Development of Earth/Climate System Models in China: A Review from the Coupled Model Intercomparison Project Perspective

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ABSTRACT

The development of coupled earth/climate system models in China over the past 20 years is reviewed, including a comparison with other international models that participated in the Coupled Model Intercomparison Project (CMIP) from phase 1 (CMIP1) to phase 4 (CMIP4). The Chinese contribution to CMIP is summarized, and the major achievements from CMIP1 to CMIP3 are listed as a reference for assessing the strengths and weaknesses of Chinese models. After a description of CMIP5 experiments, the five Chinese models that participated in CMIP5 are then introduced. Furthermore, following a review of the current status of international model development, both the challenges and opportunities for the Chinese climate modeling community are discussed. The development of high-resolution climate models, earth system models, and improvements in atmospheric and oceanic general circulation models, which are core components of earth/climate system models, are highlighted. To guarantee the sustainable development of climate system models in China, the need for national-level coordination is discussed, along with a list of the main components and supporting elements identified by the US National Strategy for Advancing Climate Modeling.

Key words: Coupled Model Intercomparison Project (CMIP), IPCC Assessment Report, atmospheric gengeneral circulation model, oceanic general circulation model, climate system model, earth system model, high-resolution model

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1. Introduction

One of the major achievements of the international climate research community since the 1970s has been the identification of climate system components along with an extension of this field of research from the atmosphere to the whole climate system. The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface, and the biosphere. Addressing the interplay among the different components or establishing the climate system's response to changes in natural (orbital factors, solar variation, and volcanic eruptions) and anthropogenic forcing agents (emissions of greenhouse gases, aerosols, and land use) requires a coupled climate system model (CSM) or earth system model (ESM) approach. Coupled CSMs and ESMs have proved to be useful tools for understanding the mechanisms of climate variability, reproducing past climate change, performing seasonal climate predictions, and projecting potential future climate change.

The worldwide development of atmospheric general circulation models (AGCMs), CSMs, and ESMs has been driven and encouraged by the World Climate Research Programme (WCRP). In the past 20 years,

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many international climate model intercomparison projects, such as AMIP (Atmospheric Model Intercomparison Project; Gates et al., 1992) and CMIP (Coupled Model Intercomparison Project; Meehl et al., 1997, 2000), have been organized and coordinated by WCRP. The successful implementations of these projects have greatly enhanced international collaboration in the field of climate model development and climate modeling activities. Both AMIP and CMIP are among the list of successful international collaborations in climate research and climate change science. The implementation of CMIP has also advanced the progress of climate change modeling and climate change projection around the world. Many peer-reviewed publications based on the outputs of CMIP models have been cited by the assessment reports of the Intergovernmental Panel on Climate Change (IPCC).

The Chinese climate research community began to develop climate models in as far back as the late 1970s, and as such, has a long history in this field. The models developed by the Chinese research community have been widely used in ocean-atmosphere interaction studies, climate variability studies, seasonal predictions, and climate change projections. The Chinese Academy of Sciences (CAS) has led climate modeling activities in China. For example, by recognizing the central importance of climate models in climate studies, the development of climate models quickly became a focus of the research activities of the Sate Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, CAS (hereafter LASG/IAP) since the establishment of the laboratory in 1985. Different versions of its AGCM, oceanic general circulation model (OGCM), land surface model, sea ice model, and the associated fully coupled models have been developed inside LASG/IAP (see Zhang et al., 1999 for a review).

As overarching geophysical modeling platforms for the Chinese climate research community, the climate models developed by LASG/IAP have been serving as powerful tools to enhance our understanding of the fundamental mechanisms of the climate system, as well as make seasonal predictions and scenario projections of future climate change. One particularly successful aspect of LASG/IAP climate model development in the past 30 years is international collaboration. For example, a variety of CSMs developed by LASG/IAP have participated in all the past phases of CMIP and contributed to the assessment reports of the IPCC. The participation in international projects such as CMIP has helped LASG/IAP scientists to identify both the strengths and weaknesses of their models, forming useful references for future improvements. In the most recent 10 years, the development of climate models has been granted high priority in China, with many research centers (e.g., the National Climate Center, also known as the Beijing Climate Center, of the China Meteorological Administration) engaged in activities to develop and improve climate models. The expansion of the climate modeling community in China has provided a solid human-resource basis for developing high-performance climate models.

From CMIP3 to CMIP5, the fully coupled physical CSM has been developed into the ESM, which additionally considers terrestrial carbon and nutrient cycling processes. The development of ESMs will be one of the frontiers of the international climate modeling community in the coming decade (Wang et al., 2004; Wang et al., 2008, 2009). The issues of global climate change and its impacts on sustainable development have been and continue to be of great concern to the Chinese government. In recent years, the level of funding that supports the development of earth/climate system models has increased rapidly. Many new research centers that work on climate modeling have been set up, which will undoubtedly enhance the nation's ability to tackle climate change issues. The achievements of China in developing high-performance hardware have also provided a solid platform for advancing climate modeling activities in the country. However, along with the opportunities and developments such as these present, the Chinese climate modeling community is also facing some great challenges. For example, the current performance levels of Chinese climate models are still generally behind those of the developed countries. How to improve the performances of Chinese models based on observational metrics posed by the international community is a challenge, and one that is not restricted to model techniques. In addition to model improvements, another challenge we face is achieving successful and efficient cooperation and coordination among the many research centers/universities in the field of earth/climate system model development. Up to now, we still do not have a national strategy for advancing climate modeling in China. The path for China to move forward into the next generation of earth/climate system models and to provide the best possible climate information for the nation remains unknown.

CMIP is among the most successful international projects organized and coordinated by WCRP. It has been nearly 20 years since WCRP launched the first CMIP project in 1995. At that time, there was only one participating Chinese climate model; but in the latest phase of the project (CMIP5), there are five models developed in China. There will be even more climate models from China participating in CMIP6 in the near future. How to coordinate the development of climate models in China and provide the best possible climate information for the nation are challenging issues for Chinese funding agencies. The aims of the current paper are to 1) summarize the contributions of Chinese models to CMIP since its inception nearly 20 years ago; 2) compare current Chinese models with other CMIP5 models in the context of technical metrics and identify the key issues that need to be addressed by the Chinese climate modeling community. We hope that this review will provide a useful reference for the Chinese climate modeling community and encourage collaboration in future model developments. The paper also provides an outlook for the future development of climate models in China.

