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C-Coupler1: a Chinese community coupler for Earth System Modelling

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Abstract

Coupler is a fundamental software tool for Earth System Modelling. Targeting the requirements of 3-D coupling, high-level sharing, common model software platform and better parallel performance, we started to design and develop a community coupler (C-Coupler) from 2010 in China, and finished the first version (C-Coupler1) recently. The C-Coupler1 is a parallel 3-D coupler that achieves the same (bit-identical) result with any number of processes. Guided by the general design of the C-Coupler, the C-Coupler1 enables various component models and various coupled model versions to be integrated on the same common model software platform to achieve a higher-level sharing, where the component models and the coupler can keep the same code version in various model versions for simulation. Moreover, it provides the C-Coupler platform, a uniform runtime environment for operating various kinds of model simulations in the same manner. Now the C-Coupler1 is ready for Earth System Modelling, and it is publicly available. In China, there are more and more model groups using the C-Coupler1 for the development and application of models.

1 Introduction

Climate System Models (CSMs) and Earth System Models (ESMs) are fundamental tools for global climate change study. They play an important role in simulating and understanding the past, present, and future climate. They are always coupled models consisting of several separate interoperable component models to simultaneously simulate the variations of and interactions among the atmosphere, land surface, oceans, sea ice and other components of the climate system. Following the fast development of science and technology, more and more CSMs, ESMs and related component models have sprung up in the world. For example, more than 50 coupled models participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5), while less than 30 coupled models in the previous CMIP3.

Coupler is an important software tool for model development. It links component models together to construct a coupled model, achieves parallel computation among multiple component models, controls the integration of the whole coupled model, and even provides a software platform to make scientists and engineers cooperate together. Most of the state-of-the-art CSMs and ESMs are constructed with coupler. With more and more component models (e.g., land ice model, chemistry model, and biogeochemical model) to be added into ESMs, coupler becomes more and more important for model development. Now, there are a number of couplers available in the world which have been widely used for model development, e.g., the Ocean Atmosphere Sea Ice Soil coupling software (OASIS) coupler (Redler et al., 2010; Valcke, 2013a), the Model Coupling Toolkit (Larson et al., 2005; Jacob et al., 2005) (MCT), the Earth System Modelling Framework (Hill et al., 2004) (ESMF), the Flexible Modelling System (FMS) coupler (Balaji et al., 2006), the CPL6 coupler (Craig et al., 2005) designed for the Community Climate System Model version 3 (Collins et al., 2006) (CCSM3), the CPL7 coupler (Craig et al., 2012) designed for the Community Climate System Model version 4 (Gent et al., 2011) (CCSM4) and the Community Earth System Model (Hurrell et al., 2013) (CESM), the Bespoke Framework Generator (Ford et al., 2006; Armstrong et al., 2009) (BFG), etc. Most of these couplers provide typical coupling functions (Valcke et al., 2012a), such as transferring coupling fields between component models, interpolating coupling fields between different grids of component models, and coordinating the execution of component models in a coupled model.

Facing the future development of CSMs and ESMs, there are potentially several new requirements for coupler development, as follows:

1. 3-D coupling. Generally, coupling occurs on the common boundaries or domains between component models. Traditionally in CSMs, the common surface between any two component models is on a 2-D horizontal surface. For example, the common surface between an atmosphere model and an ocean model is on the skin of the ocean, which is also the bottom of the atmosphere. The support for 2-D coupling therefore is enough for constructing CSMs. In ESMs, component models can

share the same 3-D domain. For example, both atmospheric chemistry model and atmosphere model simulate in the 3-D atmosphere space. When coupling them together, especially when their 3-D grids are different, 3-D coupling, including transferring and interpolating 3-D coupling fields, needs to be achieved. Some existing couplers, such as the OASIS coupler, MCT, CPL6 coupler and CPL7 coupler, already can provide 3-D coupling function.

2. High-level sharing. A component model can be shared by different coupled model versions for various scientific research purposes. In different coupled model versions, the same component model may have different coupling fields and different common boundaries or domains with other component models. For example, given an atmosphere model, when it is used as a standalone component model, there are no coupling fields. When it is used as a component in a CSM, it will provide/obtain 2-D coupling fields to/from other component models. When it is coupled with an atmospheric chemistry model, some 3-D variables with vertical levels become coupling fields. In each coupled model version, the atmosphere model can have a branch code version with a specific program for providing/obtaining the corresponding coupling fields. When more and more coupled model versions share the atmosphere model, there will be an increasing number of branch code versions, which will introduce more works even disorders to the code version control of the atmosphere model. To facilitate the code version control for sharing a component model, coupler should enable various coupled model versions to share the same code version of the component model. Similarly, coupler should enable various coupled model versions to share the same code version of it.

3. Common model software platform. To develop a model or to achieve a scientific research target, scientists always need to run various kinds of model versions. For example, to develop an atmosphere model, scientists may experience the developments of single-column model of physical processes and standalone atmosphere model, and then perhaps the evaluations and applications of air–sea

coupled models, nested models, CSMs, ESMs, etc. To facilitate model development and scientific researches, coupler should enable to integrate various component models and various coupled model versions on a common model software platform which runs various kinds of model simulations in a same manner.

4. Better parallel performance. In future, coupler will become more and more time-consuming for Earth System Modelling in several aspects. First, coupler will be asked to manage the coupling between more and more component models in a coupled model version. Second, 3-D coupling will introduce much higher communication and calculation overhead than 2-D coupling. Third, the resolution of component models coupled together gets higher and higher. Therefore, it will become more and more important to improve the parallel performance of coupler.

To address these requirements, in 2010, we started to design and develop a new coupler named "Community Coupler (C-Coupler)", and finished its first version (C-Coupler1) at the end of 2013. Besides the typical coupling functions forementioned, the C-Coupler1 achieves parallel 3-D coupling with flexible 3-D interpolation, provides the functionality of integrating external algorithms to enable the same code of the C-Coupler and component models shared by various coupled model versions, and implements a uniform runtime environment (we call it as the C-Coupler platform) which operates various kinds of model simulations in a same manner. Moreover, the C-Coupler1 supports direct coupling without a specific coupler component to improve the parallel performance. Recently, we successfully used the C-Coupler1 to build several model versions with different coupling architectures, and made these model versions share the same code of the component models and C-Coupler1, and the same C-Coupler platform for simulation.

In this paper, we will introduce the general design of the C-Coupler and show details of the C-Coupler1. The remainder of this paper is organized as follows. Section 2 briefly introduces existing couplers. Section 3 presents the general design of the C-Coupler. Section 4 presents the C-Coupler1 with details. Section 5 empirically evaluates the

C-Coupler1. Section 6 discusses the future works for the C-Coupler development. We conclude this paper in Sect. 7.

2 Brief introduction to existing couplers

In this Section, we will briefly introduce the OASIS coupler, MCT, ESMF, FMS coupler, CPL6 coupler and CPL7 coupler, which have been used for the CMIP5. More details of these couplers can be found in Valcke et al. (2012a), Redler et al. (2010), Valcke (2013a), Larson et al. (2005), Jacob et al. (2005), Hill et al. (2004), Balaji et al. (2006) and Craig et al. (2005, 2012).

