SC-ESAP: A Parallel Application Platform for Earth System Model *

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Abstract
The earth system model is one of the most complicated computer simulation software in the human development history, which is the basis of understanding and predicting the climate change, and an important tool to support the climate change related decisions. CAS-ESM, Chinese Academy of Science Earth System Model, is developed by the Institute of Atmospheric Physics(IAP) and its cooperators. This system contains the complete components of the climate system and ecological environment system including global atmospheric general circulation model(AGCM), global oceanic general circulation model(OGCM), ice model, land model, atmospheric chemistry model, dynamic global vegetation model(DGVM), ocean biogeochemistry model(OBM) and regional climate model(RCM), etc. Since CAS-ESM is a complex system and is designed as a scalable and pluggable system, a parallel software platform(SC-ESSP) is needed. SC-ESSP will be developed as an open software platform running on Chinese earth system numerical simulation facilities for different developers and users, which requires that the component models need to be standard and unified, and the platform should be pluggable, high performance and easy-to-use. To achieve this goal, based on the platform of Community Earth System Model(CESM), a parallel software application platform named SC-ESAP is designed for CAS-ESM, mainly including compile and run scripts, standard and unified component models, 3-D coupler component, coupler interface creator and some parallel and optimization work. A component framework SC-ESMF will be developed based on the framework SC-Tangram for the more distant future.

Keywords: parallel computing; earth system model; software platform; CAS-ESM

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1 Introduction

In the past decades, climate simulation has achieved great success. It has been able to provide effective climate prediction and forecasting information. However, as the climate change and its impact intensifies, people and the decision makers from all over the world are demanding more accurate global and local forecasting information. Therefore, countries, including the United States, the European Union and Japan, are formulating strategies to boost the development of Earth System Model and its dedicated high performance computer system. Alliance and unification are encouraged to meet the need of the country and to stay competitive around the world. Edwards [9] deeply discussed the concept of fundamental infrastructure and software being the computing platform. From a decade ago, scientists have realized the benefit of sharing the developing software platform among different research groups of Climate Model, for instance, the Community CESM [5, 10, 3], previously named as CCSM, and its Coupler (CPL) [13, 2] developed by NCAR, the Flexible Modeling System (FMS) from Geophysical Fluid Dynamics Laboratory (GFDL), OASIS [11] from Europe and the Earth System Modeling Framework (ESMF) [17] introduced the concept of ultra-architecture, in which a component-based way of composition is used [1, 8].

China has been actively developing Earth System Model [15]. In 2013, we(IAP, ICT, CNIC, SUGON) proposed the project named the earth system numerical simulation facilities into the national long-term guideline of national major scientific and technological infrastructure construction projects (2012-2030). Within this project, not only the dedicated high performance computers will be established but also the Chinese Academy of Science Earth System Model (CAS-ESM) as well as the supporting software platform(SC-ESSP) will be developed. The CAS-ESM contains whole climate system and ecological environment components. It integrates Atmospheric Model, Ocean Model, Seaice Model, Land Model, Atmospheric Chemistry and Aerosol Model, DGVM, OBM and WRF [4]. In addition, Space Weather Model(SWM) will be added to the system in the future. Also, the coupling between different pairs of component models will be realized. Therefore, the simulation research of Atmosphere, Current, Land Surface Procedures and Ecology will be more accurate. In order to promote the alliance, unification and cooperation of distributed research of Earth System Model and the sharing of simulating infrastructure in China, the supporting software platform need to provide convenient coupling, matching and compiling processes. A fast and convenient plan to tackle the problem is to establish SC-ESSP based on CESM, which is named as SC-ESAP. Since the component models are demanded to be plugged in and out dynamically, the total number of component models will be larger than it is in CESM. Also, the number is not the same in different tests. Thus, using the original CESM as the framework will be insufficient for the following reasons. First, CESM does not support component models such as WRF. Since there is no interfaces for them, new interfaces should be developed for them. Second, for a particular component model, interface may be inappropriate if the coupling variables change. Also, for a particular component model, the different combination of models may require different coupling variables. In addition, CESM does not support 3-D coupling. The code of the component models are different for different combination, which causes that there are several editions of models and thus it limits their development and feasibility of sharing. Besides, it is complicated to use CPL7 and MCT, because interfaces need to be altered manually to adjust the component model. It is a tedious work and only experts are able to complete it. At last, CESM does not support dynamically plugging, which is unable to fulfill various users’ demand. Therefore, we design a 3-D coupling component to support 3-D coupling, an auto-creator for coupling interfaces to create different interfaces, and to standardize and unify the component models. Correspondingly, the
compilation script and file system will be expanded and improved. Moreover, we are keen on
developing components like Earth System modeling framework based on SC_TANGRAM [6], a
general purpose framework.

