A simple earth system model for C³IAM: based on BCC_CSM1.1 and CMIP5 simulations

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Abstract

Traditional complex climate system models used in natural sciences cannot match the integrated assessment models well due to differences in temporal and spatial resolutions and especially computational complexities. In this study, we develop a simple earth system model called Beijing Climate Center Simple Earth System Model (BCC_SESM), which is based on the complex BCC_CSM1.1 model and its CMIP5 simulation results as inputs. The basic and complete processes are considered in the BCC_SESM initiating from the carbon emission, including the carbon cycle processes in atmosphere–land–ocean, the radiation forcing and temperature changes. The emission-driven simulation results for historical and RCP8.5 scenarios are selected as the default datasets, and econometric regressions are applied to calibrate the parameters. Projection analysis and sensitive experiments with the BCC_SESM show that this model is parsimonious and robust enough to reproduce results of original complex climate system model. We also compare results of parameters and projection efficacy of different mid-lower emission scenarios simulations by applying this BCC_SESM. The results show that BCC_SESM is suitable for climate projections in the integrated assessment modeling, i.e., the C³IAM.

Keywords Climate model · IAM · BCC_CSM1.1 · CMIP5 · BCC_SESM

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1 Introduction

In the field of energy and climate economics, integrated assessment models (IAMs) are widely applied to do welfare analysis for energy and climate policies analysis. Generally, the IAM has three main components: first, emission module which design different energy and emission scenarios with social–economic assumptions such as shared socioeconomic pathways (SSPs) (O'Neill et al. 2017); second, climate module which describe cause–effect chains from emissions to temperature rising (Matsuoka et al. 1995; Brenkert et al. 2003; Sokolov et al. 2005; Bouwman et al. 2006; Moss et al. 2010; Yang et al. 2015); third, economic component which optimize economic and social pathways based on calculations of mitigation costs and climate damages. With regard to the climate module, there are various climate models with different complexity levels for various destinations and applications. As summarized in Table 1, the simplest level is the statistical or empirical equations which links emissions directly to temperature rising; the second intermediate level of simple energy balance models or simple climate models (SCMs, Stocker 2011); the highest level with complex climate system models (CSMs) or earth system models (ESMs).

There are pros and cons for the three modeling strategies (van Vuuren et al. 2012). The simple statistical or empirical equations are the simplest and most straightforward; however, with the absence of constraint of dynamic physical mechanisms and laws, equations and parameters may be incorrect, and they may lose much useful information within the climate system. By contrast, the complex climate/earth system models are too computational expensive to be fully coupled with higher temporal and spatial resolutions and increasingly complicated parameterization schemes of different climate system components, i.e., the atmosphere, biosphere, hydrosphere (ocean, lakes and rivers), cryosphere (snow and ice) and geosphere (soil and rocks). As the development of scientific and computation techniques, there are also several studies working on the coupling of complex climate system models and human activity ones, such as the MIT IGSM (Sokolov et al. 2005), BNU_HESM (Yang et al. 2015). While in the IAM practice, climate modules are usually simple climate models, such as MAGICC (Wigley 1991, 1995; Wigley and Raper 2002), GCAM (Brenkert et al. 2003) and Hector (Hartin et al. 2015), which has advantages such as parsimony, transparent and computational efficiency.

The simple climate models (SCMs) in IAMs generally consist of statistic-based equations which represents the fundamental global-scale processes, such as the temperature changes, carbon cycles of the three main carbon reservoirs (atmosphere, ocean and land), and have lower spatial and temporal resolution to match other modules in IAMs. The typical processes considered in SCMs have three steps: (1) the global carbon cycle, to get the carbon redistribution in the carbon reservoirs and the concentration of greenhouse gases (GHGs) in atmosphere for given emissions pathways, such as the representative concentration pathways (RCPs) (van Vuuren et al. 2011b, c). The main difference between SCMs lies in the first step. (2) Relationship between cumulative carbon stock or GHGs concentrations and radiative forcing in atmosphere. (3) Relationship between the radiative forcing and global mean temperature change as well as other variables (such as precipitation, sea level rising and extreme climate events) (Wigley 1991; Lenton 2000; Tanaka et al. 2007; Meinshausen et al. 2011).