2.1 The OASIS coupler

CERFACS started to develop the OASIS coupler in 1991. The OASIS3 (Valcke, 2013a) is a 2-D version of the OASIS coupler. It has been widely used for developing the European CSMs and ESMs. For example, it has been used in different versions of 5 European CSMs and ESMs that have participated in the CMIP5, e.g., CNRM-CM5 (Voldoire et al., 2013), IPSL-CM5 (Dufresne et al., 2013), CMCC-ESM (Vichi et al., 2011), EC-Earth V2.3 (Hazelger et al., 2011) and MPI-ESM (Giorgetta et al., 2013; Jungclaus et al., 2013). The OASIS3 uses multiple executables for a coupled model, where the OASIS3 itself forms a separate executable for data interpolation tasks and each component model remains a separate executable. It provides a “namcouple” configuration file, which is an external configuration file written by users, to specify some characteristics of each coupling exchange, e.g. source component, target component, coupling frequency and data remapping algorithm. For data interpolation, the OASIS3 can use the remapping weights generated by the 2-D remapping algorithms in the Spherical Coordinate Remapping and Interpolation Package (SCRIP) library (Jones, 1999). The parallelism of the OASIS3 is limited to the number of coupling fields, because each process for the OASIS3 is responsible for a subset of the coupling fields.

OASIS4 is a 3-D version of the OASIS coupler, which supports both 2-D and 3-D coupling. Similar to the OASIS3, the OASIS4 also uses multiple executables for a coupled model, provides the “namcouple” configuration file, and can use the SCRIP for 2-D interpolation. As a 3-D coupler, OASIS4 supports the transfer and interpolation of 3-D fields. For 3-D interpolation, OASIS4 itself provides pure 3-D remapping algorithms, e.g., 3-D n neighbor distance-weighted average and trilinear remapping algorithms, and supports 2-D interpolation in the horizontal direction followed by a linear interpolation in the vertical. In July 2011, CERFACS stopped the development of OASIS4, and started to develop a new coupler version, the OASIS3-MCT (Valcke et al., 2012b, 2013b), which inherits the 3-D coupling function in OASIS4 and further improves the parallelism of the OASIS3.

2.2 The Model Coupling Toolkit

The Model Coupling Toolkit (MCT) provides the fundamental coupling functions: data transfer and data interpolation, in parallel. The MCT represents a coupling field into a 1-D array and uses sparse matrix multiplication to achieve data interpolation. Therefore, it can be used for both 2-D and 3-D coupling. For 2-D interpolation, the MCT can use the remapping weights generated by the SCRIP. However, the MCT rarely achieves 3-D interpolation due to the lack of 3-D remapping weights generated by existing remapping software. As a result, the MCT is not user-friendly enough in 3-D coupling and users always have to implement 3-D interpolation in the code of component models.

Different from the OASIS coupler, the MCT does not provide the “namcouple” configuration file but uses “codecouple” configuration, which means that the characteristics of coupling exchanges are specified by users in the source code of a coupled model. The MCT can be view a library for model coupling. It can be directly used to couple fields between two component models where no separate executable is generated for coupling tasks, and can also be used to develop other couplers, e.g., the OASIS3-MCT, CPL6 coupler and CPL7 coupler.

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2.3 The Earth System Modelling Framework

The Earth System Modelling Framework (ESMF) is a framework for developing models, which consists of a superstructure with coupling functions and an infrastructure with the utilities for common functions. It can use both single executable and multiple executables for a coupled model. Similar to the MCT, the ESMF uses "codecouple" configuration for model coupling. For data interpolation, besides the typical remapping algorithms such as bilinear and first order conservative, the ESMF provides a higher-order finite element-based patch recovery algorithm to improve the accuracy of 2-D interpolation. For parallelism, the ESMF can remap data fields in parallel and keep bit-identical result when changing the number of processes for interpolation.

In the CMIP5, the coupled model NASA GEOS-5 uses EMSF throughout, and the coupled models CCSM4 and CESM1 use the higher-order patch recovery remapping algorithm provided by the ESMF.

2.4 The FMS coupler

The Flexible Modelling System (FMS) is a software framework that is mainly developed by and used in the Geophysical Fluid Dynamics Laboratory (GFDL) for the development, simulation and scientific interpretation of atmosphere models, ocean models, CSMs and ESMs. The coupling between component models in the FMS is achieved by the FMS coupler in parallel. Similar to the MCT and ESMF, the FMS coupler uses "codecouple" configuration for model coupling, and can keep bit-identical result across different parallel decompositions. One key feature of the FMS coupler is the "exchange grid" (Balaji et al., 2006). Given two component models, the corresponding exchange grid is determined by all vertices in the two grids of these two component models, and the coupling between these two component models is processed on the exchange grid. For example, the coupling fields from the source component model are first interpolated onto the exchange grid and then averaged onto the grid of the target component model.

In the CMIP5, the CSMs and ESMs (Donner et al., 2011; Dunne et al., 2012) from the GFDL use the FMS as well as its coupler.

2.5 The CPL6 coupler

The CPL6 coupler is the sixth version in the coupler family developed at the National Center for Atmospheric Research (NCAR). It is a centralized coupler designed for the CCSM3, where the atmosphere model, land surface model, ocean model and sea ice model are connected to the unique coupler component and the coupling between any two component models is performed by the coupler component. Through integrating the MCT, the CPL6 coupler achieves the data transfer and data interpolation in parallel. Moreover, it provides a number of numerical algorithms to compute and merge some fluxes and state variables for component models. It uses multiple executables for a coupled model, where the coupler component forms a separate executable. Similar to the MCT, the CPL6 coupler uses "codecouple" configuration for model coupling. For data interpolation, it always uses the remapping weights generated by the SCRIP.

In the CMIP5, the CPL6 coupler as well as the model platform of CCSM3 has been widely used in Chinese coupled model versions, e.g., FGOALS-g2 (Li et al., 2013a), FGOALS-s2 (Bao et al., 2013), BNU-ESM (Ji et al., 2014), BCC-CSM, FIO-ESM, etc.

2.6 The CPL7 coupler

The CPL7 coupler is the latest coupler version from the NCAR. It has been used for the CMIP5 models CCSM4 and CESM1. It keeps most of characteristics in the CPL6 coupler, such as centralized coupler component, integration of the MCT and flux computation. The remarkable advancements from the CPL6 coupler to the CPL7 coupler include: (1) the CPL7 coupler does not use multiple executables but single executable for a coupled model and provides a top-level driver to achieve various processor layout and time sequencing of the components, to improve the overall parallel performance of the coupled model; (2) a parallel I/O library is implemented in the CPL7 coupler to improve the I/O performance.

2.7 Summary

Some existing couplers already support 3-D coupling, such as the OASIS coupler, MCT, CPL6 coupler and CPL7 coupler. However, these 3-D coupling functions should be further improved. The 3-D n-neighbor distance-weighted average, trilinear and linear remapping algorithms in the OASIS coupler can result in low accuracy in the interpolation on the vertical direction. The MCT, CPL6 coupler and CPL7 coupler always cannot interpolate but only transfer the 3-D coupling fields due to the lack of 3-D remapping weights. Moreover, limited by the implementation of sparse matrix multiplication for data interpolation, some higher-order remapping algorithms for the 1-D vertical direction, such as spline, cannot be used in 3-D interpolation, because these algorithms cannot be achieved purely by sparse matrix multiplication.

Almost all existing couplers use "codecouple" configuration except the OASIS coupler, where the characteristics of coupling are specified in the source code of a coupled model. Therefore, these couplers cannot achieve the requirement of sharing the same code version of coupler and component models among various coupled model versions. For example, when increasing coupling fields or component models based on a coupled model version, the code of coupler or component models has to be modified. Regarding the OASIS coupler, its "namcouple" configuration, which specifies how to transfer and interpolate each coupling field, can decrease the code modification when changing the corresponding characteristics of coupling. However, the OASIS coupler does not provide and manage the algorithms for calculating coupling fields, such as flux computation algorithms. When changing the procedures for calculating coupling fields, the code of component models always has to be modified.

