Development of Climate and Earth System Models in China: Past Achievements and New CMIP6 Results

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ABSTRACT

The Earth–Climate System Model (ECSM) is an important platform for multi-disciplinary and multi-sphere integration research, and its development is at the frontier of international geosciences, especially in the field of global change. The research and development (R&D) of ECSM in China began in the 1980s and have achieved great progress. In China, ECSMs are now mainly developed at the Chinese Academy of Sciences, ministries, and universities. Following a brief review of the development history of Chinese ECSMs, this paper summarized the technical characteristics of nine Chinese ECSMs participating in the Coupled Model Intercomparison Project Phase 6 and preliminarily assessed the basic performances of four Chinese models in simulating the global climate and the climate in East Asia. The projected changes of global precipitation and surface air temperature and the associated relationship with the equilibrium climate sensitivity under four shared socioeconomic path scenarios were also discussed. Finally, combined with the international situation, from the perspective of further improvement, eight directions were proposed for the future development of Chinese ECSMs.

Key words: Earth–Climate System Model (ECSM), Chinese models, Coupled Model Intercomparison Project Phase 6 (CMIP6), model performance, climate prediction and projection, outlook

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1. Introduction

The climate system concept, which was proposed in the last half of the 20th century, is an important development in modern climate research. The climate system concept emphasizes the need for integral research on the atmosphere, hydrosphere, cryosphere, geosphere, and biosphere to understand the principles and mechanisms of climate change in the past and modern eras and to predict and propose future changes from the perspective of multi-sphere interactions. Corresponding to the extension of research fields, two technology advances, i.e., numerical modeling and satellite sensing, prompted the modern climate research to take a step further. The nu-
merical modeling technique, as well as theoretical research and observation, has been the main method used to support modern climate research.

The climate system model (CSM), which is simply a computer program that includes a mass of natural laws, is a mathematical expression of the physical, chemical, and ecological processes in the climate system. Basically, it includes atmosphere, ocean, land, and sea ice components. Based on the CSM, the earth system model (ESM) additionally includes biogeochemical processes, such as carbon and nitrogen cycles, while maintaining the multi-layered and coupled core of physical climate system. For the sake of discussion, here, CSM and ESM are generally called the earth–climate system model (ECSM). The development of an ECSM requires understanding of the basic principles of the climate system, multi-disciplinary partnerships, and high-tech support to high-performance computation, and a mass storage system. An ECSM can reasonably describe the physical and chemical processes in the multi-sphere interaction; therefore, atmospheric science and earth climate system science become “testable sciences.” The ECSM has been the fastest growing area of geoscience during the last three decades. It has become an important tool to understand the mechanisms underlying climate change and is an indispensable approach to predicting and planning for the future climate.

The ECSM is also an important platform for multi-disciplinary, multi-sphere integral research (Zhou et al., 2018). Developing ECSMs is at the frontier of the international geoscience field, especially for competing in the global change area. The developmental level of ECSMs has become an important indicator to measure the science and technology strength of a country. Most of the developed countries have successively launched national-level model research and development (R&D) projects to prompt the development and application of domestic models (Wang et al., 2008). The United States of America implemented “A National Strategy for Advancing Climate Modeling,” in which it explicitly states that “climate models are among the most sophisticated simulation tools developed by mankind, and are the foundation for understanding and projecting climate and climate-related changes and are thus critical tools for supporting climate related decision making. Over the next two decades, the U.S. climate modeling enterprise will have to evolve substantially to meet national needs and stay internationally competitive” (National Research Council, 2012). The U.S. science communities pay a great deal of attention to model development.

Following a 30-yr exploration period, the R&D of the ECSM in China is currently entering a rapid development stage. We aim to summarize the progresses of ECSM development in the last five years based on an overview of its earlier achievements and to look into the future development.

2. International and domestic patterns in climate model development

During the past 40 years, the climate model development overseas has gone through several key stages, which are summarized as follows. The first stage is the rapid development of an Atmospheric General Circulation Model (AGCM) in the mid-1970s. The second stage is the coupling of the AGCM with a land model in the mid-1980s, while sea surface temperature and sea ice were prescribed. The third stage is the coupling of the AGCM with a “slab” ocean in the early 1990, which was used to run climate projection experiments in the First Assessment Report (FAR) of the Intergovernmental Panel on Climate Change (IPCC).

In the fourth stage, which occurred in approximately 1995, the AGCM began to include sulfate aerosol and volcanic aerosol and started coupling with an Oceanic General Circulation Model (OGCM). A fully coupled system including the atmosphere, ocean, land, and sea ice was used for climate projection experiments in the Second Assessment Report (SAR) of the IPCC.

In the fifth stage, which occurred in approximately 2001, the runoff process was added to the land model to close the hydrological cycle. In this period, the AGCM could better deal with the aerosols and the OGCM could describe the Meridional Overturning Circulation (MOC). Many models began to take the carbon cycle in the climate system into account. The physical processes in the models supporting the Third Assessment Report (TAR) of the IPCC were more comprehensive.

In the sixth stage, which occurred in approximately 2007, dynamic vegetation was first introduced into the land model, and the AGCM began to include atmospheric chemical processes. These new models were used for climate projection experiments in the Fourth Assessment Report (AR4) of the IPCC. At this stage, an important advance was that the “flux correction” technique was no longer employed by most models.

The seventh stage occurred in approximately 2013. In this stage, the CSM was gradually evolving into the ESM. A comprehensive improvement was observed in terms of simulating the biogeochemical cycle in the oceanic ecosystem module and addition of the global vegetation dynamic module in the land model.

