A View of Earth System Model Development*

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ABSTRACT

This paper describes the three phases involved in the development of Earth System Model (ESM), from physical climate system model (the fundamental phase) to earth climate system model (the transitional phase) and finally to ESM (the prototype phase), based on reviews of existing literature. The authors emphasize the strategic significance for establishing the ESM and introduce some scientific research plans on the development of ESM at home and abroad. They also provide a perspective on the future development of ESM based on current status and trends of the models that participated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), with the hope to guide future development of ESM in China.

Key words: physical climate system model, earth climate system model, Earth System Model (ESM)

1. Introduction

Earth System Model (ESM) is an important tool to understand the evolution of past and current climate and environment and to predict global climate change in future. Over the past century, earth climate has experienced a noticeable change mainly characterized by a global warming. This change has had evident impacts on ecological environment, and contributed to rising sea-level, melting of glacier and Arctic sea-ice, shrinking lakes, decreasing river runoff, shortening and even disappearance of river-flow paths, increasing mudslides and landslides, intensifying desertification, and so on. Global warming has also led to an increase in frequency and intensity of extreme weather and climatic events, such as drought, heavy rainfall, hail, lightning, windstorm, heat waves, and severe cold weather. Weather and climate disasters have happened more frequently in China, as well as all over the globe.

To protect our ecological environment from further deterioration and to reduce losses caused by weather and climate disasters, it is imperative to conduct research in order to understand the causes and mechanisms of global changes, to project future trends, and to establish corresponding adaptation measures. In this regard, a key to success is to improve our understanding of the complex interactions among various spheres of the earth system, namely the atmosphere, hydrosphere, lithosphere, cryosphere, and biosphere. As such, the ESM that couples all the spheres has become one of the most important research tools. Under the influence of the most complicated underlying surface conditions, the East-Asian monsoon climate has its unique features and distinct regional characteristics, which has a far-reaching influence on global climate changes. At the same time, the complicated land-sea configuration and the highest plateau, the Tibetan Plateau, challenge numerical modeling of East-Asian climate, making it the Gordian Knot in climate simulation (Yu et al., 2000; Kang et al., 2002; Wang et al., 2005). Therefore, it is particularly important to expedite the development of ESM that has a focus on the East-Asia climate.

ESM is an important platform to integrate interdiscipline research in earth sciences. It is a milestone for earth system science and its development, and a nation's modeling capability has become one of the important criteria to evaluate general earth science research of that country. ESM is widely related

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to various research subjects; not only is it involved in all subjects of earth sciences but also closely related to computing science. In another word, the existence and ability of ESM in a country not only reflects its research ability in earth sciences but also shows its comprehensive capability in science and technology. Therefore, as one of the countries with acclaimed academic renown both in earth sciences and in science and technology, China should naturally recognize and develop its own ESM.

2. De¯nition of Earth System Mo del

What is ESM? Until now, there has been no clear definition of ESM. At the beginning of the 21st century, with infiltration and confluence of various branches of earth sciences, the concept of earth system emerged and the notion of ESM was put forward. Because the earth system takes the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere as a whole, some old research methods and techniques could no longer meet the need of modern scientific research of the earth system. To understand the interaction among various spheres, which is the most important characteristic in earth system evolution and a key issue in earth system sciences, it is imperative for the earth system researchers to develop a numerical model that could reflect such an interaction among the various spheres. This model is the ESM as we understand. Based on the dynamical, physical, chemical and biological processes of the earth system, a series of mathematical equations (including dynamic equations and parameterized schemes) are used to quantify these spheres and their interaction. These equations compose the mathematical-physical model of the earth system, which are then solved numerically by computers through a large comprehensive computing program. This program provides an important scientific tool for modeling and predicting complex behaviors and processes of the earth system, which we call ESM. Because of the complexity of the earth system, this program requires large memory and fast computing speed, and it could only be performed on the most advanced high-performance computer. Japanese scientists used their "Earth Simulator" to represent the combination between the ESM and high-performance computer, which has been used as a basic tool for scientific research and an important platform for interdiscipline studies and collaborations among various branches of earth system sciences.

The development of ESM could be divided into three phases: a fundamental phase, a transitional phase, and a prototype phase. We are presently in the fundamental phase, that is, the model is a physical climate system mode1, which mainly incorporates earth's fluids (the atmosphere and ocean) and only takes into consideration the physical processes on earth's surface to represent a part of the solid earth. In the transitional phase of the next 5–15 years, the model will include atmospheric chemistry, biogeochemical processes (both on land-surface and in ocean), and humanistic processes in the physical climate system model. The model will have the ability to describe carbon and nitrogen cycles quantitatively. However, application, evaluation, improvement and perfection of the physical climate system model will still be one of the foci during this phase. In the final prototype phase, the model will further take into account the interaction among the earth climate system, solid-earth processes (earthquakes, volcanic eruptions, tectonic movement and geomorphological change) and space weather. The model in this phase is a comparatively complete numerical model–the so-called ESM.

The commonly mentioned "climate system model" is actually the "physical climate system model," which is the most rudimental part of ESM. The present so-called ESM should be referred to as the "earth climate system model." If the purpose of developing the physical climate model is to understand the physics of interactions among various spheres, then the purpose of developing the earth climate system model should be to investigate the rules of the energetic, ecological, and metabolic processes of the earth by studying the exchange of energy, momentum and mass among the atmosphere, land-surface and ocean, and to unravel the climate responses to changes of land-surface cover, land use and greenhouse gas emission through these processes. In particular, we should pay attention to the roles of the biogeochemical coupling processes of carbon, nitrogen and iron cycles in climate system and to the influences of human activities on these cycles and on climate change. However, the real significance of developing ESM is that scientists can then study not only the aforementioned issues more objectively but also any problems related to geography, geophysics, earth-surface physics and chemistry, and even probe quantitatively the interactions among earth fluid motions and solid earth processes and the impact of space weather on earth system.

