An integrated assessment of INDCs under Shared Socioeconomic Pathways: An implementation of C^3IAM

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Abstract:

A series of global actions have been made to address climate change. As a recent

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developed climate policy, Intended Nationally Determined Contributions (INDC) have renewed attention to the importance of exploring temperature rise levels lower than 2 degrees Celsius (°C), in particular a long-term limit of 1.5°C, compared to the preindustrial level. Nonetheless, achieving the 2°C target under the current INDCs depends on dynamic socioeconomic development pathways. Therefore, this study conducts an integrated assessment of INDCs by taking into account different Shared Socioeconomic Pathways (SSPs). To that end, the CEEP-BIT research community develops the China's Climate Change Integrated Assessment Model (C^3IAM) to assess the climate change under SSPs in the context of with and without INDCs. Three SSPs, including "a green growth strategy" (SSP1), "a more middle-of-the-road development pattern" (SSP2) and "further fragmentation between regions" (SSP3) form the focus of this study. Results show that after considering INDCs, mitigation costs become very low and they have no evident positive changes in three SSPs. In 2100, a temperature rise would occur in SSP1-3, which is 3.20°C, 3.48°C, and 3.59°C, respectively. There is long-term difficulties to keep warming well below 2°C and pursue efforts toward 1.5°C target even under INDCs. A drastic reduction of greenhouse gas emissions is needed in order to mitigate potentially catastrophic climate change impacts. This work contributes on realizing the hard link between the earth and socioeconomic systems, as well as extending the economic models by coupling the global CGE model with the economic optimum growth model. In C^3IAM, China's energy consumption and emissions pattern are investigated and refined. This study can provide policy makers and the public a better understanding about pathways through which different scenarios could unfold toward 2100, highlights the real mitigation and adaption challenges faced by climate change and can lead to formulating effective policies.

Key words:
Climate Change; Integrated Assessment Modeling; C^3IAM; Shared Socioeconomic Pathways; INDCs; Mitigation and Adaption

1. Introduction

Depending on whether carbon dioxide equivalent (CO_2) concentration stabilization maintains at around 450 parts per million (ppm) through 2100, the global average temperature increase is expected to limit to 2 degrees Celsius (°C), relative to pre-industrial levels. To accomplish it, global GHG emissions need to be reduced to 30-50 $GtCO_2$eq by 2030 (IPCC 2014). Motived by this purpose, international communities have taken a number of measures to adapt to and mitigate climate change. Leading up to the launch of COP 21 (United Nations Framework Convention on Climate Change (UNFCCC), Conference of the Parties), industrialized and developing countries submitted their Intended Nationally Determined Contributions (INDCs) to the UNFCCC, indicating their emissions reduction commitments for 2025 or 2030. As INDCs were submitted from more than 196 countries covering around 90% of global emissions, we can assess the future contribution of INDCs to longer-term global climate strategy. In recent years, a number of studies have examined the implications of the INDCs for future emissions (e.g., Fawcett et al. 2015; Iyer et al. 2015; Damassa et al. 2015; Rogelj et al. 2016; Aldy et al. 2016; Rose et al. 2017). Notably, INDCs represent our best understanding of the climate actions countries intend to pursue after 2020 and they have become an indispensable policy scenario in the assessment of climate change influence (Rogelj et al. 2016).

Climate change strongly relates to the dynamic socio-economic development context. To anticipate future global and regional climate change, greenhouse gas (GHG) emissions with or without any policy interventions should be framed under different socioeconomic and technological scenarios (Nakicenovic and Swart 2000). Therefore, some scholars proposed the concept of Shared Socioeconomic Pathways scenarios (SSPs). SSPs were proposed as new scenarios, which can be a basis of future climate change research and can be used to explore a range of future societal circumstances that exhibit a wide range of challenges to adaptation and mitigation (van Vuuren et al. 2014). Riahi et al. (2017) presented the narratives and characteristics of SSPs that can describe the change of future climate and different socioeconomic development tendencies. Based on SSPs, the scenarios analysis simulates long-term consequences of near-term decisions effectively and contributes to researchers to explore different results caused by uncertainties. Five SSPs were defined, including “a green growth strategy” (SSP1), “a more middle-of-the-road development pattern” (SSP2), “further fragmentation between regions” (SSP3), “an increase in inequality across and within regions” (SSP4) and “fossil fuel based economic development” (SSP5).

Whether the 2°C target is achieved depends on different socioeconomic and technological pathways. China has been the largest emitter of carbon emissions in the world. If China does not take measures to control GHG emissions, its CO_2 emissions may reach as high as 18 Gt by 2030 (Tol 2013), in which case the global 2°C target would be unlikely to be achieved. Under the framework of SSPs, how the world's temperature, emissions, energy, land use, economic activity and social costs would be like? With the influence of INDCs, how the pathways would change and whether the global mean surface temperature could be limited not to exceed 2°C? When and how would China reach its peak CO_2 emissions? Furthermore, what would China's contribution to control and reduce global GHG emissions? In this paper, we will discuss the assessment results by applying China's Climate Change Integrated Assessment Model (C^3IAM model) and quantification of SSPs for the Business As Usual (BAU) scenario and eight climate change stabilization levels.

C^3IAM is a system of inter-related component models developed by the Center for Energy and Environmental Research, Beijing Institute of Technology (CEEP-BIT). CEEP-BIT research community have completed a serious studies about integrated assessment of climate policies, uncertainty in climate change, equity across time and space, endogeneity of technological change, greenhouse gases abatement mechanism, and enterprise risk in climate policy models (eg., Wei et al. 2013, 2014, 2015). Since climate change is a complex and comprehensive process, it can only be understood on the basis of the interdisciplinary insights. In recent years, the need for integration of information among "earth system" (ES), "vulnerability, impact, and adaptation assessment" (VIA) and "integrated assessment" (IA) communities has become stronger (Moss et al. 2010). Motived by this need, C^3IAM is designed to hard link ES, VIA and IA models to realize the possible feedbacks between the human and earth systems on the global scale. Six worldwide Integrated Assessment Models (IAMs) have quantified the five SSPs: AIM (Asia Pacific Integrated Model) (Fujimori S et al. 2017); GCAM (Global Change Assessment Model) (Calvin K et al. 2017); IMAGE (Integrated Model to Assess the Greenhouse Effect) (van Vuuren et al. 2017); MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) (Fricko et al. 2017); REMIND-MAgPIE (Regionalized Model of Investments and Development-the Model of Agricultural Production and its Impact on the Environment) (Kriegler et al. 2017) and WITCH (World Induced Technical

Change Hybrid Model) (Emmerling J et al. 2016). Six IAMs communities have made outstanding contributions as research pioneers, however, as far as we know none of them has considered INDCs under the scenario analysis of SSPs yet. Note that the emissions pathway and pattern of China are often not made explicit in previous research. Motivated by this aim, we intend to apply an integrated assessment of INDCs under SSPs using the C^3IAM model to analyze how the emissions pathway change corresponding to different socioeconomic scenarios and address the following questions.

(1) After applying INDCs emission targets, how will the world's energy, economy and climate systems change over the period 2011 to 2100? How much would the social cost of carbon be like?

(2) Whether the increase in global mean temperature can be kept to well below 2°C in 2100 above the preindustrial level?

(3) What does "a green growth strategy" (SSP1), "a more middle-of-the-road development pattern" (SSP2) and "further fragmentation between regions" (SSP3) mean exactly, in terms of challenges to adaptation and mitigation?

(4) Whether the newly developed integrated assessment model (C^3IAM) is valid for assessing the climate change under SSPs?

With a continuously increasing volume of academic outputs, this study goes beyond the former studies in several aspects:

(1) We take into account INDCs and corresponding baseline emission predictions in the context of different SSPs;

(2) Considering the calculation uncertainty of INDCs targets, we develop "CEEP-I" (carbon emission evolution principle by intensity) and "CEEP-S" (carbon emission evolution principle by structure) to determine each country's target year emissions;

(3) GHG emissions and temperature pathway toward 2100 under regional-level INDCs are assessed.

The rest of the paper is divided into four sections. Section 2 presents an overview of the modeling framework with primary focus on the C^3IAM methodology, scenario assumption, data specifications. Research results without and with INDCs are presented and discussed in Section 3. Section 4 offers the conclusions and the policy implications of this study. Future research prospects are provided in Section 5. Further information on the implementation of SSPs in C^3IAM, as well as additional results are available in the Supplementary material.

2. Methodology

2.1 Modeling framework of C^3IAM

Our analysis couples the socioeconomic system with the earth system to establish the C^3IAM model. More specifically, C^3IAM, an integrated assessment model integrates the global CGE, economic optimum growth, revised earth system， land-use and impact models, dynamically captures the long-term optimal economic growth and climate change mitigation and adaptation. We set the base year in the C^3IAM model to 2011 due to the latest available data from the Global Trade Analysis Project (GTAP 9.0 database). This analysis covers the period 2011-2100.

C^3IAM consists of various analytical models developed to analyze policy issues within a specific set of sectors as shown in Fig.1. These models are interlinked to provide an integrated system for assessing the impact of climate change. C^3IAM considers factors such as global multiregional, multisector economic development, GHG emissions, emission reduction costs, modular climate change losses modular etc. It can not only depict the social economic system in detail, but also realize a long-term balanced growth path. The current version of the integrated system has seven analytical models, including the Global Energy & Environmental Policy Analysis model (C^3IAM/GEEPA), the Global Multi-Regional Economic Optimum Growth model (C^3IAM/EcOp), the Multi-Regional China Energy & Environmental Policy Analysis model (C^3IAM/MR.CEEPA), the National Energy Technology model (C^3IAM/NET), the Climate System Model developed by the Beijing Climate Center

(C^3IAM/BCC_CSM), the Ecological Land Use model (C^3IAM/EcoLa), and the Climate Change Loss model (C^3IAM/Loss).

Due to great uncertainties in the economic development, we use the scenario matrixes with different social economic assumptions to analyze climate policy variations under different radiative forcing targets. Following van Vuuren et al. (2014), a scenario matrix method is used to obtain potential combinations of socioeconomic assumptions and climate strategies. In order to quantify emission reduction scenarios, both radiative forcing targets and climate policy variables (climate, policy, and variations) are considered simultaneously.

In summary, compared with other IAMs, C^3IAM pays more attention to clarify the comprehensive impacts of climate change and it has a better performance in the following various aspects:

(1) More in-depth depiction of China: to refine the emissions pathway from the perspective of regional and sectoral, the multiregional CGE model (C^3IAM/MR.CEEPA) that covers 31 provinces and the multisector technology model (C^3IAM/NET) that covers eight energy-intensive industries are developed and integrated;

(2) Extension of economic model: to capture the long-term optimal economic growth and climate change mitigation and adaptation dynamically, C^3IAM integrates the global CGE model (C^3IAM/GEEPA) and the comprehensive evaluation model (C^3IAM/EcOp);

(3) Realizing the hard link between the earth and socioeconomic systems: The economic models are integrated with earth system model and the two-way feedback could be achieved. Specifically, earth system model in C^3IAM is from BCC_CSM developed by the Beijing Climate Center, which is one of the earth system models that participated in Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations for the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2014);

(4) Applications of INDCs: to explore policies and mechanisms coping with climate change, we take into account INDCs and corresponding baseline emission predictions in the context of different SSPs.