At each stage above, the model resolution was also be-
Climate model development in China began in the 1980s, nearly at the same time as developed countries. After a more than 30-yr endeavor, remarkable achievements have been made in the AGCM, OGCM, land-process model, coupled model, and so on (see the review article of Wang et al., 2008). Corresponding to the model development, R&D teams in China are growing increasingly larger. Taking the Chinese models involvement in every IPCC scientific assessment report and CMIP activity as an example (Table 1), the evolution of CSM R&D pattern in China can be clearly observed. In the 1992 IPCC Supplement to the FAR, a Chinese model was included that involves a two-layer atmospheric model coupled with a mixed-layer ocean model developed in the OGCM and the “flux correction” technique was used in the air–sea coupling (Zhang et al., 1992; Chen et al., 1997a, b). Thereafter, a Global Ocean–Atmosphere–Land System model (GOALS) was established based on a 20-layer OGCM and a 9-layer spectral AGCM. The second version, GOALS2, participated in the First Phase of the CMIP (CMIP1; Wu et al., 1997; Yu and Zhang, 1998). In 2001, the IPCC TAR cited the results from the CMIP2 models, to which GOALS4, which was developed by the IAP/CAS, contributed. Compared with GOALS2, GOALS4 had an improved diurnal cycle of solar radiation (Shao et al., 1998) and freshwater flux exchange process in air–sea coupling (Zhou et al., 2001). Due to a major improvement in GOALS, Flexible GOALS (FGOALS) was developed, which first realized direct coupling in China without the “flux correction” based on the coupler framework (Yu et al., 2004). The first version of FGOALS, i.e., FGOALS-g1.0, participated in the CMIP3, which was cited by the IPCC AR4 in 2007. During nearly 20 years from the FAR to AR4, the CSM from CAS supported China’s entry into the international competition in climate modeling and projection. From the CMIP1 to CMIP3, the number of participating international models increased from 10 to 18 and then to 23, in which the CSM from CAS was the only model from a developing country (see the review article by Zhou et al., 2014). This R&D pattern in China was dramatically changed in the CMIP5.

The CMIP5 results were cited by the IPCC AR5 in 2013. There were 35 models worldwide that participated in the CMIP5, among which 6 models were from China (Table 2). They are as follows: FGOALS-g2 and FGOALS-s2, which are from the IAP/CAS; BCC-CSM and BCC-CSM1.1m, which are from the Beijing Climate Center and include the carbon cycle (Wu et al., 2014); BNU-ESM from the Beijing Normal University; and FIO-ESM from the First Institute of Oceanography.

### Table 1. The models from China used for IPCC AR1–4

| IPCC   | CMIP   | Model     | Horizontal resolution of atmospheric model | Horizontal resolution of oceanic model |
|--------|--------|-----------|---------------------------------------------|----------------------------------------|
| FAR    | CMIP1  | IAP       | 4° × 5°, L2                                 | Mixed layer ocean model                |
| SAR    | CMIP2  | GOALS2    | 4° × 5°, L2                                 | 4° × 5°, L20                           |
| TAR    | CMIP2  | GOALS4    | R15 (4.5° × 7.5°), L9                       | 4° × 5°, L20                           |
| AR4    | CMIP3  | FGOALS-g1.0| 2.8° × 2.8°, L26                           | 1.0° × 1.0°, L30                       |

*FAR: First Assessment Report; SAR: Second Assessment Report; TAR: Third Assessment Report; and AR4: Fourth Assessment Report

### Table 2. The models from China that participated in CMIP5 and used in IPCC AR5

| Model   | Institute | Horizontal resolution of atmospheric model | Horizontal resolution of oceanic model |
|---------|-----------|--------------------------------------------|----------------------------------------|
| BCC-CSM1.1 | BCC      | 2.8° × 2.8°                               | 0.8° × 1.0°                           |
| BCC-CSM1.1 (m) | BCC | 1.1° × 1.1°                               | 0.8° × 1.0°                           |
| BNU-ESM | BNU      | 2.8° × 2.8°                               | 0.9° × 1.0°                           |
| FGOALS-g2 | LASG-CESS | 3.0° × 2.8°                               | 0.9° × 1.0°                           |
| FGOALS-s2 | LASG     | 1.7° × 2.8°                               | 0.9° × 1.0°                           |
| FIO-ESM | FIO      | 2.8° × 2.8°                               | 0.9° × 1.0°                           |
under the Ministry of Natural Resources (Former State Oceanic Administration) of China. Both BNU-ESM and FIO-ESM were developed based on the third version of the Community Climate System Model (CCSM3; Collins et al., 2006). BNU-ESM updated the OGCM in CCSM3 and introduced an independently developed land model, while FIO-ESM first brought small-scale waves into CSM through a vertical mixing process to represent the controlling effect of waves to the upper ocean and climate (see the review article of Zhou et al., 2014). The increasing number of Chinese models in the CMIP reflects the expansion of the R&D teams focusing on modeling. Since the CMIP5, the CSM R&D pattern in China has transformed from the dominant status of the CAS into a tripartite situation involving the CAS, ministries, and universities. This situation will be reinforced in the CMIP6 (Zhou et al., 2019).

3. Chinese ECSMs participating in CMIP6 and the Earth System Science Numerical Simulator Facility

3.1 Chinese ECSMs participating in CMIP6

The Coupled Model Intercomparison Project Phase 6 (CMIP6) was planned in 2013, officially launched in 2016, and is currently being implemented. The CMIP6 will directly support the preparation of the IPCC Sixth Assessment Report. Globally, there are 33 model R&D teams participating in the CMIP6, with 13 new teams that did not participate in the CMIP5. There are 112 model versions\(^1\) registered by these 33 institutions participating in the CMIP6. Ten model teams in China have signed up for the CMIP6. Compared with the CMIP5, the model teams that are independently participating in the CMIP for the first time include the ESM teams from the Chinese Academy of Sciences, the Chinese Academy of Meteorological Sciences (CAMS), Nanjing University of Information Science & Technology (NUIST), Tsinghua University (THU), and the Research Center for Environmental Changes (RCEC), Taiwan, China (Zhou et al., 2019).

Although the number of climate models participating in the CMIP6 in mainland China has increased significantly compared with that in the CMIP5, the basic R&D team pattern, i.e., the three-component configuration involving the Chinese Academy of Sciences, ministries, and universities, remains unchanged. There are three model versions from the Chinese Academy of Sciences, namely, CAS FGOALS-g3, CAS FGOALS-f3, and CAS-ESM; the three models from the ministries are BCC-CSM (and BCC-ESM) from the National/Beijing Climate Center, China Meteorological Administration, CAMS-CSM from the Chinese Academy of Meteorological Sciences, and FIO-ESMv2.0 from the First Institute of Oceanography, Ministry of Natural Resources (MNR); the three models from the universities include BNU-ESM-1-1 from Beijing Normal University, CIESM from Tsinghua University, and NESM v3 from Nanjing University of Information Science & Technology. The active participation of universities in the R&D of CSMs is a new trend in the past five years, which is important for the cultivation of R&D talents for model development. The main technical features of the Chinese models participating in CMIP6 are summarized as follows. The main technical metrics are shown in Table 3. The table shows that three of the ECSMs are based on the Community Earth System Model (CESM) from the NCAR of the U.S. In addition, the ocean component models of the three ECSMs are based on the Modular Ocean Model (MOM) from the Geophysical Fluid Dynamics Laboratory (GFDL) of the U.S. It is noted that the model from Beijing Normal University is the same as that in CMIP5 (Ji et al., 2014), which was introduced in the previous review on Chinese contributions to the CMIP5 (Zhou et al., 2014) and will not be repeated here. Below is an overview of the remaining model versions.