The remainder of the paper is organized as follows. In Section 2, we summarize the contributions of Chinese models to the past phases of CMIP, i.e., from CMIP1 to CMIP4. The technical features of Chinese models are compared with CMIP models. In Section 3, the major improvements of climate models from CMIP1 to CMIP4 are synthesized. In Section 4, the characteristics of ongoing CMIP5 models are described, providing a reference for assessing Chinese models. Characteristics of the five Chinese models that participated in CMIP5 are summarized in Section 5. Section 6 outlines the challenges for global climate model development in China. Section 7 clarifies the opportunities for the Chinese climate modeling community. Finally, concluding remarks are provided in Section 8, along with a list of national strategies for advancing the climate modeling enterprise in the next two decades in the United States of America based on a national strategic report published by the US National Research Council (NRC).

2. Review of CMIP1 to CMIP4 and the involvement of Chinese climate models

In 1995, the Joint Scientific Committee (JSC) and CLIVAR sponsored Working Group on Coupled Models (WGCM), part of the World Climate Research Program, launched the Coupled Model Intercomparison Project (CMIP). Since then, phases 2–5 have subsequently also been conducted. The basis for the results of the various CMIPs is the assessment of the performance of climate models, simulations of current climate change, and projections of future climate change scenarios, which are used to inform corresponding IPCC reports released every five to seven years. For example, the results based on CMIP1 were used to inform the IPCC's Second Assessment Report (SAR), released in 1995; the results based on CMIP2 were used to inform the IPCC's Third Assessment Report (TAR), released in 2001; the results based on CMIP3 were used to inform the IPCC's Fourth Assessment Report (AR4), released in 2007; and the results based on the ongoing CMIP5 are being used to inform the IPCC's Fifth Assessment Report (AR5), released in 2014.

CMIP provides a community-based infrastructure in support of climate model validation, intercomparison, process diagnosis, climate change attribution, and climate change projection. The CMIP multi-model dataset has provided the basis for thousands of peer-reviewed papers and played prominent roles in past IPCC assessment reports of climate variability and climate change. Note that CMIP is not organized solely for the purpose of the IPCC reports, and so referring to the models as "IPCC models", as is the case in many peer-reviewed papers and reports, is not accurate. Instead, they should be referred to as "CMIP models." In fact, from their independent beginnings, CMIP and the IPCC's reports have grown naturally to promote one another. Before CMIP1 was launched by WCRP in 1995, the IPCC's First Assessment Report (FAR), released in 1990, used the results derived from 22 AGCMs coupled with mixed-layer ocean models, and 4 fully coupled GCMs (Table 1). FAR and the corresponding supplementary report, released in 1992, increased the attention of the climate community to climate model research, and partly prompted the establishment of CMIP by WCRP in 1995.

From CMIP1 to CMIP3, the model developed at IAP was the only model from China that participated in CMIP. The supplementary report of IPCC FAR released in 1992 used future climate projections made by a two-level IAP AGCM coupled with a mixed-layer ocean model (Wang et al., 1993), which represented some of the earliest model results on climate warming (Table 1).

Table 1. The models used for IPCC FAR

Model name	Institute	Horizontal and vertical resolutions of atmospheric model	Horizontal and vertical resolutions of oceanic model
	GFDL (USA)	R15, 4.5×7.5, L9	4.5×3.75, L12
	MPI (Germany)	T21, 5.6×5.6, L19	4×4, L11
	NCAR (USA)	R15, 4.5×7.5, L9	5×5, L4
	UKMO (UK)	2.5×3.75, L11	2.5×3.75, L17
	BMRC (Australia)	R21, 3.2×5.6, L9	Mixed-layer ocean model
CCM1	YALE (USA)	R15, 4.5×7.5, L12	Mixed-layer ocean model
CCM1	SUNY (USA)	R15, 4.5×7.5, L12	Mixed-layer ocean model
	CSIRO (Australia)	R21, 3.2×5.6, L9	Mixed-layer ocean model
CCM	NCAR (USA)	R21, 3.2×5.6, L9	Mixed-layer ocean model
	LMD (France)	5×7.5, L11	Mixed-layer ocean model
	IAP (China)	4×5, L2	Mixed-layer ocean model

Ten models participated in CMIP1 (Meehl et al., 1997, 2000). The Chinese model was GOALS2, developed by LASG/IAP (Wu et al., 1997; Zhang et al., 2000), which consisted of a 9-level AGCM with a horizontal resolution of R15, a 20-layer OGCM with a horizontal resolution of 5° × 4°, an SSiB land surface model, and a thermodynamic sea-ice model. A prediction-correction monthly flux anomaly coupling scheme was used during the air-sea coupling (Yu and Zhang, 1998). Only heat fluxes and wind stresses were included in the air-sea coupling, while the surface salinity was restored to the climatology, since ocean-atmospheric freshwater exchange was not included. The CMIP1 model results were used in IPCC SAR, released in 1995 (Table 2).

Eighteen models participated in CMIP2 (Meehl et al., 2005). The Chinese model was GOALS4, developed by LASG/IAP. Relative to the previous version GOALS2, the daily variation of solar radiation was introduced in GOALS3 through collaboration with Nanjing University (Shao et al., 1998). GOALS4 improved the coupling processes by including ocean-atmospheric freshwater exchange (Zhou et al., 2000, 2001), which is a key process for simulating and understanding the responses of thermohaline circulation to global warming. The CMIP2 model results were used in IPCC TAR, released in 2001 (Table 3).

The IAP's CSM was the only model from a developing country among the 10 models that participated in CMIP1 and the 18 models that participated in CMIP2. Therefore, this model objectively represented the participation of the developing world in international activities relating to climate modeling and projection coordinated by CMIP. This was one of the key achievements of LASG/IAP in an assessment of state key laboratories in 2000, and ultimately was a

Table 2. The models used for IPCC SAR

Model name/ Institute	Horizontal and vertical resolutions of atmospheric model	Horizontal and vertical resolutions of oceanic model
BMRC (Australia)	R21, 3.2×5.6, L9	3.2×5.6, L12
CCC (Australia)	T32, 3.8×3.8, L10	1.8×1.8, L29
CERFACS (France)	T42, 2.8×2.8, L31	1×2, L20
COLA (USA)	R15, 4.5×7.5, L9	3×3, L16
CSIRO (Australia)	R21, 3.2×5.6, L9	3.2×5.6, L12
GFDL (USA)	R30, 2.25×3.75, L14	2×2, L18
GISS (USA)	4×5, L9	4×5, L13
GISS (USA)	4×5, L9	4×5, L16
IAP (China)	4×5, L2	4×5, L20
LMD/OPA (France)	3.6×2.4, L15	1×2, L20
MPI (Germany)	T21, 5.6×5.6, L19	5.6×5.6, L11
MPI E2/OPY (Germany)	T21, 5.6×5.6, L19	2.8×2.8, L9
MRI (Japan)	4×5, L15	0.5–2×2.5, L21
NCAR (USA)	R15, 4.5×7, L9	1×1, L20
UCLA (USA)	4×5, L9	1×1, L15
UKMO (UK)	2.5×3.8, L19	2.5×3.8, L20

major contributing factor to LASG/IAP receiving an excellent score①.