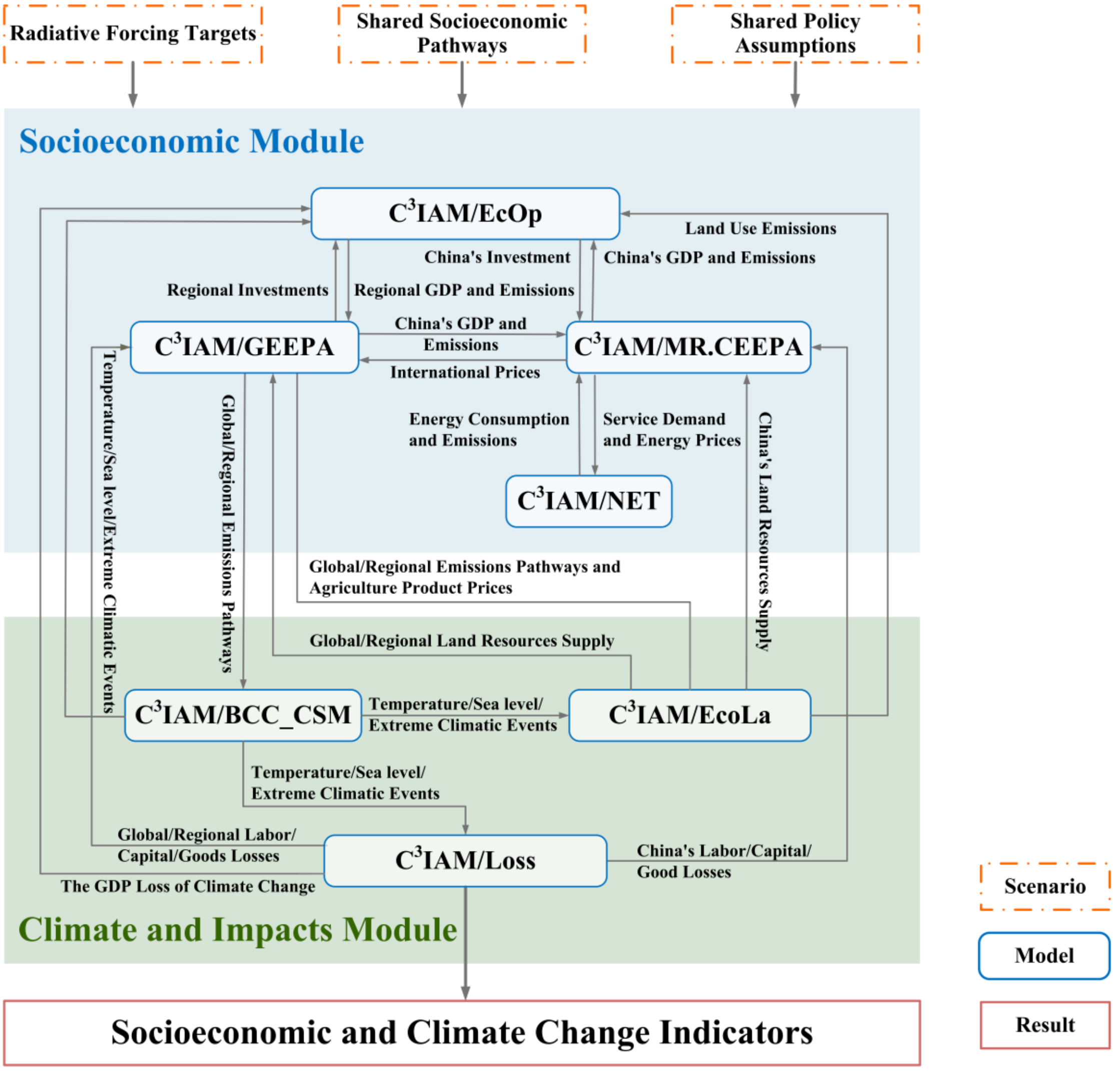

Fig.1. The general structure of C^{3}IAM.

Note: The blue boxes represent the seven analytical models of C^{3}IAM, which are integrated to generate internally consistent scenarios. The orange dotted boxes represent socioeconomic and climate scenarios. The red box represents the results of C^{3}IAM.

2.1.1 C^{3}IAM/EcOp

The Global Multiregional Economic Optimum Growth model (C^{3}IAM/EcOp) is established based on the theory of optimal economic growth and consists of two modules (economic and climate module) (as shown in Fig.2). The economic module describes the cost and damage of climate change under a certain level of economic development. While the climate module, which is refined from C^{3}IAM/BCC_CSM, presents the GHG concentration growth, radiative forcing and temperature change thereafter. The Mitigation, Adaptation and Loss module is refined from C^{3}IAM/Loss.

To maximize global welfare, the model optimizes regional consumption and investment. Therefore, national optimal climate policies and adaptation decisions could be provided.

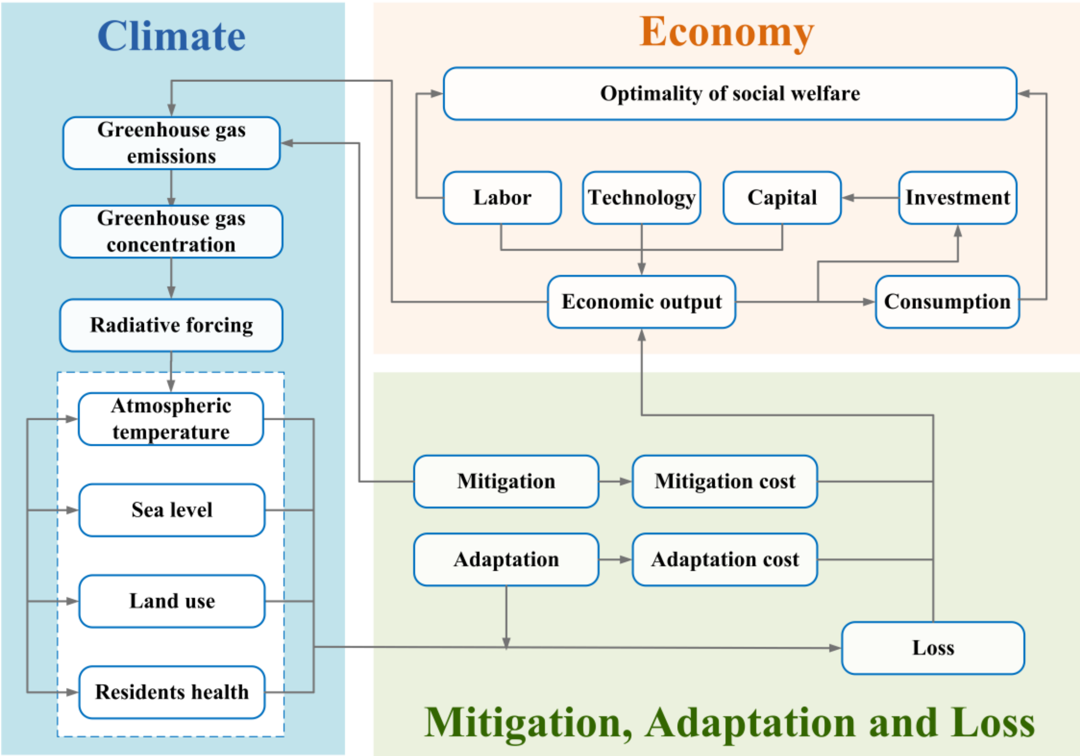

Fig.2. The framework of C^{3}IAM/EcOp.

2.1.2 C^{3}IAM/GEEPA

The core model of economic system is C^{3}IAM/GEEPA (version 1.0). C^{3}IAM/GEEPA is a recursive general equilibrium model that describes the interactions among different agents in macroeconomic systems of all regions. We divide the world into 12 regions, which are United States, China, Japan, Russian Federation, India, Other Branches of Umbrella Group, European Union, Other West European Developed Countries, Eastern European CIS excluding Russian Federation, Asia excluding China, India and Japan, Middle East and Africa and Latin America (see Fig.3 and Table A.1).

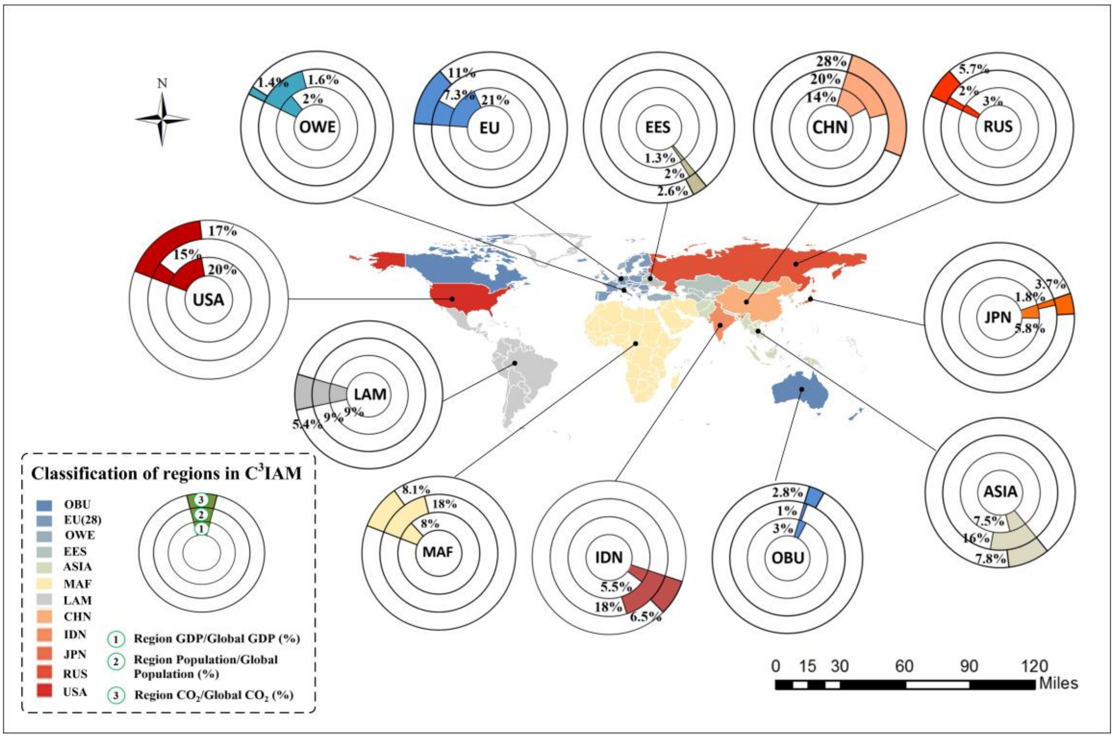

Fig.3. The classification of regions in C^{3}IAM.