With regard to the described input datasets for the global carbon cycle, there are two types of simulation datasets in the Fifth Coupled Model Intercomparison Project (CMIP5). The first is emission-driven simulations for the carbon cycle experiments; the other is CO₂ concentration-driven simulations, i.e., the model integrated with the prescribed CO₂

Table 1 Different category of climate models in IAMs

Category	IAMs	References
Simple model without carbon redistribution	<i>AIM</i> , considering processes from GHG emissions to temperature increase	Kainuma et al. (2003)
	<i>FUND</i> , as climate damage factor for the economics and policy models, majorly considering temperature changes	Tol (2009)
	<i>MERGE</i> , temperature changes related to equilibrium temperature and delay	Mann and Richels (2005)
	<i>PAGE</i> , temperature changes related to equilibrium temperature and delay	Hope et al. (2007)
	<i>DICE-2013R</i> , geophysical relationship equations including the carbon cycle, radiative forcing, climate change and climate damage. Three boxes describe carbon flows between atmosphere, land and ocean	Nordhaus and Sztorc (2013)
Simple climate model with carbon cycle	<i>GCAM</i> , a partial equilibrium focused IAM, atmospheric composition and global mean climate changes using the corresponding model for MAGICC	Brenkert et al. (2003)
	<i>Hector</i> , an open-source, object-oriented, simple climate carbon cycle model	Hartin et al. (2015)
	<i>IMAGE</i> , pattern scaling for climate parameters, with terrestrial and ocean carbon cycle processes	Bouwman et al. (2006)
	<i>MAGICC</i> , upwelling-diffusion energy balance model for climate, mass balance model for carbon cycle with 6 boxes. CO ₂ fertilization and temperature feedback on terrestrial biosphere were described	Wigley (1991, 1995) and Wigley and Raper (2002), http://www.cgd.ucar.edu/cas/wigley/magicc
	<i>MIT IGSM</i> , an intermediate complex earth system model coupled with IAMs. Outputs of the combined anthropogenic and natural emissions models provide the driving forces for the coupled atmospheric chemistry and climate models	Sokolov et al. (2005)
Complex climate model coupling with carbon cycle from human emissions	<i>iESM</i> , joint human/climate system, coupling IAM and ESM into a common modeling infrastructure	Collins et al. (2015)
	<i>OSCAR v2.2</i> , all components of the Earth system necessary to simulate future climate change represented	Gasser et al. (2016)
	<i>BNU_HESM</i> , the complicated earth system model coupled with a simple economic and climate damage component	Yang et al. (2015)

Part of the model review is adopted from van Vuuren et al. (2011a)

concentration. The differences between these two experiments are that the CO_2 concentration is simulated by complex climate/earth model systems in the first type, rather than is prescribed in the second-type experiments (Fig. 1).

The aim of this study is to build a simple earth system model based on a Chinese complex earth system model, in order to contribute to the climate modeling society and satisfy the needs of IAM modeling. We employ the archetype complex climate system model Beijing Climate Center Climate System Model (BCC_CSM1.1) and its CMIP5 simulation results to develop the simplified climate model, i.e., Beijing Climate Center Simple Earth System Model (noted as BCC_SESM) for the China Climate Change Integrated Assessment Model (C³IAM, Wei et al. 2018).

The BCC_SESM design is introduced in Sect. 2, followed by the information of complex climate model and necessary datasets for the BCC_SESM model in Sect. 3. The parameter regressions and validation, as well as the projections with the BCC_SESM are presented in Sect. 4. The conclusions and discussions are in Sect. 5.

2 Model design of BCC_SESM

In this study, we develop the climate module in the BCC_SESM model based on DICE model which was developed by the 2018 Nobel laureate in economics, Nordhaus (1992); meanwhile, we make some adjustments according to variables in BCC_CSM1.1 simulation outputs (Wu et al. 2013) in order to satisfy needs from C³IAM.

There are three modules in the BCC_SESM model. First is the carbon module, which describes the global carbon cycle process; second is the radiative forcing module, which

Fig. 1 Framework of the BCC_SESM model

simulates the relationship between GHGs concentrations in atmosphere and the radiative forcing of the atmosphere; third is the temperature module, which simulates the relationship between the atmospheric radiative forcing and the temperature change in atmosphere and ocean.