There were 23 models in CMIP3, 4 of which were from China (2 from BCC and 2 from LASG/IAP). The LASG/IAP model was FGOALS-g1.0 (Yu et al., 2002, 2004). The atmospheric component of this model has 26 levels in the vertical direction and a horizontal resolution of $2.8° \times 2.8°$. The oceanic component has 30 levels in the vertical direction and a horizontal resolution of $1.0° \times 1.0°$. The land surface model and sea-ice model are the community land model (CLM) and community sea-ice model (CSIM), respectively, both derived from NCAR. These four components were coupled together by using the NCAR Community Climate System Model (CCSM) coupler (Yu et al., 2004, 2008; Zhou et al., 2007). The CMIP3 model results were used in IPCC AR4, released in 2007 (Table 4). Another version of FGOALS (FGOALS-s1.0) developed by LASG/IAP did not participate in CMIP3 due to its incomplete representation of the processes of various greenhouse gases and aerosols in the atmospheric radiation package (Zhou et al., 2005a, b, 2007). Due to some technical problems, the CSM developed by BCC withdrew from CMIP3.

CMIP3 is so far the most successful and significant international coupled model intercomparison project. As of December 2010, over 1 Pbyte of data have been downloaded among the 3000+ registered users. Over 550 journal articles, based at least in part on the dataset, have been published. The daily peak of downloaded CMIP3 data reached 1 TB from the PCMDI (Program for Climate Model Diagnosis and Intercomparison) server during 2004–2010. To date, there are still many research results based on CMIP3 data to be published.

Following CMIP3, CMIP4 was organized, in which the models were forced separately by natural variability and anthropogenic external forcing for 20th-century global climate change (Meehl et al., 2007). CMIP4 is regarded as a transition program between CMIP3 and CMIP5 and has been relatively less influential. The separated experiments based on natural variability and anthropogenic external forcing are usually considered as "tier experiments" of CMIP3. Due to the significance of this type of experiments on the detection and attribution of climate change, these experiments have also been performed in CMIP5.

There are over 40 CSMs and ESMs from over 20 modeling groups worldwide participating in the ongoing CMIP5 (Taylor et al., 2012), among which there are 5 Chinese models (Table 5). The inclusion of more than two models from one country in CMIP has only before been achieved by the United States, France, Japan, Australia, and the United Kingdom, providing a clear indication of the rapid growth in the number of climate model developers in China.

3. Improvements of climate models from CMIP1 to CMIP4

The structures and physical processes in climate system models exhibited significant improvements from CMIP1 to CMIP4. The "climate model

① Zhou Tianjun, 2000: The development and application of LASG global ocean-atmosphere-land system model. Presentation for the assessment of state key laboratories on earth science in 2000. Institute of Atmospheric Physics/Chinese Academy of Sciences.

Table 3. The models used for IPCC TAR

Model name	Institute	Horizontal and vertical resolutions of atmospheric model	Horizontal and vertical resolutions of oceanic model
ARPEGE/OPA1	CERFACS (France)	T21, 5.6×5.6, L30	2.0×2.0, L31
ARPEGE/OPA2	CERFACS (France)	T31, 3.9×3.9, L19	2.0×2.0, L31
BMRCa	BMRC (Australia)	R21, 3.2×5.6, L9	3.2×5.6, L12
BMRCb	BMRC (Australia)	R21, 3.2×5.6, L17	3.2×5.6, L12
CCSR/NIES	CCSR/NIES (Japan)	T21, 5.6×5.6, L20	2.8×2.8, L17
CGCM1	CCCma (Canada)	T32, 3.8×3.8, L10	1.8×1.8, L29
CGCM2	CCCma (Canada)	T32, 3.8×3.8, L10	1.8×1.8, L29
COLA1	COLA (USA)	R15, 4.5×7.5, L9	1.5×1.5, L20
COLA2	COLA (USA)	T30, 4×4, L18	3.0×3.0, L20
CSIRO MK2	CSIRO (Australia)	R21, 3.2×5.6, L9	3.2×5.6, L21
CSM1.0	NCAR (USA)	T42, 2.8×2.8, L18	2.0×2.4, L45
CSM1.3	NCAR (USA)	T42, 2.8×2.8, L18	2.0×2.4, L45
ECHAM1/LSG	DKRZ (Germany)	T21, 5.6×5.6, L19	4.0×4.0, L11
ECHAM3/LSG	DKRZ (Germany)	T21, 5.6×5.6, L19	4.0×4.0, L11
ECHAM4/OPYC3	DKRZ (Germany)	T42, 2.8×2.8, L19	2.8×2.8, L11
GFDL_R15a	GFDL (USA)	R15, 4.5×7.5, L9	4.5×3.7, L12
GFDL_R15b	GFDL (USA)	R15, 4.5×7.5, L9	4.5×3.7, L12
GFDL_R30_c	GFDL (USA)	R30, 2.25×3.75, L14	1.875×2.25, L18
GISS1	GISS (USA)	4.0×5.0, L9	4.0×5.0, L16
GISS2	GISS (USA)	4.0×5.0, L9	4.0×5.0, L13
GOALS	IAP/LASG (China)	R15, 4.5×7.5, L9	4.0×5.0, L20
HadCM2	UKMO (UK)	2.5×3.75, L19	2.5×3.75, L20
HadCM3	UKMO (UK)	2.5×3.75, L15	1.25×1.25, L20
IPSL_CM1	IPSL/LMD (France)	5.6×3.8, L15	2.0×2.0, L31
IPSL_CM2	IPSL/LMD (France)	5.6×3.8, L15	2.0×2.0, L31
MRI1	MRI (Japan)	4.0×4.0, L15	2.0×2.5, L21
MRI2	MRI (Japan)	T42, 2.8×2.8, L30	2.0×2.5, L23
NCAR1	NCAR (USA)	R15, 4.5×7.5, L9	1.0×1.0, L20
NRL	NRL (USA)	T47, 2.5×2.5, L18	1.0×2.0, L25
DOE PCM	NCAR (USA)	T42, 2.8×2.8, L18	0.67×0.67, L32
CCSR/NIES2	CCSR/NIES (Japan)	T21, 5.6×5.6, L20	2.8×3.8, L17
BERN2D	PIUB (Switzerland)	10×ZA (zonal mean), L1	10×ZA (zonal mean), L15
UVIC	UVIC (Canada)	1.8×3.6, L1	1.8×3.6, L19
CLIMBER	PIK (Germany)	10×51, L2	10×ZA (zonal mean), L11

evaluation" chapter in every IPCC report systematically summarizes the improvements of climate models over each 5-yr period. Based on these chapters in IPCC FAR, SAR, TAR, and AR4, the major improvements can be summarized as follows.