Note: The colored boxes represent 12 regions of the world. The doughnut chart shows the proportions of region to global. The innermost annulus, the middle annulus and the outmost annulus stand for the proportion of global regional GDP, population and CO_2 emissions of the year 2011, respectively. Original GDP and population data are drawn from IIASA SSPs database, and CO_2 emissions come from IEA.

C^{3}IAM/GEEPA includes 27 sectors, which are Paddy rice, Wheat, Cereal grains, Vegetables & Fruit & Nuts, Oil seeds, Sugar cane & Sugar beet, Plant-based fibers, Crops, Cattle & Sheep & Goats & Horses, Animal products, Raw milk, Wool & Silk-worm cocoons, Forestry, Fishing, Coal, Oil, Gas, Other minerals, Other Manufacturing, Energy-intensive manufacturing, Roil, Electricity, Gas manufacture & Distribution, Water, Construction, Transportation service industry and Other services (shown in Table A.2). C^{3}IAM/GEEPA is composed of five basic modules, i.e. production, income, expenditure, investment and foreign trade module. Basic assumptions for each sub-module are shown in supplementary information (shown in Appendix B.).

2.1.3 C^3IAM/MR.CEEPA

C^3IAM/MR.CEEPA (version 1.0) is a one-year-step recursive and dynamic general equilibrium model that covers 31 provinces and municipalities (without Hong Kong, Macao and Taiwan) of China and includes 23 sectoral classifications (see Table A.3 and Table A.4).

The assumptions, model structure and mathematical formulae of C^3IAM/MR.CEEPA are similar to that of C^3IAM/GEEPA. Furthermore, the set and the emission factors of air pollution emissions and GHG emissions in C^3IAM/MR.CEEPA are all consistent with that in C^3IAM/GEEPA. The framework of C^3IAM/MR.CEEPA is shown in Fig.4. The main difference between C^3IAM/GEEPA and C^3IAM/MR.CEEPA is that in C^3IAM/MR.CEEPA we established Central Government (CG), which gains a certain percentage of taxes and capital income as its revenue, and transfers payment to Household (HH), Enterprise (En), and the rest of China.

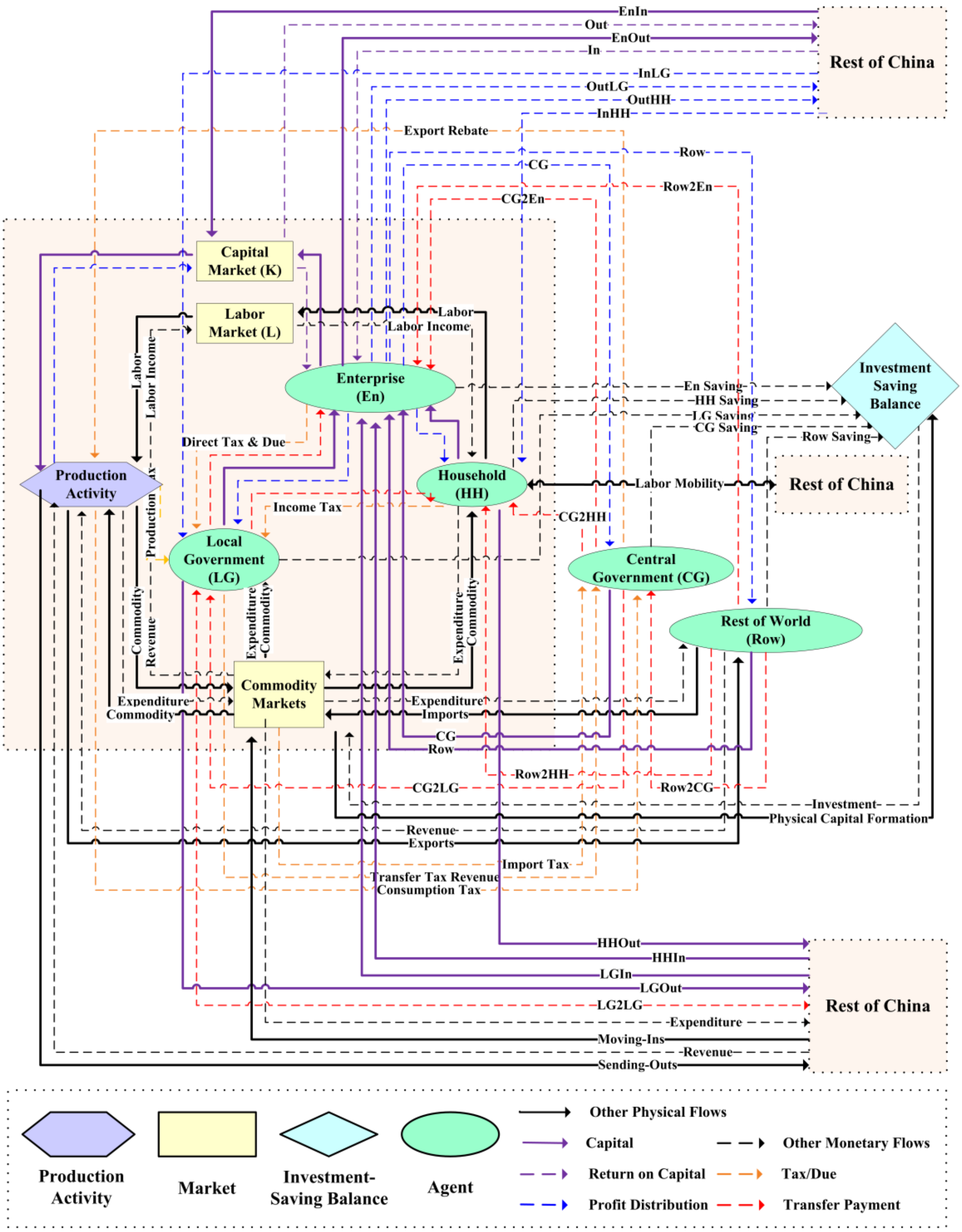

Fig.4. The framework of C[3]IAM/MR.CEEPA.

2.1.4 C[3]IAM/BCC_CSM

The C[3]IAM/BCC_CSM model represents the climate component and the emission information generated from C[3]IAM/GEEPA is fed into C[3]IAM/ BCC_CSM (see Fig.5). We used C[3]IAM/ BCC_CSM to calculate climate indicators such as global mean temperature changes and radiative forcing. The C^3IAM/ BCC_CSM model is developed based on the Beijing Climate Center Climate System Model (BCC_CSM), which is one of the earth system models that participated in CMIP5 simulations for the IPCC AR5. It has four component models, i.e. global atmosphere model (BCC_AGCM2.1), land surface model (BCC_AVIM1.0), global ocean model (MOMO4_L40v1) and global thermodynamic sea ice model (SIS). These component models are interrelated and interacted with each other through fluxes of energy, momentum and water. The flux coupler was based on that of NCAR/CCSM2. The detailed model information can be referenced in Wu et al. (2013). The BCC_CSM is a fully coupled climate-carbon cycle model, including oceanic and terrestrial carbon cycle with dynamical vegetation. The atmospheric CO_2 concentration and its temporal evolution can be well reproduced when forced by anthropogenic emissions of CO_2 (Wu et al. 2013, 2014). Besides, in addition to the long-term climate change simulations and projections, BCC_CSM has also been used for short-term climate predictions, as well as the Sub-seasonal to Seasonal (S2S) Prediction Project.

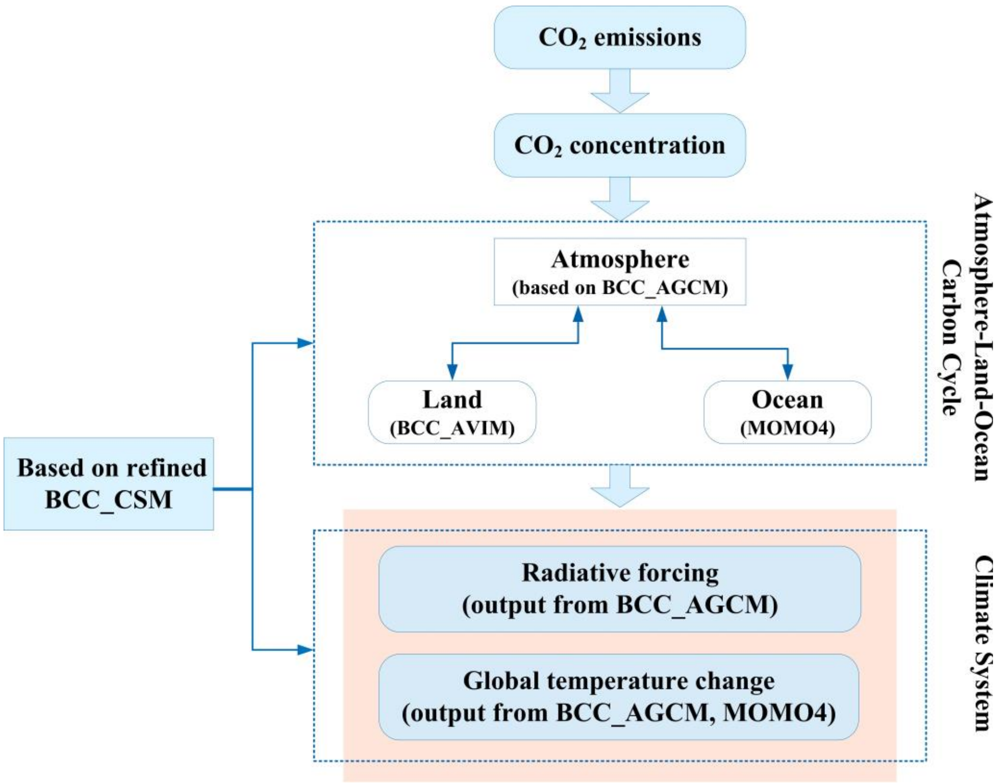

Fig.5. The framework of C^3IAM/BCC_CSM.

2.1.5 C^3IAM/EcoLa

The future patterns of land use have direct influence on GHG emissions and mitigation potential for land-use sector and food supply. The C^3IAM/EcoLa model is a global multi-regional land use allocation optimization model, which covers the agricultural and forestry sectors (see Fig.6). It can be used to analyze land use change in a long-term period. The primary objective of the model is to minimize the total cost of production under consideration of agricultural demand in 12 regions. Major types of cost in C^3IAM/EcoLa are: (1) Production costs of crop and livestock production, which are obtained by a total sum of the costs of labor, capital and intermediate inputs divided by the land area obtained from C^3IAM/GEEPA; (2) Land conversion costs which are exogenously determined by the cost of new additional land and investment into infrastructure (Schmitz et al. 2012; Sohngen et al. 2008); and (3) Carbon emissions costs which consider the carbon costs caused by land use change in mitigation scenarios.