2.1 Carbon module

Considering that critics were made in relation to the DICE carbon cycle settings (Wu et al. 2014a), we make some important changes to the carbon cycle module. In DICE model, the three reservoirs are: the atmosphere, the upper ocean and biosphere, and the deep ocean. However, in terms of BCC_CSM1.1 and other complicated climate/earth system model, the carbon cycle processes include atmosphere, terrestrial (vegetation and soil) and ocean. We separate biosphere as an individual terrestrial carbon sink, while set the upper ocean including the surface ocean, marine biota and dissolved organic carbon as an individual carbon sink. Thus in this study, the three reservoirs for carbon cycle are: the atmosphere reservoir, the land reservoir and the ocean reservoir. Equations (1)–(3) represent the equations of the carbon cycle.

$$M_{\text{atm}}(t) = E(t) + a_{11}M_{\text{atm}}(t-1) + a_{21}M_{\text{land}}(t-1) + a_{31}M_{\text{ocean}}(t-1) \quad (1)$$

$$M_{\text{land}}(t) = a_{12}M_{\text{atm}}(t-1) + a_{22}M_{\text{land}}(t-1) \quad (2)$$

$$M_{\text{ocean}}(t) = a_{13}M_{\text{atm}}(t-1) + a_{33}M_{\text{ocean}}(t-1) \quad (3)$$

$$s.t. a_{11} + a_{12} + a_{13} = 1, \quad a_{21} + a_{22} = 1, \quad a_{31} + a_{33} = 1, \quad a_{ij} \in (0, 1), \quad (i = 1 \sim 3, j = 1 \sim 3).$$

While t denotes time period 1–50, 5 years as one period, from 1850 to 2100, 2015 is the base year. M_{atm} , M_{land} and M_{ocean} represent carbon stocks in three carbon reservoirs: atmosphere, land and ocean. E represents cumulative GHGs emissions during each time period.

Since carbon sinks are in the form of stocks in three reservoirs, while they are in the form of fluxes in the BCC_CSM1.1 outputs, we need to add initial stock values. According to the IPCC Fifth Assessment Report (IPCC 2013), initial carbon stocks in the three reservoirs prior to the Industrial Era (1850) were 589 PgC in atmosphere, 450–650 PgC in biosphere (we use 450 PgC), and 1603 PgC for upper ocean. The BCC_CSM1.1 simulated cumulative changes of anthropogenic carbon in these three reservoirs over 1850–2015 were 260 PgC, 148 PgC and 235 PgC, respectively. Therefore, the current carbon stocks in three carbon reservoirs are 867 PgC, 685 PgC and 1751 PgC in 2015. For the land reservoir, we only use the biosphere, while exclude the carbon stock in soils which is about 1500–2400 PgC; for the ocean reservoir, we exclude the carbon stock in intermediate and deep sea which is about 37,100 PgC. The reason is that these values are different in magnitude, which may cause troubles in regressions. One caveat here is that we may over-simplify the carbon cycle mechanisms in biosphere and ocean (Svirezhev et al. 1999), which may over-estimate the carbon stock in atmosphere, and thus the atmosphere temperature increases (Wu et al. 2014a).

2.2 Radiative forcing module

The next process is to calibrate the relationship between the accumulation of GHGs in atmosphere and the change of radiative forcing of atmosphere. This relationship is derived from empirical measurements and widely used in many simple climate models.

$$F(t) = F_{\text{EX}}(t) + b_1 \left\{ \log_2 \left[M_{\text{atm}}(t) / M_{\text{atm}}(1750) \right] \right\} \quad (4)$$

F is the change in total radiative forcing of GHGs since pre-industrial era, i.e., the year of 1750. F_{EX} is exogenous forcing, the same as DICE model, to represent the radiative forcing effects from other GHGs excluding CO_2 and other mechanisms (such as volcanic eruptions, aerosols and cloud albedo effects). In this study, F_{EX} is regarded as constant in the regression equation. $M_{\text{atm}}(1750)$ is 589 PgC in atmosphere in the year of 1750.

2.3 Temperature module

The higher radiative forcing in atmosphere directly causes the warming of atmosphere and upper ocean, while lags in the carbon system are mainly due to the diffusive inertia of different reservoirs. The temperature changes in atmosphere and ocean are described in Eqs. (5) and (6), respectively.

$$T_{\text{atm}}(t) = c_1 F(t) + c_2 T_{\text{atm}}(t-1) + c_3 T_{\text{ocean}}(t-1) \quad (5)$$

$$T_{\text{ocean}}(t) = c_4 T_{\text{atm}}(t-1) + c_5 T_{\text{ocean}}(t-1) \quad (6)$$

T_{atm} and T_{ocean} represent the global mean atmosphere and upper oceans temperature, respectively.