There are three new models developed by the National (Beijing) Climate Center that participated in the CMIP6, including BCC-ESM1.0, medium-resolution climate model BCC-CSM2-MR, and high-resolution climate model BCC-CSM2-HR. The ice model component is the Sea Ice Simulator (SIS) developed by GFDL, and the land surface model for each model is BCC-AVIM2.0. BCC-AVIM2.0 was developed from the earlier version BCC-AVIM1.0, in which the parameterization scheme was improved to calculate the threshold temperature to initiate the freezing (thawing) of soil water (ice), and included the parameterization of snow surface albedo as well as the description of rice paddies in the vegetation module, and so on (Li W. P. et al., 2019). The ocean model is MOM4-L40 in BCC-ESM1.0 and BCC-CSM2-MR, which use a tripolar grid with a resolution of 0.3° in the tropics, increased to 1.0° in the polar region. In BCC-CSM2-HR, the ocean model is MOM5-L50 with a resolution of 0.25°. There is large discrepancy between the atmospheric models of BCC-ESM1.0, BCC-CSM2-MR, and BCC-CSM2-HR. In BCC-ESM1.0, the atmospheric model is BCC-AGCM3-chem, which has a horizontal

\(^1\)https://rawgit.com/WCRP-CMIP/CMIP6_CVs/master/src/CMIP6_source_id.html
The atmospheric model of BCC-CSM2-MR is BCC-AGCM3-MR, which has a horizontal resolution of T34 (~280 km) and 26 vertical layers. The top of the model is at 2.917 hPa. The chemistry module and aerosol process are included in BCC-AGCM3-chem.

The atmospheric model of BCC-CSM2-HR is BCC-AGCM3-HR, which has a horizontal resolution of T26 (~120 km) and 46 layers in the vertical direction, with the model top at 1.450 hPa. In BCC-AGCM3-MR, the schemes of the atmospheric radiation, deep convection process, and the gravity wave drag were improved, and the indirect effects of aerosols were included (Wu et al., 2019a, b). The atmospheric model of BCC-CSM2-HR is BCC-AGCM3-HR, which has a horizontal resolution of 45 km and 56 layers in the vertical direction, with the model top at 0.1 hPa. The details of these models can be found in Xin et al. (2019).

The CAMS-CSM has an atmospheric component based on the ECHAM5 (v5.4) from the Max Planck Institute for Meteorology (MPI-M). The horizontal resolution of the model is T106 (~120 km) with 31 vertical layers extending from the surface to 10 hPa. Compared with ECHAM5, major improvements of the CAMS-CSM atmospheric model include the following: (1) a Two-step Shape Preserving Advection Scheme (TSPAS) is used for water vapor transport; (2) a relevant k-distribution scheme (BCC_RAD) developed by Beijing Climate Center is adopted for radiative transfer parameterization. The ocean component of the CAMS-CSM is MOM4. The MOM4 component uses a tripolar grid with a zonal resolution of 1° globally and a meridional resolution of 0.25° in the tropics, and it changes to 1° poleward of 30°S (N). There are 50 vertical layers, and the top 23 layers have an even resolution of 10 m. The sea ice component is the SIS from GFDL. The land surface component is the Common Land Model (CoLM) and the unfrozen water below 0°C in soil is considered in the CoLM model. The details of CAMS-CSM can be found in Rong et al. (2019).

The ESM developed by the CAS is named CAS-ESM. The atmospheric component model of CAS-ESM is the IAP AGCM5, which has a horizontal resolution 1.4°
FGOALS-g3. In FGOALS-f3-L, the ocean model has a
ent model LICOM3, which is the same as that in the CAS
face model of CAS FGOALS-f3 is the Community Land
sorption, FAMIL2.2 uses an explicit convective precipita-
ordinate system with a mode top of 2.16 hPa (approxim-
are 32 levels in the vertical direction, and a mixed co-
horizontal resolution is 1° (~100 km), while it is
The horizontal resolution of the atmospheric model in
FGOALS-f3-L is approximately 1° (~100 km), while it is
approximately 0.25° (~25 km) in FGOALS-f3-H. There
are 32 levels in the vertical direction, and a mixed co-
ordinate system with a mode top of 2.16 hPa (approximately 45 km) is used. For the physical process parameter-
famil2.2 uses an explicit convective precipitation
scheme developed by IAP-LASG, which improves
s of tropical cyclones, Madden–Julian Oscilla-
, and extreme precipitation (He B. et al., 2019;
He S. C. et al., 2019; Li J. X. et al., 2019). The land sur-
face model of CAS FGOALS-f3 is the Community Land
Model version 4.0 (CLM4). The ocean model component
is LICOM3, which is the same as that in the CAS
FGOALS-f3-L, the ocean model has a
horizontal resolution of approximately 1° and 30 levels
in the vertical direction, while in FGOALS-f3-H, a hori-
tzontal resolution of 0.1° and 55 layers in the vertical di-
rection are used. The sea ice component of CAS
FGOALS-f3 is CICE4 and the coupler is CPL7.