For the projection of land use change, C^3IAM/EcoLa works on a time step of five years in a dynamic recursive mode. Future demand for regional agricultural and forest products (e.g., rice, wheat, cereals, vegetables, oil seeds, sugar, fibers, other crops, livestock and forestry) is exogenous, it relies on income per capita, and population projection of different regions (Schmitz 2013) based on GTAP database (2017). Additionally, primary agricultural products considered in the model are listed in Table A.5. The livestock activities are connected with the feed requirement per animal product. Following Alcamo's work (2011), the model currently considers ruminants for livestock activities such as cattle and sheep but non-ruminants are not included. The total forage demand is calculated by multiplying livestock unit with average forage consumption per livestock unit during one year (Alcamo et al. 2011). Moreover, technical change for agricultural sector depends on different biophysical and socioeconomic factors (Ewert et al. 2005; Wirsenius et al. 2010). Changes of agricultural productivity and crop productivity among 12 regions are different, what's more, SSP1-3 have different product specific rates. Trade in food and forest products across the various regions are not considered in the study.

For the reference land use area distribution used in the base year 2011, croplands are produced by eight crop categories which contain 149 crop types (see Table A.5). According to Food and Agriculture Organization (FAO) definition, grass is from permanent pastures and can be used to graze (Souty et al. 2012). Forest sector is divided into managed forests and no-managed forests. The primary forest products are supplied from managed forests (Havlík et al. 2014). The built-up, water and ice areas are assumed constant during the study period.

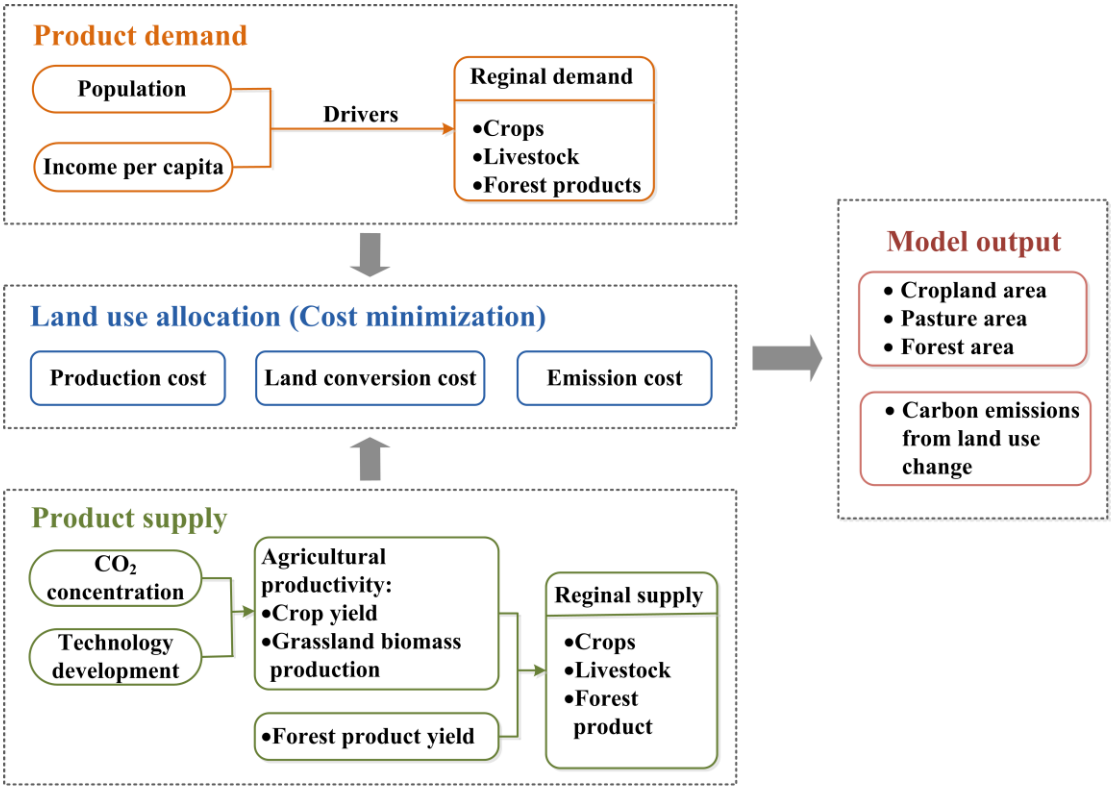

Fig.6. The framework of C[3]IAM/EcoLa.

It should be noticed that, C[3]IAM/MR.CEEPA, C[3]IAM/NET and C[3]IAM/Loss models are under development. This study only refers to the sub-models mentioned above.

2.2 Scenario framework in C^3IAM

This section provides an overview of scenario framework in C^3IAM, which contains “Shared Socioeconomic Pathways Scenario” and “INDCs Scenario”. Following the previous work of van Vuuren et al. (2014), we establish the three-dimensional scenario bubble diagram that contains socioeconomic, climate conditions and mitigation costs. Furthermore, in order to assess the impact of INDCs and related policy statements on future energy and climate trends, we apply global and regional INDC emission targets as a new policy scenario.

2.2.1 SSPs narratives and framework

Similar to the Special Report on Emissions Scenarios (SRES), SSPs contain both narratives and quantitative information. The SSPs are designed to represent different mitigation and adaptation challenges, and the resulting narratives and quantifications span a wide range of different futures broadly representative of the current literature (Riahi et al. 2017). The SSPs consist first-of-all of a narrative, quantified population, GDP and urbanization trajectories, and qualitative assumptions on the energy and land use sectors. These elements served as the starting point for the further quantitative elaboration of SSPs using IAM models. According to the narratives, SSP1-3 span a range of low, medium, and high challenges to both mitigation and adaptation. SSP5 is characterized with high socioeconomic challenges to mitigation and low socioeconomic challenges to adaptation. Conversely, SSP4 has low challenges to mitigation, but high challenges to adaptation.

The scenario framework of this study contains socioeconomic conditions and climate conditions. The socioeconomic dimension includes the five SSPs, and the climate condition dimension includes climate mitigation targets represented by eight Representative Concentration Pathways (RCP) (5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0 and 8.5W/m^2). The framework enables us to separate these elements to study the effects of climate policies. Each combination of SSP and RCP is denoted as, for instance, SSP-BL and SSP-5.0W in the rest of this paper.

2.2.2 An overview of INDCs

On 12 December 2015, representatives from 196 countries to the UNFCCC's 21 st Conference of Parties (COP-21) in Paris reached a landmark climate agreement limiting global temperature increase, which will require balancing GHG emissions and sinks after mid-century (Paris Agreement). The most important achievement in the agreement is to set up emission reduction target by commitment submitted by each country with the form of National Determined Contributions (NDCs). Nations that are parties to the agreement are required to submit INDCs that outline future reductions in GHG emissions out to 2030 (as shown in Table 1). Parties may adjust their INDCs at any time, but must revise and update INDCs every five years. A rich literature analyzes INDC targets and many suggest that the treaty is less ambitious to effectively control climate change (Magnan et al. 2017). Rogelj et al. (2016) point that the median emissions gap between GHG emission levels resulting from INDCs and the 2°C limit by 2030 is estimated to be between 11 and 14 $GtCO_2eq$. That means the emission reduction targets inside INDCs could not match with the emission pathway for the global to keep a temperature rise in this century well below 2°C and to drive efforts to limit the temperature increase even further to 1.5°C above preindustrial levels. Thus, it is important for countries to do more than their commitment in INDCs, especially in near term.

As a new international climate policy, Paris Agreement have renewed attention to the importance of exploring temperature levels even lower than 2°C, in particular a long term limit of 1.5°C. Therefore, we implement SSPs under INDC targets of 12 regions to make this research more practical.

More than 60% countries choose Business As Usual (BAU) scenarios as the reference, however, it is difficult to determine their BAU emissions exactly. Worse still, countries have different statistical caliber that make it harder to calculate INDC emissions targets. Motived by this plight, CEEP-BIT research community develop carbon emission evolution principle from the perspective of carbon intensity (carbon emission evolution principle by intensity, CEEP-I) and carbon emission evolution principle from the perspective of the relationship between economic development and

CO_2 emissions (carbon emission evolution principle by structure, CEEP-S) to simulate the BAU scenario in the process of determine each country's target year emissions under INDCs. Because of data limitation, in this study, we give priority to using the computed results of CEEP-I.

Table 1 Summary of INDCs.

	Countries that have submitted INDCs	
	Annex I countries	Non-Annex I countries
Emissions ratio (2011)	34.79%	62.03%
Number of countries that submitted INDCs	Full submission	90
Main items covered in INDCs	Give priority to mitigation	Most cover mitigation, adaptation, and the need for international capital, technical assistance, and even some vulnerable countries cover losses and damage
Target year	Most of them are 2030 A few countries are 2025 (like USA, Brazil and Gabon)	
Target type	Absolute emission reduction target Unconditional emission reduction commitment	Most are relative reduction targets. The majority also proposed a conditional reduction commitment for international assistance.
Baseline	Most of them are 1990	Most of them are BAU scenario
Gases covered in INDCs	Most of them covers CO_2, CH_4, N_2O, HFCs, PFCs, SF6 and NF_3	Most of them covers CO_2, CH_4 and N_2O

2.2.3 Demographic and economic drivers

SSPs have enriched the social economic background with a range of socioeconomic drivers' projections (e.g., population, education rate, urbanization rate and GDP) (Riahi et al. 2017; van Vuuren et al. 2017; Fricko et al. 2017; Fujimori et al. 2017; Calvin et al. 2017; Kriegler et al. 2017). Previous studies such as O'Neill et al. (2017) have presented narrative descriptions, which are a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. One key step in developing SSPs is the translation of qualitative narratives into quantitative. The International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR) developed population and urbanization scenario. The team from the Organization for Economic Cooperation and Development (OECD) projected GDP under different SSPs. To implement SSPs with C^3IAM, we use the demographic and economic assumptions developed by Dellink et al. (2017) and KC and Lutz (2017). Optimistic, middle and pessimistic parameter values were set to express the range in observed data or existing research. A full list of the assumptions and individual SSP parameterization schemes are shown in Table A.6.

2.3 Evaluating model outcomes

One of the primary objectives of this study is to evaluate the quantified SSPs in terms of their consistency with their narratives. What does “the green road”, “a middle-of-the-road” and “a rocky road” mean exactly? Several criteria can be used for evaluation of the general outcomes of IAMs (Schwanitz 2013). Through this process, the validity of C^3IAM for assessing the climate change under SSPs can be tested.

(1) Population and economic developments have strong implications for the anticipated mitigation and adaptation challenges. For instance, a larger and poorer population will have more difficulties to adapt to the detrimental effects of climate change (O’Neill et al. 2014). Overall, both the population and GDP developments in SSP2 are designed to be situated in the middle of the road between SSP1 and SSP3.

(2) Based on the previous studies, the most fundamental feature is the degree of challenge to mitigation. Therefore, mitigation cost (such as carbon price, GDP loss and consumption loss) measures are appropriate indicators to represent challenges to mitigation.

(3) In order to describe regional development, we evaluate trade dependency (import ratio to domestic consumption).

(4) Technological development is a key element in the narratives of scenario. Thus, we choose energy and carbon intensity improvement rates to represent energy-related technologies.

