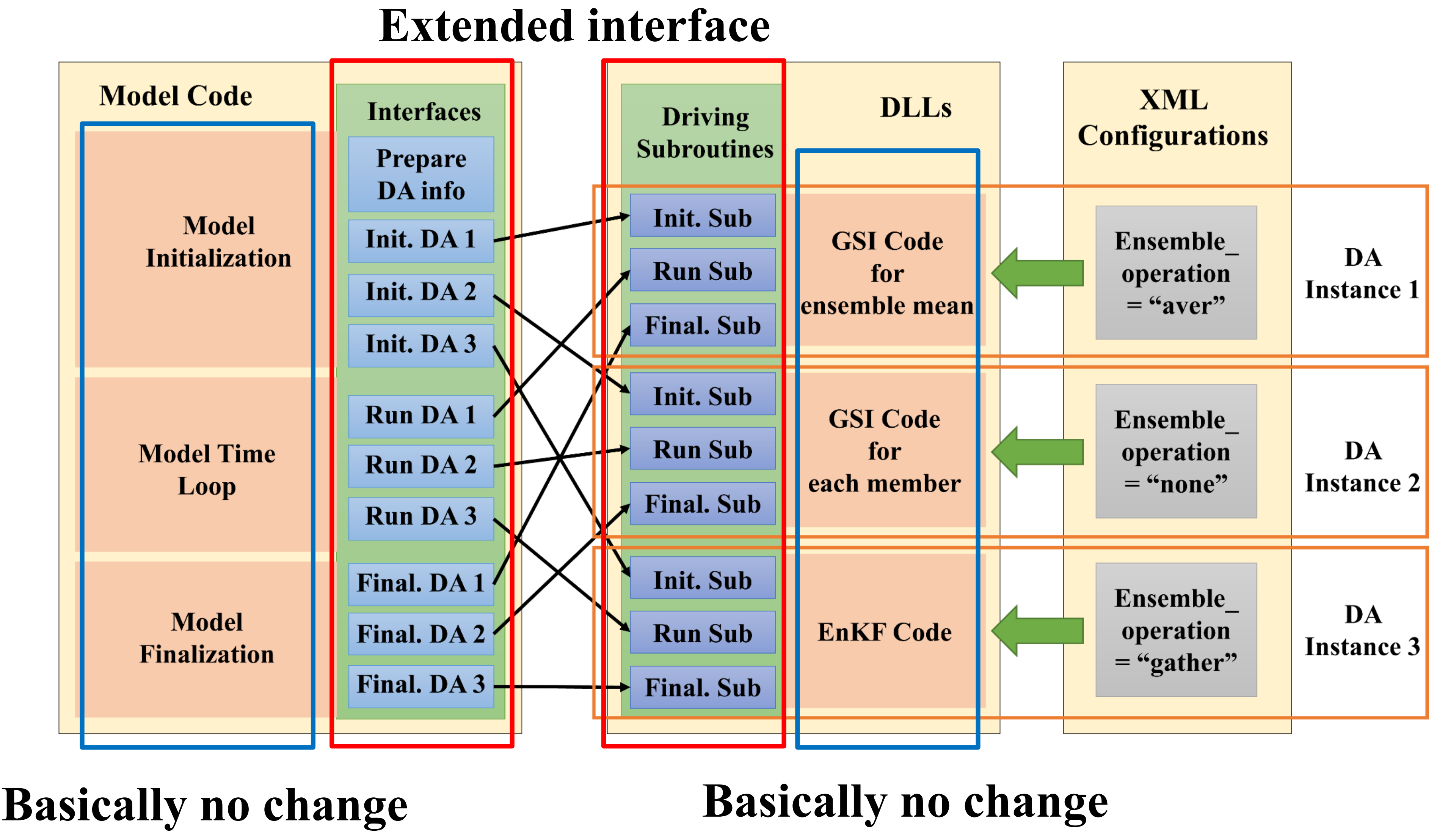
An example weakly coupled ensemble DA system



GSI/EnKF



FIO-AOW


Extended interface
Model Code
Model Initialization
Model Time Loop
Model Finalization
Interfaces
Prepare DA info
Init. DA 1
Init. DA 2
Init. DA 3
Run DA 1
Run DA 2
Run DA 3
Final. DA 1
Final. DA 2
Final. DA 3
Driving Subroutines
Init. Sub
Run Sub
Final. Sub
Init. Sub
Run Sub
Final. Sub
Init. Sub
Run Sub
Final. Sub
DLLs
GSI Code for ensemble mean
GSI Code for each member
EnKF Code
XML Configurations
Ensemble_ operation = “aver”
Ensemble_ operation = “none”
Ensemble_ operation = “gather”
DA Instance 1
DA Instance 2
DA Instance 3
Basically no change
Basically no change