The CAS FGOALS-g3 is also developed by the IAP/
CAS. The atmospheric model component is GAMIL3.
Compared with the previous version, i.e., GAMIL2, the
horizontal resolution is increased from 2.8° to 2° (~200 km), and the water vapor advection scheme is further
modified to strictly guarantee the water vapor conserva-
in the polar region. A two-dimensional instead of a
one-dimensional Message Passing Interface, with both
zonal- and meridional-split flows, is introduced (Liu L. et
al., 2014). The improvements of the physics parameteriz-
ations include the following: inclusion of the convective
momentum transport and stratospheric aerosols (Nie et
al., 2019), a stratiform cloud scheme based on the estim-
ated inversion temperature (Guo and Zhou, 2014), a new
stratus cloud amount scheme, a boundary layer scheme
based on turbulent flow energy, and an aerosol module
developed by the MPI-M (MACv2-SP). The ocean com-
ponent is LICOM3 with a tripolar grid. The horizontal
resolution is 1°, which is increased to 0.5° at the equator.
The GM (Gent–McWilliams) vertical mixing and tidal
mixing are improved. The land surface model is CAS-
LSM, which was developed based on CLM4.5 by coupling
with a scheme that considers the lateral flow of
groundwater, the use of water by human activities,
changes in the soil freezing and melting interface, and
the effects of river nitrogen transport processes. The sea
ice is CICE4 and the coupler is CPL7. The details can be
found in Tang et al. (2019).

Based on the NCAR Community Earth System Model
(CESM1.2.1), Tsinghua University, in collaboration with
several institutes in China, developed the Community In-
tegrated Earth System Model (CIESM1.1). The atmo-
pheric component is based on the Community Atmo-
spheric Model version 5 (CAM5), which has a horizontal
grid spacing of ~100 km and 30 vertical levels with
the model top at 1 hPa. The modifications to the atmo-
spheric model include a modified deep convection
scheme, a four-stream shortwave radiation scheme, a diag-
nostic statistical cloud macrophysics scheme, a single-
ic microphysics scheme, and prescribed aerosol radiat-
ive effects. These modifications alleviate some long-last-
ing systematic biases in the CESM, such as the underes-
timated marine boundary layer clouds and the double
ITCZ problem. The ocean model is based on the LANL
Parallel Ocean Program version 2 (POP2) and has a nomi-
inal grid of 1° with 60 vertical layers. Modifications to
POP2 include a new ocean grid, a more efficient baro-
tropic solver, modified mixing schemes, and a new air–sea flux exchange method. The land model is based on CLM4, with use of new soil texture and organic matter content data and a new thermal roughness parameterization. The sea ice model is CICE4.1, with the same grid structure as the ocean model. A few modifications related to the physics and dynamics of sea ice, such as the salinity-dependent freezing temperature and the floe-size dependent lateral melting rates are introduced. The Community Coupler version 2 (C-Coupler2) is employed in the CIESM to handle various model coupling functions, such as data transfer and data interpolation, among others. All the testing and experiments were conducted on the “TaihuLight” supercomputer at Wuxi, China. More details can be found in Lin et al. (2019).

The FIO-ESM v2.0, developed by the FIO, MNR of China, contains the following five model components: the atmospheric model of CAM5, the land surface model of CLM4, the sea ice model of CICE4, and the ocean model of the modified POP2 incorporating the Marine Science and NUmerical Modeling (MASNUM) surface wave model. The horizontal resolutions of CAM5 (with 30 vertical layers) and CLM4 are approximately 100 km, and a nominal 1° is applied for POP2, the MASNUM surface wave model, and CICE4. Four distinctive physical processes are included, which are the surface wave-induced vertical mixing, air–sea flux modulated by stokes drift, heat flux associated with sea spray, and SST diurnal cycle. Further information on FIO-ESM v2.0 can be found in Song et al. (2019).

The 3rd version of the NUIST Earth System model (NESM v3) has been developed in recent years and is a newcomer to the CMIP6. The NESM v3 consists of the ECHAM v6.3 atmospheric model, which is directly coupled with the JSBACH land surface model, the Nucleus for European Modelling of the Ocean (NEMO) model v3.4, the CICE v4.1 sea ice model, and the OASIS3-MCT_3.0 coupler. The ECHAM v6.3 and JSBACH are adopted from the Max Planck Institute ECHAM serial model. The horizontal resolution of the atmospheric component model is T63, which corresponds to approximately 200 km in the meridional and zonal directions. The 47 vertical layers extend from the surface up to 0.01 hPa. Improvements in the atmospheric component model include the development of cumulus parameterization, macro-/microphysics, and a boundary layer scheme. The horizontal resolution of the land surface model is the same as that of the ECHAM v6.3, but with 5-layer soil. The ocean component model is NEMO v3.4 with a horizontal resolution of approximately 1° × 1°. The resolution in the meridional direction is refined to 1/3° over the tropical region. There are 46 layers in the vertical direction, with the first 15 layers in the top 100 m. A “stiffer” oceanic equation of the state and the mix layer brine rejection process are incorporated in the ocean model. The sea ice component model is CICE v4.1, which was originally developed at LANL. Its resolution is approximately 1° × 1/2° in the meridional and zonal directions, with four sea ice layers and one snow layer on the top of the ice surface. Both the sea ice and snow albedo schemes are improved in the sea ice component model. Further information on NESM v3 can be found in Cao et al. (2019).

The ESM developed by the Academia Sinica, Taiwan, China, is named TaiESM. The model is an improved version of CESM1.2.2. The atmospheric model is CAM5.3, which has two horizontal resolutions of ~100 and ~200 km and 30 layers in the vertical direction. The ocean model is POP2, with a horizontal resolution of 1.0° and 70 layers in the vertical direction. The land surface model is CLM4, and the sea ice model is CICE4. The land surface, ocean, and sea ice components of TaiESM remain unchanged compared to CESM version 1.2.2. The main improvements are the deep convective parameterization scheme, the cloud macroscopic physical process, the aerosol module, and the inclusion of the effects of the topography on solar radiation.

3.2 The National 12th Five-Year Major Science and Technology Infrastructure “Earth System Science Numerical Simulator Facility”

In the past five years, in addition to the great achievement in the R&D of ECSMs in China, considerable progress has also been made in the construction of the R&D platform of ECSMs. The National 12th Five-Year Major Science and Technology Infrastructure “Earth System Science Numerical Simulator Facility,” named “EarthLab,” has undergone project application, feasibility research, preliminary program planning, and budgetary calculation, and it was officially started in the autumn of 2018 with approval by the National Development and Reform Commission of China. The facility was built by the IAP/CAS and Tsinghua University. The facility includes five major systems, i.e., earth system numerical simulation software, regional high resolution environmental simulation software, technical support and management for super computing, supported database and data assimilation and visualization, and high performance computers for earth science. The total investment is more than 1.2 billion RMB, and the construction period is 4 yr.