As noted in FAR and the corresponding supplementary report (Gates et al., 1990, 1992), the large-scale structure of the ocean and atmosphere could be simulated with some skill in the coupled general circulation models (CGCM) that participated in CMIP1. In those models, an adjustment was sometimes made to the surface heat and salinity fluxes. The effects of clouds remained a major area of uncertainty in the modeling of climate change, although the treatment of clouds in CGCMs was becoming more complex. The report also pointed out that a lack of adequate observational data remained a serious impediment to climate model improvement.

As noted in SAR (Gates et al., 1995), sea ice and land surface components were introduced in CGCMs, although flux adjustment was used. Land surface processes could be modeled more realistically, and the simulated large-scale distribution of temperature, salinity, and sea ice was much improved. The major areas of uncertainty in climate models included clouds and their radiative effects, the hydrological balance over the land surface, and the heat flux at the ocean surface. The comprehensive diagnosis and evaluation

Table 4. The models used for IPCC AR4

Model name	Institute	Horizontal and vertical resolutions of atmospheric model	Horizontal and vertical resolutions of oceanic model
BCC_CM1.0	BCC (China)	T63, 1.9×1.9, L16	T63, 1.9×1.9, L30
BCCR_BCM2.0	BCCR (Norway)	T63, 1.9×1.9, L31	0.5–1.5×1.5, L35
CCSM3	NCAR (USA)	T85, 1.4×1.4, L26	0.3–1×1, L40
CGCM3.1(T47)	CCCma (Canada)	T47, 2.8×2.8, L31	1.9×1.9, L29
CGCM3.1(T63)	CCCma (Canada)	T63, 1.9×1.9, L31	0.9×1.4, L29
CNRM-CM3	CNRM (France)	T63, 1.9×1.9, L45	0.5–2×2, L31
CSIRO-MK3.0	CSIRO (Australia)	T63, 1.9×1.9, L18	0.8×1.9, L31
ECHAM5/MPI-OM	MPI (Germany)	T63, 1.9×1.9, L31	1.5×1.5, L40
ECHO-G	MIUB/MRI (Germany-Korea)	T30, 3.9×3.9, L19	0.5–2.8×2.8, L20
FGOALS_g1.0	IAP/LASG (China)	T42, 2.8×2.8, L26	1.0×1.0, L16
GFDL_CM2.0	GFDL (USA)	2.0×2.5, L24	0.3–1.0×1.0
GFDL_CM2.1	GFDL (USA)	2.0×2.5, L24	0.3–1.0×1.0
GISS_AOM	GISS (USA)	3×4, L12	3×4, L16
GISS_EH	GISS (USA)	4×5, L20	2×2, L16
GISS_ER	GISS (USA)	4×5, L21	4×5, L13
INM-CM3.0	INM (Russia)	4×5, L21	2×2.5, L33
IPSL_CM4	IPSL (France)	2.5×3.75, L19	2×2, L31
MIROC3.2(hires)	UT, JAMSTEC (Japan)	T106, 1.1×1.1, L56	0.2×0.3, L47
MIROC3.2(medres)	UT, JAMSTEC (Japan)	T42, 2.8×2.8, L20	0.5–1.4×1.4, L43
MRI-CGCM2.3.2	MRI (Japan)	T42, 2.8×2.8, L30	0.5–2.0×2.5, L23
PCM	NCAR (USA)	T42, 2.8×2.8, L26	0.5–0.7×1.1, L40
UKMO-HadCM3	UKMO (UK)	2.5×3.75, L19	1.25×1.25, L20
UKMO_HadGEM1	UKMO (UK)	1.3×1.9, L38	0.3–1.0×1.0, L40

Table 5. The models used for IPCC AR5

Model name	Institute	Horizontal resolution of atmospheric model	Horizontal resolution of oceanic model
ACCESS1-0	CSIRO-BOM (Australia)	1.3° × 1.9°	0.6° × 1.0°
BCC_CSM1.1	BCC (China)	2.8° × 2.8°	0.8° × 1.0°
BCC_CSM1.1(m)	BCC (China)	1.1° × 1.1°	0.8° × 1.0°
BNU-ESM	BNU (China)	2.8° × 2.8°	0.9° × 1.0°
CanCM4	CCCMA (Canada)	2.8° × 2.8°	0.9° × 1.4°
CanESM2	CCCMA (Canada)	2.8° × 2.8°	0.9° × 1.4°
CCSM4	NCAR (USA)	0.9° × 1.3°	0.6° × 0.9°
CNRM-CM5	CNRM-CERFACS (France)	1.4° × 1.4°	0.6° × 1.0°
CSIRO-Mk3-6-0	CSIRO-QCCCE (Australia)	1.9° × 1.9°	1.9° × 0.9°
EC-Earth	EC-Earth (EU)	1.1° × 1.1°	1.0° × 1.0°
FGOALS-g2	LASG-CESS (China)	3° × 2.8°	0.9° × 1.0°
FGOALS-s2	LASG (China)	1.7° × 2.8°	0.9° × 1.0°
GFDL-CM3	GFDL (USA)	2.0° × 2.5°	0.9° × 1.0°
GFDL-ESM2M	GFDL (USA)	2.0° × 2.5°	0.9° × 1.0°
GISS-E2-R	GISS (USA)	2.0° × 2.5°	1.0° × 1.3°
HadGEM2-CC	Hadley Center (UK)	1.3° × 1.9°	0.8° × 1.0°
HadCM3	Hadley Center (UK)	2.5° × 3.8°	1.3° × 1.3°
inmcm4	INM (Russia)	1.5° × 2°	0.5° × 1.0°
IPSL-CM5A-LR	IPSL (France)	1.9° × 3.8°	1.2° × 2.0°
MIROC5	AORI-NIES-JAMSTEC (Japan)	1.4° × 1.4°	0.8° × 1.4°
MIROC4h	AORI-NIES-JAMSTEC (Japan)	0.6° × 0.6°	0.2° × 0.3°
MIROC-ESM	AORI-NIES-JAMSTEC (Japan)	2.8° × 2.8°	0.7° × 1.2°
MIROC-ESM-CHEM	AORI-NIES-JAMSTEC (Japan)	2.8° × 2.8°	0.7° × 1.2°
MPI-ESM-LR	MPI-M (Germany)	1.9° × 1.9°	0.8° × 1.4°
MRI-CGCM3	MRI (Japan)	0.6° × 0.6°	0.5° × 1.0°
NorESM1-M	NCC (Norway)	1.9° × 2.5°	0.5° × 1.1°

of both component and coupled models were essential parts of model development, but a lack of observations still limited progress, so a comprehensive global climate observing system was urgently needed.