With the supplement to the sketch of ESM (Brasseur, 2002‡), a more complete schematic diagram of ESM is provided in Fig. 1. It is basically composed of five functional modules: physical climate system (light blue), biogeochemical system (saffron yellow), humanistic (or social scientific) system related to human activities (purple), solid earth (dark blue), and space weather related to solar activities (red). The influences of solid earth and space weather are simplified in the physical climate system model and the earth climate system model with known information as unilateral forcing, which could be described objectively only in ESM.

As shown in Fig. 2, different scientific issues are focused on in each of the three phases of ESM. In the first phase of physical climate system model, the key scientific issues investigated through the coupling of air-sea-land-ice in numerical models are the mechanisms of their interactions, of which the most representative progresses have been achieved in the past 20 years. In the second phase of earth climate system model, models are expected to help scientists to understand the impacts of biogeochemical processes and human activities on and their responses to global climate change, and to study the mechanism of carbon and nitrogen circles, etc., as well as their roles in the evolution of the climate system, by including biogeochemical and humanistic processes into the physical climate system model. In the final phase, i.e., the phase of ESM, the model development will focus on the interactions among the processes inside the solid earth and the earth climate system, and the impacts of solar-activity variations. The purpose is to understand underlying laws and impact factors of the earth system more comprehensively and objectively.

The processes included in ESM are much more comprehensive and complicated than those in present climate system models. The integrated physical, chemical and biological processes cover almost all the major research branches in earth sciences. At the same time, model development is highly related to technology development of the hardware and software of computers, which is a huge engineering undertaking that could not be completed by one person, one team, or even one institute. At present, ESMs have been developed under massive research projects that are supported either nationally or internationally by an alliance of countries, such as the European Union.

3. Current status of major projects on ESM

From the perspective of scientific advancement, the rudiment of ESM—the physical climate system model—has been a hot topic of international frontier research during the past 20 years. The developed countries, one after another, established various research projects of climate system models and so-called ESMs by injecting huge funds. These projects, on the one hand, focused on the influences of global changes on human and the mechanisms at work, and on the other hand, provided refined forecasts of atmospheric-oceanic environment, which are used by military as well.

The coupled climate system model is a rudimental form of ESM. Development of the coupled climate system model is a cornerstone of the Climate Variability and Predictability (CLIVAR) project under the World Climate Research Program (WCRP), whose main aim is to describe, simulate, and predict global climate variations on timescales ranging from seasonal to interannual, decadal and centennial. For this purpose, the WCRP Joint Scientific Committee (JSC) and the CLIVAR Scientific Steering Group (SSG) have jointly

‡Brasseur, Guy P., 2002: Past Accomplishments and Vision for the Future. The Max Planck Institute for Meteorology, PPT, 85 pp.

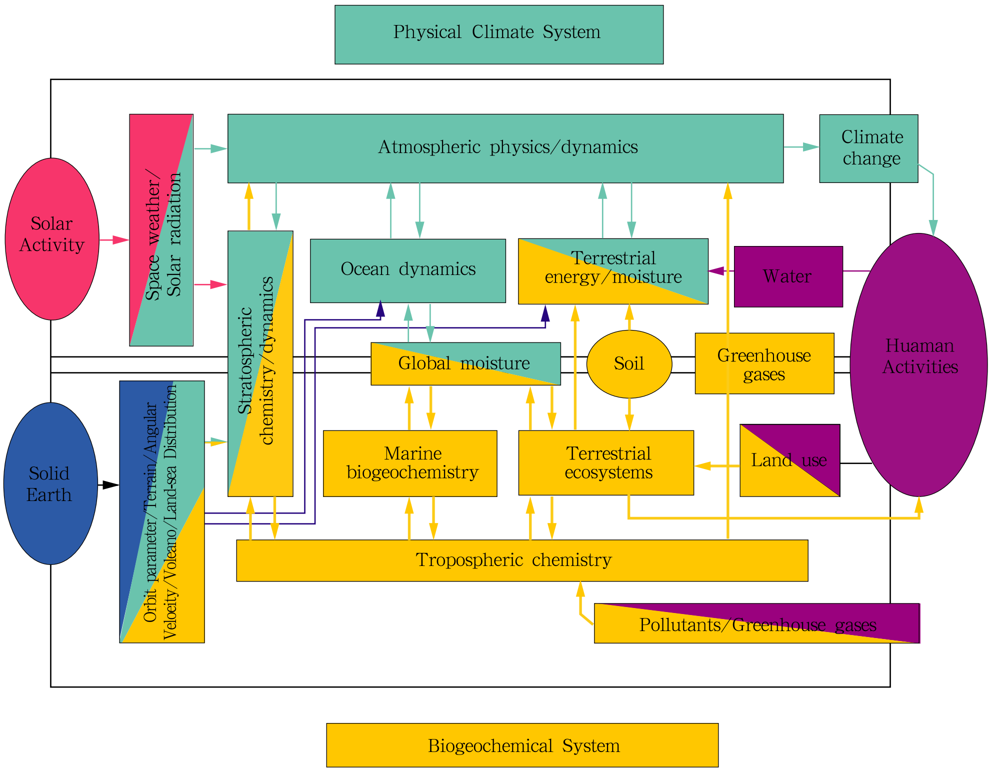

Fig.1. Schematic diagram of Earth System Model.