The scientific goals of the EarthLab are to deeply un-
nderstand the basic laws of the complex system of the earth’s environment; to explore the physical, chemical, and biological processes of the earth’s atmosphere, hydrosphere, cryosphere, biosphere, and lithosphere; to explore the impacts of each sphere and the associated interactions on the earth system and the regional environment of China; to fuse the simulation and the observation data to improve the prediction accuracy; to achieve quantitative characterization and simulation of the complex process of the earth system at the mesoscale; to provide scientific support for major issues, such as national disaster prevention and mitigation, climate change, and atmospheric environmental governance; to promote interdisciplinary integration and fusion between different disciplines of Earth System Science; and to promote the advancement of China’s Earth System Science to the world-class level.

The hardware construction target of the EarthLab is a dedicated structure of a high-performance computer system with a peak value of not less than 15 Petaflops and a storage of not less than 80 PB. The overall performance will be significantly higher than other high-performance computers currently dedicated to earth system numerical simulations. The proposed ESM includes the subsystems of the atmosphere, ocean, land surface, aerosol and atmospheric chemistry, terrestrial vegetation ecosystem, marine biochemical system, terrestrial biochemical system, and the associated coupled models; and it will have complete, self-consistent, and rigorous dynamic, physical, chemical, and ecological processes, with Chinese independent intellectual property and original characteristics. The resolution will reach a globally advanced level. The ESM will have a horizontal resolution of approximately 10–25 km, which will significantly improve the model’s ability to simulate past and future climate changes. Moreover, we will develop a high resolution regional environmental model with a spatial resolution of 1–3 km for high resolution simulations of weather, air pollution, long-term climate change risks, and agricultural drought at the cloud resolving scale in China and in the surrounding areas.

4. CMIP6 historical simulations and projections from four Chinese models

Up to now, four Chinese model groups, i.e., BCC-CSM2-MR, CAMS-CSM1.0, CAS FGOALS-g3, and NESM3, have officially published their model results of some CMIP6 experiments to the Earth System Grid Federation (ESGF) through the Earth System Grid (ESG) node. To demonstrate the basic performance of the Chinese models that participated in the CMIP6, we will show the ensemble mean results from these four model in terms of climatology, historical climate changes in the 20th century, and future projections. The third realization from BCC-CSM2-MR is used, while the first realization from the other three models is used.

Figure 1 shows the observed and simulated December–January–February (DJF) means and the June–July–August (JJA) mean surface air temperature (SAT) during 1995–2014 and the corresponding model biases. The ensemble mean of the four Chinese models well captures the spatial distributions of observed SAT in both boreal summer and winter, but tends to overestimate the SAT over most oceans, the Northeast Eurasian continent in boreal winter, and the center of Eurasia in boreal summer (0.50 to 4.00°C); and it tends to underestimate the SAT over most land regions and the Arctic (−0.50 to −4.00°C). The evident cold biases in the high latitude region of the Northern Hemisphere in boreal winter may be associated with the overestimated sea ice. The performance of the ensemble mean is better than that of the individual model (Table 4).

The observed and simulated DJF mean and JJA mean precipitation during 1995–2014 and the corresponding model biases are shown in Fig. 2. The precipitation in the observation ranges from 0.20 to 10.00 mm day$^{-1}$, with the center in the tropical ocean (7.00–10.00 mm day$^{-1}$) and global monsoon regions in summer (~7.00 mm day$^{-1}$). The ensemble mean of the four Chinese models well reproduces the observed patterns (Table 4). Some biases are also obvious. Wet biases are seen over the ITCZ regions, the Australian monsoon region, the southern South Asian monsoon region in boreal summer, East Asia in boreal winter, the western coast of North America, and most regions in the Southern Hemisphere in boreal winter (0.50–4.00 mm day$^{-1}$), while dry biases are seen over the northern Eurasian continent, East Asia, southern Asia, South America, Southern Hemisphere in boreal summer, and southern Atlantic Ocean in boreal winter (~2.00 mm day$^{-1}$). In the tropics, the “double ITCZ” model bias is evident. The “double ITCZ” bias commonly exists in other CMIP3 and CMIP5 models (Lin, 2007; Li and Xie, 2014). Previous studies suggest that this kind of model bias may be associated with a too-strong Bjerknes feedback and SST–latent heat flux feedback but a too-weak SST–shortwave feedback (Lin, 2007), or the biases in the SST initialization over the center of the Pacific (Liu et al., 2012), or the inaccurate atmospheric model simulations of clouds (Li and Xie, 2014).

To compare the performance of the Chinese models...
with other CMIP6 models, we show the root mean square errors (RMSEs) of simulated global SAT and precipitation from the 4 Chinese models and 16 other CMIP6 models (Fig. 3). Compared with the other CMIP6 models, the Chinese models have relatively large biases in the simulation of precipitation in boreal winter. In summer, the global SAT and precipitation simulated by the Chinese models are comparable to the other CMIP6 models in terms of the RMSE. Spatially, the biases in the Chinese models are also shown in the other models (figures omitted). In addition, the biases in the ensemble mean of the four Chinese models are smaller than those of most of the CMIP6 models, and the performance of the Chinese model’s ensemble mean is close to the performance of ensemble means of 20 CMIP6 models.

China is mainly affected by the Asian monsoon. Therefore, the model’s monsoon simulation is always a focus of Chinese model R&D teams. Figure 4 shows the spatial distributions of JJA mean wind fields at 850 hPa and the corresponding biases relative to the Japanese 55-yr Reanalysis (JRA55). The Chinese models well reproduce the spatial distribution of the observed Asian summer monsoon circulation (PCC = 0.96). Some biases are also evident. The simulated Northwest Pacific Subtropical high (NPSH) and South Asian summer monsoon are weaker than the observed. The location and strength of the NPSH determine the water vapor transport for the East Asian summer rain belt, and such biases could directly influence the simulation of monsoon rainfall.