In econometrics regressions, Eqs. (1)–(3) and (5)–(6) are simultaneous equations. We use *systemfit* package in the *R* software to do the simultaneous regressions.

3 Data for BCC_SESM model establishment

In the BCC_SESM model, the variables in Eqs. (1)–(6) are from the complex climate model BCC_CSM1.1, and the input data for these variables are based on the output of BCC_CSM1.1 which participated in CMIP5 simulations. Here, we briefly introduce the original BCC_CSM1.1 model and the input data for the variables in the BCC_SESM model.

3.1 Brief introduction of BCC_CSM1.1 model

The Beijing Climate Center Climate System Model version 1.1 (BCC_CSM1.1) was one of the numerical models to participate in CMIP5 simulations for the IPCC AR5 (IPCC 2013). It had four component models, i.e., global atmosphere model *BCC_AGCM2.1*, land surface and dynamical vegetation model *BCC_AVIM1.0*, global ocean model *MOM4_L40v1* and global thermodynamic sea ice model *SIS*. These components models interact with one another at their interfaces through fluxes of energy, momentum and water. Detailed model information can be referenced in Wu et al. (2013). The BCC_CSM1.1 is a series of fully coupled climate–carbon cycle models, including oceanic and terrestrial carbon cycle with dynamical vegetation (Wu et al. 2013, 2014a, b).

Although in the context of earth sciences, only the models that explicitly describe the chemistry processes can be named as an earth system model, while in that of other

sciences, models that describe the dynamical vegetation can also be named as the earth system model. Therefore, here we named the simplified model as BCC_SESM.

3.2 Variables from BCC_CSM1.1 simulation experiments of CMIP5

Two model versions of BCC_CSM with different horizontal resolution had been used to run the CMIP5 experiments. In this study, we use simulations with coarser atmospheric and land resolution (approximately 2.8125×2.815) version, i.e., BCC_CSM1.1.

A large amount of simulations with the BCC_CSM1.1 are available and applied extensively for studies on global climate simulations and projections. Results have shown that BCC_CSM1.1 performed well in reproducing present-day climate compared with other CMIP5 models (especially the spatial pattern and seasonal features of surface air temperature and rainfall) and projecting climate changes up to 2100–2300 (IPCC 2013; Wu et al. 2014a, b).

The chain cycles in IAM models from carbon cycle to surface air temperature increase include the following four processes (variables), i.e., CO₂ emissions, CO₂ concentration, radiative forcing and temperature (Fig. 1). The idealized models should include all of the processes and simulate/project the related variables. But because of the complexity of the real world and the inevitable gaps between inter-discipline models, the present climate models mostly take CO₂ emission or CO₂ concentration as its forcing datasets. As stated previously, there are two kinds of simulations in CMIP5 experiments, i.e., one is CO₂ emissions driven and one is CO₂ concentration driven. The concentration-driven experiments include historical and RCPs scenarios, which prescribed atmosphere CO₂ as a predefined input to simulate climate and carbon cycle processes between carbon reservoirs. Emissions could not be provided by this kind of experiments. On the other hand, CO₂ emissions-driven simulations (e.g., esmHistorical and esmrcp85) prescribed CO₂ emissions as the input data and atmosphere CO₂ was an internally calculated element of the climate system model. For most experiments that use simulated model results, the emission-driven experiment is the best choice to ensure consistency of model integrations. Thus, we apply emission-driven experiments as the input datasets in this study.

Variables for the BCC_SESM and corresponding variables in BCC_CSM1.1 simulation outputs are listed in Table 2. They are CO₂ emission (forcing data from PCMDI), CO₂ concentration (simulation by emission-driven experiments, or forcing data from CO₂-concentration experiments), surface air temperature (*tas*) and sea surface temperature (*tos*), carbon exchanges on the atmosphere-land (*nep*) and atmosphere-ocean (*fgCO2*). Note that CO₂ emissions include the main sources, such as fossil fuel combustion, cement, land use change and forestry. CO₂ concentrations are measured as equivalent of all the other main GHGs (including CO₂, CH₄, N₂O, CF_x, H-gases, F-gases, etc.). The radiative forcing (RF) is not provided in the lists of CMIP5 experiment outputs; thus in this paper, we calculate the RF by the sum of the top of atmosphere radiation budget and the linear change of temperature with the feedback parameter (related to the equilibrium climate sensitivity of BCC_CSM1.1), which is calculated by using Gregory regression method (Gregory et al. 2004) with two CMIP5 simulations, i.e., the instantaneous quadrupling of CO₂ and then hold fixed (abrupt4xCO2) experiment and pre-industrial control (piControl) experiment (IPCC 2013). The RF is close to the RCP8.5 scenario in the MAGICC model (<http://live.magicc.org/>) with the variable as total RF including volcanic effects (i.e., *RF_total_incl_volcanic*) (see Fig. 2e).