It was noted in TAR (McAvaney et al., 2001) that the simulations of clouds and humidity were much improved in the coupled models that participated in CMIP2. Some models that did not use flux adjustment maintained good stability and exhibited reasonable performance. The warming trend in 20th-century surface air temperature was reproduced when driven by radiative forcing due to increasing greenhouse gases and sulphate aerosols. Simulation of the El Niño–Southern Oscillation (ENSO) was also much improved, although the simulated strength was generally underestimated. A realization that no single model could ever be considered "best" came to the fore, along with the importance of utilizing results from a range of coupled models. Coupled models were now recognized by the community as suitable tools for providing useful projections of future climates.

As noted in AR4 (Randall et al., 2007), most CGCMs that participated in CMIP3 no longer used flux adjustments. There had been ongoing improvements to model resolutions, computational methods, and parameterizations, and additional processes (e.g., interactive aerosols) were beginning to be included in an increasing number of models. An explicit treatment of the carbon cycle had been introduced in a few climate CGCMs and some ESMs of intermediate complexity. The shortwave impact of changes in boundary-layer clouds, and to a lesser extent mid-level clouds, constituted the largest contribution to intermodel differences in global cloud feedbacks.

4. Characteristics of CMIP5 models

The CMIP5 experiments include three types (Taylor et al., 2012). The first is long-term integration, in which the integration time is longer than 100 yr and there are two core experiments: (1) The Atmospheric Model Intercomparison Project (AMIP) experiment, in which the observed sea surface temperature (SST) and sea ice are specified for the past 100 years; and (2) the climate system model experiment. The second type of experiments is near-term integrations, which mainly refer to decadal-scale prediction experiments. These experiments consider both external forcing changes (e.g., greenhouse gases, anthropogenic aerosols, solar variability, volcanic eruptions) and the initial state of the ocean to perform 10- and 30-yr climate predictions by using the CSM. The third type is high-resolution atmospheric model experiments. The core experiments here include the AMIP experiments spanning the period 1979–2008 and future climate time-slice simulations for the period 2026–2035. Although the time range is relatively short, the computer resources required are still huge in these experiments due to the higher resolution.

It is important to note that the model resolution requirement is different in each of the above three types of experiments. Models carrying out the long-term integrations often adopt a medium-to-low resolution because huge computer resources are necessary. The near-term integration times are often short, so these experiments require high-resolution designs. However, in practice it has been revealed that decadal prediction skill is not due to the model resolution but the initial scheme, so a medium-level resolution tends to be used in this type of experiments. The third type of experiments is designed for high-resolution climate models or numerical forecast models.

Of the 35 CMIP5 models, 24 are CSMs, and 13 of these include an atmospheric chemistry component. The remaining 11 are ESMs, 5 of which include both the land and ocean carbon cycle and an atmospheric chemistry process, a further 5 include the land and ocean carbon cycle only, and 1 includes the ocean carbon cycle only (Flato et al., 2013). In terms of model resolution, the CMIP5 models present the following characteristics.

(1) There are 13 models participating in both long-term integrations and near-term integrations. The atmospheric model horizontal resolution spans from 2.8° to 0.8°, with an average of 1.5°. The ocean model horizontal resolution spans from 2.0° to 0.5°, with an average of 1.0°.

(2) There are 19 models participating in long-term

integrations only. The atmospheric model horizontal resolution spans from 4.5° to 1.1°, with an average of 2.1°. The ocean model horizontal resolution spans from 2.0° to 0.2°, with an average of 0.9°.

(3) There are seven models participating in near-term integrations only. The atmospheric model horizontal resolution spans from 2.5° to 0.5°, with an average of 1.3°. The ocean model horizontal resolution spans from 1.3° to 0.3°, with an average of 0.8°.

(4) The horizontal resolution of the high-resolution atmospheric models participating in the time-slice integrations spans from 0.6° to 0.2°, with an average of 0.4°.

The CMIP5 experiments performed by the five Chinese models mainly belong to the first and second of the aforementioned types. However, as shown in Fig. 1, the models with the lowest horizontal resolution in these experiments are from China, indicating that the resolution of Chinese models used for climate change research has fallen behind the international standard (Table 5 and Fig. 1). Increasing model resolution is not only a technical problem, but also involves the overall ability of the model development team and cooperation with high-performance computing experts. How to effectively utilize the world's leading computing resources in climate modeling is a common problem for the climate modeling and high-performance computing fields.

An important development since CMIP3 is the more widespread implementation of ESMs in CMIP5. As shown in Table 6, there are 10 ESMs including both land and ocean carbon components in CMIP5 (Anav et al., 2013). The parameterization of marine biology can be classified into three types in the ocean carbon component: (1) nutrient-based models, where the export of carbon below the surface ocean is a function of the surface nutrient concentration; (2) nutrient-restoring models, in which biological carbon fluxes are set to the rates required for maintaining observed nutrient concentration gradients against dissipation by ocean mixing; and (3) models that explicitly represent the food chain, involving nutrients, phytoplankton, zooplankton, and detritus (NPZD models). Most of the current ESMs in CMIP5 are NPZD models. NPZD models include seven different parts: nutrient (phosphate, nitrate, and iron), phytoplankton, zooplankton, dissolved organic matter (DOM), and particulate organic matter.

Process-based terrestrial models used in ESMs are dynamic global vegetation models (DGVMs) (Anav et al., 2013; Shao et al., 2013), which include three components: (1) a biogeographical component, which describes the climatic constraints of survival and establishment; (2) a biogeochemical component, which simulates the growth of vegetation, including photosynthesis and respiration; and (3) a vegetation dynamics component, which represents changes in ecological characteristics such as phenology, physiology, morpho-

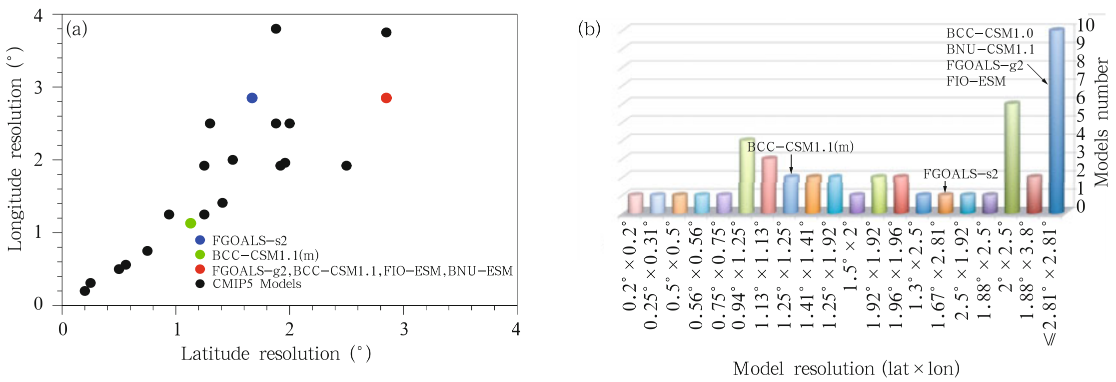

Fig. 1. (a) A comparison of AGCM horizontal resolutions of CMIP5 AGCMs and CGCMs. The abscissa is for the latitude resolution while the ordinate is for the longitude resolution (°), and one dot corresponds to one CMIP5 model. (b) Total number of models at different horizontal resolutions. The abscissa is for the model resolution while the ordinate is the number of models at different horizontal resolutions. The Chinese models are marked.