There are several model software platforms corresponding to existing couplers which have been successfully used for model development, such as the CCSM3 platform corresponding to the CPL6 coupler, the CCSM4/CESM platform corresponding to the

CPL7 coupler, and the FMS. These platforms can configure, compile and run different kinds of model versions for simulation. For example, the CCSM4/CESM platform can run standalone component model versions, CSMs, ESMs, etc. However, to make a new standalone component model run on the CCSM4/CESM platform, users have to dramatically modify the code of the component model.

Improving parallel performance is always a focus in coupler development. A typical example is the CPL7 coupler. It concerns the parallel performance of both the coupler and the whole coupled model. Similarly, we will concern about the parallel performance of both the coupler and coupled models in the long-term development of the C-Coupler.

3 General design of the C-Coupler

In this section, we will briefly introduce the general design of the C-Coupler. The C-Coupler can be viewed as a family of the community coupler developed in China, and the C-Coupler1 is the first version following the general design. The future versions of the C-Coupler will also follow the general design. In the following context, we first define a general term of "*experiment model*" for the C-Coupler, and then introduce the architecture of the experiment models with the C-Coupler and the general software architecture of the C-Coupler.

3.1 A general term for the C-Coupler: experiment model

An experiment model is a model version which can run on the C-Coupler platform for simulation. Generally, it can be any kind of model versions, such as single-column model, standalone component model, regional coupled model, air–sea coupled model, nested model, CSM, ESM, etc. A component model can be viewed as an element for constructing an experiment model.

3.2 Architecture of the experiment models with the C-Coupler

To achieve the target of integrating various models on the same common model software platform for a high-level sharing of the component models and for facilitating the construction of a new experiment model, we have designed a new architecture of the experiment models with the C-Coupler. Figure 1 shows an example of this architecture with a typical CSM, where "ATM", "ICE", "LND" and "OCN" stand for the component models in the CSM. The key ideas of this design include:

1. All experiment models share the same code of the C-Coupler. Given an experiment model, there could be a simple coupler component which manages the coupling between the component models, while the direct coupling without a coupler component is also supported to improve the parallel performance. For example, the red lines in Fig. 1 stand for the direct coupling, where no separate executable is generated for the coupling tasks, and all coupling tasks, such as the data transfer, data interpolation and flux computation, are performed through the uniform C-Coupler Application Programming Interfaces (APIs) called by the component models.

2. When a component model is shared by multiple experiment models, it keeps the same code version in all these experiment models. The code of coupling interfaces in the component model only specifies the input fields that the component model wants and the output fields that the component model can provide, but does not specify how to get the input fields and how to provide the output fields. For example, the source component models, the target component models and the flux calculation of the coupling fields are not specified in the code of the coupling interfaces.

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3.3 General software architecture of the C-Coupler

Under the guidance of the key ideas, we designed the general software architecture of the C-Coupler, which consists of a configuration system, a runtime software system and a coupling generator, as shown in Fig. 2.

3.3.1 Configuration system

In different experiment models, a component model always has different procedures for the input and output fields. For example, given an atmosphere model, in its standalone component model version, the ocean surface state fields (such as sea surface temperature) is obtained from the I/O data files, while in an air–sea coupled model version, the ocean surface state fields are obtained from the ocean model through coupling. Moreover, in these two model versions, the algorithms for computing the air–sea flux (such as evaporation, heat flux and wind stress) can be different. To make the same code version of a component model shared by various experiment models, the same C-Coupler APIs must be able to achieve any procedures for the input and output fields. We therefore designed a configuration system in the C-Coupler. Besides the functions achieved by the “namcouple” configuration file in the OASIS coupler, the configuration system of the C-Coupler can further specify various procedures each of which consists of a list of algorithms. In the following context of this paper, we call the procedures specified by the configuration system as *runtime procedures*, and call the algorithms in the runtime procedures as *runtime algorithms*. We classify the runtime algorithms into two categories: internal algorithms and external algorithms. The internal algorithms are implemented intra the C-Coupler, including the data transfer algorithms, data remapping algorithms, data I/O algorithms, etc. The external algorithms are always provided by the component models, coupled models and users. The external algorithms could be the private algorithms of a component model, and could be common algorithms such as flux computation algorithms which can be shared by various experiment models.

The configuration system manages the configuration files of software modules and the runtime configuration files of model simulations. The software modules include component models, experiment models and external algorithms. In detail, the configuration files of a component model specify some characteristics of the component model, e.g., the input and output fields, how to generate the input namelists, how to compile the code of the model, etc. The configuration files of an experiment model specify how to organize the components, e.g., the components in the experiment model, how each component to get the input fields and provide the output fields, etc. The configuration files of an external algorithm specify the input and output fields of the algorithm. The runtime configuration files specify how to run an experiment model for a simulation, e.g., how to organize the internal algorithms and external algorithms into the runtime procedures for the input and output fields of the components, the coupling frequencies, the start time and stop time of the simulation, etc.

3.3.2 Runtime software system

The runtime software system can be view as a common, flexible and extendible library for constructing experiment models and for running model simulations. It enables various kinds of experiment models to share the same code of the C-Coupler.

First, it provides auniform APIs for integrating component models. With these APIs, a component model can register the model grids, parallel decompositions and input/output fields, and get the input/output fields from/to I/O data files or other components, etc.

Second, the runtime software system provides uniform APIs for integrating external algorithms. A component model can register its private subroutines as external algorithms of the C-Coupler. Common algorithms like flux computation algorithms can also be registered as external algorithms. Therefore, the runtime software system is an extendible library which can integrate more and more common external algorithms, and thus users can have more choices for model simulations. For example, given an air–sea coupled model, if there are several different algorithms for calculating air–sea flux, users can select one of them in a simulation of the air–sea experiment model, or two or more of them for sensitivity experiments.

Third, the runtime software system provides a number of managers (shorted as MGR in Fig. 2), including communication manager, grid manager, parallel decomposition manager (shorted as decomposition MGR in Fig. 2), remapping manager, timer manger, data manager, restart manager, runtime process manager (shorted as process MGR in Fig. 2), etc. In detail, the communication manager is responsible for allocating and managing the communicators of each component and the whole experiment model. The grid manager manages the grids registered by the component models. The grid can be 1-D, 2-D, 3-D even 4-D. The parallel decomposition manager manages the parallel decompositions registered by the component models. The remapping manager manages the remapping algorithms used for coupling. Users can select different remapping algorithms in different simulations of the same experiment model. The timer manager provides timers for triggering the execution of internal and external algorithms. Each algorithm has a timer, and it is executed only when its timer is on. The timer manager can also provide time information for the whole experiment model through the corresponding APIs. The data manager provides uniform APIs for getting the attributes and memory space of fields. A component model can register model fields (including the memory space) as external fields to the data manager. For the internal fields, the data manager will allocate their memory space automatically. The restart manager is responsible for reading fields from the restart I/O data files in a restart run of a model simulation, and writing fields into the restart I/O data files when the timer for the restart writing is on. The runtime process manager manages the internal algorithms and the registered external algorithms, organizes these runtime algorithms into a number of runtime procedures, and executes the runtime procedures in a model simulation.

3.3.3 Coupling generator

The runtime software system takes the runtime configuration files of a model simulation as input. To build a model simulation, users can directly prepare the corresponding runtime configuration files, which will introduce a lot of works to do. To facilitate the works for building a model simulation, we propose to design and develop a coupling generator, which can automatically generate the runtime configuration files according to the configuration files of the component models, experiment model and external algorithms. Moreover, the coupling generator can automatically optimize the parallel performance of the whole model simulation. For example, for the direct coupling between two component models with different horizontal resolutions, the coupling generator can make the corresponding data interpolation run in the runtime procedures of the component model with higher resolution, to minimize the data size of the fields transferred between these two component models.