Table 2 Variables in BCC_SESM and BCC_CSM1.1 CMIP5 simulations

	Variables in BCC_SESM	Variables from BCC_CSM1.1 CMIP5 simulations and computation methods
CO ₂ emission Carbon cycle	E	CO ₂ emission data from CMIP5 RCPs scenarios, http://www.pik-potsdam.de/~mmalte/rcps
	M_{atm}	total atmospheric mass of CO ₂ (M_{atm})
	M_{land}	N_{ep} : net carbon mass flux out of atmosphere due to net ecosystem productivity on land, added in the biosphere carbon stock (M_{land})
	M_{ocean}	$fgCO_2$: surface downward CO ₂ flux between atmosphere and ocean, added in the upper ocean carbon stock (M_{ocean})
Radiative forcing	F	$rsdt$: shortwave radiation incident at the top of the atmosphere (TOA); $rsut$: TOA outgoing shortwave radiation; $rlut$: TOA outgoing longwave radiation; The F is the differences between TOA radiative budget and linear changes of temperature (with feedback parameter)
		T_{atm} : near-surface air temperature
		T_{ocean} : sea surface temperature
Temperature	T_{atm}	
	T_{ocean}

Fig. 2 The time series of outputs of variables in BCC_CSM1.1 and as inputs in BCC_SESM: **a** carbon emissions, **b** atmosphere carbon stock, **c** upper ocean carbon stock, **d** biosphere carbon stock, **e** radiative forcing, **f** atmosphere temperature, **g** ocean temperature. Note: variables of **a–d** are 5-year sum; other variables are 5-year average. The historical line uses the esmHistorical results. For variables in **c**, **d**, **f**, **g**, the DICE model differs with those used in this study due to different definitions

All the original grid data are calculated as global average using the pattern scaling. With regard to the time scale, all variables are calculated as 5-year average from original monthly data, except for three variables, i.e., the *nep*, *fgCO₂* and *cumulative of CO₂ emissions*, were summed up.

3.3 Data for BCC_SESM parameters regression

In this study, we apply BCC_CSM1.1 simulated CMIP5 experiments of *esmHistorical* and *esmRCP8.5* (rename them as ESM RCP8.5 data) in the regressions to calibrate the parameters. Historical data go from 1850 to 2010, while future projection data go from 2011 to 2100. In addition, we also test the robustness of this set of parameters for predicting three other CO₂-concentration-driven scenarios simulated from BCC_CSM1.1, i.e., RCP2.6, RCP4.5 and RCP8.5. The timeframe of all the variables from 1850 to 2100 is presented in Fig. 2, as well as the baseline scenario in DICE model for comparison.

4 Results

4.1 Parameters from regression and validation of the BCC_SESM

Based on Eqs. (1)–(6), using the *R* software to do the regression, we can get the parameters for Eqs. (1)–(6) in Table 3, respectively. We mainly focus on the default ESM RCP8.5 results. We also estimate the parameters for RCP8.5, RCP4.5 and RCP2.6 experiments for comparison.

From the ESM RCP8.5 results, we can find that most of the parameters are strongly significant at significance level $p < 0.001$, and the adjusted *R*-squares for each equation are all as high as 0.99, which prove the regression method and results are solid for this BCC_SESM model.

In order to test the validation of these parameters values as well as the entire BCC_SESM model, we use the *esmHistorical* data to project the *esmrcp8.5*. Here, we use the BCC_SESM model and parameters in Table 3 to predict the ESM RCP8.5 inputs data itself, with only the input variable CO₂ emissions are exogenous and given, while other variables are endogenous and are calculated based on the above equations.