Historical temperature change in the 20th century is a fundamental metric for evaluating the model’s performance. Figure 5 shows the series of annual SAT anomalies between 60°S and 60°N from the observation and models. In observation, global mean temperature in-

| Model       | Temperature | Precipitation |
|-------------|-------------|---------------|
|             | PCC | RMSE | PCC | RMSE | PCC | RMSE | PCC | RMSE |
| MME         | 0.99 | 1.65 | 0.99 | 2.11 | 0.84 | 1.44 | 1.42 |
| BCC-CSM2    | 0.99 | 2.83 | 0.99 | 2.47 | 0.82 | 1.66 | 1.74 |
| CAMS-CSM    | 0.99 | 2.10 | 0.98 | 3.18 | 0.74 | 1.93 | 1.74 |
| FGOALS-g3   | 0.99 | 2.17 | 0.99 | 2.96 | 0.71 | 2.10 | 1.69 |
| NESM3       | 0.99 | 1.92 | 0.99 | 2.35 | 0.80 | 1.75 | 1.89 |
The warming of 4 Chinese models ensemble mean is 0.73°C, with a range of [0.63–0.91]°C, which is close to the observation. The strongest warming is found in FGOALS-g3 (0.91°C), while the weakest is 0.63°C in CAMS-CSM1.0, and the warming in NESM3 (0.68°C) and BCC-CSM2-MR (0.71°C) are in between. In CAS FGOALS-g3, the change of external forcing (greenhouse gas and aerosol) in CMIP6 is one of the main factors that induce stronger warming trend compared to that in CMIP5 (Nie et al., 2019). An increasing trend is also seen in observed global land precipitation but obvious difference between observation and models are found. One of the reasons is that observational rainfall datasets have large uncertainties, especially in the early 20th century. Moreover, the changes of precipitation ex-

Fig. 2. As in Fig. 1, but for precipitation (mm day\(^{-1}\)). The observed precipitation is derived from GPCP data.

Fig. 3. (a) DJF and (b) JJA mean root mean square error (RMSE) of simulated global surface air temperature (°C) and precipitation (mm day\(^{-1}\)) from four Chinese models (red dot) and other 16 models (gray dot) that participated in CMIP6. The RMSE of the four Chinese models ensemble mean (red triangle) and 20 CMIP6 models ensemble mean (black triangle) are also presented.
hibit evident regional features, which are strongly influenced by the internal variability.

The tier-1 experiments of projections in CMIP6 include the projections under the Shared Socioeconomic Pathway (SSP) 1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

Figure 6 shows the projected changes of the global SAT and land precipitation from these four scenarios. In the near-term (2021–2040) projection, the temperature warming (0.55–0.71°C) and precipitation change (0.76%–1.63%) are similar among the four scenarios;
while the differences of projected SAT changes are evident in the mid-term (2041–2060), but the differences of projected precipitation changes are still not evident. In long-term (2081–2100) projection, there are significant differences among the four scenarios in the projected SAT warming (0.72–3.13°C); in contrast, the differences of projected precipitation changes among different scenarios are not so evident as in temperature changes and show large uncertainty.

Figure 7 shows spatial patterns of the long-term (2081–2100) projected SAT changes under SSP1-2.6 and SSP5-8.5 scenarios. The largest warming is seen in high latitude regions of the Northern Hemisphere. The warming over land is larger than that over ocean. The warming amplitude is rather different between the two scenarios. The SAT warming in high latitude regions of the Northern Hemisphere exceeds 7.00°C in SSP5-8.5, while it is just 1.00–2.00°C in SSP1-2.6. Moreover, there are also large differences in the projected SAT changes among the four models (Table 5). In SSP1-2.6, the warming in NESM3 is strongest (1.18 ± 0.13°C), while that in FGOALS-g3 is weakest (0.48 ± 0.10°C), and the warming in BCC-CSM2 (0.72 ± 0.09°C) and that in CAMS-CSM (0.67 ± 0.16°C) are within this range. In SSP5-8.5, the warming in NESM3 is also strongest (4.27 ± 0.37°C), while that in CAMS-CSM1.0 (2.52 ± 0.20) is weakest, and the warming in BCC-CSM2 (3.13 ± 0.23°C) and that in FGOALS-g3 (2.75 ± 0.23°C) are within this range.

Figure 8 presents the changes of long-term projected precipitation under SSP1-2.6 and SSP5-8.5 scenarios. The spatial patterns of projected changes are similar in the two scenarios, but the changes under SSP5-8.5 scenario are significantly larger than those in SSP1-2.6. In 2081–2100, precipitation would increase significantly over equatorial ocean and high latitude regions (0.50–3.00 mm day$^{-1}$), while decrease significantly in the subtropics (~0.50 to ~1.00 mm day$^{-1}$) except for the subtropical ocean and Asian monsoon and North Africa monsoon regions in boreal summer.

How should we understand the significant disagreement in the projected climate changes across the different models under the same emission scenario? Actually, this disagreement is directly related to the differences in the distinct sensitivity that the models show to greenhouse gas emissions. One of the metrics to measure the model sensitivity is the Equilibrium Climate Sensitivity (ECS), which is the ultimate change in the global mean surface air temperature (GMST) under a doubled CO$_2$ concentration relative to the pre-industrial level. ECS is a core index to represent the sensitivity of the model response to greenhouse gas emissions, which is closely related to the uncertainty in the long-term climate projection (Chen and Zhou, 2015; Zhou and Chen, 2015). The ECS values of 5 Chinese models in the CMIP6 are 3.03°C (Wu et al., 2019a), 2.27°C (Chen et al., 2019), 2.98°C, 2.84°C, and 4.65°C, respectively, for BCC-CSM2-MR, CAMS-CSM, FGOALS-f3, FGOALS-g3, and NESM3. Ensemble mean of the 5 models is 3.16 ± 0.89°C. Figure 9 shows the relation between projected long-term GMST changes (2081–2100) and ECS across 4 Chinese models (projection data of FGOALS-f3 under all scenar-
rios and NESM3 under SSP3-7.0 scenario unavailable currently). Higher model ECS corresponds to larger warming in the projection. Because greenhouse gas is the dominant agent of climate change under high emission scenario (e.g., SSP5-8.5), positive correlation between warming and ECS is more significant than that under low emission scenario (e.g., SSP1-2.6).