Table 6. Summary of names, land and ocean carbon cycle components of CMIP5 ESMs

Model	Land carbon cycle component	Ocean carbon cycle component	Reference
BCC-CSM1.1	BCC_AVIM1.0	OCMIP2	Wu et al. (2013)
BCC-CSM1.1-M	BCC_AVIM1.0	OCMIP2	Wu et al. (2013)
BNU-ESM	CoLM + BNU-DGVM	iBGC	Ji et al. (2014)
CanESM2	CLASS2.7 + CTEM1	CMOC	Arora et al. (2011)
CESM1-BGC	CLM4	BEC	Long et al. (2013)
FIO-ESM	CASA	OCMIP2	Qiao et al. (2013)
GFDL-ESM2G	LM3	TOPAZ2	Dunne et al. (2012)
GFDL-ESM2M	LM3	TOPAZ2	Dunne et al. (2012)
HadGEM2-CC	JULES+TRIFFID	Diat-HadOCC	Collins et al. (2011) Jones et al. (2011)
HadGEM2-ES	JULES+TRIFFID	Diat-HadOCC	Collins et al. (2011) Jones et al. (2011)
INM-CM4	Simple model into INM-CM4 atmospheric component	Simple model into INM-CM4 ocean component	Volodin et al. (2010)
IPSL-CM5A-LR	ORCHIDEE	PISCES	Dufresne et al. (2013)
IPSL-CM5A-MR	ORCHIDEE	PISCES	Dufresne et al. (2013)
IPSL-CM5B-MR	ORCHIDEE	PISCES	Dufresne et al. (2013)
MIROC-ESM-CHEM	MATSIRO + SEIB-DGVM	NPZD	Watanabe et al. (2011)
MIROC-ESM	MATSIRO + SEIB-DGVM	NPZD	Watanabe et al. (2011)
MPI-ESM-LR	JSBACH + BETHY	HAMOCC5	Ilyina et al. (2013) Giorgetta et al. (2013)
MPI-ESM-MR	JSBACH + BETHY	HAMOCC5	Ilyina et al. (2013) Giorgetta et al. (2013)
NorESM-ME	CLM4	HAMOCC5	Tjiputra et al. (2013)

logy, and species competition.

5. Characteristics of the Chinese models in CMIP5

Five models developed by Chinese institutions have participated in CMIP5. The performances of these five models have been systematically assessed by using same observational metrics in Zhou et al. (2014a). The technical details of the five Chinese models participating in CMIP5 (Table 5) are summarized in this section.

5.1 FGOALS CSMs (IAP, CAS)

Two versions of the Flexible Global Ocean-Atmosphere-Land System model (FGOALS) are used to implement the CMIP5 experiments (see Zhou et al., 2014b for a review book edited by LASG/IAP climate system model development team). One is FGOALS-g2 (Li et al., 2013), in which the atmospheric component is GAMIL (Grid Atmospheric Model of LASG/IAP), a grid-point model. The horizontal resolution of GAMIL is approximately 2.8° × 2.8° with 26 model levels. The ocean model resolution is also approximately 2.8° × 2.8° in the horizontal direction and it has 30 levels in the vertical direction. The land and ice components are CLM3 (Community Land Model version 3) and CICE4 (Los Alamos sea-ice model version 4.0). All components are coupled via the CPL6 coupler. The tuning work and basic control experiments are accomplished at LASG/IAP. Other experiments are carried out on the computing platform in the Department of Computer Science and Technology, Tsinghua University. The other version of FGOALS is FGOALS-s2 (Bao et al., 2013), in which the atmospheric component is SAMIL (Spectral Atmospheric Model of LASG/IAP), a spectral model. SAMIL is truncated by R42 (approximately 2.8° × 1.4°) with 26 model levels. The coupling framework is similar to FGOALS-g2, except that the ice component is CSIM5 (Community Sea-Ice Model version 5). All experiments of FGOALS-s2 are completed at IAP. The two versions have performed all of the core experiments and part of the tier experiments for CSMs. A terrestrial carbon cycle model called “Vegas” and basic ocean carbon cycle processes are involved in FGOALS-s2 to construct an ESM version of the model, FGOALS-s2-ESM. This version has performed the core experiment for ESMs in CMIP5. In addition, to reduce the huge computing cost of the millennium simulation, FGOALS-gl, a version with coarse resolution, is used to perform the last millennium experiment at IAP (Zhou et al., 2008, 2011; Man and Zhou, 2011, 2014; Zhang et al., 2013).

5.2 BCC-CSM and BCC-ESM

Two versions of the BCC's model are involved in CMIP5. One is BCC_CSM1.1, for which the atmospheric component is BCC_AGCM2.1 with T42 truncation (approximately 2.8°) and 26 model levels. The ocean component is MOM4 with a horizontal resolution of 1/3° (approximately 30 km) and 40 levels. The land component is BCC_AVIM1.0. The other version of the BCC model is BCC_CSM1.1 (m). The major advance relative to BCC_CSM1.1 is that the atmospheric component has been updated to BCC_AGCM2.2, with a higher horizontal resolution of T106 (approximately 1.1°). Both of the two model systems include simple carbon cycle processes, belonging to the ESM group. The BCC models have performed all of the core experiments and part of the tier experiments for CSMs and ESMs (Wu et al., 2010, 2013a, b, 2014; Xin et al., 2012).

5.3 BNU-ESM (Beijing Normal University)

This model is an ESM based on CCSM2. With the NCAR coupler, it couples the AGCM CAM3.5, the ice model CICE4.0, the Common Land Model CoLM3.0 developed at BNU (Beijing Normal University), and the ocean model MOM4p1 developed in the Geophysical Fluid Dynamics Laboratory, NOAA. The atmospheric component employs a spectral dynamical framework with T42 truncation (approximately 2.8°) and 26 model levels (Wu et al., 2013; Ji et al., 2014).

5.4 FIO-ESM (First Institute of Oceanography, State Oceanic Administration)

This model is also an ESM based on CCSM2. The atmospheric component is CAM3.0 with a horizontal resolution of T42 (approximately 2.8°) and 26 model levels. The ocean component is POP2 with a horizontal resolution of 1.1° (enhanced near the equator by 0.3°–0.5°) and 40 levels. The land and ice components are CLM3 and CICE4 respectively. A significant feature is that a sea-wave model is coupled in the system with a horizontal resolution of 2.0° × 2.0°. The terrestrial carob cycle model is CASA and the ocean carbon cycle model is OCMIP-2. The model preforms part of the core and tier experiments for CSMs and the control experiments for ESMs (Qiao et al., 2004, 2013; Song et al., 2011, 2012).