Experimental setup

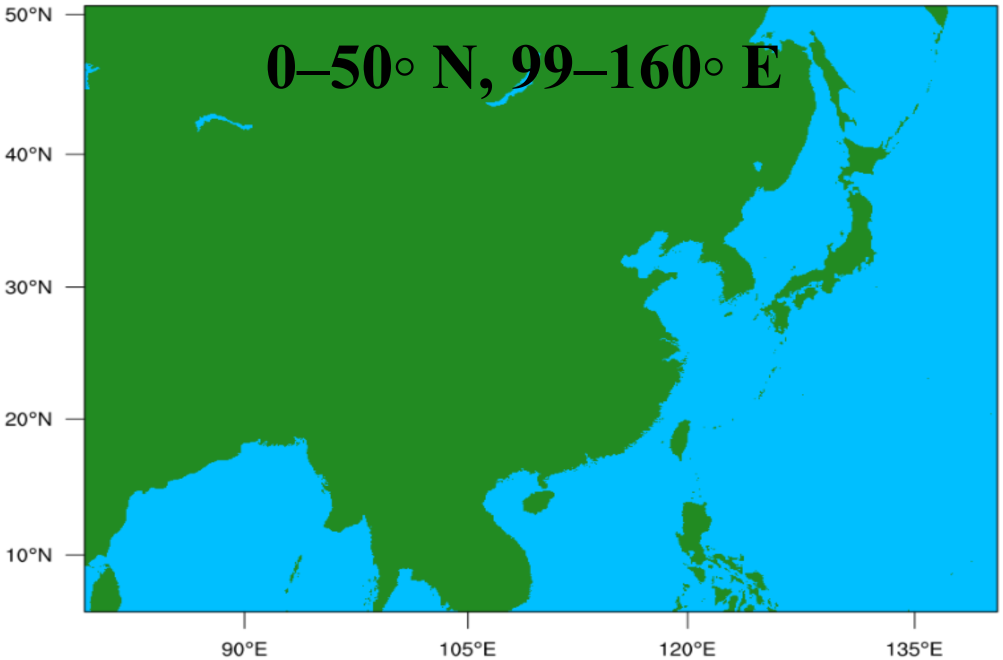


Table 1. Horizontal resolutions and time steps of WRF.

Horizontal resolution	Total horizontal Grid points	Time step
45 km	160 × 120	180 s
30 km	240 × 180	120 s
15 km	480 × 360	60 s

- One day integration on 1 June 2016 is used for running the WRF-GSI/EnKF;
- NCEP global GDAS including conventional observation data and satellite radiation data, are assimilated every 6h;
- The air temperature (T), specific humidity (QVAPOR), longitude and latitude wind (UV), and column disturbance dry air quality (MU) are the assimilated variables.

Experimental setup

Table 2. Setup of four experiment sets in terms of horizontal resolution, number of ensemble members and number of processes.

Experiment set	Horizontal resolution	Number of ensemble members	Processes for each ensemble member	Label marks
Set 1	15 km	5	160	15KM_5mem_160proc
		10		15KM_10mem_160proc
		15		15KM_15mem_160proc
		20		15KM_20mem_160proc
Set 2	15 km	10	40	15KM_10mem_40proc
			80	15KM_10mem_80proc
			160	15KM_10mem_160proc
			320	15KM_10mem_320proc
Set 3	45 km	10	80	45KM_10mem_80proc
	30 km			30KM_10mem_80proc
	15 km			15KM_10mem_80proc
Set 4	45 km	10	40	45KM_10mem_40proc
	30 km		80	30KM_10mem_80proc
	15 km		320	15KM_10mem_320proc