5. Short-term and near-term climate predictions

In addition to support to the climate change research, an important direction of the CSM development is to support the short-term climate prediction and application. For example, BCC has developed a new generation operational climate model prediction system (Wu et al., 2013b), which is based on the BCC-CSM (Wu et al., 2010, 2013a, b). This prediction system has three subsys-

- **CMIP6 annual mean surface air temperature anomalies (°C) from the 1995–2014 reference period for selected time periods and Shared Socioeconomic Pathways (SSPs).** The multi-model mean ± 1 standard deviation ranges across the individual models are listed and the 5%-95% ranges from the models’ distribution (based on a Gaussian assumption and obtained by multiplying the CMIP6 ensemble standard deviation by 1.64) are given in brackets. The values tabulated here are for single simulations from the four models that have thus far contributed to the CMIP6 exercise. The models are BCC-CSM2-MR, CAMS-CSM1.0, FGOALS-g3, and NESM3.

| Model and period               | MME 2021–2040 | BCC-CSM2-MR: 2081–2100 | CAMS-CSM1.0: 2081–2100 | FGOALS-g3: 2081–2100 | NESM3: 2081–2100 |
|-------------------------------|---------------|-------------------------|------------------------|----------------------|-------------------|
|                               | SSP1-2.6 (°C) | SSP2-4.5 (°C)           | SSP3-7.0 (°C)          | SSP5-8.5 (°C)        |                   |
| MME 2021–2040                 | 0.55 ± 0.22 (0.18, 0.87) | 0.59 ± 0.21 (0.24, 0.93) | 0.58 ± 0.09 (0.42, 0.73) | 0.71 ± 0.23 (0.33, 1.08) |
| 2041–2060                     | 0.75 ± 0.33 (0.21, 1.29) | 1.05 ± 0.26 (0.62, 1.47) | 1.14 ± 0.19 (0.82, 1.45) | 1.46 ± 0.43 (0.76, 2.16) |
| 2081–2100                     | 0.76 ± 0.30 (0.28, 1.25) | 1.61 ± 0.37 (1.00, 2.22) | 2.43 ± 0.38 (1.81, 3.04) | 3.17 ± 0.78 (1.89, 4.44) |
| BCC-CSM2-MR: 2081–2100        | 0.72 ± 0.09 (0.57, 0.87) | 1.63 ± 0.13 (1.42, 1.84) | 2.84 ± 0.23 (2.46, 3.21) | 3.13 ± 0.23 (2.75, 3.51) |
| CAMS-CSM1.0: 2081–2100        | 0.67 ± 0.16 (0.42, 0.93) | 1.31 ± 0.12 (1.12, 1.51) | 2.10 ± 0.21 (1.75, 2.44) | 2.52 ± 0.20 (2.20, 2.84) |
| FGOALS-g3: 2081–2100          | 0.48 ± 0.10 (0.32, 0.64) | 1.36 ± 0.10 (1.19, 1.53) | 2.34 ± 0.26 (1.92, 2.77) | 2.75 ± 0.23 (2.38, 3.12) |
| NESM3: 2081–2100              | 1.18 ± 0.13 (0.97, 1.39) | 2.13 ± 0.11 (1.94, 2.32) | –                      | 4.27 ± 0.37 (3.67, 4.87) |

Note: NESM3 does not provide the projection under SSP3-7.0 scenario.
BCC’s prediction model is the only model in China that has participated in the World Meteorological Organization (WMO) international program of sub-seasonal to seasonal (S2S) prediction. After the improvement in the initialization scheme and optimization of the model, its credible prediction skill for the MJO is extended to 23 days, which is comparable to the multi-model ensemble of S2S (Liu et al., 2017, 2019).

In recent years, the Chinese Academy of Sciences began to pay attention to the applications of the research-type models in operational forecasting. For example, the IAP has developed a weather–climate dynamic ensemble prediction system based on the CAS FGOALS-f2 (Bao et al., 2019). The reanalysis products produced by the FGOALS-f2 prediction system through the nudging assimilations have been compared to the shipboard GPS sounding measurements obtained during the 2018 Eastern Indian Ocean Open Cruise (Wang et al., 2019). The R&D team of the FGOALS-f2 has developed a seamless experimental real-time prediction system by using the time-lagged method to generate ensemble members, which can conduct extended-range to seasonal forecasts for the El Niño–Southern Oscillation, the Arctic sea ice, etc. over the global key regions such as the Silk Road Economic Belt and surrounding countries, and the 21st-Century Maritime Silk Road. Evaluations of the hindcast experiments have confirmed the high prediction skills of this system for ENSO, MJO, and tropical cyclones. At present, the system has been incorporated into the China Multi-Model Ensemble (CMME), which is coordinated
by the Beijing Climate Center (Ren et al., 2019).

The fusions of the research-type model and operational model are also reflected in some nascent “research-type operational applications.” For example, the climate prediction for the future 1–10 yr (near-term) is a new hotspot in the research community of climate prediction, which is a concern for the policymakers and stakeholders in the fields of agriculture, urban planning, healthcare, and civil aviation. Near-term climate prediction fills the gap between seasonal to interannual forecasts and medium- to long-term climate projections, and it plays an important role in seamless climate services. Thus, major international modeling centers have been actively developing their near-term climate prediction system. A decadal climate prediction system named IAP-DecPreS was constructed in the IAP/CAS; it is based on a fully coupled model FGOALS-s2 and a newly developed initialization scheme, referred to as EnOI-IAU (Wu et al., 2017, 2018). The EnOI-IAU can assimilate the observational data, including the observational sea surface temperatures (SSTs) from HadISST version 1.1 and the upper 700-m oceanic temperature profiles from the EN4 dataset version 1.1 of the Hadley Centre of the UK Met Office under the coupled model framework. The systematic decadal hindcast experiments reveal that the IAP-DecPreS has high skill in the prediction of the PDO-related SST anomalies in the midlatitude North Pacific and AMO-related SST anomalies in the tropical North Atlantic (Fig. 10). The IAP-DecPreS also participated in a multi-national plan sponsored by the UK Met Office, referred to as “the Decadal forecast exchange,” which is an early attempt at the quasi-operational near-term predictions organized by WMO. In addition, the IAP-DecPreS has also been used to study some scientific problems such as the impacts of full-field and anomaly initialization on seasonal predictions (Sun et al., 2018; Hu et al., 2019a, b). At present, the EnOI-IAU initialization scheme has been transplanted into the coupled models of the Chinese Academy of Meteorological Sciences and the Beijing Climate Center.