The rest of this paper is organized as follows. Section 2 gives a brief introduction of CAS-ESM and SC-ESSP. Section 3 to Section 6 introduces our main work about SC-ESAP. In Section 7, some discussions are given and some results of simulation of CAS-ESM are illustrated.

2 Model and Platform

The CAS-ESMv1.0 is designed and developed based on the CESM version 1.0. The CAS-ESM [12] is composed of seven separate component models and one central coupler component. It can be employed to conduct fundamental research for the Earth’s climate states. In the CAS-ESM system, in addition to the original component models of CESM, some models developed by Chinese researchers are added, for example, IAP AGCM4.0 [16] is an atmospheric model developed by the IAP, LASG/IAP Climate System Ocean Model (LICOM) [7] Version 2.0 is an ocean model developed by the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) of the IAP, the Common Land Model (CoLM) is a land component model developed by Beijing Normal University, the DGVM [18] is a model developed by IAP, the Global Environmental Atmospheric Transport Model (GEATM) is an atmospheric chemical component model developed by the IAP, and the Ocean Biogeochemistry General Circulation Model(OBGCM) is ocean biogeochemistry model developed by IAP. The Advanced Research WRF version 3.2 is put into the CAS-ESM modeling system. In the future, more component models will be added to the CAS-ESM platform. The model structure of the CAS-ESM system is presented in Figure 1. The models in dotted ovals are optional. The

SC-ESSP is the supporting software platform for the earth system model CAS-ESM, including SC-ESAP and SC-ESMF. SC-ESAP is a simple platform based on CESM for short-term demands of CAS-ESM, and SC-ESMF is a componentized framework based on run-time system for long-term goals. The major work of SC-EASP will be discussed in this paper. Some already-equipped functions of CESM are employed in CAS-ESM, such as MCT and cpl7, parallel I/O, MPI Communication Library, Compilation Scripts, etc.. Moreover, a 3-D coupling method for some component models such as WRF and GEATM is introduced in the system. Also a coupler interface creator is developed for easily plugging new models to the CAS-ESM and realizing different combinations of the models on one unified platform. The structure of SC-ESSP is shown in Figure 2.
3 Compilation Scripts

Compilation scripts file system is a complex and important part in CAS-ESM. It provides the integration of a variety of component models and the functions of the user interface. At the same time, compilation scripts file system also has the function of unified version and model extension. This scripts file system references the structure of CESM similar system and adds some new component models and functions.

3.1 Structure of Compilation Scripts File System

Scripts are written with Perl and Shell. As is shown in Figure 3, there are two main modules which are shared-compilation-scripts module and component-compilation-scripts module. Shared-compilation-scripts module is used to control the compilation process and copy other scripts and configuration files. Users can create new cases, configure and build their cases by calling these scripts. Besides, component compilation scripts are independent compilation scripts of each component model. For CAS-ESM developers, they need to write these scripts to copy namelists and save configuration information of each component model. The XML format file which is called and analyzed by scripts is used in the system to set related variables. Users can change the configuration of their case just by modifying these XML files.

3.2 Addition of A New Component Model

CAS-ESM is an extensible platform for the earth system model. Users can add a new component model to CAS-ESM by the following steps.

Firstly, shared-compilation-scripts module should be modified to support the new component model. On one hand, users need to add some new component sets to config_compsets.xml and some new grids to config_grid.xml. This new component model may be used by these component sets and grids. Other environment variables which are used by this new component model can be added in config_definition.xml. As ConfigCase.pm is used to read and parse these xml files, it should also be modified to add some group variables. On the other hand, users
should modify script `create_newcase` to copy the new component compilation scripts and other new component xml files. If this new component model needs to change some environment variables before configuration, try to modify configure script file.

Secondly, component-compilation-scripts module should be written by users. `$component.cpl7.template` is the most important component compilation script file which is used for creating namelist script, creating build script, reading and parsing component xml file. Definition files are some XML files which define some variables like processor division, supported blocks division and so on.