2.4 Data specifications

The latest Global Trade Analysis Project (GTAP 9.0 database) and energy balance tables (International Energy Agency 2013) are used as a basis for the Social Accounting Matrix (SAM) and energy balance table. In C^3IAM model, we consider both GHG emissions and traditional air pollutant emissions. Besides energy-related carbon dioxide (CO_2), CO_2 from other sources, methane (CH_4), and nitrous oxide (N_2O) are treated as GHGs in the model. The traditional air pollutants considered are carbon monoxide (CO), sulfur dioxide (SO_2), nitrous oxides (NOx), ammonia (NH_3), black carbon (BC), organic carbon (OC) and non-methane volatile organic compounds (NMVOC). All the GHGs and air pollutants in the base year are drawn from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) (GAINS 2011). The energy-related emissions and non-energy-related emissions can be differentiated through activity types within a sector for every discharge in GAINS model. Thus, a sector's emissions factor is determined by total energy-related emission divided by corresponding energy consumption or total non-energy-related emission divided by corresponding gross output.

For the agricultural statistics, such as historical agricultural production data and harvested areas are provided by FAOSTAT (Food and Agriculture Organization of the United Nations). Land use data is obtained from FAOSTAT (Food and Agriculture Organization of the United Nations 2017) and GTAP (Avetisyan et al. 2011). Carbon stock density is derived by GCAM (Kyle et al. 2011) and Houghton (1999).

3 Results analysis and discussions

In order to illustrate the exact implication of "a green growth strategy" (SSP1), "a more middle-of-the-road development pattern" (SSP2), "further fragmentation between regions” (SSP3), “an increase in inequality across and within regions” (SSP4) and “fossil fuel based economic development” (SSP5), we use C^3IAM to explain how the narratives have been translated into quantitative assumptions. Because the relative relation between each index of SSP1 and SSP4, SSP3 and SSP5 contains various uncertainties, in this research, we mainly discuss the results of SSP1, SSP2 and SSP3, which have relatively fixed relationships. Therefore, based on the results, a brief overview of economic and climate developments over the 21st century under SSP1-3 are provided. In addition, the influence of INDCs impact is further discussed in this section.

Mitigation costs and the attainability of alternative forcing targets across the SSPs are shown in Fig.7. The horizontal ordinate represents climate condition, which includes climate mitigation targets and the baseline (the baseline case does not include a climate mitigation policy). Mitigation costs are shown in terms of the global carbon prices, which is represented by the size of each circular. Consistent with the SSPs narratives, carbon price is found lower in SSP1 and SSP4 relative to SSP3 and SSP5. The area above baseline indicate either incompatible or not being generated in this study. Reaching the stricter climate mitigation target RCP4.5 and RCP2.6 are found not possible.

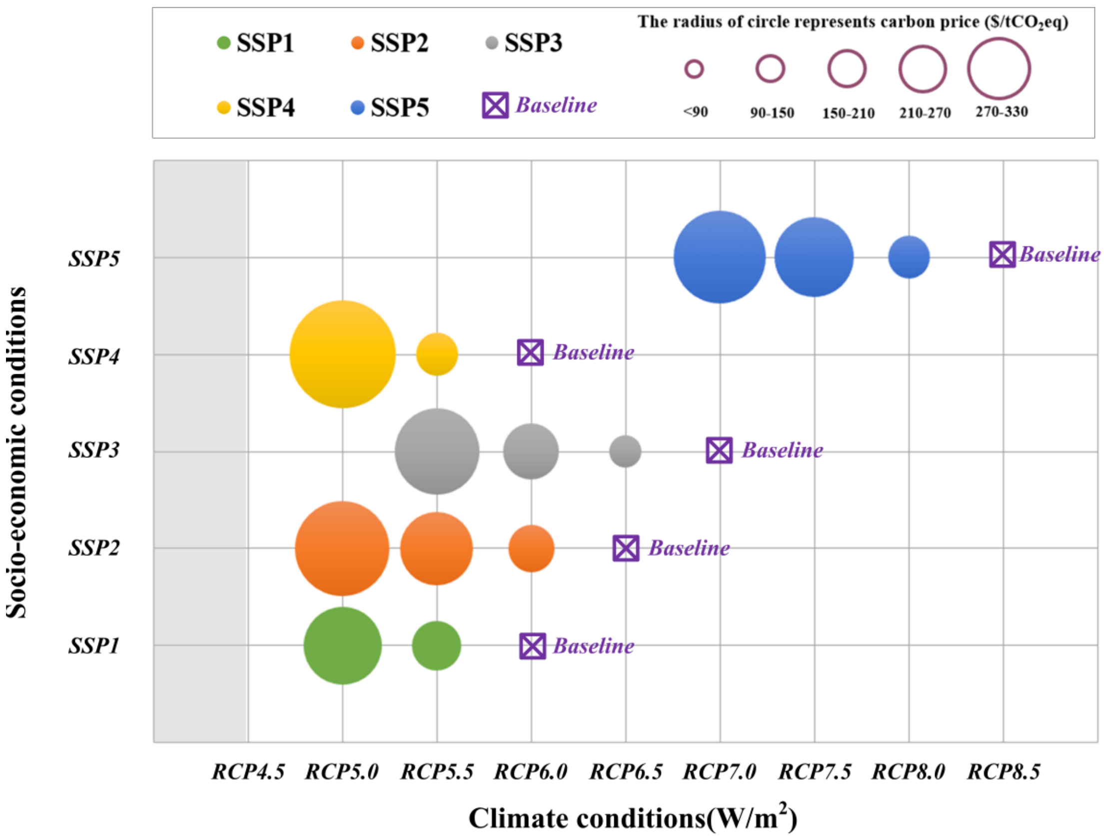

Fig.7. Mitigation costs and the attainability of alternative forcing targets across the SSPs

Notes: Carbon prices and the attainability of alternative forcing targets across the SSPs. The colors of the cells represent different SSPs and the size of circulars are indicative of the carbon price in 2100. The cross refers to the baseline of each SSP.

3.1 What does "a green growth strategy", "a more middle-of-the-road development pattern" and "further fragmentation between regions" mean directly?

In this section, we describe the development pathway of the energy and economic systems, as well as changes in land use, GHG and air pollutant emissions, radiative forcing and temperature variation, mitigation costs in the SSP1, SSP2 and SSP3 without consideration of INDCs.

3.1.1 The scale and structure of primary energy supply

Energy production and consumption account for two thirds of the world's greenhouse gas (GHG) emissions (IEA 2015). Thus, the scale and structure of future energy supply in SSPs are critical determinants of the challenges for mitigation and adaptation. According to narratives, SSP3 has a heavy reliance on fossil fuels with an increasing contribution of coal to the energy mix. On the contrary, the share of renewables and other low-carbon energy is increasing in SSP1. Since described as "middle of the road", energy development in SSP2 is balanced compared to other SSPs.

Fig.8 shows the global primary energy supply and energy sources for the BAU scenario and other climate policy cases in 2100 under SSP1, SSP2 and SSP3. In BAU scenario, SSP2-BL reaches 1183 EJ/year in 2100, with the same trend of SSP3-BL. However, the total energy supply of SSP3-BL is 22 EJ/year higher than that of SSP2-BL. Interestingly, SSP1-BL has substantial difference compared with the other SSPs, reaching 882 EJ/year in 2100. In different SSPs, there are different compositions of the energy sources. For instance, as described in narrative, SSP3-BL is oriented by coal and depend on fossil fuel. Comparing with SSP2-BL, the coal consumption of SSP3-BL is 347 EJ/year and is 81 EJ/year higher, which is consistent with the narrative. At the other extreme, there exists a large difference in nuclear energy production between SSP2-BL and SSP3-BL. The nuclear consumption of SSP3-BL is 4 EJ/year in 2100 and has a much lower development than that of SSP2. According to the narrative of SSPs, SSP1-BL is described as sustainability development, which has an increasing share of renewable energy. In 2100, SSP1-BL has the maximum renewable energy supply among SSPs, which is in consistent with the narrative.

The primary energy supply in 2100 by SSPs and different climate policies are also illustrated in Fig.8. The coal and oil decline greatly compared with BAU cases in all SSPs. Taking SSP3-6.0W and SSP2-6.0W into comparison, the share of fossil fuel in SSP3-6.0W is 11%, which is higher than that in SSP2-6.0W. It means that SSP3 is more urgent to decline the fossil fuel energy supply. Additionally, SSP3 has greater challenges to reduce CO_2 emissions. One of the challenges is that non-CO_2 emissions in SSP3-BL are higher than that in SSP2, which indicates that SSP3 has less reduction potential in the mitigation scenarios. In contrast, the share of renewable energy in

SSP1 is the highest in all SSPs-BL and it reduces dependency on fossil fuel.

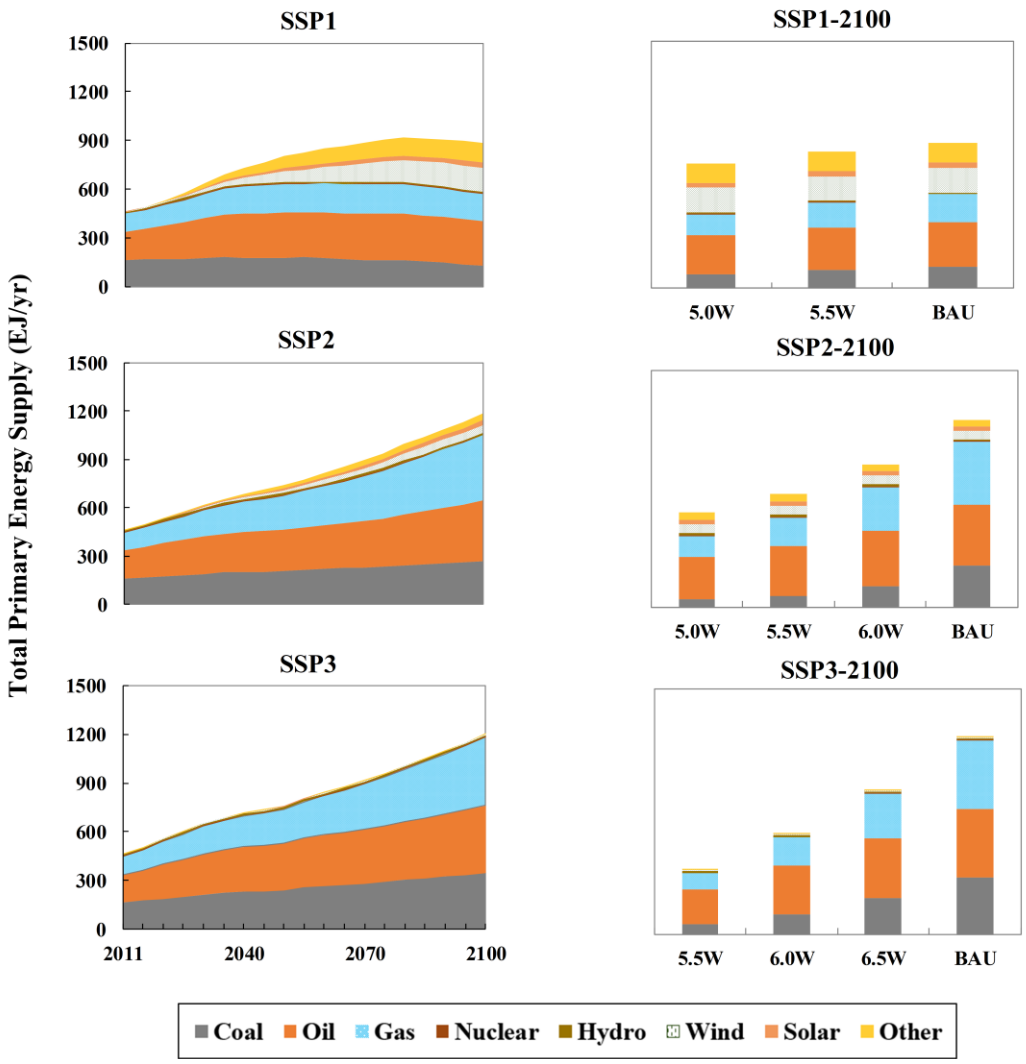

Fig.8. Global primary energy supply under the BAU scenario (left) and four mitigation cases in 2100 (right) for SSP1, SSP2 and SSP3.