It proves that all the variables are fitted very well. First, the historic values when $t = 1$ –32 from 1850 to 2010 were given. The projection results (when $t = 33$ –50 from 2015 to 2100) fit very well with the original data; the projection difference for the atmosphere carbon stock, land surface carbon stock and ocean carbon stock variables are within (0, 8%), (−7.5%, 0) and (−1.7%, 0.7%) compared to the original results. The projection difference for the radiative forcing variable is within (−8.3%, 13.6%) compared to the original results. The projection differences for the atmosphere temperature and ocean temperature variables are within (−0.5%, 0.7%) and (−1.3%, 0%) compared to the original results, which shows very high projection ability of this BCC_SESM model (Table 4). Figure 3 shows difference percentages of the atmosphere and ocean temperatures of the original values compared with the predicted ones. Furthermore, we also test that only one-period historic values were given (when $t = 1$ at 1850). The projection results (when $t = 2$ –50 from 1855 to 2100) also fit well enough (Table 4).

Table 3 Regression results of ESM RCP8.5 experiment in BCC_SESM

Equation		Dependent variable	Parameters	Independent variable	Coefficients
I Carbon cycle	(1)	M_{atm}	a_0	E	1
			a_{11}	$M_{\text{atm}}(-1)$	0.9472***
			a_{21}	$M_{\text{ocean}}(-1)$	0.0104***
			a_{31}	$M_{\text{land}}(-1)$	0.0093***
			Adj R^2		0.9991
	(2)	M_{land}	a_{12}	$M_{\text{atm}}(-1)$	0.0221***
			a_{22}	$M_{\text{land}}(-1)$	0.9896***
			Adj R^2		0.9986
	(3)	M_{ocean}	a_{13}	$M_{\text{atm}}(-1)$	0.0308***
			a_{33}	$M_{\text{ocean}}(-1)$	0.9907***
			Adj R^2		0.9993
II Radiative forcing	(4)	F	b_0	Constant	-0.2622***
			b_1	$\log_2(M_{\text{atm}}/589)$	4.6461***
			Adj R^2		0.9837
III Temperature	(5)	T_{atm}	c_1	F	0.2291***
			c_2	$T_{\text{atm}}(-1)$	0.2954**
			c_3	$T_{\text{ocean}}(-1)$	0.5495***
			Adj R^2		0.9981
	(6)	T_{ocean}	c_4	$T_{\text{atm}}(-1)$	0.0794***
			c_5	$T_{\text{ocean}}(-1)$	0.9394***
			Adj R^2		0.9966

The significance level ** $p < 0.01$, *** $p < 0.001$

Table 4 Projection deviation of ESMRCP8.5 scenario (unit: %)

Variables	Range	M_{atm}	M_{land}	M_{ocean}	F	T_{atm}	T_{ocean}
$t = 1$ given	Median	-4.7	4.8	0.1	-16.5	-1.7	-0.9
	(min, max)	(-14.3, 7.7)	(-5.3, 11.1)	(-2.8, 1.4)	(/ , /)	(-3.4, 1.1)	(-3.5, 1.9)
$t = 1-32$ given	Median	5.6	-5	-1.2	5.9	0	-0.7
	(min, max)	(0, 7.9)	(-7.5, 0)	(-1.7, 0.7)	(-8.3, 13.6)	(-0.5, 0.7)	(-1.3, 0)

Numbers are the ranges of the percentage difference of the projection results compared to the original results. The RF results are not reported in the second row because it varies too much due to its wavy line

4.2 Projection experiments of other scenarios

Since the aim of this study is to establish BCC_SESM framework via equations and calibrate parameters to represent the complex BCC_CSM1.1 model results, we need to test the projection efficiency of these equations and parameters for other scenarios.