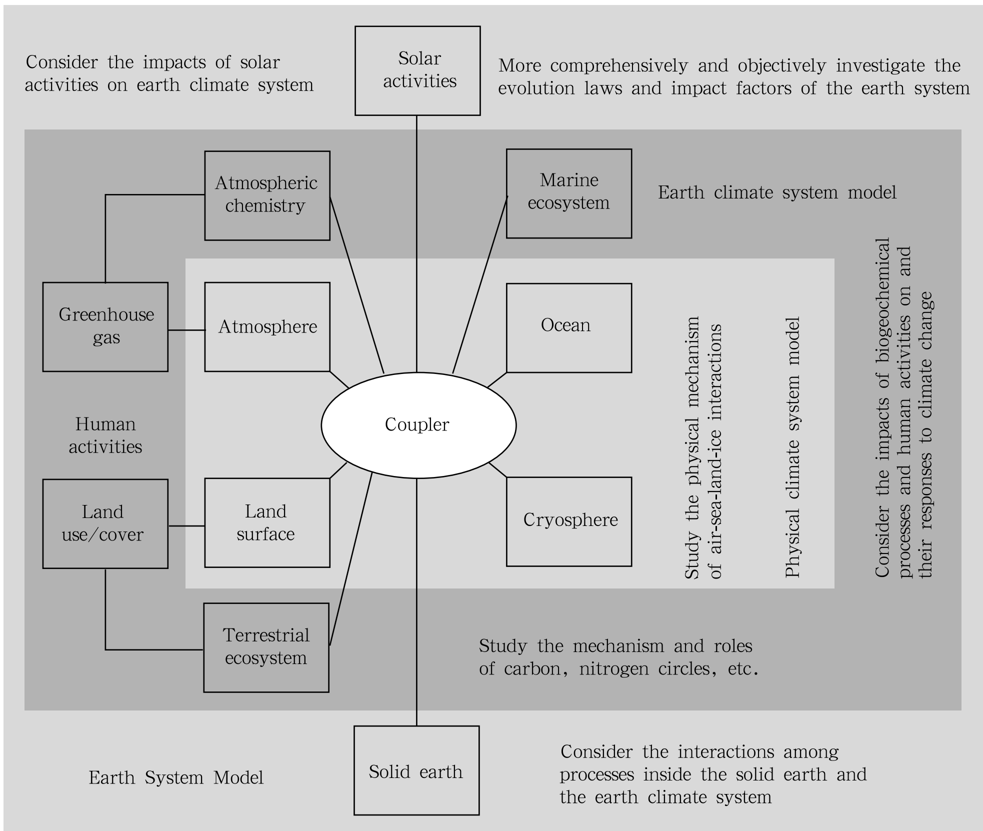

Fig.2. Framework of Earth System Model and related scientific issues.

constituted the WCRP/CLIVAR Working Group on Coupled Modeling (WGCM). On the one hand, it aims to evaluate and support the development of the coupled climate system model, including organization of model intercomparison (e.g., the Coupled Model Intercomparison Project, CMIP), which is the basis for model validation and diagnosis. On the other hand, it aims to expedite coordinated research and experiments of the coupled models in order to obtain more reliable projections of climate system responses to natural and anthropogenic forcing. It is apparent that the great importance of the coupled climate system model is widely recognized. In particular, some developed countries established research plans, one after another, and input huge funds and human resources to develop their own climate system models. Because most existing climate system models only took the dynamics and physical processes of the earth climate system into account, ignored the biogeochemical processes and humanistic system, and did not embody the interaction among solid earth processes and climate system nor the influence of space weather, they were limited in simulating the mechanisms and causes of global changes and predicting future changes. Therefore, development of ESM has become the mainstream in the field of coupled models and one of the main scientific targets for countries around the world.

The National Center for Atmospheric Research (NCAR), under the auspice of the US National Science Foundation (NSF) and the Department of Energy (DOE), put forward "Community Climate System Model" (CCSM, 2001–2005) project in 2000 and organized a research community composed of senior scientists, supporting staff and participants from other major universities and institutes in the US. In 2004, the CCSM was built, which was used for the climate change simulation/projection experiments of the Fourth Assessment Report (AR4) of Intergovernmental Panel on Climate Change (IPCC). Among the research teams that used CCSM, there was a biogeochemical group that studied biogeochemical processes with a focus on carbon cycles, whose mission was not just for the CCSM model then but for a much longer range goal. It is worth mentioning that under the joint support of the National Aeronautics and Space Administration (NASA), the Department of Defense (DOD), and the NSF in US, the Earth System Modeling Framework (ESMF, 2001–2010) was also started in 2001 and 19 renowned research organizations participated in the research and implementation of the project.

The European Union proposed "European Network for Earth System Modeling (ENES)" in 2000, which was composed of two sub-projects: "Program for Integrated Earth System Modeling" (PRISM) and "Climate Data Storage and Distribution." The PRISM was a joint research project based on the proposal of European CLIVAR (Euroclivar) in 2000 and started in December 2001. Twenty-two research bodies from European countries took part in the research and implementation of the project. The project aimed to develop a set of flexible, highly efficient, convenient and user-friendly earth system simulation and climate prediction programs, including atmospheric model, model of atmospheric chemistry, land-surface model, sea-ice model, model of marine biogeochemistry, and regional climate model. These models were connected by a coupler and composed a complete model system, which was a typical framework of moduled earth climate system model.

Besides USA and Europe, Japan had put forward two climate research projects under the support of the Japan Science and Technology Agency, the Japan Atomic Energy Research Institute, the National Space Development Agency of Japan, the Japan Marine Science and Technology Center, and the Institute of Physical and Chemical Research. One of the projects is the "Frontier Research System for Global Change" (FRSGC) started in 1997, which aimed to predict disasters, such as extreme climate, global warming, ecological damage, and so on. At the same time, the project of "Earth Simulator" was started. As one of its achievements, a supercomputer with the fastest peak speed at that time, named after "Earth Simulator," was completed by February 2002, and came into use on March 11, 2002. Another focus of the project is to develop the high-resolution climate system model to represent real earth states and to project future climate changes by using the supercomputer.