3.1.2 Changes in cropland, pasture and forest for the SSPs

Land use development trend has direct influences on future GHG emissions and mitigation potential (Fricko et al. 2017; Popp et al. 2014), and is one of the key parameters in SSPs (Fujimori et al. 2017). For example, CO_2 can be emitted from direct human-induced impacts on forestry and other land use. Agricultural activities such as biomass burning and fertilizer use contribute to CH_4 and N_2O emissions. As shown in Fig.9, by 2100, the global cropland area in SSP1-3 BAU scenario would increase to 1627.85, 1773.12 and 1862.55 Mha, respectively. Cropland area in SSP3-BL is the largest compared to other SSPs, which is mainly caused by the relative low agricultural productivity and strongly increasing demand for agricultural products. Meanwhile, there is a high deforestation rate in SSP3-BL. In comparison, the SSP1-BL shows a sustainable land use pathway with little pressure on cropland resource due to its low population projection and high agricultural productivity. Thus, SSP1-BL has a much lower growth rate (0.28%) of cropland area. Forest area, in contrast, takes the largest proportion in SSP1-BL and the smallest in SSP3-BL. Land cover area in 2100 under the combination of SSPs and climate policies are also illustrated in Fig.9, which are obviously discrepant under different climate policy cases. The cropland and pasture area decrease gradually when more stringent climate policy is introduced, but the forest area is vice versa and has an increasing tendency in policy scenarios, which is obviously larger than that in BAU scenario.

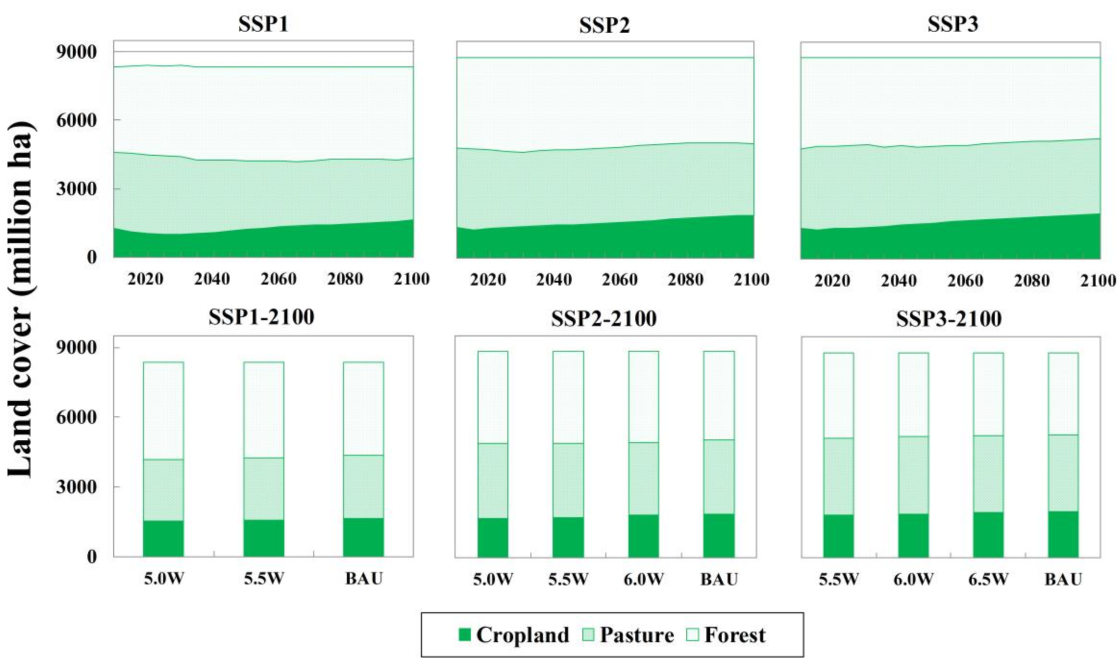

Fig.9. Land cover under the BAU scenario (left) and four mitigation cases in 2100 (right) for SSP1, SSP2 and SSP3.

3.1.3 The trajectories and amount of GHG emissions and its major components

GHG emissions are currently at the crux of political, environmental technological and cultural discussions due to climate change. The pathways for the energy and land use cover changes in SSPs translate into a wide range of GHG and pollutant emissions. Kyoto gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF6 and NF_3) and its major components (CO_2, CH_4, and N_2O) are illustrated in Fig.10. The emission trajectories under different SSPs are distinctly different, which are mainly reflected in the following aspects. BAU emissions in 2100 under SSP1-SSP3 are 67, 105, 117 $GtCO_2eq$, respectively. SSP1 would peak at 70 $GtCO_2eq$ in 2075 while SSP2 and SSP3 would keep increasing through the century. However, emissions under SSP2 keep growing at nearly uniform rate and increase sharply during 2020-2030 under SSP3. The shape of emission trajectories slightly change under different RCPs, while the peak value or terminal value in 2100 varies from each baseline emissions. To stabilize radiative forcing to 5.5W/m^2, 5.0W/m^2 and 4.5W/m^2 under SSP1, Kyoto gases emissions would peak at 61 $GtCO_2eq$ in 2070, 53 $GtCO_2eq$ in 2050, and 46 $GtCO_2eq$ in 2045, respectively. To stabilize at 5.5W/m^2, reaching the peak that is 54 $GtCO_2eq$ in 2055 is much earlier under SSP2.

CO_2 emissions are strongly correlated with the future challenges for mitigation. The trend of CO_2 emissions is similar to the Kyoto gases, while the declination is faster in all SSPs. The high dependence on fossil fuels in SSP3-BL result in higher CO_2 emissions. Conversely, low fossil fuel dependence and increased development of non-fossil energy sources in SSP2 results in lower CO_2 emissions. As shown in Fig.10, BAU CO_2 emissions in 2100 under SSP1-3 are 56, 84 and 92 $GtCO_2eq$, respectively.

CH_4 is also a main contributor to global warming, which is the highest in SSP3 and lowest in SSP1. In SSP1, the CH_4 emissions sharply decrease after 2060. SSP2 and SSP3 show an opposite trend in which emissions increase throughout the 21st century. Since population growth and food demand is a strong driver of future CH_4 emissions across all SSPs, the results are in accordance with SSPs storyline.

Agricultural soils and fertilizer use are the largest contributors of N_2O emissions. Emissions are the highest in SSP3 and lowest in SSP1, featuring agricultural practices and population assumption. The emission trajectories of N_2O are similar to CH_4 under different RCPs.

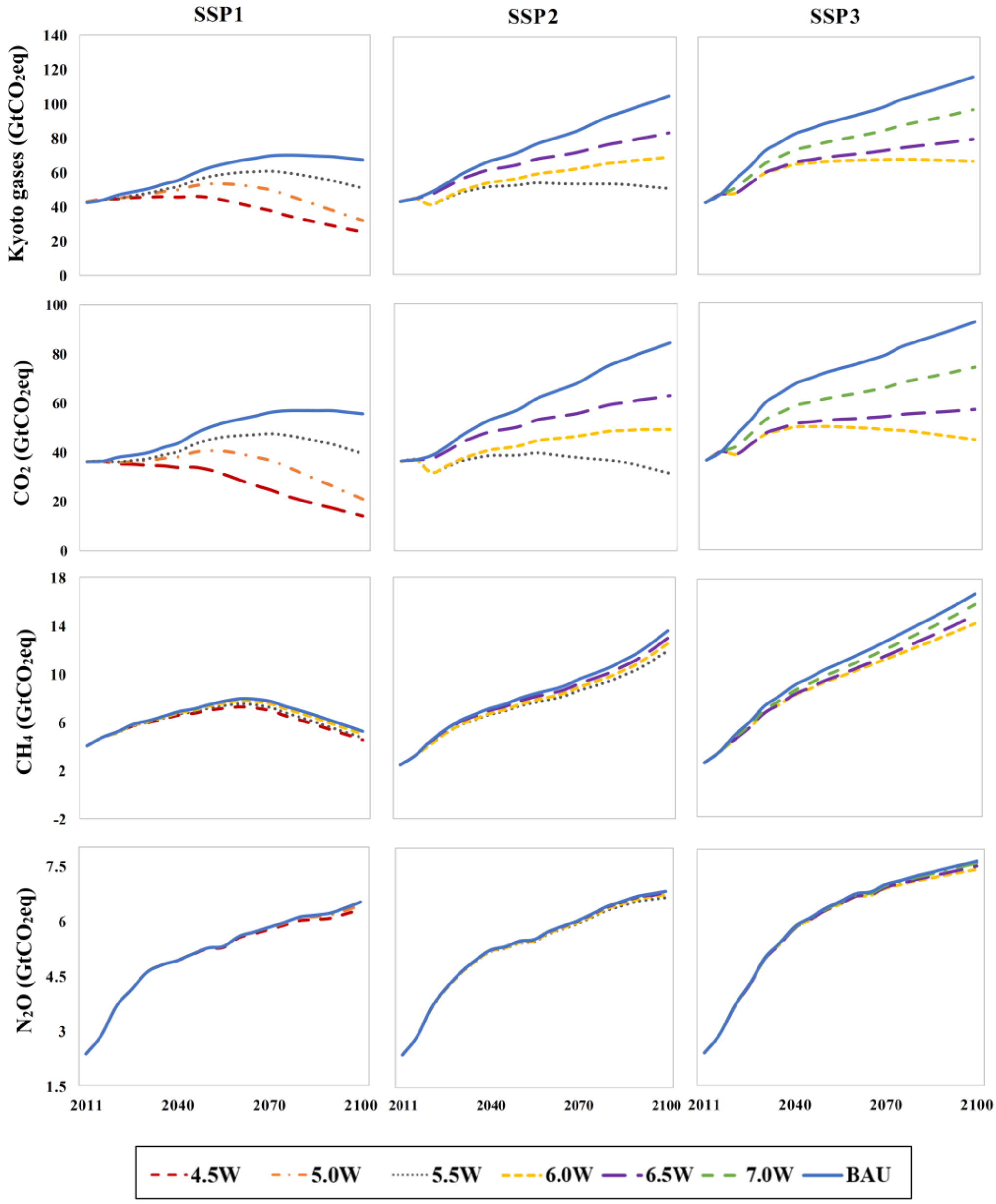

Fig.10. Global GHG (Kyoto gases), CO_2, CH_4, and N_2O emissions (from top to bottom) related to the six mitigation cases and BAU scenario for SSP1, SSP2, and SSP3.