Here, we use RCP2.6 and RCP4.5 emissions as exogenous inputs. It is interesting to see that projection results fit pretty well for RCP2.6 and RCP4.5 as well (Table 5). The projection differences for atmosphere temperature and ocean temperature variables in RCP2.6 are

Fig. 3 Comparison of projected values from BCC_SESM and original values for **a** atmosphere temperature and **b** ocean temperature

Table 5 Projection deviation of two RCP scenarios (%)

Variables	Range	M_{atm}	M_{land}	M_{ocean}	F	T_{atm}	T_{ocean}
RCP45	Median	2.2	-1.8	-0.5	10.7	1.2	0.7
	(min, max)	(-5.1, 4.1)	(-2.9, 5.3)	(-0.9, 1.4)	(-11.9, 15.8)	(-0.6, 4.7)	(-0.3, 6.2)
RCP26	Median	-1.0	1.1	0.0	0.7	1.3	2.1
	(min, max)	(-12.3, 2.3)	(-2.7, 15.3)	(-0.7, 2.3)	(-31.2, 12.9)	(-0.4, 3.7)	(-0.3, 6.4)

Numbers are the ranges of the percentage difference of the projection results compared to original results. Historic values are given (when $t=1-32$), while the future periods ($t=33-50$) are projection results

within $(-0.4\%, 3.7\%)$ and $(-0.3\%, 6.4\%)$ compared to the original results; the projection differences for the atmosphere temperature and ocean temperature variables in RCP4.5 are within $(-0.6\%, 4.7\%)$ and $(-0.3\%, 6.2\%)$ compared to original results, both prove high projection ability of this BCC_SESM for representing the original BCC_CSM1.1 model.

4.3 Parameter sensitivity test of BCC_SESM

Besides the emission-driven simulation experiments, we also apply the BCC_CSM1.1 simulated concentration-driven results (RCP2.6, RCP4.5 and RCP85) as inputs for regression of the parameters in BCC_SESM for sensitivity analysis purpose. With the parameters derived from the specific simulations, we have conducted projection experiments of different scenarios and inter-compared the results.

The results reveal that higher scenarios such as the RCP85 data will over-estimate the variables for other lower scenarios (such as RCP4.5 and RCP2.6); thus, it has *upward bias*. On the contrary, parameters from lower RCP scenarios underestimate the variables for other higher RCPs; thus, they have *downward bias*. While either the upward bias or the downward bias is within acceptable ranges ($\pm 5\%$) for all the variables. In conclusion, the BCC_SESM has very high capability to reproduce the original BCC_CSM1.1 model.

5 Conclusions and discussions

The traditional complex climate system models are too large to match the integrated assessment model. Thus, the aim of this study is to use simulation results from BCC_CSM1.1 to calibrate a simple earth system model called BCC_SESM, in order to match the C³IAM model. In this study, we follow climate module settings in DICE while making necessary changes. Emission-driven experiments (esmHistorical and esmrp85) are selected as default simulation results and inputs to calibrate the parameters. In sensitivity analysis, we test results from different scenarios such as RCP2.6 and RCP4.5, and find that the default setting of this simple climate model is reasonable and solid. Parameters regression results and projection results show that this BCC_SESM model is robust with high projection ability and can well represent the original results of BCC_CSM1.1 model, which can be widely used for climate projection in many other fields such as climate economics, environment and energy modeling.

In future research, we will further explore more specific settings in the BCC_SESM model, such as more boxes for carbon cycle, disaggregate the global into different regions, improve pattern scaling skills and add more key variables such as the precipitation and sea level rising, extreme climate events, etc., in order to satisfy the needs from climate impact modeling and climate economic modeling.