It is worth noting that the above-mentioned three-representative research projects share the following commonalities:

1) The great importance of developing ESM has been commonly recognized. Now, human society is faced with more and more challenges from the changes of earth environment caused by human activities, which might in turn change humans themselves. Until now, knowledge on the mechanisms of environment changes is very limited, due to the very complex nature of the problem that is related to all branches of earth sciences. Therefore, the study of these mechanisms should be based on the spherical interactions and collaboration among scientists with different backgrounds. The research and application of ESM only provide such a platform, which could synthesize the newest knowledge or theories of different subjects on earth environment changes and help to understand the mechanisms of these changes.

2) These projects all take observation systems and processing techniques (data assimilation) as an integrated entity for earth system simulation, and consider data storage, distribution, and sharing technique as the bottom-layer software supporting system of the common technological platform. These have catered to the needs of the scientists involved in obtaining conveniently the related observational data, which, without question, would be very beneficial for the development of the model. Especially, based on model simulations and observations, a deeper understanding of the important physical and biogeochemical processes could be obtained, which could help to improve the model and to reduce uncertainties in simulations. Obviously, ESM development is not only a process of developing model software on a computer but also connected to enormous observation systems and research supporting systems. Therefore, the establishment of an ESM center could facilitate the development of observation, theory, and simulation research of earth sciences and improve the research capacity comprehensively.

3) These projects are either on a national or regional scale, coordinated and organized by some special organizations, supported by stable and long-term funding sources, and coordinately jointed by many related research bodies and scientists through the aforementioned platform. It is suggested that the human and financial resources of a country or a region be concentrated to develop a state-of-the-art model system. Scientists could make their own contributions to model development on the public platform freely with their own specialties. In this way, waste of resources due to multi-input and low-level repetition could be effectively avoided. European PRISM and Japanese FRSGC have provided successful examples for us.

4) They all think highly of the importance of developing a technical platform for the general structure of ESM that can evolve in a sustainable manner. This platform plays a very important role in implementing the aforementioned projects. It is pivot to combine various research organizations and researchers toward one ESM framework, from which these research projects can all take advantage. The development of the platform includes the development of the bottom-layer software supporting system and research of various algorithms. Under the support of the bottom-layer technological platform, scientists specialized in various branches of earth sciences could study different scientific issues and advance the development of the model framework.

It is worth mentioning that although these projects aim to develop ESM, the models developed are still earth climate system models, because none of these projects has taken into account the interaction between the earth climate system and the solid earth nor the impacts of space weather. However, there have been reports on solid earth simulation. In the 2nd chapter of the Annual Report of the Earth Simulator Center (April 2005–March 2006), it has in particular introduced a series of successes in solid earth simulations by Japanese geologists, including simulations of geodynamo, mantle convection, earthquake, lithosphere activities, etc. (The report is available from http://www. jamstec. go.jp/esc/publication/annual/annual2005/). There have been few other reports on this aspect. Obviously, the research on solid earth has been advanced from qualitatively to quantitatively in

Japan, taking a leading role in the research of ESM.

4. Survey of CMIP3 models for the IPCC AR4

Twenty-four coupled climate system models were included in CMIP3 (CMIP Phase 3) experiments for the IPCC AR4, which came from 18 originating groups of 12 countries. To a large degree, these models represented the current-level, developing phase and the trend in the development of ESM in the world (see Table 1 for more details). We analyze the current performance and most-recent advancement of these models, and briefly introduce them here. Among the 24 models, seven were from U.S., three from Japan, two from each of the following countries: Canada, China, France, Germany and U.K., and the remaining four from Australia, Italia, Norway, and Russia. The two models from China were provided respectively by the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), and the Beijing Climate Center. One of the models from Germany was a collaborative effort with Korea.

These models all contain four components (spheres), namely, the atmosphere, ocean, sea-ice, and land-surface, and include the dynamics and physical processes of their interactions. These models are physical climate system models, which represent the current phase and state of ESM in the world. Although they could not fully simulate atmospheric chemistry, dynamic vegetation, marine ecology, indirect effects of aerosols, carbon cycles, etc., they could well reproduce some known physical phenomena and help us to understand the rules and mechanisms of climate system evolution. Next, coupling schemes and components of these models are introduced.

4.1 Coupling scheme

In terms of coupling scheme, these models all used “direct flux coupling,” which is a major advancement in the development of physical climate system model compared to the “flux adjustment” scheme used before 2000. This new scheme eliminates subjective “human adjustment” and describes exchange of energy and substance among different components (spheres) more realistically. There are two primary ways of coupling. One adopts “plug-in” module framework, which uses a coupler to integrate the four-component model to form the physical climate system model (Fig. 3). The other uses non-module coupling framework without a specific coupler. It exchanges flux directly at the interface between any two of the four-component models: it usually takes the land-surface model as a part of the atmospheric general circulation model (AGCM), and takes the sea-ice model (SIM) as a part of the oceanic general circulation model (OGCM). It works like an ”air-sea” coupling scheme (Fig. 4). Though the non-modular coupling is simpler in programming and faster in calculation, it has no potential for continuing development and could not survive the transition from physical climate system model to earth climate system model. In contrast, the modular scheme, while is more complicated in programming and slower in calculation, is highly desirable for a sustainable development, and has become the mainstream for the development of earth climate system model and the future ESM. Some important research projects in the world, such as the aforementioned ESMF, PRISM, Earth Stimulator,

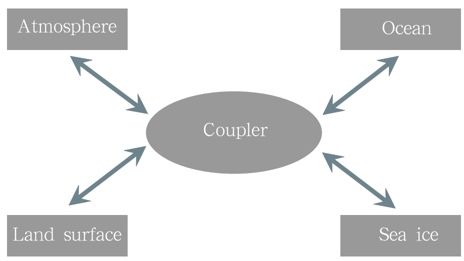

Fig.3. Schematic diagram of physical climate system model with a modular coupling.