The general software architecture of the C-Coupler is similar to the architecture of modern computer systems. The configuration files of the component models, experiment models and external algorithms can be viewed as the programs in high-level programming languages like Fortran and C/C++. The runtime time configuration files of model simulations can be viewed as the programs in low-level binary language. The runtime software system can be viewed as a CPU which takes the binary programs as input to run model simulations. The coupling generator can be viewed as a compiler which transforms the high-level programs to low-level programs, and optimizes the parallel performance at the same time.

4 C-Coupler1: first released version of the C-Coupler

The C-Coupler1 is the first version of the C-Coupler for public use. As the initial version of the C-Coupler, it does not include the coupling generator currently. However, we carefully developed the configuration system and the runtime software system, which makes the C-Coupler1 achieve most of characteristics in the general design of the C-Coupler and reach the target of sharing the same code version of the C-Coupler and component models among different experiment models. Moreover, we designed and developed the C-Coupler platform, which enables users to operate various model simulations in the same manner.

The C-Coupler1 is a 3-D coupler, where the coupling fields can be 0-D, 1-D, 2-D, or 3-D. It uses multiple executables for the coupled models, each component of which has a separate executable. It can be used to construct a simple coupler component with a few lines of code, and can also be used for direct coupling between component models without separate executable specifically for the coupling tasks. It does not use the "codecouple" configuration but develops a powerful configuration system. As a 3-D coupler, it can interpolate both 2-D and 3-D fields. The runtime software system of the C-Coupler1 has been parallelized using the Message Passing Interfaces (MPI) library, while the bit-identical result is kept when changing the number of processes for the C-Coupler1.

In the following context of this section, we will respectively present the runtime software system, configuration system and C-Coupler platform in the C-Coupler1.

4.1 The runtime software system

The runtime software system is a parallel software library programmed mainly in C++. It provides APIs mainly in Fortran as most of component models for Earth System Modelling are programmed in Fortran. In the following context, we will introduce the technical features of the runtime software system, including the APIs, each manager and the parallel implementation.

4.1.1 The APIs

Table 1 lists out the APIs provided by the C-Coupler1, which can be classified into four categories: the main driver, registration, restart function and time information. Besides

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the brief description of each API in Table 1, we would like to further introduce two APIs, *c_coupler_execute_procedure* and *c_coupler_register_model_algorithm*.

The API *c_coupler_execute_procedure* takes the name of a runtime procedure as an input parameter, while the algorithm list of the runtime procedure is specified in the corresponding runtime configuration files. Thus, a runtime procedure can keep the same name in various experiment models, and users can make the same runtime procedure perform different works through modifying the runtime configuration files that can be viewed as a part of input of a model simulation. As a result, a component model can keep the same code version in various experiment models sharing it.

Almost all APIs are in Fortran except the *c_coupler_register_model_algorithm*. The *c_coupler_register_model_algorithm* is in C++ because most of Fortran versions do not support function pointer. The algorithm (or subroutine) of a component model registered through this API do not have parameters and return value.

4.1.2 The implementation of managers in the runtime software system

The communication manager

The communication manager adaptively allocates and manages the MPI communicators for the MPI communications intra and between the components of an experiment model. It also provides some utilities for other managers in the runtime software system, such as getting the id of a process in the communicator of a component or in the global communicator.

The grid manager

The grid manager utilizes a multi-dimensional **Co**mmon **R**emapping (CoR) software (Liu et al., 2013a, b; it can be downloaded through "*svn–username=guest–password=guest co http://thucpl1.3322.org/svn/coupler/CoR1.0*") to manage the grids with dimensions from 1-D to 4-D. In a model simulation, the grids of component models are registered to the grid manger with a script of the CoR, where the grid data (such the latitude, longitude and mask corresponding to each grid cell) is always read from I/O data files. Besides the support of multiple dimensions of grids, another advantage of using the CoR for grid management is that the CoR can detect the relationship between to two grids, for example, a 2-D grid is the horizontal grid of a 3-D grid with vertical levels.

The parallel decomposition manager

Most of component models for Earth System Modelling have been parallelized using the MPI library, where the whole domain of each component model, which is always a 3-D grid with vertical levels, is decomposed into a number of sub domains for parallelization and each process of the component model is responsible for a sub domain. We call the decomposition from the whole domain into sub domains as parallel decomposition. In the C-Coupler1, each parallel decomposition managed by the parallel decomposition manager is based on a 2-D horizontal grid which has been registered to the grid manager, while the parallel decomposition on the vertical sub-grid of the 3-D grid is not supported yet. To register a parallel decomposition, each process of a component model enumerates the global index (the unique index in the whole domain) of each local cell (each cell in the sub domain of this process) in the corresponding horizontal grid. A component model can register multiple parallel decompositions on the same horizontal grid, while each parallel decomposition has a unique name which is treated as the keyword of it.

The remapping manager

The remapping manager utilizes the CoR to achieve the data interpolation function. There are several remarkable advantages of using the CoR for interpolation. First, the CoR can help the Coupler1 to remap the field data on 1-D, 2-D and 3-D grids. Second, the CoR can generate remapping weights using its internal remapping algorithms and can also use the remapping weights generated by other software, such as the SCRIP. Third, the CoR is designed to be able to remap field data between two grids with any structures, which makes the C-Coupler1 able to be used more extensively. Similar to other couplers such as the MCT and the CPL6 coupler, the C-Coupler1 can utilize the remapping weights generated offline by remapping software such as the CoR and the SCRIP. It can also generate remapping weights online for the C-Coupler1 in the execution of a model simulation. The I/O data files for the offline remapping weights are specified in a script of the CoR, the same script for registering the grids. In different simulations of the same experiment model, users can select different remapping algorithms through modifying the script.

The CoR makes the C-Coupler1 flexible in 3-D interpolation than existing couplers. First, the CoR supports the “2-D + 1-D” approach to interpolate data between two 3-D grids, where a 2-D remapping algorithm is used for the interpolation between the 2-D horizontal sub-grids and a 1-D remapping algorithm is used for the interpolation between the 1-D vertical sub-grids. Given that there are M 2-D remapping algorithms and N 1-D remapping algorithms, there are $M \times N$ selections for 3-D interpolation. Second, the CoR supports both sparse matrix multiplication and equation group solving for interpolation calculation. Thus, the CoR can provide some higher-order remapping algorithms that require equation group solving to support, such as spline.

Now, there are several remapping algorithms available in the CoR. For the 2-D horizontal interpolation, the CoR provides three remapping algorithms: first order conservative, bilinear and 2-D n-neighbor distance-weighted average. For the 1-D vertical interpolation, the CoR provides two remapping algorithms: linear and spline. Currently, there are no pure 3-D remapping algorithms implemented.

The timer manager

In the runtime software system of the C-Coupler1, each coupling field can have a set of timers for periodically triggering the operations on it. For example, a coupling field always has a timer for the data transfer and a timer for the data interpolation. Moreover, each external algorithm has a timer to periodically trigger its execution. There are three elements in a timer: the unit of frequency, the count of frequency and the count of delay. The unit and the count of frequency specify the period of the timer. The count of delay specifies a lag of the time during which the corresponding operation or algorithm will not be executed. The unit of frequency can be “years”, “months”, “days”, “seconds” and “steps”, where “steps” means the time step of calling the API c_coupler_advance_timer. For example, timer < 10, steps, $15 >$ means that the corresponding operation or algorithm will be executed at the steps with number $10 \times N + 15$, where N is a nonnegative integer.

Besides managing all the timers, the timer manager provides interfaces for getting the time information in a model simulation, such as the current model time during the simulation.

The data manager

The fields managed by the data manager include the external fields which are registered by the components with APIs and the internal fields which are automatically allocated by the data manager. Besides the memory space, there are other attributes for a field, including the field name, data type, name of the corresponding parallel decomposition and name of the corresponding grid. A 2-D field and a 3-D field can share the same parallel decomposition while their corresponding grids are different, where the 2-D grid corresponding to the 2-D field is a sub grid of the 3-D grid corresponding to the 3-D field. For the scalar field which is not on a grid, the corresponding parallel decomposition and grid are marked as “NULL”.