Of course, the model added to the CAS-ESM should be firstly unified for different combinations. There are several kinds of component models which are atmosphere, land, ocean, sea ice, land ice and regional model, etc. After our work, all these parts can be freely combined with active models and optional or data models.

## 4 3-D Coupling Component

The current CAS-ESM system employs CPL7 to complete the coupling processes between different component models. Model Coupling Toolkits (MCT) are used to provide functions for transferring data between different models through coupler. With proper interfaces, component models can be easily plugged in to the whole system. However, in the current implementation of CAS-ESM, some coupling procedures, such as the coupling between AGCM and WRF, involve 3-D data coupling. In the cases of 3-D couplings, CPL7 only plays as a role of data communicating tool, pushing the coupling data from one component to the other without the necessary processing of it. The processing procedures of data are integrated in the component models. For instance, in the case of WRF, there is a pre-processing module that handle the received data to adjust it into the form that WRF needs. Therefore, the current mechanism of 3-D coupling is inefficient and we are working on the optimization.

The current implementation of CAS-ESM that uses CPL7 to complete 3-D couplings needs to
be altered and the 3-D couplings should not be using CPL7 any longer. CPL7 is not appropriate for the following reasons. Here, the coupling of AGCM-WRF is taken as an example. First, there are unnecessary steps caused by using CPL7 for 3-D coupling in the current implementation. The data processing steps in CPL7 are redundant since WRF has its own pre-processing step to handle the raw data received from coupling. In addition, because of the huge size of 3-D data, the converting and processing procedures could involve enormous calculation. Moreover, the model of WRF itself contains mass integral computation. Thus, it is unwise to put two modules with mass computation together in a particular component. The more concentrated the load is, it is more likely to cause load imbalance which leads to inefficiency.

The plan of optimization is to introduce a new dedicated coupler component for 3-D couplings. The 3-D coupler will be based on MCT and it will be serving as a component of the earth system. With the 3-D coupler set up, the pre-processing procedures of WRF will be moved into the 3-D coupler’s module. Therefore, the workload of WRF component will be spread to the 3-D coupler. In addition, in this way, the 3-D coupler and component model are able to run concurrently in a pipeline to achieve higher efficiency.

Figure 4 illustrates the coupling flow of 3-D coupling using the newly introduced 3-D coupler. As is shown, the pre-process steps (METGRID and REAL in the figure) of WRF is completed by the 3-D coupler. Thus, the mass computational work of mapping and rearranging of 3-D data is separated from the integration, which also contains heavy computation work. Since the 3-D coupler and WRF employ distinct computational resource, ideally, the pre-process and integration can be run concurrently in a pipeline. In this way, higher efficiency can be achieved because of higher level of parallelism and less load imbalance. In current implementation of CAS-ESM, the direct 3-D coupling of AGCM-WRF has been realized when AGCM and WRF are of the same processor decomposition. According to test results, the time of the communication step between AGCM and WRF has been reduced by almost 50%. The coupling of AGCM-WRF with different processor decomposition is under development. In this plan, a new component, serving as the exclusive 3-D coupler between AGCM and WRF. Also, the processors that AGCM and WRF use are none overlapping. The communication are realized by calling communicating functions among the combined communication group of AGCM and 3-D coupler as well as the one of WRF and 3-D coupler. Thus, theoretically, AGCM and WRF can run concurrently.
5 CAS-ESM Coupler Interface Auto-creator

Coupler is an important part of the Earth System Model for model development. It connects several separate interoperable component models in order to simultaneously simulate the variations of components models and interactions among the atmosphere, land surface, oceans, sea ice and other components of the climate system. However, CESM does not include WRF and other component models like DGVM. CAS-ESM is composed by component models which are inserted into CESM with the CPL coupler interface. However, when component model experts add component models into CAS-ESM, they not only need to read coupler interface but also to understand the complex internal coupler of the system, the repeated work of which can be replaced by automation.

Three parts need to be automatically generated. Firstly, the file under the name of ccsm_comp_mct.F90 is the top level of coupler. It includes many component models attributes such as MCT global segment maps and control flags, and some functions which would call middle level functions. Secondly, the middle level consists of functions such as mapping and merge. The number of mapping and merge functions depends on the number of component models. Different from top level coupler, component models from mapping function needs to interact with other models; as that from merge function, it needs to gather some models. Thirdly, the active module coupler of any component models needs to be automatically generated although models are in endless variety.