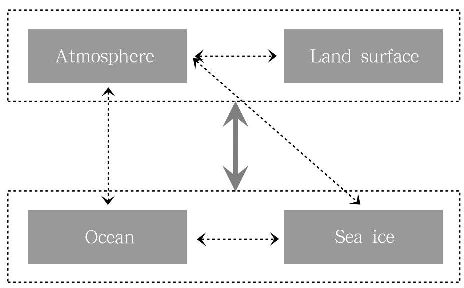

Fig.4. Schematic diagram of physical climate system model with a non-modular coupling.

etc., all adopt such a module framework.

Currently, the two most representative couplers in the world are the Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) Coupler developed by the Centre European de Recherche et Formation Avancees en Calcul Scientifique (CERFACS), France (Valcke and Redler, 2006), and the Coupler (CPL) developed by NCAR (Craig et al., 2005). For all the models presented in the IPCC AR4 (Table 1), the couplers used most are OASIS 2.2, OASIS 3, CPL5 and CPL6. The climate system model from China−the Flexible Global Ocean-Atmosphere-Land Surface System Model (FGOALS_g1.0)−used CPL5 (Yu et al., 2008). These versions of coupler could support 2-D coupling at present, but few of them could support 3-D coupling. For physical climate system models, the interface between any two components is 2-D and therefore these versions are sufficient. However, in the second phase of earth climate system model, the interface between components may not be 2-D; for example, the interface between the AGCM and the atmospheric chemistry model is 3-D. Therefore, most of the current couplers will not meet the need of future model development. It is necessary to use the versions that support 3-D coupling, or develop new versions capable of supporting 3-D coupling. For example, OASIS 4, a recent version of OASIS, supports both 2-D and 3-D couplings, which obviously is an ideal coupler for the development of earth climate system model. For more details on main couplers in the world, readers are referred to Zhou et al. (2004).

Table 1. CMIP3 models that participated in the IPCC AR4 and their originating groups (available online from http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php)

Originating Group(s)	Country	Model
BCC (Beijing Climate Center)	China	BCC-CM1
LASG/IAP/CAS (Chinese Academy of Sciences)	China	FGOALS-g1.0
BCCR (Bjerknes Centre for Climate Research)	Norway	BCCR-BCM2.0
CCCma (Canadian Centre for Climate Modelling & Analysis)	Canada	CGCM3.1(T47)
CCCma	Canada	CGCM3.1(T63)
Météo-France/CNRM (Centre National de Recherches Météorologiques)	France	CNRM-CM3
IPSL (Institut Pierre Simon Laplace)	France	IPSL-CM4
CSIRO (Australian Commonwealth Scientific and Research Organization)-Atmospheric Research	Australia	CSIRO-Mk3.0
MPI (Max Planck Institute for Meteorology)	Germany	ECHAM5/ MPI-OM
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA (Korea Meteorological Administration), Model and Data group.	Germany/Korea	ECHO-G
NCAR	U.S.A.	CCSM3
NCAR	U.S.A.	PCM
US Dept. of Commerce/NOAA (National Oceanic & Atmospheric Administration)/GFDL (Geophysical Fluid Dynamics Laboratory)	U.S.A.	GFDL-CM2.0
US Dept. of Commerce/NOAA/GFDL	U.S.A.	GFDL-CM2.1
NASA (National Aeronautics and Space Administration)/ GISS (Goddard Institute for Space Studies)	U.S.A.	GISS-AOM
NASA/GISS	U.S.A.	GISS-EH
NASA/GISS	U.S.A.	GISS-ER
Instituto Nazionale di Geofisica e Vulcanologia	Italia	INGV-SXG
INM (Institute for Numerical Mathematics)	Russia	INM-CM3.0
CCSR (Center for Climate System Research)/The University of Tokyo, NIES (National Institute for Environmental Studies), and FRCGC/JAMSTEC	Japan	MIROC3.2(hires)
CCSR/The University of Tokyo, NIES, and FRCGC/JAMSTEC	Japan	MIROC3.2 (medres)
MRI (Meteorological Research Institute)	Japan	MRI-CGCM2.3.2
Hadley Centre for Climate Prediction and Research/ UKMO (United Kingdom Meteorological Office)	U.K.	UKMO-HadCM3
Hadley Centre for Climate Prediction and Research/UKMO	U.K.	UKMO-HadGEM1

4.2 Atmospheric general circulation model

AGCM is one of the fundamental components in physical climate system model. Presently, AGCMs adopt two types of framework: spectral and grid-point. Among the 18 AGCMs used in the 24 coupled models of the IPCC AR4, 10 used spectral framework and the rest used grid-point framework, in contrast to the situation before the Third Assessment Report (TAR) of the IPCC when spectral framework dominated. Much different from before, the grid-point framework includes not only the finite difference dynamical core but also the semi-Lagrangian core that uses the semi-implicit time integration scheme and finite volume core based on global quasi-uniform polygon grids. One of the Chinese models that participated in the IPCC AR4, FGAOLS_g1.0 (Yu et al., 2008), used the grid-point model GAMIL1.0 (Wang et al., 2004; Wang and Ji, 2006) as its atmospheric component, whose dynamical core is based on the semi-implicit energy conserving difference scheme proposed by Wang and Ji (2006). It maintains important physical conservations for the integrals of effective energy and total mass, and it has good computational stability. The other Chinese model, the Beijing Climate Center-Climate Model version 1 (BCC-CM1; Ding et al., 2004), adopted a spectral atmospheric model. Currently, this model has been improved by introducing a unique reference atmosphere and reference surface air pressure, which better fit into the thermal structures of the atmosphere at upper levels of the troposphere and in the stratosphere (Wu et al., 2008a, b).