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References

- Bouwman AF, Kram T, Goldewijk KK (2006) Integrated modelling of global environmental change: an overview of IMAGE 2.4. The Netherlands Environmental Assessment Agency, Bilthoven
- Brenkert AL, Steven SJ, Kim SH et al (2003) Model documentation for the MiniCAM. Pacific Northwest National Laboratory, Richland
- Collins WD, Craig AP, Truesdale JE et al (2015) The integrated Earth system model version 1: formulation and functionality. *Geosci Model Dev* 8:2203–2219
- Gasser T, Ciais P, Boucher O et al (2016) The compact Earth system model OSCAR v2.2: description and first results. *Geosci Model Dev*. <https://doi.org/10.5194/gmd-2016-149>
- Gregory JM, Ingram WJ, Palmer MA (2004) A new method for diagnosing radiative forcing and climate sensitivity. *Geophys Res Lett* 31(3):L03205
- Hartin CA, Patel P, Schwarber A et al (2015) A simple object-oriented and open-source model for scientific and policy analyses of the global climate system-Hector v1.0. *Geosci Model Dev* 8(4):939–955
- Hope C, Alberth S, Hope C (2007) US climate change impacts from the PAGE2002 integrated assessment model used in the Stern report. *J Med Virol* 84(4):624–631
- IPCC (2013) Climate change 2013: the physical science basis. Working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
- Kainuma M, Matsuoka Y, Morita T (2003) Climate policy assessment: Asia-Pacific integrated modeling. Springer, Berlin
- Lenton TM (2000) Land and ocean carbon cycle feedback effects on global warming in a simple Earth system model. *Tellus* 52(5):1159–1188
- Mann AS, Richels RG (2005) Merge: an integrated assessment model for global climate change. In: Loulou R, Waub JP, Zaccour G (eds) Energy and environment. Springer, New York
- Matsuoka Y, Kainuma M, Morita T (1995) Scenario analysis of global warming using the Asian Pacific integrated model (AIM). *Energy Policy* 23(4–5):357–371
- Meinshausen M, Raper SCB, Wigley TML (2011) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: model description and calibration. *Atmos Chem Phys* 11(4):1417–1456
- Moss RH, Edmonds JA, Hibbard KA et al (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463(7282):747–756
- Nordhaus W (1992) The DICE model: background and structure of a dynamic integrated climate-economy model of the economics of global warming. 1992, Cowles Foundation Discussion Paper No. 1009
- Nordhaus W, Sztorc P (2013) DICE 2013R: introduction and user's manual, 2nd edn. Yale University. http://www.econ.yale.edu/%7Enordhaus/homepage/documents/DICE_Manual_100413r1.pdf
- O'Neill BC, Kriegler E, Ebi KL et al (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob Environ Change* 42:169–180
- Sokolov AP, Schlosser CA, Dutkiewicz S et al (2005) The MIT integrated global system model (IGSM) version 2: model description and baseline evaluation. MIT, Cambridge
- Stocker T (2011) Model hierarchy and simplified climate models. In: Introduction to climate modelling. Advances in geophysical and environmental mechanics and mathematics. Springer, Berlin
- Svirezhev Y, Brovkin V, von Bloh W et al (1999) Optimisation of reduction of global CO₂ emission based on a simple model of the carbon cycle. *Environ Model Assess* 4(1):23–33
- Tanaka K, Kriegler E, Bruckner T et al (2007) Aggregated carbon cycle, atmospheric chemistry, and climate model (ACC2)-description of the forward and inverse models. Max Planck Institute for Meteorology, Hamburg
- Tol RSJ (2009) The feasibility of low concentration targets: an application of FUND. *Energy Econ* 31(Supplement 2):S121–S130
- van Vuuren DP, Lowe J, Stehfest E et al (2011a) How well do integrated assessment models simulate climate change? *Clim Change* 104(2):255–285
- van Vuuren DP, Edmonds JA, Kainuma M et al (2011b) A special issue on the RCPs. *Clim Change* 109(1–2):1–4
- van Vuuren DP, Edmonds J, Kainuma M et al (2011c) The representative concentration pathways: an overview. *Clim Change* 109(1–2):5–31
- van Vuuren DP, Batlle LB, Chuwah C et al (2012) A comprehensive view on climate change: coupling of Earth system and integrated assessment models. *Environ Res Lett* 7(2):24012–24021
- Wei Y, Han R, Liang Q et al (2018) An integrated assessment of INDCs under shared socioeconomic pathways: an implementation of C3IAM. *Nat Hazards* 92(2):585–618
- Wigley TML (1991) A simple inverse carbon cycle model. *Global Biogeochem Cycles* 5(4):373–382

- Wigley TML (1995) Global-mean temperature and sea level consequences of greenhouse gas concentration stabilization. *Geophys Res Lett* 22:45–48
- Wigley TML, Raper SCB (2002) Reasons for larger warming projections in the IPCC third assessment report. *J Clim* 15:2945–2952
- Wu T, Li W, Ji J et al (2013) Global carbon budgets simulated by the Beijing Climate Center Climate System Model for the last century. *J Geophys Res Atmos* 118(10):4326–4347
- Wu J, Zhu QT, Liu CX et al (2014a) Comparison of the carbon cycle models in DICE/RICE. *Acta Ecol Sin* 34(22):6734–6744
- Wu T, Song LC, Li WP et al (2014b) An overview of BCC climate system model development and application for climate change studies. *Acta Meteorol Sin* 1:34–56
- Yang S, Dong WJ, Chou JM et al (2015) A brief introduction to BNU-HESM1.0 and its earth surface temperature simulations. *Adv Atmos Sci* 32(12):1683–1688

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