In order to generate codes automatically, three methods have been proposed. Firstly, reusing the duplicate codes so as to get unification codes into template files, and replace different attributes with labels like “{}”. An annotation line under label “{list}” in front of the special labels exists to prompt users. Secondly, User configuration files are provided to component model experts to fill up the corresponding contents of variables including the kind of arrays which covers component model attributes. One-dimensional array can be used to replace top level label from template files and loop traversal. Mapping and merge functions would require multi-dimensional array. Both one-way and two-way nesting exist in mapping, so the array includes one component model, another component model and their nesting directions. One component merges with one or more others, so the lengths of each array element will not be the same. Dictionary which consists of mapping instead of array benefits merge variable expressions. Thirdly, the contents being replaced by arrays provided by user configuration files from the special labels in the template files can be inserted into final codes, to complete automated generation. Python programming language with regular library can be used to complete replacement. Moreover, XML inserting modules are provided for experts to insert special codes which cannot get from template files.

In addition, in this way, the codes can be automatically generated when component model is accessed to CAS-ESM coupler. This would then benefit component model experts in a way that they need only to fill user configuration files rather than to understand the complex internal coupler of system.

6 Model Optimization Work

The timeliness and accuracy of the models are equally important in the practical simulation. The integrated CAS-ESM has higher computational complexity, so some work are done to improve the parallel efficiency. The followings are some of them.
The original IAP AGCM4.0 uses one-dimensional domain decomposition method, which prevents it from running on more than dozens of CPU cores. The computation of the physical process in the IAP AGCM4.0 needs to use related data on the grid points in the vertical direction $k$ and has to be done in sequence. Therefore, the computation task of the physical process can be decomposed in the horizontal direction. The computation of the dynamic core on each grid point needs to use not only related data on the grid points in the vertical direction $k$ and direction $j$ of longitudinal circle but also related data on the grid points in the direction $i$ of latitudinal circle. Meanwhile, a part of the computation in the direction $i$ or $k$ needs to be done in sequence. To solve this, the hybrid 2-D decomposition method is used. When the computation in the direction $i$ needs to be done in sequence, the global domain is decomposed by latitude and vertical level, as is shown in Figure 6 left. When the computation in the direction $k$ needs to be done in sequence, the decomposition way of the task is shown in Figure 6 right. Obviously, it is necessary to convert the data from a kind of decomposition way to another one during the whole computing of the dynamical core.

After the two-dimension domain decomposition for the IAP AGCM4.0, it can scale reasonably to more than 1000 CPU cores. To evaluate parallel performance of the IAP AGCM4.0, an ideal climate simulation experiment for 61 model days is designed to run on Sugon cluster. In this case, the computing time of the IAP AGCM4.0 is shown in Table 1. The result indicates that the parallelization of the IAP AGCM4.0 with MPI reduces the computing time of 2787.82 seconds on 32 cores to 739.07 seconds on 256 cores, for a speedup of about 3.8. But the computing time on 512 cores begins to increase.

### 6.2 Solving load imbalance of METGRID

During assessing the feasibility and capability of the CAS-ESM in simulation, it is found that the METGRID module of the WRF in the CAS-ESM exists the load imbalance. It is very crucial...
for improving real-time computation performance of the CAS-ESM to solve the METGRID load imbalance and improve its processing speed for massive data. The idea of the optimizing algorithm is that each process stores the traversal record of executing the first for-loop code for all the vertexes before the search\textunderscore extrap (a function of the METGRID module) is called for the first time. When the search\textunderscore extrap is called later, each process reads the traversal record instead of executing the first loop again [14]. In this way, the total amount of the first loop in the search\textunderscore extrap can be decreased effectively. Then, the problem of the load imbalance is solved effectively.

In the 5 days of simulation for the CAS-ESM, 64 CPU cores are used to compute firstly. Figure 7 illustrates the METGRID running time of all the 64 MPI ranks before and after the optimizing. The computing speed of the METGRID after the optimizing is about 10 times faster than before and the total computing time of the CAS-ESM with WRF decreases to 1/3.