Experimental results

Blue： Execution time of offline DA Red： Execution time of online DA

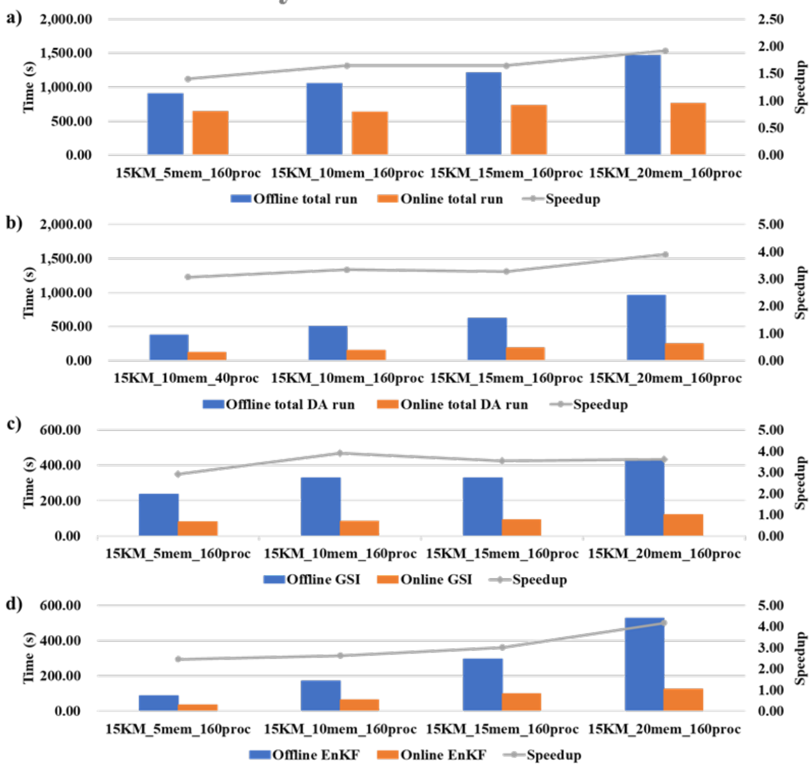
Gray： ratio of offline execution time to online execution time