3.1.4 Air pollutant emissions and its decomposition analysis for SO_2 and NO_X

Two main global air pollutants emissions (SO_2 and NO_x) for SSP1, SSP2 and SSP3 are presented in Fig.11. Generally, in BAU scenario, air pollutant emissions show a decreasing trend in all SSPs, and in SSP3-BL are the highest, followed by SSP2-BL. The SO_2 emissions in 2100 would be 6 MtSO_2/year for SSP1-BL, 12 MtSO_2/year for SSP2-BL and 24 MtSO_2/year for SSP3-BL, respectively. And the NOx emissions in 2100 would be 14 MtNOx/year for SSP1-BL, 22 MtNOx/year for SSP2-BL and 30 MtNOx/year for SSP3-BL, respectively. Agricultural soils and fertilizer use are by far the largest contributors of N_2O emissions. Emissions are the highest in SSP3 due to high population and/or fertilizer use. This is coincident with SSPs storylines (Kriegler and O'Neill et al. 2012; O'Neill and Kriegler et al. 2014).

The global SO_2 and NO_x decomposition analysis under SSPs are shown in Fig.12. Obviously, GDP per capita commonly increases SO_2 and NO_x emissions in all SSPs. The population factor shows an increasing contribution in SSPs, and even decreases the two kinds of air pollutants emission during 2075-2100. Emission intensity, in general, reduces the two pollutants in SSPs, and emission intensity plays the most effective role in pollutant reduction during the examined period compared with the other three factors. However, the contribution from energy intensity shows a declining change with time. Notably, there is a smaller reduction in energy intensity of SO_2 and NO_x, even energy intensity in SSP3 induces the increment of these two pollutants emission ever since 2055.

As shown in Fig.12, the corresponding mitigation cases in all SSPs have a lower emission than that of BAU scenarios. An important reason might be that SO_2 and NOx emissions are directly associated with fossil fuel combustion, and thus, they can be reduced by decreasing the use of fossil fuels and improving energy intensity. Other air pollutants such as NMVOC, BC, OC, NH_3, show small differences between the BAU and mitigation scenarios. Since the major emission sources of these air pollutants are associated with land-use, they are not easy to be reduced. Additionally, there is slight difference between the mitigation scenarios in SSP1, because SSP1-BL has already implemented stringent policies to control air pollutants and there is less potential for emission reduction.

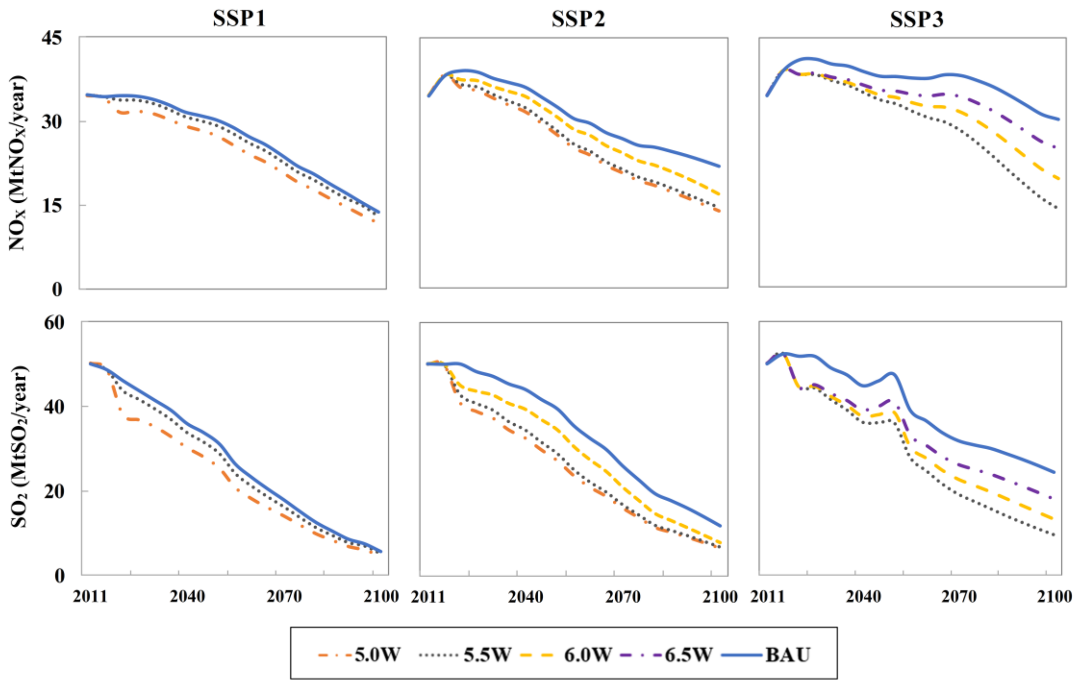

Fig.11. Global NOx and SO_2 emissions associated with the four mitigation cases for SSP1, SSP2 and SSP3. The units in NOx and SO_2 are $MtNO_X$/year and $MtSO_2$/year.

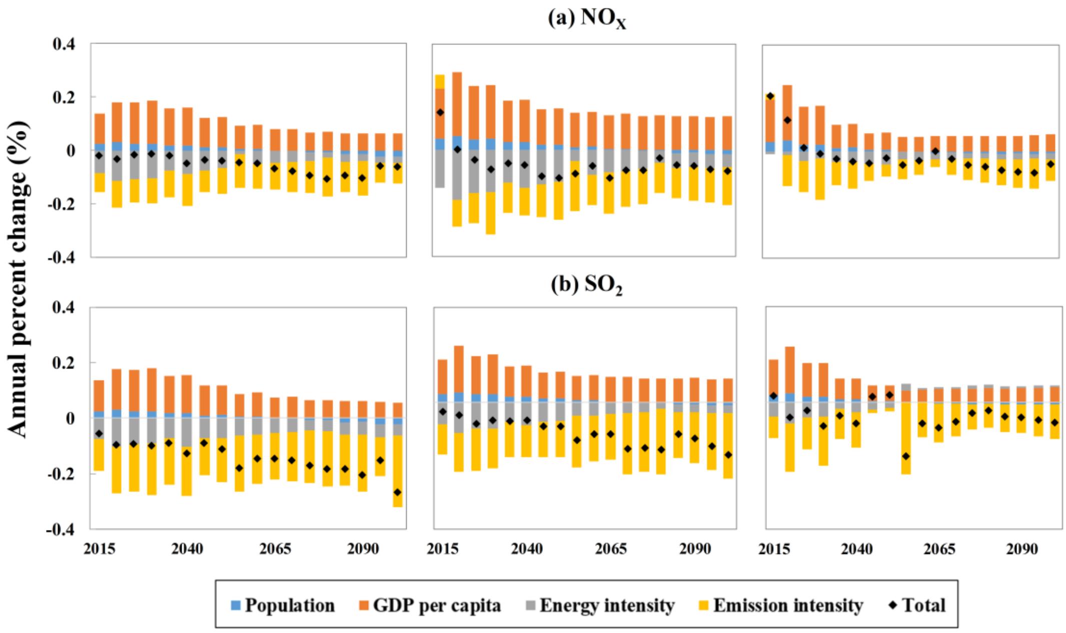

Fig.12. Global NOx and SO_2 decomposition results under SSP1, SSP2, and SSP3 in BAU scenarios.

3.1.5 Radiative forcing and temperature change toward 2100

The scenarios have been evaluated in terms of their expected impact on climate change. Here, we present the results of the C^3IAM/BCC_CSM calculations. Radiative forcing of the climate system is shown in the top of Fig.13. With no aggressive carbon sink technology in place, the level keeps increasing under all SSPs. At the end of this century, the radiative forcing in BAU scenario under SSP1-3 would reach 5.8W/m^2, 6.6W/m^2 and 7.1W/m^2, respectively. The order follows the GHG emissions level for each SSP and in accord with narratives. Low dependence on fossil fuels and wide application of renewable energy under SSP1 means that total radiative forcing absent the inclusion of mitigation only reaches 5.8W/m^2 in 2100. Delayed climate response and the effect of cumulative GHG emissions leads to a high diversity of forcing after 2050. Mitigation challenges play the dominant role that affect the values of radiative forcing under different SSPs.

It is remarkable that the lowest radiative forcing can only be 5.3W/m^2. Since low carbon technology like Carbon Capture and Storage (CCS) plays an important role in many of the mitigation scenarios. However, in the current version of C^3IAM, large-scale application of CCS cannot be realized, thus, reaching the stricter climate mitigation target such as RCP4.5 and RCP2.6 were found not possible. In order to reach radiative forcing levels below 5.5W/m^2, it is necessary to introduce climate mitigation policies.

In terms of temperature, the scenarios follow the trends in forcing with some delay, as shown at the bottom of Fig.13. By the end of this century, the temperature ends up at a warming of around 3.21°C under SSP1, 3.54°C under SSP2 and 3.79°C under SSP3. Even in SSP1, temperature would further increase by 1.2°C compared with 2°C target.

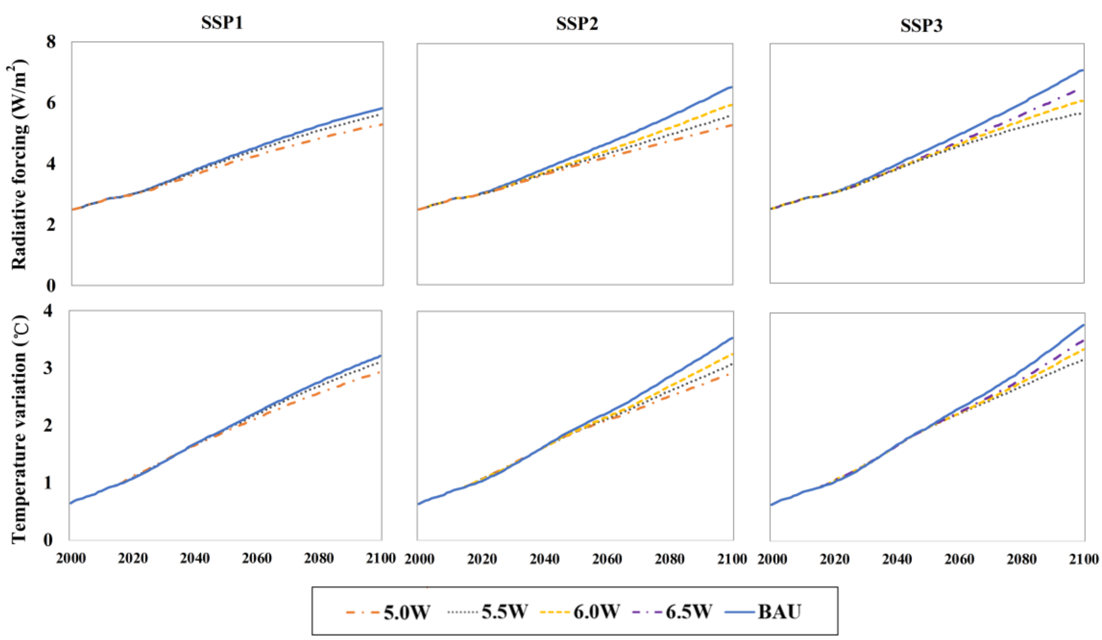

Fig.13. Global radiative forcing (top) and temperature variations (bottom) associated with the four mitigation cases and BAU scenario for SSP1, SSP2, and SSP3.