The selection of advection scheme for solving the moisture equation in AGCMs is very important for rainfall simulation. Among the aforementioned 18 AGCMs, 11 adopted semi-implicit/semi-Lagrangian scheme for solving the moisture equation, which has become the commonly used scheme internationally, and the rest used upwind scheme or semi-implicit finite volume scheme. GAMIL1.0 used the two-step shape-preserving advection scheme developed by Yu (1994).

The horizontal resolution of the AGCMs of the AR4 has improved significantly compared with the IPCC TAR. These AGCMs have an average grid size of $2°$–$3°$ with the highest resolution of about $1.1°$ (T106) and the lowest resolution of $4° \times 5°$, which was the average resolution of the TAR models. The grid spacings of the two Chinese AGCMs are approximately $1.875° \times 1.875°$ (T63) and $2.8° \times 2.8°$, respectively, both close to the average resolution. Most models use pressure-topography-mixed vertical coordinates (p-σ) and only a few use topography (σ) or height-topography-mixed vertical coordinates (z-σ). The vertical resolution is much more refined than that of the IPCC TAR, whose AGCMs had only 9–18 layers. With an average of 26 layers, the highest vertical resolution model has 56 layers and the lowest has only 12 layers. For all the AGCMs in the IPCC AR4, only the AGCM from the UK Hadley Center, UKMO-HadGEM1, used the atmospheric equations with non-hydrostatic equilibrium.

Progresses in research of the physical processes of AGCMs have also been achieved since the IPCC TAR. For example, He and Dickinson (2006) proposed a new scheme to calculate cloud cover with physical significance according to the positive correlation between radiative cooling of large-scale cloud top and dry energy transported from the free atmosphere and the surface latent-heat flux. This scheme significantly improved the calculation of cloud cover compared with the empirical linear scheme of low-layer stratus. Dai et al. (2005) developed a low-cloud parameterization scheme based on statistics, which improved the model simulation of subtropical low clouds. Khairoutdinov et al. (2001, 2005) proposed successively 2-D and 3-D cloud super-parameterization (SP) approach, which coupled the Cloud Resolving Model (CRM) directly with Community Atmospheric Model (CAM) on each grid. The 2-D SP improved the performance of simulating western Pacific summer precipitation, diurnal variation of drizzle, and intra-seasonal variability of rainfall, including the ones caused by the Madden-Julian Oscillation (MJO). Further, the 3-D SP improved the distribution of summer precipitation in the tropical western Pacific and eliminated double ITCZ when momentum feedback is included. Li et al. (2005) put forward the new correlated k-distribution (CKD) gas radiation transportation scheme, after having reconsidered the mathematic basis of the k-distribution, and improved the simulation accuracy of radiation significantly.

4.3 Oceanic general circulation model

OGCM is another fundamental component in physical climate system model. The OGCMs used in the climate system models for the IPCC AR4 mostly adopted depth coordinate (z-coordinate), only a few used other types of vertical coordinates. For example, the two Chinese OGCMs, LICOM1.0 (Liu H. L. et al., 2004) and IAP L30T63 (Jin et al., 1999), used topography-following η-coordinate; the OGCM from U.S., the AOM4×3-OGCM, and that from Russia, the INM OGCM, used topography-following σ-coordinate; the version of the Miami Isopycnic Coordinate Ocean Model (MICOM 2.8) from Norway used isodensity coordinate (ρ-slab) and the COCO3.3-OGCM from Japan used mixed vertical coordinate (σ-z). Though isodensity coordinate models could simulate complicated regional flows better than z-coordinate models (Drange et al., 2005), their simulations of the relatively dense water mass in the Mediterranean Sea and at the ocean bottom near the South Pole, etc., were distorted to some degree. The potential advantages of these different types of OGCMs will not be fully recognized until they are further improved. In order to reduce the systematic errors caused by virtual salinity flux, most OGCMs these days used freshwater flux. It is a good strategy to treat the singularity of OGCMs at the North Pole with dipolar or tripolar mesh on extended curve horizontal coordinates (Murray, 1996), which move the singular points to land to avoid the computational instability. Therefore, many OGCMs have adopted this kind of horizontal coordinate. In addition, most models used free surface as their upper boundary condition and few kept the rigid-lid approximation.

The horizontal resolution of the OGCMs is somewhat improved compared with those before the IPCC TAR. With an average horizontal grid size of 1°–2°, the highest resolution reaches 0.28°×0.19°, which is capable of resolving mesoscale vortex, and the lowest is 4°×5° that is the average resolution of the TAR OGCMs. To better resolve equatorial wave guide, a few models increased their meridional resolutions in the tropics. With an average vertical resolution of 26 layers, the highest vertical resolution model has 56 layers, and the lowest has only 13 layers. It was found that with an increased horizontal resolution (capable to resolve mesoscale vortex), models could more realistically simulate narrow and fast ocean currents (jets), vortex-induced transports of heat and tracers, and short-term oceanic variability, reproduce large-scale climatic characteristics evoked by local air-sea coupling, improve the simulations of oceanic circulation characteristics, shorten the adjustment time of the freshwater balance in the Atlantic basin, increase the performance of regional climate modeling, but could hardly improve the simulation at the timescale of El Niño variability according to Guilyardi et al. (2004).