The restart manager

For reading/writing fields from/into the restart I/O data files, the restart manager iterates on each field managed by the data manager. For the internal fields, the restart manager can automatically detect the fields which are necessary for restarting the model

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simulation. For each external field, the corresponding component can specify whether this field is necessary for restarting when registering this field with the C-Coupler API. Therefore, a component model can easily achieve the restart function through registering all fields for restart as external fields to the data manager.

The runtime process manager

The runtime process manager is responsible for running the list of runtime algorithms in each runtime procedure in a model simulation. Besides the external algorithms including the private algorithms registered by the component models and the common flux computation algorithms, there are several algorithms internally implemented in the runtime software system, e.g., the data transfer algorithm, data remapping algorithm, data I/O algorithm, etc. The data transfer algorithm is responsible for transferring a number of fields from one component to another. The fields transferred by the same data transfer algorithm can have different number of dimensions, different data types, different parallel decompositions, different grids, different frequency of transfer, etc. The data transfer algorithm packs all fields that are to be transferred at the current time step into one package to improve the communication performance.

The data remapping algorithm uses the corresponding algorithm in the CoR as a kernel for implementation. It can remap several fields at the same time for better parallel performance. The multiple fields in a data remapping algorithm share the same parallel decomposition, the same grid and the same timer, while the data types can be different.

The data I/O algorithm currently utilizes the serial I/O to read/write multiple fields which are managed by the data manager from/into the data I/O files. The multiple fields in a data I/O algorithm share the same timer, while can have different parallel decompositions, different grids and different data types. The fields of a data I/O algorithm are specified in the corresponding runtime configuration file. For the future version of the C-Coupler, we will further improve the I/O performance with parallel I/O for higher-resolution models.

4.1.3 Parallelization

As aforementioned, the runtime software system has been parallelized using the MPI library and achieves bit-identical result when changing the number of processes. Here we would like to further introduce some details, including the parallelization of the data transfer algorithm, the parallelization of the data remapping algorithm and the default parallel decomposition.

Parallelization of the data transfer algorithm

For a coupling field transferred by the data transfer algorithm, it has a parallel decomposition in the source component and another parallel decomposition in the target component, and these two parallel decompositions share the same horizontal grid. A process in the source component will transfer the data of this field to a process in the target component only when the corresponding sub domains on these two processes have common cells. As this implementation does not involve collective communications and there are always multiple processes to execute the source component and the target component respectively, the data transfer algorithm can transfer the coupling fields in parallel.

Parallelization of the data remapping algorithm

The data remapping algorithm interpolates a number of fields from the source grid to the target grid. To make the fields interpolated in parallel, an internal parallel decomposition is generated according to the parallel decomposition corresponding to the target grid and the remapping weights of the data remapping algorithm. Thus, the data remapping algorithm first rearranges the fields from the parallel decomposition corresponding to the source grid to the internal parallel decomposition using the data transfer algorithm, and then interpolates the fields locally on each process of the component. This implementation avoids the reduction for sum between multiple processes of the component, which is a kind of collective communication, and makes the data remapping algorithm achieve bit-identical result when using different numbers of processes.

Default parallel decomposition

In an experiment model, not all parallel decompositions are specified by the component models through registration. For example, the parallel decompositions in a coupler component are not determined by the component models. Therefore, the runtime software system provides a default parallel decomposition. Given the number of processes *N*, the default parallel decomposition partitions a horizontal grid into *N* distinct sub domains without common cells, and the number of cells in each sub domain is around the average number.

4.2 Configuration system

As we did not develop the coupling generator in the C-Coupler1, we did not develop the configuration files of experiment models accordingly. In the following context of this sub section, we will respectively introduce the configuration files of the component models, the configuration files of the external algorithms and the runtime configuration files of the model simulations.

4.2.1 The configuration files of the component models

Each component model has a set of configuration files which specify the following information of the component model: (1) how to generate the input namelists; (2) where the source code is; (3) how to compile the code, including the compiling options for the component model; (4) the information of the fields that will be registered to the C-Coupler1.

4.2.2 The configuration files of the external algorithms

Each external algorithm has several configuration files which specify the input fields and the output fields of the algorithm. Each input field or output field is marked with a list of attributes, e.g., the field name, the data type, the number of dimensions of the corresponding grid. For the external algorithm registered by a component model, there are no input fields and no output fields.

4.2.3 The runtime configuration files of the model simulations

Corresponding to the design and implementation of the runtime software system, the runtime configuration files contain the following information of a model simulation: (1) the configuration files of the corresponding components and external algorithms; (2) a CoR script to specify the grids and the weights for remapping algorithms; (3) the configuration files for each runtime procedure in each component; (4) the namelist of the model simulation that is common to all components, including the start time, stop time, run type (initial run or restart run), etc.

4.3 The C-Coupler platform

To facilitate operating the simulation of various experiment models with the C-Coupler1, we designed and developed the C-Coupler platform. Figure 3 shows its general architecture. It manages the input data and the software modules for the experiment models, including standardized component models, external algorithms, runtime configuration files of the model simulations and the runtime software system. There are four steps for operating a model simulation on the C-Coupler platform: “create case”, “configure”, “compile” and “run case”. “create case” means creating a model simulation. There are two approaches for creating a model simulation: creating a default simulation of an experiment model using the script “create_newcase” and creating a model simulation from an existing model simulation. The C-Coupler platform facilitates the second approach. At each time of "configure" of a model simulation, a package of the corresponding experimental setup is automatically generated and stored. This package can be used to reproduce the existing model simulation or develop new model simulations. After creating a model simulation, users can modify the experimental setup, such as the namelist, parallel settings, hardware platform, compiling options, output settings, start and stop time, etc. After the modification of the experiment setup, users should "configure" the model simulation, and then users can "compile" and "run case". For various experiment models on various hardware platforms, users can use the same operations for various model simulations. For more information about the C-Coupler platform, please read its users' guide (Liu et al., 2014).

5 Evaluation

To evaluate the C-Coupler1, we used the C-Coupler1 to construct several experiment models, including the FGOALS-gc, GAMIL2-sole, GAMIL2-CLM3, MASNUM-sole, POM-sole, MASNUM-POM and MOM4p1-sole. The FGOALS-gc is a CSM version based on the CSM FGOALS-g2 (Li et al., 2013a), where the original CPL6 coupler in the FGOALS-g2 is replaced by the C-Coupler1. The GAMIL2-sole is a standalone component model version of the atmosphere model GAMIL2 (Li et al., 2013b), the atmosphere component in the FGOALS-g2, which participated in the Atmosphere Model Intercomparison Project (AMIP) in the CMIP5. The GAMIL2-CLM3 is a coupled model version consisting of the GAMIL2 and the land surface model CLM3 (Oleson et al., 2004). The MASNUM-sole is a standalone component model version of the wave model MASNUM (Yang et al., 2005). The POM-sole is a standalone component model version based on a parallel version of the ocean model POM (Wang et al., 2010). The MASNUM-POM is a coupled model version consisting of the MASNUM and POM. The MOM4p1-sole is a standalone component model version of the ocean model MOM4p1 (Griffies et al., 2010).

In the following context of this section, we will evaluate the C-Coupler1 in several aspects, including the coupler component, direct coupling, 3-D coupling, code sharing, parallel performance and the work amount for integrating a standalone component model version onto the C-Coupler platform.