For the five Chinese models in CMIP5, the simulated climate mean state, intra-seasonal oscillation, interannual ENSO variability, global and East Asian monsoons, climate evolution of the 20th century, major atmospheric teleconnections, Indian Ocean warming, and many other features show reasonable performance (Bellenger et al., 2013; Sperber et al., 2013; Wu and Zhou, 2013; Dong and Zhou, 2014; Dong et al., 2014; He and Zhou, 2014; Song and Zhou, 2014; Song et al., 2014; Zhang and Zhou, 2014; Zhou et al., 2014a). However, a distinct spread in climate sensitivity to greenhouse gases forcing is apparent across the models (Chen et al., 2014; Zhou et al., 2014a).

The CMIP5 experimental design and data size are unprecedented. Compared with previous CMIPs, a new feature in CMIP5 for IAP/LASG is the alliances and collaborations formed with other research centers. For example, IAP/LASG joined forces with FIO/SOA to construct the coupling framework of the FGOALS2 system, and it also cooperated with the Department of Computer Science and Technology and the Center for Earth System Science (CESS) of Tsinghua University to optimize the code and improve the efficiency for GAMIL and FGOALS-g2. Most of the projection experiments of FGOALS-g2 have been undertaken by the high-performance computer at Tsinghua University. LASG/IAP and LAPC/IAP jointly developed the initial version of FGOALS-s2-ESM. "Alliance and collaboration" should be advocated as the scientific culture in the ESM developer community in China.

6. Challenges for global climate model development in China

There are many types of metrics available for evaluating the overall level of climate model development, among which comparison with CMIP5 models is an effective approach. Taking the CMIP5 models as reference criteria, the main gaps for current Chinese climate models compared with the international standard are discussed in this section.

Firstly, the resolutions of nearly all Chinese models lag behind the international average. The development of high-resolution models in China falls seriously behind the level of other nations. Compared with non-Chinese CMIP5 models, the disadvantages of Chinese models in the area are very clear (Table 5 and Fig. 1). At present, the average horizontal resolution of international atmospheric models, which can be used in long-term climate simulations, reaches approximately 1.5°. The resolutions of some models developed by internationally advanced modeling centers are even higher than 1.0°. For the short-term climate simulations, high-resolution atmospheric models with resolutions of around 0.2°–0.6° have emerged. In contrast, the resolutions of the atmospheric components of the Chinese models participating in CMIP5 are around 2.8°, which is far lower than the international average. High-resolution models can resolve finer physical processes on smaller spatial scales, and thus obtain higher modeling skill levels. Meanwhile, high-resolution models can simulate some basic atmospheric and oceanic phenomena that cannot be simulated by low-resolution models, such as tropical cyclones and the fine structure of the Meiyu front in the atmosphere, and mesoscale eddies in the ocean. Therefore, resolution is an important metric for evaluating the skill of atmospheric models. Even though there are five Chinese models participating in CMIP5, we should recognize that the overall level of Chinese models lags far behind those of developed countries. In fact, the lag is becoming increasingly larger, especially with respect to high-resolution models and ESMs.

Secondly, China falls behind in terms of ESM development. There are 11 ESMs participating in CMIP5 (Anav et al., 2013), and for the Chinese models, although BCC, BNU, FIO, and FGOALS-s2 include the carbon cycle, they all simplify both the land and oceanic carbon cycle processes. It is important to improve the simulations of the land and oceanic carbon cycle processes in Chinese models through integrating studies on land and oceanic biogeochemical cycle components with original physical CSMs. In this way, the development of ESMs in China can begin to reach the same level as that achieved elsewhere in the international research community.

Thirdly, China does not have a sufficient workforce operating in the development of atmospheric and oceanic circulation models, both of which are key components of ESMs. There are 10 earth/climate system models currently being developed in China (Table 7). However, only IAP/CAS and BCC are engaged in the development of atmospheric models, and only IAP/CAS is engaged in the development of oceanic circulation model. Those institutions that are new to the development of coupled climate models generally use atmospheric and oceanic components developed abroad, which of course has the tendency to reduce sample sizes when it comes to performing multi-model ensemble simulations.

The above three aspects can be summarized into one point; that is, China needs to enhance its capacity for innovation in the development of CSMs. Model development involves the dynamics, thermodynamics, and physical processes of the atmosphere, ocean, sea ice, land, and their interactions. It also involves the expression of the above processes on a high-performance computer. For many of these aspects, China falls behind the more advanced level shown internationally. Several China's models originate from overseas models via different degrees of modification. In fact, the bigger challenge is to make improvements to the dynamic core and physical processes of a model based on the existing structure. For the development of high-resolution models, in addition to the aforementioned efforts, support from high-performance supercomputer hardware and software developments is also needed. Therefore, we still need long-term unremitting efforts to shorten the gap between the current state-of-the-art in China and that achieved elsewhere internationally.

7. Opportunities for developing ESMs in China

Despite the apparent lagging behind of China

Table 7. List of current earth/climate system models developed in China

	Model name	Institute	Atmospheric model	Oceanic model	Land model	Ice model	Coupler
1	BCC-ESM (Wu et al., 2014)	National Climate Center	BCC-AGCM (2.8° × 2.8°)	MOM4 (1.0° at high latitudes; closer to 0.3° in the tropics)	AVIM	CICE	CPL
2	BNU-ESM (Ji et al., 2014)	BNU	CAM3.5 (2.8° × 2.8°)	MOM4p1 (1.0° at high latitudes; closer to 0.3° in the tropics)	CoLM	CICE4	CPL
3	CAMS-CSM	Chinese Academy of Meteorological Sciences	ECHAM5 (2.8° × 2.8°)	MOM4 (1.0° at high latitudes; closer to 0.3° in the tropics)	JSBACH	FMS-SIS	FMS-coupler
4	CAS-ESM (Sun et al., 2012)	ICCES, IAP	IAP4 AGCM (1.4° × 1.4°)	LICOM (1.0°, 0.5° in the meridional direction over the tropics)	CLM	CICE	CPL
5	FIO-ESM (Qiao et al., 2013)	FIO	CAM3.5 (2.8° × 2.8°)	POP2 (1.1° at high latitudes; closer to 0.3° –0.5° in the tropics)	CLM	CICE	CPL
6	FGOALS-s2 (Bao et al., 2013)	LASG/IAP	SAMIL (1.6° × 2.8°)	LICOM (1.0°, 0.5° in the meridional direction over the tropics)	CLM	CICE	CPL
7	FGOALS-g2 (Li et al., 2013)	LASG/IAP	GAMIL (2.8° × 2.8°)	LICOM (1.0°, 1.0°, 0.5° in the meridional direction over the tropics)	CLM	CICE	CPL
8	CICSM/CIESM[2]	Tsinghua University	FDAM (1.0° × 1.0° /2.8° × 2.8°)	FDOM (0.5° × 0.5° /1.0° × 1.0°)	CLM4	CICE4-LASG	C-coupler
9	ICM (Huang et al., 2014)	CMSR, IAP	ECHAM5 (3.75° × 3.75°)	NEMO2.3 (2.0°, 0.5° over the tropics)	JSBACH	LIM2	OASIS3
10	NIUST model 1.0[3]	Nanjing University of Information Science & Technology	ECHAM4 (2.8° × 2.8°)	NEMO (3.0°, 0.6° over the tropics)	JSBACH	CICE	OASIS3