The existing horizontal diffusion schemes for tracers in OGCMs could not well describe the non-uniform deep-ocean vertical mixing over rough ocean bottoms and steep slopes, which influences the simulation of Atlantic thermohaline circulation. Therefore, to develop new comprehensive parameterization schemes and to apply them in coupled climate models have become a very important research topic. In addition, the parameterization scheme of bottom boundary layer has come into use in OGCMs and some coupled climate models.

4.4 Sea-ice model

In the IPCC AR4 models, most sea-ice component models used the same horizontal resolution as the corresponding ocean component models'. There were generally 1–4 vertical layers for sea-ice and one layer for snow on top of the sea-ice. These sea-ice models (SIMs) adopted various time integral schemes. Compared with those in the IPCC TAR, an important progress is the inclusion of dynamic processes in SIMs. Two new schemes to solve dynamic sea-ice equations were proposed: the more accurate description of dynamic sea-ice on orthogonal curve mesh (Hunke and Dukowicz, 2002) and the Lagrangian scheme to solve viscoplastic equations (Lindsay and Stern, 2004). In addition, Bitz and Lipscomb (1999) established a thermodynamic module with energy conservation according to the dependency relationship of the conduction and thermal capacity with salinity. Lipscomb (2001) and Hutchings et al. (2004) developed a re-mapping approach and an implicit amendment scheme to calculate the thickness distribution and sea-ice intensity, which is more applicable to coupled climate models. Liu et al. (2005, 2007) proposed a more reasonable parameterization scheme of sea-ice surface reflectivity and a parameterization scheme to describe the surface melting-pool variation.

4.5 Land-surface model

Compared with the IPCC TAR, the main progresses in the land-surface component of the IPCC AR4 coupled models are: the improvement of root parameterization scheme (Arora and Boer, 2003), the application of high-resolution runoff module (Ducharne et al., 2003), the consideration of soil freeze-thawing through a multi-layer snow module (Warrach et al., 2001; Dai et al., 2003), the introduction of sub-grid parameterization scheme of snow, the inclusion of snow-vegetation interaction and wind-snow re-distribution (Essery et al., 2003, 2004), the description of organic soil in high latitudes (Wang et al., 2002), and the coupling of underground water module into the land-surface model (e.g., Liang et al., 2003).

5. Current status of model development in China

Chinese scientists have made significant progresses in the development of ESM. Especially, the recent 30-yr efforts have brought astonishing success in the development of atmospheric, oceanic, and land-surface models and their coupling.

In as early as the 1980s, Chinese meteorologists had recognized the significance of numerical simulation in studying climate changes and started the development of numerical climate models (Qian, 1985; Zeng et al., 1989). Over the past 20 years, from the very basic climate model–AGCMs (e.g., Zeng et al., 1989), OGCMs (Zhang and Liang, 1989), and air-sea coupled models (e.g., Zhang et al., 1992; Guo et al., 1996), Chinese scientists have developed coupled climate system models (e.g., Wu et al., 1997; Zhang et al., 2000; Yu et al., 2002; Zhou et al., 2005c; Yu et al., 2008; Zhou et al., 2008b). Moreover, a series of research related to climate problems have been carried out using the coupled climate system models, including the influences of human activities on climate changes (e.g., Yu et al., 2007), ocean variability (e.g., Zhou et al., 2000a; Zhou, 2003; Zhou et al., 2005a,b), Indonesian throughflow (Li et al., 2005), tropical intraseasonal oscillation (e.g., Li and Yu, 2001; Liu Yunyun et al., 2006), offshore ocean currents (Liu Q. Y. et al., 2006), annual variability of sea-ice (Liu et al., 2005), air-sea interaction (e.g., Zhou et al., 2000b, 2002; Yu et al., 2005), tropical bias of coupled models (e.g., Li et al., 2004; Zhang et al., 2007), modeling of climate changes in the 20th century (e.g., Ma et al., 2004; Zhou and Yu, 2006; Li et al., 2007a,b; Zhou et al., 2008a,b), and simulations of the past 1,000-yr climate (e.g., Liu J. et al., 2004), orbital-scale paleoclimate (e.g., Wang and Zeng, 1992; Wang, 1999, 2002; Jiang et al., 2003; Wei and Wang, 2004; Ju et al., 2007; Zheng et al., 2008), and tectonical-scale paleoenvironment (Yu et al., 2004; Jian et al., 2006). Coupled models were also applied to theoretical studies and implemented to operational short-term (seasonal to annual) climate predictions (e.g., Zeng et al., 1997; Lin et al., 1999; Zhou and Zeng, 2001), showing good performance on operational predictions of precipitation anomaly, El Niño-Southern Oscillation, and so on.

At the same time with the development and application of climate system models, Chinese scientists also fully recognized that model developments involve a huge engineering component and need collaboration and support from researchers of related fields. Under the promotion of the National Natural Science Foundation of China (NSFC), CAS, the China Meteorological Administration (CMA), and other Chinese agencies, a draft version of "Joint Research Plan on Global Climate System Model" (2001–2005; http://web.lasg.ac.cn/) was proposed for the first time in January 2002 jointly by the LASG of the IAP and several other research institutions, including the National Climate Center (NCC), the Chinese Academy of Meteorological Sciences (CAMS) and the Department of Atmosphere at Nanjing University. Based on this plan, the LASG assisted the NSFC to draft a proposal entitled "China should speed up development of its own climate system model" in the same year. The proposal was published in the NSF Briefing No. 8 in 2002 that was reported to the State Council of the People's Republic of China. This plan has caught the attention of the State leaders.