5.1 Coupler component

To construct the FGOALS-gc, we use the C-Coupler1 to develop a coupler component according to the CPL6 coupler. All flux computation algorithms in the CPL6 coupler are integrated into the C-Coupler1 as external algorithms. These algorithms can be treated as public algorithms that can be shared by other experiment models. Figure 4 shows the main driver of the coupler component in the FGOALS-gc. It is very simple with a few lines of code, most of which call the C-Coupler APIs, while the main driver of the CPL6 coupler has about 1000 lines of code. Figure 5 shows a part of the runtime configuration file of the algorithm list for the coupler component, where each line corresponds to a runtime algorithm. In sum, the runtime configuration file clearly lists out 91 runtime algorithms. Figure 6 shows the runtime configuration file of the runtime procedures for the coupler component, where each line corresponds to a runtime procedure and specifies the start index and end index of the runtime algorithms in the algorithm list in Fig. 5.

Our tests show that the FGOALS-gc achieves the same (bit-identical) simulation result with the FGOALS-g2. This result demonstrates that the C-Coupler1 can be used to construct a coupler component for a complicated coupled model, such as CSMs, without changing the simulation result of the existing coupled models. The FGOALS-g2 and FGOALS-gc can be downloaded through "*svn–username=guest–password=guest co http://thucpl1.3322.org/svn/coupler/CCPL_CPL6_consistency_checking*."

5.2 Direct coupling

When constructing the experiment models GAMIL2-CLM3 and MASNUM-POM, we did not build a coupler component but used the direct coupling where no separate executable is generated for coupling. For the GAMIL2-CLM3, as the GAMIL2 and CLM3 share the same horizontal grid, there is only data transfer between them. For the MASNUM-POM, as the grid of the MASNUM is different from the grid of the POM, there are both data transfer and data interpolation between these two component models.

5.3 Parallel 3-D coupling

In the MASNUM-POM, there is only one coupling field, the wave-induced mixing coefficient (Qiao et al., 2004), a 3-D field from the MASNUM to POM. As the horizontal grids and vertical grids in these two component models are different, 3-D interpolation is required during coupling. In detail, we use the CoR to generate the remapping weights for the 3-D interpolation. The corresponding 3-D remapping algorithm is generated through cascading two remapping algorithms: a bilinear remapping algorithm for the horizontal grids and a 1-D spline remapping algorithm for the vertical grids. For the 1-D vertical interpolation, the MASNUM and POM have different kinds of vertical grids: a *z* grid for the MASNUM and a *sigma* grid for the POM.

As aforementioned in Sect. 5.2, the MASNUM-POM uses direct coupling without a coupler component. As the resolution of the MASNUM is lower than the resolution of the POM, we put the calculation of the 3-D interpolation in the runtime procedure of the POM, in order for better parallel performance. Therefore, the 3-D interpolation shares the same processes with the POM. When the POM runs with multiple processes, the 3-D interpolation is computed in parallel. Our evaluation shows that the 3-D interpolation keeps the same (bit-identical) result with different numbers of processes.

5.4 Code sharing

The experiment models FGOALS-gc, GAMIL2-CLM3 and GAMIL2-sole share the same atmosphere model GAMIL2. In the FGOALS-gc, the surface fields required by the GAMIL2 are origin from other component models, e.g., the land surface model CLM3, the ocean model LICOM2 (Liu et al., 2012) and an improved version of the sea ice model CICE4 (Liu, 2010), and computed by the coupler component with the C-Coupler1. In the GAMIL2-CLM3, the surface fields required by the GAMIL2 are origin from the CLM3 and the I/O data files which contain ocean fields and sea ice fields, and computed by the flux algorithms intra the GAMIL2. The GAMIL2-sole is similar to the GAMIL2-CLM3, while the difference is that the GAMIL2-sole directly calls a land surface package to simulate the surface fields from the land. Therefore, in these three experiment models, the GAMIL2 has different procedures for the surface fields.

However, we make the GAMIL2 share the same code version in these three experiment models. All algorithms for computing the input surface fields in the GAMIL2 have been registered to the C-Coupler1 as the private external algorithms. In different experiment models, the same runtime procedures of the GAMIL2 have different lists of runtime algorithms. As a result, all these experiment models keep the same (bit-identical) simulation result with the original model versions without the C-Coupler1.

The MASNUM-POM and MASNUM-sole share the same wave model MASNUM, and the MASNUM-POM and POM-sole share the same ocean model POM. Similarly, we respectively make the MASNUM and POM share the same code in these experiment models that keep the same (bit-identical) simulation result with the original model versions without the C-Coupler1.

5.5 Parallel performance

To evaluate the parallel performance of the C-Coupler1, we use a high-performance computer named Tansuo100 in Tsinghua University in China. It consists of more than 700 computing nodes, each of which consists of two Intel Xeon 5670 6-core CPUs sharing 32GB main memory. All computing nodes are connected by a high-speed Infiniband network with peak communication bandwidth $5\,\mathrm{GB\,s^{-1}}$. We use the Intel C/C++/Fortran compiler of version 11.1 and Intel MPI library of version 4.0 for the compilation of the experiment models, where the optimization level is O2 ~ O3.

In this evaluation, we focus on the internal algorithms implemented in the runtime software system. We only evaluate the parallel performance of the data transfer algorithm and the data remapping algorithm, without the consideration of the serial data I/O algorithm.

5.5.1 Parallel performance of the data transfer algorithm

We evaluate the parallel performance of the data transfer algorithm based on the MASNUM-POM, where the 3-D field, the wave-induced mixing coefficient, is directly transferred from the MASNUM to the POM. For the horizontal grid, both the MASNUM and POM have about 400 000 grid cells. For the vertical grid, the MASNUM has 18 vertical levels while the POM has 30 vertical levels. Table 2 shows the performance of the data transfer, when increasing the number of processes for the MASNUM and POM gradually from 1 to 48. In all test cases in Table 2, we force the MASNUM and POM to not share the same computing nodes. In other words, the data transfer from the MASNUM and POM must go through the infiniband network.

Generally, the time for the data transfer gets smaller when increasing the number of processes for the MASNUM or POM, as shown in Table 2. However, when increasing the processes number from 1 to 48 for each component model, the data transfer algorithm only achieves about 7-fold performance speedup. This relatively low speedup is because, when the number of processes for component models gets bigger, the data size for each MPI communication gets smaller so as that the communication bandwidth achieved in each MPI communication gets smaller.

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5.5.2 Parallel performance of the data remapping algorithm

Similarly, we evaluate the parallel performance of the data remapping algorithm based on the MASNUM-POM, where the 3-D field, the wave-induced mixing coefficient, is interpolated from the 3-D grid of MASNUM to the 3-D grid of POM on the processes for POM. Table 3 shows the time for the data interpolation, when gradually increasing the number of processes from 1 to 48. From Table 3, we can find that, the data remapping algorithm achieves good scaling performance.

5.6 Integration of a standalone component model version

We use the ocean model MOM4p1 to evaluate the work amount for integrating a standalone component model version onto the C-Coupler platform. To make the standalone version of the MOM4p1 run on the C-Coupler platform, we wrote 5 simple configuration files and only added less than 10 lines of source code to the main driver of the MOM4p1. When further coupling the MOM4p1 with other component models on the C-Coupler platform, about two code files for linking the parallel decomposition and coupling fields to the C-Coupler APIs need to be added.

6 Discussion of future developments

Now, the C-Coupler is ready for model development with its first version C-Coupler1. As the C-Coupler is a community coupler, we welcome more and more scientists and engineers to use it and contribute to it in various aspects, such as providing component models, coupled models, flux algorithms, model simulations, bug reports, etc. We wish more and more model groups will use the C-Coupler for model development. Any new requirement about the C-Coupler from scientists, engineers and model groups is possible to be considered into the future plan for the C-Coupler development. In China, there are more and more users of the C-Coupler, and more and more component models and coupled models integrated on the same C-Coupler model platform.