![Figure 7: Comparison of the Run Time for each MPI Rank Before and After Optimization](image)

### Table 1: Computing time (s) of the IAP AGCM4.0 with default decomposition

<table>
<thead>
<tr>
<th>Nodes(Cores)</th>
<th>AGCM($P_y \times P_z$)</th>
<th>Computing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2(32)</td>
<td>$32 \times 1$</td>
<td>2787.82</td>
</tr>
<tr>
<td>4(64)</td>
<td>$32 \times 2$</td>
<td>1577.49</td>
</tr>
<tr>
<td>8(128)</td>
<td>$32 \times 4$</td>
<td>1038.58</td>
</tr>
<tr>
<td>16(256)</td>
<td>$32 \times 8$</td>
<td>739.07</td>
</tr>
<tr>
<td>32(512)</td>
<td>$32 \times 16$</td>
<td>775.03</td>
</tr>
<tr>
<td>69(1092)</td>
<td>$42 \times 26$</td>
<td>1519.98</td>
</tr>
</tbody>
</table>

### 6.3 An improved grid decomposition algorithm for LICOM

The Ocean model LICOM is a very important component model in CAS-ESM. Figure 8 shows the original and the improved grid decomposition methods of LICOM. Here, $N$ is grid number, $np$ is MPI process number, and $n$ equals to the greatest integer no more than $N/np$. In the original method, $N - (n+1)*(np-1)$ should be bigger than zero, so the MPI process number $np$ is limited. The improved method let the grids divide equally to the MPI processes and spread the rest grids evenly to several processes, which can expand the process number limitation.
7 Result and Discussion

7.1 Long-term Climate Simulation

This experiment is setting up with pre-industrial (1800 AD) climate forceings. CAS-ESM is spun up for 50 years. To ensure the continuity of the climate system, we select the data from years 11-50 for analysis. Annual mean 2-meter air temperature and sea surface temperature (SST) are displayed in Figure 9 (a) and (c). It is shown that the simulation result is consistent with the Japanese 25-year reanalysis (JRA-25) dataset and Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST).

![Figure 9: Comparision of The Model Simulation Result and Observation](image)

7.2 Torrential Rainfall Simulation

To evaluate the coupling performance of the CAS-ESM with WRF, the paper uses the CAS-ESM to simulate the extreme precipitation event over Beijing on 21 July 2012 (00:00 UTC 21 July 2012 to 00:00 UTC 22 July 2012). The $1^\circ \times 1^\circ$ resolution National Centers for Environmental Prediction Final analysis (NCEP-FNL) data at 12:00 UTC 20 July 2012 is used to provide the
initial conditions. Figure 10 shows the daily-accumulated rainfall in the simulation, which is close to the observation. It means that the CAS-ESM can be used for the regional weather forecast.

Then, the simulating results for the CAS-ESM with the default decomposition strategy on 64, 128, 256, 512 and 1024 CPU cores respectively are analyzed to test the scalability of the system. Comparing with the 64 CPU cores, the parallel efficiency of the CAS-ESM on 1024 CPU cores can reach about 70% when the grid size of WRF is $1024^3$, as shown in Figure 11. On the whole, the CAS-ESM has desirable parallel performance and strong scalability.

Figure 10: Daily-accumulated Rainfall in the Simulation

Figure 11: Parallel efficiency and Speedup of the CAS-ESM with different grid scales.

7.3 Discussion and conclusion

We have established a software platform SC-ESAP for the earth system model CAS-ESM based on CESM for the purpose of multi-disciplinary crossing research and collaboration development. In SC-ESAP, a compilation script referencing the CESM system is designed for the CAS-ESM, the CPL7 interface is used and modified as 2-D coupler and a new 3-D coupler is developed based on MCT, a coupler interface auto-creator is finished to decrease the operational difficulty of adding a new component models into CAS-ESM. Finally, CAS-ESM is constructed with SC-ESAP and some parallel optimization algorithms are developed to improve its computational efficiency. However, there are a lot of places need to be improved such as standardization flow of 3-D coupler and coupler interface auto-creator, synergy development among compiler scripts, coupler and coupler creator, more experiments to verify its validity and robustness, etc. There is some advanced software platform technology can be introduced for CAS-ESM.
We have started the work to build the component like Earth System modeling framework based on SC-TANGRAM. The current component models need to be reconstructed and it is a challenging and long-term work.

References