With the joint financial support of the NSFC, CAS, and the Ministry of Science and Technology (MOST), the group at LASG soon established the FGOALS version 1.0 in May 2004 (Zhou et al., 2005; Yu et al., 2008), a moduled physical climate system model based on coupler technique. Meanwhile, with the support of the CMA, the NCC developed its own physical climate system model–BCC-CM1 (Ding et al., 2004). These two models were used in climate change simulations and participated in scenario predictions for the IPCC AR4. It was the first time that two Chinese climate models participated in the IPCC experiments. In the three IPCC assessment reports prior to the AR4, there was only one model from China each time, namely the LASG model, which took part in the experiments for these reports. Though there are still shortcomings in these models, they have laid an important foundation for future development of ESM.

6. Discussion on future development of ESM in China

Great achievements in climate model development have been made in China through several generations' continuous efforts. However, the development of Chinese ESM still falls behind those of developed countries, especially in terms of the continuity of model development. It is alarmed that the gap between China and some advanced countries tends to increase due to faster development of ESM in these countries in recent years. Therefore, we should summarize our previous experience earnestly, learn more advanced technology and methodology from advanced modeling groups, foresee the developing trend of ESM, adopt effective strategies and expedite the development of ESM in China. After a comprehensive analysis of the strategies on model developments in some developed countries, we emphasize the following three aspects.

1) One of the important new strategies is "evaluation, improvement, and further-evaluation, further-improvement" instead of "starting all over again." This new strategy makes the model development more sustainable and heritable. "Starting all over again" means to completely get rid of the existing basis and make a fresh start, which would waste a lot of time on repeating technical work and slowing down the model development.

2) More attention should be paid to the development of bottom-layer technique-supporting platform, through which different research institutions and scientists specialized in different fields can contribute to the development of the same model system. Particularly, with the application of such a platform, it is possible to evaluate and improve the various component models in a coupled framework and obtain more complete and systematic knowledge of the advantages and disadvantages of the component models than previously could through evaluations of individual component models.

3) The development of ESM should be based on operational forecast/prediction models in whice major model physical processes have undergone long-term tests by operational weather forecasts and seasonal predictions. The ESM developed on the basis of operational models is more applicable to operational predictions, benefiting improvement of operational predictions, and getting improved in turn through operational verifications. In this way, a progressive cycle of model development can be established.

The main factors that dragged the ESM development in China in the past are the lack of continuity, collaboration, and cooperation with operational applications. In addition, the research funding that supported the model development was not properly allocated, and thus key projects that aimed at the development of the state-of-the-art model systems were not focused on through joint efforts and collaborations of various research groups. Therefore, we put forward the following suggestions.

1) Change the "starting all over again" strategy to "evaluation, improvement, and further-evaluation, further-improvement." An important way to advance

the model is to deepen our understanding of model performance, to identify the main causes that lead to model deficiencies, and consequently to improve the model. Observational data is indispensable. It is crucial for the improvement of main physical processes of the model. Extensive 3-D field observations and process studies coordinated by various key national projects need to be carried out in the sensitive regions of "atmosphere-ocean" and "land-atmosphere" interactions.

2) There is a need to develop our own coupler, to establish uniform input/output standards for model data files, and to realize the modulization, parallelization, and standardization of models. Not only does the coupler technique support the modulization and parallelization of models, but also provide the model system with a bottom-layer supporting software platform, which is an important platform to allow scientists from various branches of earth sciences to work together.

3) Coordinate the development of Chinese ESM from the national level, unify the management system so that the financial support and human resources can be better prioritized. Combine model development with weather forecast/operational prediction so that the established model come from and in turn serve the operational systems. Apply the model to quantitative studies of important scientific issues related to global changes, and take part in global model comparisons. For this purpose, it is necessary to organize a group of scientists for coordinated development of Chinese ESM under the support of the MOST and NSFC and together with the participation of CAS, CMA and various universities.

4) Increase the resolutions of physical climate system model components, and improve model performance to simulate fine structures of the earth system. Not only does the increase of resolutions need to resolve computational instability of dynamic core, but also requires continuingly refining the model representation of the physical, chemical, and biological processes. To establish high-resolution coupled climate system model should be one of the central tasks of model development.

5) Develop biogeochemical model, including atmospheric chemistry model, dynamic global vegetation model, and oceanic ecosystem model, which include carbon and nitrogen cycles. Couple biogeochemical model with physical climate system model under a coupler framework, and build the framework of earth climate system model.

6) Pay attention to the development of solid earth model and space weather model to lay a solid foundation for considering processes of solid earth and solar activities in the realistic ESM in the near future.

7) Pay attention to the development of regional earth system model, probe into well-posed lateral boundary schemes for two-way nesting with global ESM, reduce the uncertainties in dynamical downscaling, and provide a new effective approach for studying the mechanisms and factors governing extreme regional climate events and for improving model performance on climate prediction/projection.

8) Advance computer technology to ensure ESM development by accommodating increasing requirements of computational speeds and memories due to the increased and refined processes in the model and the improvement of model resolutions. At present, the model development is moving from physical climate system model to earth climate system model, which requires the running speed of 100,000–1,000,000 GFLOPS and the memory of 10–100 TB. In the third phase of ESM, computer systems with a running speed of 10,000,000 GFLOPS and a memory of 10 PB will be needed.

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News and Up dates

The publication cycle of *Acta Meteorologica Sinica (AMS)* is now bimonthly: six issues per year are expected to come out around the end of every other month such as February, April, ···, and December. This change was advised by the 26th Editorial Committee Meeting on 15 October 2008, and is being implemented from the 1st issue of 2009. The change is an effort of the Editorial Committee and all the editorial staff to improve the quality and impact of *AMS*, following its inclusion in the Science Citation Index Expanded (SCIE) in January 2007.