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As the first version, the C-Coupler1 does not achieve all targets of the C-Coupler. For the future versions of the C-Coupler, we will consider about at least the following several aspects:

1. Coupling generator. The C-Coupler1 does not provide the coupling generator, so as that the runtime configuration files for model simulations have to be written manually by users. We plan to develop the coupling generator in the C-Coupler2, the second version of the C-Coupler, and then the runtime configuration files can be generated automatically.
2. Single executable. The C-Coupler1 uses multiple executables for a coupled model. A typical problem of this approach is that the processor time will be wasted when the components do not run concurrently. The CPL7 coupler has demonstrated that, the approach of single executable with a top-level driver, which manages the processor layout and time sequencing between the components, can solve this problem so as to improve the overall parallel performance of the whole coupled model. For the future versions of the C-Coupler, we will think about how to achieve a similar top-level driver in a simple way, under the general design of the C-Coupler. For example, the top-level driver should be as simple as the main driver of the coupler component in the FGOALS-gc, as shown in Fig. 4.
3. Parallel performance optimization. As shown in Sect. 5.5, the parallel performance of the data transfer algorithm is not as good as the data remapping algorithm. For the future work, we will try to further improve the data transfer algorithm. Moreover, we will think about how to make the C-Coupler help improve the parallel performance of the whole experiment model, especially when the resolution of models gets higher and higher in future. For example, the C-Coupler will provide a parallel I/O library and the coupling generator will automatically improve the overall performance when generating runtime configuration files.
4. More functions. As demonstrated in Sect. 5, the C-Coupler1 is able to unify various standalone component models and coupled models onto the same model

platform. In order to unify more kinds of models onto the same model platform, the future versions of the C-Coupler will provide more functions to support one-way even two-way model nesting, interactive coupled ensemble (Kirtman and Shukla, 2002), etc. In addition, we will consider how to make the C-Coupler able to integrate various assimilation systems and diagnostic systems onto the same model platform.

5. More remapping algorithms. Recently, we merged the development of the CoR and C-Coupler together. The available 2-D remapping algorithms in the CoR are of low order currently. In future, we will develop more 2-D remapping algorithms with higher order, to provide more selections for model coupling and scientific researches. Moreover, we will consider developing some pure 3-D remapping algorithms in the CoR, such as the 3-D n-neighbor distance-weighted average and trilinear remapping algorithms used in the OASIS coupler, and compare them with the "2-D + 1-D" approach.

7 Conclusion

The C-Coupler1 is a parallel 3-D coupler, which achieves good parallel performance and bit-identical simulation result with different numbers of processes. Guided by the general design of the C-Coupler, the C-Coupler1 enables the same code of runtime software system and component models to be shared by multiple experiment models, and enables multiple experiment models to work on the same model platform. It can be used to construct a coupler component with a few lines of code for constructing a complex coupled model like CSM, and can also be used as direct coupling for better parallel performance of the whole coupled model. The C-Coupler1 is ready for developing CSMs and ESMs. In China, there are more and more models using the C-Coupler for development. Now we start to develop a uniform model platform which will integrate various component models, experiment models and model simulations together. We believe that the C-Coupler will help advance Earth System Modelling.

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Table 1. The APIs provided by the C-Coupler1.

Classification	API	Brief description
Main driver	c_coupler_initialize	This API initializes the runtime software system. A component model can obtain its MPI communicator with this interface.
	c_coupler_finalize	This API finalizes the Runtime software system.
	c_coupler_execute_procedure	This API invokes the runtime software system to run the corresponding runtime procedure which consists of a list of runtime algorithms specified by the corresponding runtime configuration files. The corresponding runtime procedure could be empty without any runtime algorithms. A component model can have multiple different runtime procedures.
Registration	c_coupler_register_model_data	This API registers a field of component model to enable the runtime software system to access the memory space of this field.
	c_coupler_withdraw_model_data	This API withdraws a field of component model from the runtime software system which has been registered before.
	c_coupler_register_decomposition	This API registers a parallel decomposition to the runtime software system. A component model can register multiple different parallel decompositions, even on the same horizontal grid.
	c_coupler_register_model_algorithm	This API registers an algorithm (also known as a subroutine) of a component model as an external algorithm of the runtime software system.
Restart function	c_coupler_do_restart_read	This API reads in the data value of fields in a restart run of model simulation.
	c_coupler_do_restart_write	This API writes out the data value of fields for restart run.

Table 1. Continued.

Classification	API	Brief description
Time information	c_coupler_get_current_calendar_time	This API gets the calendar time of the current step.
	c_coupler_get_nstep	This API gets the number of the current step from the start of the model simulation.
	c_coupler_get_num_total_step	This API gets the number of total steps of the model simulation.
	c_coupler_get_step_size	This API gets the number of seconds of the time step.
	c_coupler_is_first_restart_step	This API checks whether the current step is the first step of a restart run.
	c_coupler_is_first_step	This API checks whether the current step is the first step of an initial run, which also means whether the number of the current step is 0.
	c_coupler_advance_timer	This API advances the time of simulation.
	c_coupler_check_coupled_run_finished	This API checks whether the model simulation ends.
	c_coupler_check_coupled_run_restart_time	This API checks whether the current step is time for writing fields into I/O data files for restart run.
	c_coupler_get_current_num_days_in_year	This API gets the number of days elapsed since the first day of the current year.
	c_coupler_get_current_year	This API gets the year of the current step.
	c_coupler_get_current_date	This API gets the date of the current step.
	c_coupler_get_current_second	This API gets the second of the current step.
	c_coupler_get_start_time	This API gets the start time of the model simulation
	c_coupler_get_stop_time	This API gets the end time of the model simulation.
	c_coupler_get_previous_time	This API gets the time of the previous step.
	c_coupler_get_current_time	This API gets the time of the current step.
	c_coupler_get_num_elapsed_days_from_start	This API gets the number of days elapsed since the start time of the model simulation.
	c_coupler_is_end_current_day	This API checks whether the current step is the last step of the current day.
	c_coupler_is_end_current_month	This API checks whether the current step is the last step of the current month.

Table 2. The parallel performance of transferring the 3-D field wave-induced mixing coefficient from the MASNUM to the POM when changing the number of processes. Each process takes a physical CPU core.

Number of processes for the MASNUM	Number of processes for the POM	Time (seconds) for data transfer
1	1	0.147501
1	2	0.109173
2	1	0.126196
2	2	0.079122
2	6	0.054423
6	2	0.093099
6	6	0.035394
6	12	0.037981
12	6	0.04546
12	12	0.036984
12	24	0.040856
24	12	0.032871
24	24	0.030616
24	48	0.025566
48	24	0.021918
48	48	0.020783

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Table 3. The time (seconds) for interpolating the 3-D field wave-induced mixing coefficient on the POM when increasing the number of processes. Each process takes a physical CPU core. When the number of processes does not exceed 12, only one computing node is used.