In addition, based on the fully coupled model, i.e., FGOALS-g2, and the dimension-reduced projection four-dimensional variational data assimilation (DRP-4DVar) (Wang et al., 2010), the world’s first initialization and the corresponding decadal prediction system based on the four-dimensional ensemble variational data assimilation scheme were established (He et al., 2017). Systematic decadal hindcast experiments have also been conducted, which indicate that the advanced initialization method can obviously improve the decadal prediction skills of FGOALS-g2, including predictions of the decadal variability of GMST anomalies (He et al., 2017), the SST in the northern Pacific, the PDO, the Aleutian low, the PNA, and the AMO.

![Fig. 10.](a) Spatial pattern of the temporal correlation skill of the annual mean SSTs derived from the decadal prediction experiments averaged over the hindcast years 2–5. White dots denote values passing the 5% significance level. (c) As in (a), but for detrended SSTAs. (b, d) As in (a, c), but for the hindcast years 6–9. Adopted from Wu et al. (2018).)
6. Outlook

Following over 30 years of great efforts, we have made impressive progress in the R&D of CSM and ESM during the past five years, which include more models taking part in the CMIP6, better model performance, and a larger R&D modeling team. We should realize that there are several problems in the model development, such as the abundant-but-weak issue, the tendencies toward low-level repetition and fragmentation development, and the inadequate originality and less international impact. Based on the experiences of developed countries, solving these problems requires strengthening the top-level design, and the overall planning and coordination of the research funding management. Domestic scientists in China have repeatedly made requests and suggestions in these regards (Wang et al., 2004, 2008; Zhou et al., 2014). Coordination is a difficult problem internationally. “Any initiative involving institutional optimization or optimization of financial management will inevitably bring about a marked tension, because it will touch the interests of various institutions and their management departments engaged in climate model research and development” (National Research Council, 2012). Here, we refer to the international situation, from the perspective of development, put forward several directions that need to be strengthened in the future research and R&D of climate models in China.

The first suggestion is to enhance the development of models for seamless weather–climate prediction. Traditional weather forecasts generally use a high-resolution atmospheric model coupled with a land surface model, in which the processes associated with ocean and sea ice are considered. On the other hand, traditional climate simulations and predictions are based on state-of-the-art coupled models consisting of atmosphere, ocean, land, and sea ice, but their resolutions are always lower than the weather forecasting model. Currently, the gap between weather forecasting and climate prediction is narrowing in international research institutes. Developing the models that support seamless weather–climate prediction will be a research focus in the next 5–10 years. In science, this is related to the design of a dynamic core suitable for multi-scale variability, the development of multi-scale adaptive physical parameterization, and coupled assimilation. In the organization for R&D, this involves effective connections between the model for scientific research and the model for operational application. China should introduce a seamless weather–climate model as soon as possible.

The second suggestion involves collaborations between development of the ESM and development of the CSM. The ESM is based on the CSM. However, because the biogeochemical cycle processes in the ESM are computationally intensive, in terms of resolution alone, the ESM generally falls behind the CSM by approximately 10 years. How to apply the latest improvements in the CSM to the ESM is one of the current concerns of the international community. For the development of CSMs, in-depth studies of physical processes, especially ocean mixing, sea–air fluxes, and cloud physical processes, are the keys to improving climate models.

Third, high-resolution simulations of regional climate should be developed. Traditional regional climate simulations mostly use regional climate models with higher resolution in dynamic downscaling of global model results on relatively low resolution. In recent years, the resolution of the global climate models has increased rapidly, and the highest resolution of the atmospheric model participating in the CMIP6 has reached 25 km, which is close to the resolution of the traditional regional climate model. Internationally, the convection-permitting model (CPM) with a resolution of kilometers has been used in climate prediction research. How to coordinate the development of high-resolution global and regional models in regional simulations is an issue that needs attention in the future.

Fourth, the simulation infrastructure, data standard, and protocol issue should be studied. With the development of high-performance computers and the improvement of model resolution, the storage and sharing of big data has become a prominent issue. It is increasingly important to build international standards and engineering/technology protocols that support numerical simulations. From the perspective of climate simulations and prediction, the WCRP WGCM has realized the importance of uniform standards, so it has set up an infrastructure panel to develop model data sharing policies and technical standards (Zhou et al., 2019), but these measures are far from being able to solve the challenges that are currently being faced.

Fifth, the applications of new observations, such as satellite remote sensing in model evaluations, and the important role of climate models in the design, development, and optimization of observing systems, need to be studied. Observational data are references for testing model performance. Moreover, numerical simulation and prediction approaches also have new requirements for the construction of observing systems. Simulation studies can also provide guidance for the construction and optimization of observing systems.
Sixth, the diagnosis and assessment of climate models and the construction of corresponding observational metrics need further study. Weather forecasting models and climate models have traditionally been treated differently in performance evaluations. The observational metrics used to assess their performance are also significantly different. However, with the development of the weather–climate seamless model, there is an urgent need to construct new observational metrics for the model evaluation. With reference to successful international practices, it is necessary to establish an observation network to match the model R&D.

Seventh, multi-model ensemble approaches and uncertainties in simulation and prediction need further study. From the perspective of climate simulation and prediction, decision makers need reliable prediction results. The uncertainties of the current model results mainly come from three aspects, including uncertainty caused by the model differences in the dynamic core and physical parameterization, uncertainty in the same model from the use of different parameter combinations, and uncertainty in terms of the internal variability introduced by different initial values. The three ensemble approaches demonstrated correspond to the three different sources of uncertainties. The development of an optimal ensemble approach is essential for providing users with reliable simulation and projection products.

Eighth, achieving a good model–user connection is needed. Climate simulation and climate projection/prediction not only support basic scientific research but also serve society, which in turn helps to promote the development of the model itself. The Future Earth program emphasizes collaboration between scientists, research funding agencies, and users through designing collaborative research, and it advocates problem-oriented research and useful science. To address the sustainable development of the human society, the WCRP proposed seven grand challenges, including “melting ice and global consequences”, “clouds, circulation and climate sensitivity”, “regional sea level change and coastal impacts”, “water for the food baskets of the world”, “weather and climate extremes”, “carbon feedbacks in the climate system”, and “near-term climate prediction.” By strengthening the connection and collaboration with the Future Earth program, the climate simulation research in China is expected to better serve global climate change research, and thus better serve the society.

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