Total time

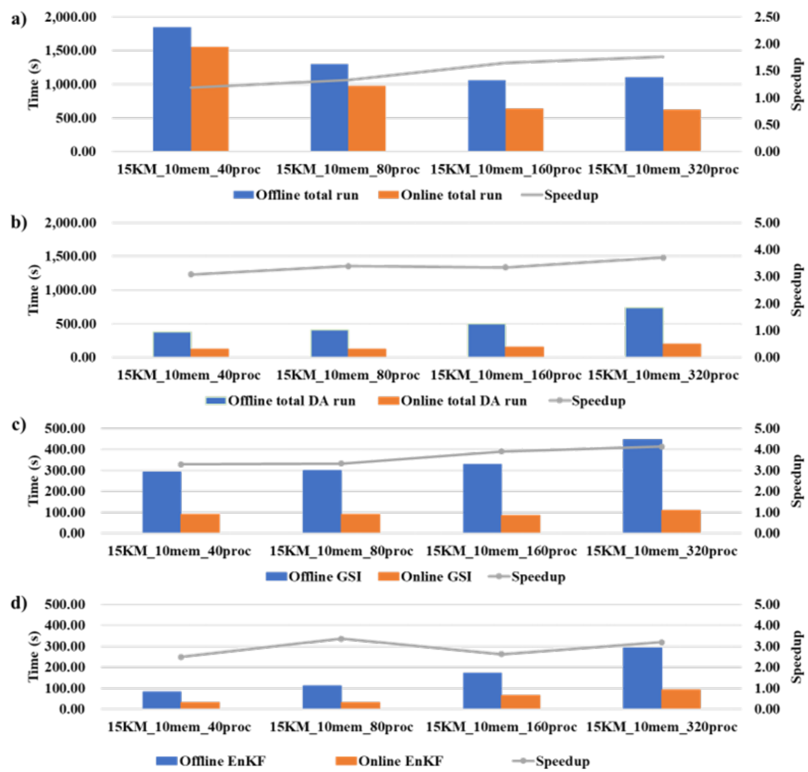
DA time

GSI

EnKF



Set 1 Enlarging ensemble size



Set 2 Increasing the number of cores

Experimental results

Blue： Execution time of offline DA Red： Execution time of online DA

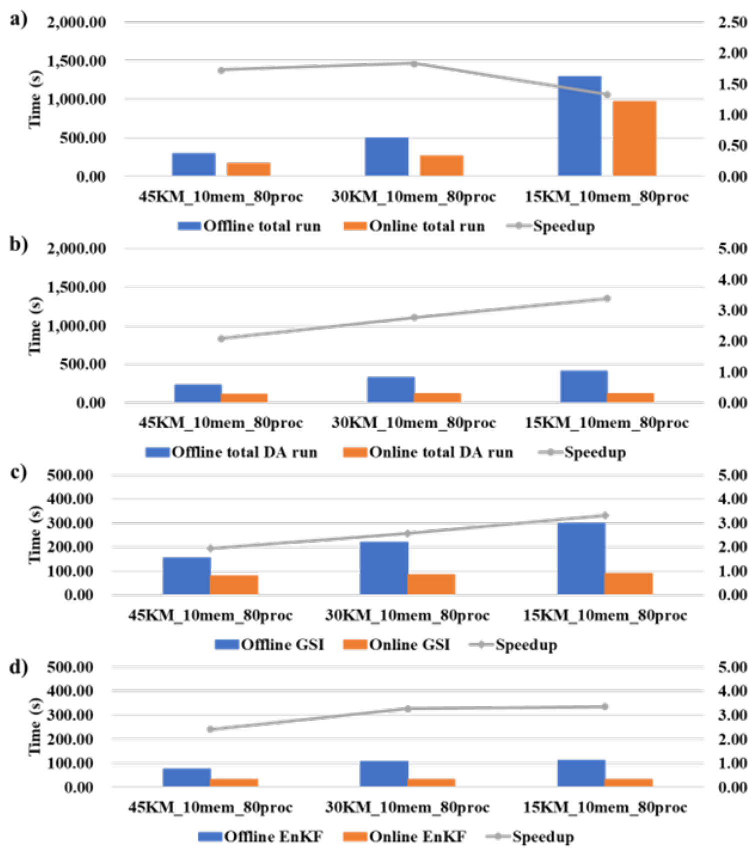
Gray： ratio of offline execution time to online execution time

Total time

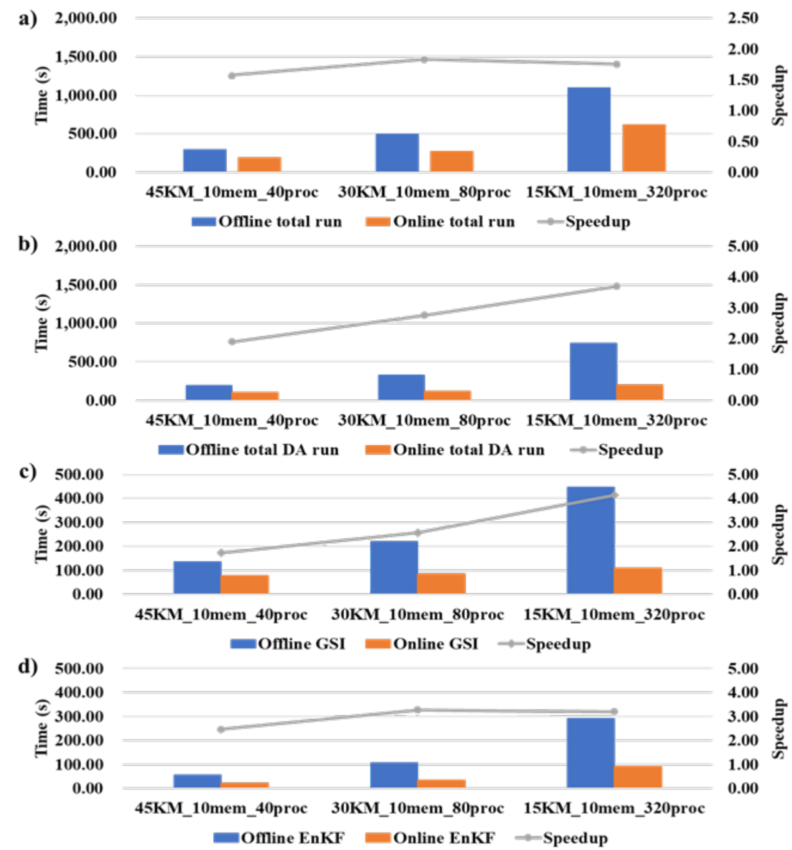
DA time

GSI

EnKF



Set 2 Finer resolution



Set 4 Increasing the number of cores with finer resolution

Outline

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- **Summary**

Summary

- C-Coupler3 is a common software with fast initialization and various frameworks.

- C-Coupler3 can be fully compatible to C-Coupler2

Thanks!