Number of processes	1	2	6	12	24	48
Time	3.08	1.59	0.58	0.37	0.17	0.09

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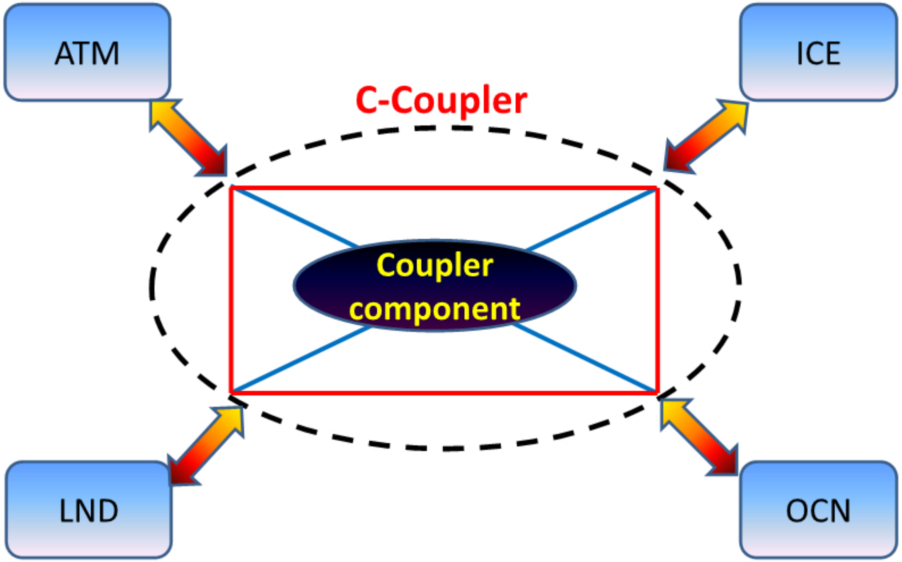

Figure 1. The architecture of the models with the C-Coupler.

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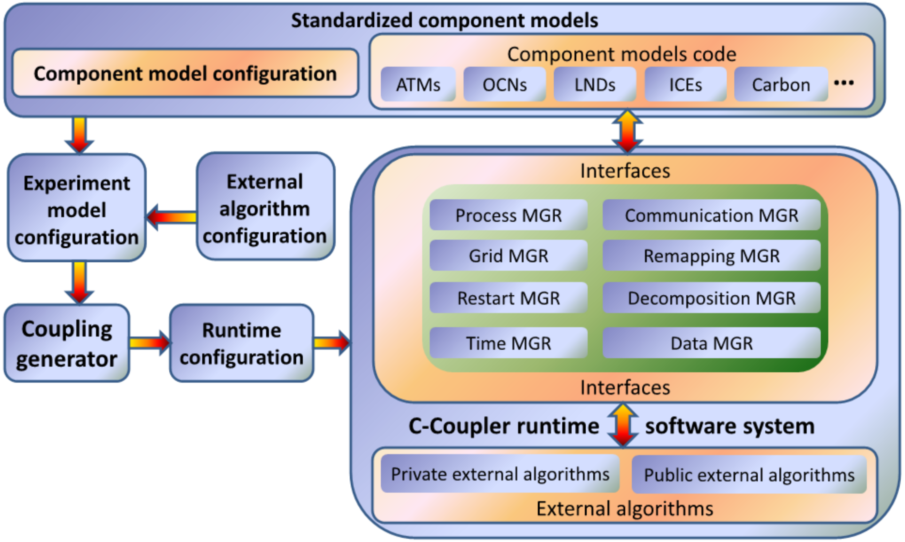

Figure 2. The general software architecture of the C-Coupler.

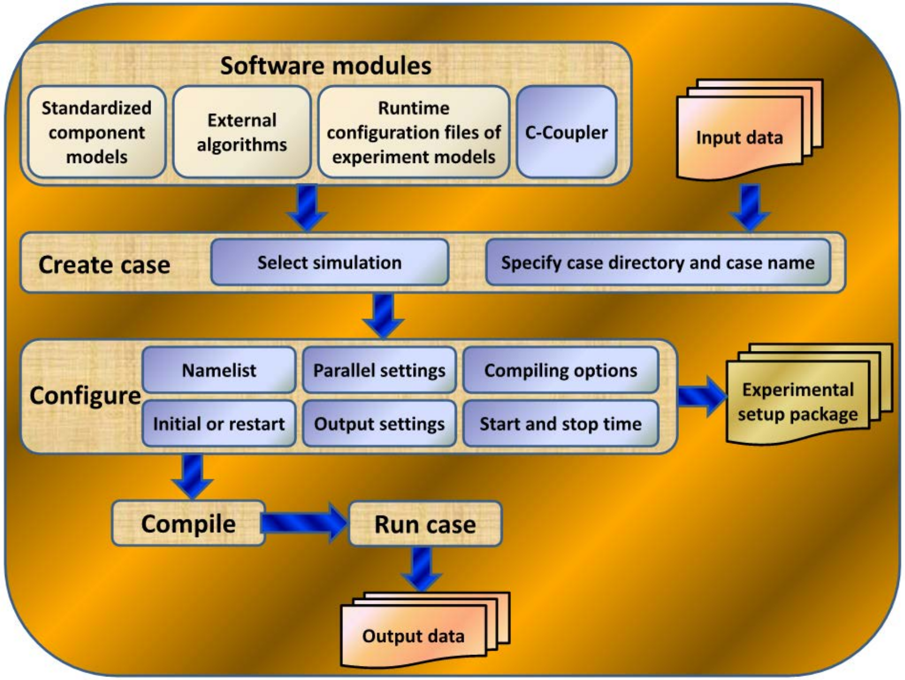

Figure 3. The general software architecture of the C-Coupler platform.

```
program cpl

   use cpl_read_namelist_mod
   use c_coupler_interface_mod

   implicit none
   integer comm

   call c_coupler_initialize(comm)

   call parse_cpl_nml

   call c_coupler_execute_procedure("calc_frac", "initialize")
   call c_coupler_execute_procedure("sendalb_to_atm", "initialize")
   call c_coupler_execute_procedure("check_stage", "initialize")
   call c_coupler_do_restart_read
   if (c_coupler_is_first_restart_step())  call c_coupler_advance_timer

   do while (.not. c_coupler_check_coupled_run_finished())
      call c_coupler_execute_procedure("kernel_stage", "kernel")
      call c_coupler_do_restart_write()
      call c_coupler_advance_timer()
   enddo

   call c_coupler_finalize()

stop
end program cpl
```

Figure 4. The code of the main driver of the coupler component in the FGOALS-gc. The C-Coupler APIs are marked in blue.

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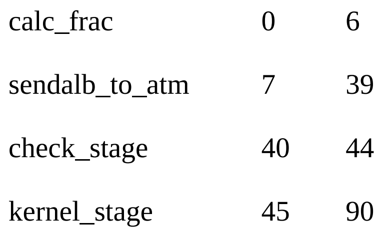
```
transfer       runtime_transfer_cpl_a2c_areac_recv.cfg
transfer       runtime_transfer_cpl_o2c_areac_recv.cfg
transfer       runtime_transfer_cpl_i2c_areac_recv.cfg
normal         frac_init_step1.cfg
remap          frac_init_remap.cfg
normal         frac_init_step2.cfg
transfer       runtime_transfer_cpl_c2lg_2D_send.cfg
transfer       runtime_transfer_cpl_r2c_areac_recv.cfg
normal         areafact_init.cfg
transfer       runtime_transfer_cpl_i2c_2D_recv.cfg
transfer       runtime_transfer_cpl_l2c_2D_recv.cfg
transfer       runtime_transfer_cpl_o2c_scalar_recv.cfg
transfer       runtime_transfer_cpl_o2c_2D_recv.cfg
transfer       runtime_transfer_cpl_a2c_2D_recv.cfg
normal         areafact_o2c.cfg
normal         areafact_i2c.cfg
normal         areafact_a2c.cfg
normal         areafact_l2c.cfg
normal         areafact_r2c.cfg
remap          runtime_remap_Xr2c.cfg
```

Figure 5. Part of the runtime configuration file of the algorithm list for the coupler component in the FGOALS-gc. The first column specifies the type of each runtime algorithm. *Transfer* specifies the data transfer algorithms, *remap* specifies the data interpolation algorithms, and *normal* specifies the external algorithms. The second column specifies the configuration file of each runtime algorithm.



```
calc_frac          0      6
sendalb_to_atm     7      39
check_stage        40     44
kernel_stage       45     90
```

Figure 6. The runtime configuration file of the runtime procedures for the coupler component in the FGOALS-gc.