compared to the international community, as mentioned in the previous section, the development of ESMs nevertheless faces unprecedented favorable opportunities in the following three aspects:

Firstly, national attention and financial support are both sufficient. China has boosted support for the development of climate models through various research projects, including the "973" and "863" projects of the Ministry of Science and Technology, CAS Strategic Priority Research Programs, Special Scientific Research Funds of the State Oceanic Administration and China Meteorological Administration, the National Natural Science Foundation, and other funding sources. According to statistics, there are several "973" projects that are directly related to the development of climate models. For example, a major scientific project entitled "Development and Evaluation of High-Resolution Climate System Models" involves the construction of a 50-km AGCM with good stability and physical conversion, as well as a 30–50-

[2] Wang Bing, 2013: Preparing for CMIP6 in China. WGCM17 meeting, 1–3 Oct, 2013, Victoria, Canada.

[3] http://xcb.nuist.edu.cn/tjxw/top3/2014-04-26/8067.shtml

km OGCM. Meanwhile, the objective of a project entitled “Research of Key Processes Associated with the Carbon Cycle and Its Coupling with the Climate System” is to achieve a three-dimensional coupling of the carbon cycle in the atmosphere, land, and ocean, and use it to enhance the research of the interactions between climate change and the carbon cycle. Furthermore, another project entitled “Development and Improvement of Ecological and Environmental System Models” aims to develop our own global vegetation ecosystem dynamical model, global aerosols and atmospheric chemistry model, and global land and ocean biological process models (mainly for carbon and nitrogen cycles), and to ultimately form a complete ecological and environmental system. The objective of an “863” key project entitled “Research of Efficient Parallel Algorithms for ESMs and the Development of a Parallel Coupler” is to design efficient parallel algorithms for an ESM, construct a parallel application framework, and finally build a modular parallel coupler with intellectual property in China, which applies innovative, high-performance algorithms, and software implementation techniques to the development of a physical CSM. Lastly, the objective of CAS Strategic Priority Research Programs under the heading “Uncertainties of Simulation and Projection by Climate Models” is to study the key physical processes associated with the uncertainties of model simulations, design parameterization schemes, and finally develop an ESM at CAS via internal and external collaboration.

Secondly, the rapid development of high-performance computers provides a solid computing platform to develop ESMs and facilitate their participation in international competitions. Taking the supercomputers “Tianhe One” and “Tianhe Two” as symbols of success, China has become one of the countries able to develop a petaflop supercomputer. Taking IAP as an example, LASG/IAP used thousands of cores to conduct quasi-global ocean circulation simulations with a 10-km resolution on “Tianhe One” in 2012. It has also used approximately 1000 core computing resources to test its global atmospheric circulation model with 12.5- and 6-km resolutions. This has greatly promoted research and development of high-resolution climate models.

Thirdly, the research and development (R&D) community in the climate model field is growing stronger, with an increasing number of young scientists rapidly emerging to the fore in this area of work in China. In recent years, teaching and research institutions able to train young scientists has gradually increased. In addition to IAP/CAS, Nanjing University, and Beijing University, with their long histories in model development, other units such as Beijing Normal University, Tsinghua University, Nanjing University of information Science & Technology, and the Chinese Academy of Meteorological Sciences/China Meteorological Administration have also begun to establish departments or research centers to develop climate models and train young scientists in recent years. Therefore, our R&D community of climate modelers is growing year on year. At a national level, once climate model development teams are able to maintain a certain volume, the overall level of climate model development in China will be improved through positive competition and collaboration.

8. Concluding remarks

CSMs have evolved from physical CSMs to ESMs. The purpose of developing physical CSMs is to understand the physics of interactions among various spheres, whereas the purpose of developing ESMs is to understand the roles of energetic, ecological, and metabolic processes of the earth by investigating 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 emissions through these processes. Therefore, the development of ESMs should be open and collaborative because of the multidisciplinary characteristics involved. Such an approach has underpinned the successes around developing ESMs in the developed world.

As many as 10 earth/climate system models are currently being developed in China (Table 7). How to achieve a structured development of earth/climate system models at a national level is now an urgent problem for funding agencies. To achieve this, China can turn to many strategies from elsewhere around the world. Here, we list nine such strategies as concluding remarks to this paper, which were recommended in the book entitled "*A National Strategy for Advancing Climate Modeling*", released by the US National Academy of Sciences. The strategic framework was produced by the National Research Council (NRC) to guide the process of the US's climate modeling enterprises over the next 10–20 years. In response, the NRC appointed the Committee for the National Strategy for Advancing Climate Modeling. The committee recommends a national strategy for advancing climate modeling enterprises in the next two decades, consisting of four main new components and five supporting elements as follows:

1) Evolve a common national software infrastructure that supports a diverse hierarchy of different models for different purposes, and which supports a vigorous research program aimed at improving the performance of climate models on extreme-scale computing architectures; 2) Convene an annual climate modeling forum that promotes tighter coordination and more consistent evaluation of the US regional and global models, and helps knit together model development and user communities; 3) Nurture a unified weather-climate modeling effort that better exploits the synergies between weather forecasting, data assimilation, and climate modeling; and 4) Develop training, accreditation, and continuing education for "climate interpreters" who will act as a two-way interface between modeling advances and diverse user needs. At the same time, the nation should nurture and enhance ongoing efforts to 5) Sustain the availability of state-of-the-art computing systems for climate modeling; 6) Continue to contribute to a strong international climate observing system capable of comprehensively characterizing long-term climate trends and climate variability; 7) Develop a training and reward system that entices the most talented computer and climate scientists into climate model development; 8) Enhance the national and international information technology infrastructure that supports climate modeling data sharing and distribution; and 9) Pursue advances in climate science and uncertainty research.

The elements of this strategic report should be a useful reference to Chinese funding agencies in the process of decision-making. The key scientific issues identified by the report have also provided guidance for climate change and variability studies in China.

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