3.1.6 Changes in global energy and carbon intensity toward 2100

Global energy and carbon intensity reduction rates toward 2100 are shown in Fig.14 (carbon intensity here considers only energy-related CO_2 emissions), which presents how the introduction of climate policies leads to concurrent improvements of both the energy and carbon intensity of the economy. Historical intensity reduction rates from 1990 to 2015 are extrapolated and shown as dashed lines in the figure. In terms of the BAU scenario, values of SSP2 are most similar to historical trends. SSP3 shows lower reduction rates in both dimensions (7% and 20%), and on the contrary, SSP1 shows higher rates (44% and 75%). In SSP3, the slow energy intensity improvement is derived from the assumption of slow autonomous energy efficiency improvement and high final consumption of energy-intensive fuels. Carbon intensity improves slowly due to the assumption of a high dependence on the fossil energy consumption and low preference for renewable energy.

Emissions reduction is achieved by decarbonizing energy system, including the rapid upscaling of low-carbon energy (CCS, renewables and nuclear). Energy intensity improvements have small impact on emissions reduction. Carbon intensity in SSPs decreases continually and presents a large decrease in carbon emissions per unit of energy.

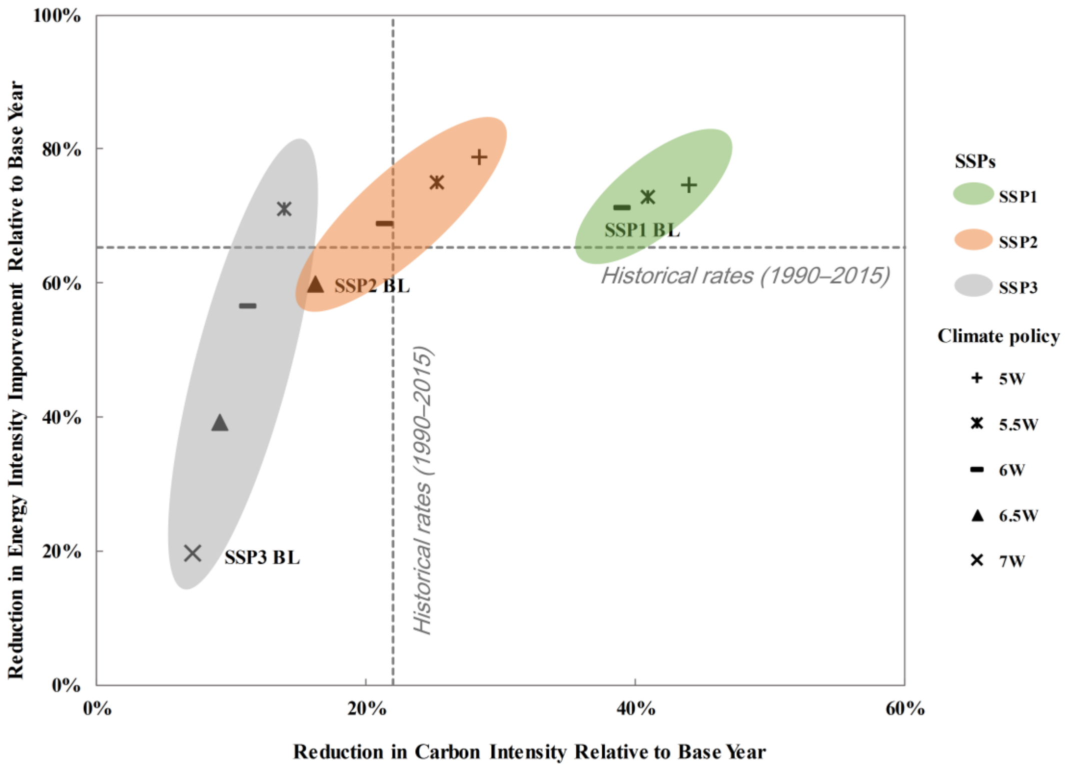

Fig.14. Global energy and carbon intensity reduction rate toward 2100. The dashed lines are extrapolation of historical rates (1990–2015). The text in the plotted area refers to the mitigation case. Carbon intensity is fossil fuel related CO_2 emissions divided by GDP, and energy intensity is total primary energy supply divided by GDP.

3.1.7 Global trade dependency of coal, oil, gas, rice, wheat, and coarse grains

Global trade dependencies of coal, oil, gas, rice, wheat, and coarse grains for BAU cases are shown in Fig.15. The trade dependency is defined as total imports divided by total consumption (the total consumption corresponds to the primary energy supply of energy commodities for coal, oil and gas). Generally, the overall trend of SSP1-3 in the oil, gas and wheat is the same. Nevertheless, for rice, the trend in SSP2 would decline continuously. While in the other two scenarios, it decreases first and then increases. For coarse grain, the trend in SSP1 increases continuously while in the other two scenarios it increases first and then decreases. In all SSPs, the order of trade dependence from high to low is oil, gas, coal, wheat, coarse grain and rice.

Trade dependence is affected by the change of regional compositions and the level of trade dependency in the base year. For instance, if a region has a high level of trade dependency in the base year and decreases its trade share in the global market, the global total dependency would decrease. Coarse grain is a typical example with increasing trade dependency first and then decreasing. Taking China as an example. At present, China's trade dependence on coarse grain is high and its share in the global market is high. While in the SSP2-BL, it assumes that, the growth of population in China is at a slow rate and population would start to decrease in 2040. Therefore, the demand for coarse grain in China would increase first and then decrease. As a result, trade dependence of total coarse grain would increase first and then decrease.

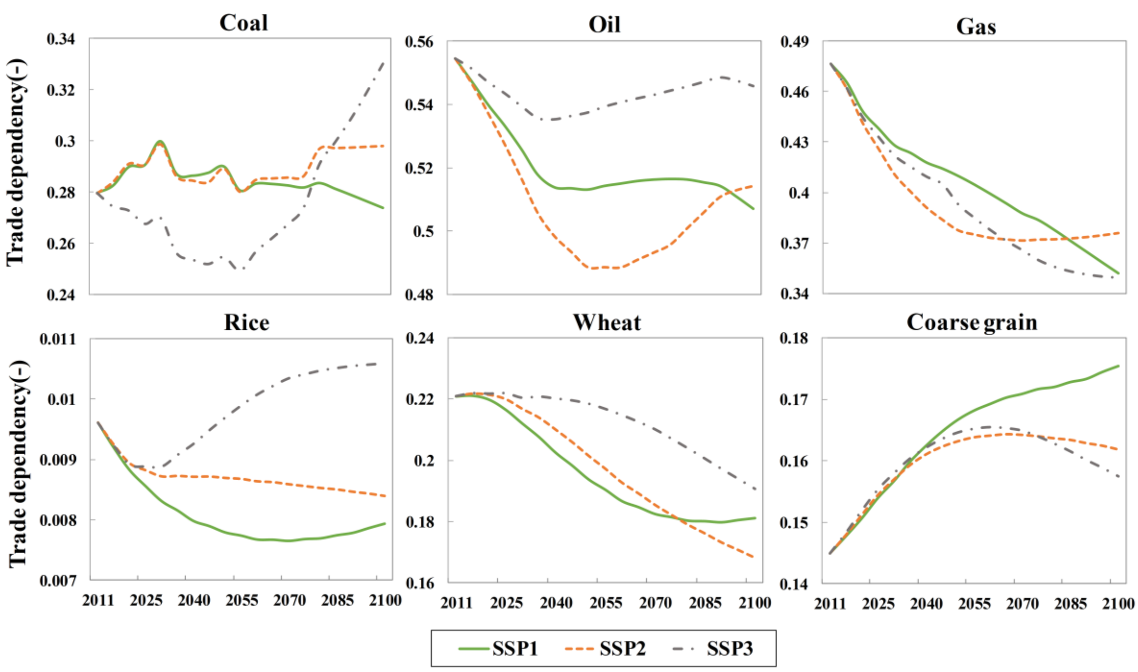

Fig.15. Global trade dependency (oil, gas, coal, rice, wheat, and coarse grains) in SSP1, SSP2, and SSP3. Trade dependency is defined as total imports divided by total consumption.

3.1.8 Mitigation costs and attainability

Mitigation costs can be measured at various level: project, technology, sector or macroeconomic level. In this study, we use the carbon price, GDP loss and consumption loss to measure the climate mitigation costs (see Fig.16). Of which, GDP and consumption loss refer to the percentage changes in mitigation scenarios relative to the BAU scenarios. In SSP3, carbon prices rise gradually over time. SSP2 shows the similar trend, but the magnitude in SSP3 is increasing significantly. As described in narratives, SSP3 has a higher challenge to mitigation than SSP2, which is reflected by carbon price. For example, in SSP3-6.0W, the carbon price is 90 \$/tCO_2eq in 2100, while the carbon price is only 62 \$/tCO_2eq in SSP2-6.0W. Similarly, in SSP3-5.5W and SSP2-5.5W, the carbon price is 211 \$/tCO_2eq and 156 \$/tCO_2eq, as compared to SSP1-5.5W where the carbon price is only 73 \$/tCO_2eq. In addition, under the scenario of SSP2-5.0W, the increase of carbon price is more significant, reaching 260 \$/tCO_2eq, while under SSP1-5.0W the carbon price is around 178 \$/tCO_2eq.

SSP3 has the largest GDP loss in all climate mitigation scenarios in 2100, which is 4.8% and 8.4% for SSP3-6.0W and SSP-5.5W, respectively. The corresponding GDP loss is lower in SSP2, with only 3.2% and 6.0%. Additionally, SSP1 and SSP2 can meet the 5.0W/m^2 mitigation target, whereas SSP3 can only achieve the level of 5.5W/m^2.

Consumption loss shows a similar trend among all the three SSPs. Interestingly, it has smaller rate relative to GDP loss. This is mainly because C^3IAM/GEEPA is investment-driven closure. Moreover, we assume that the total investment is exogenous and is unaffected by climate policies. At the same time, trade effect is considered as well. Total GDP includes consumption, investment and net exports. It means that GDP loss includes consumption loss and net export loss.

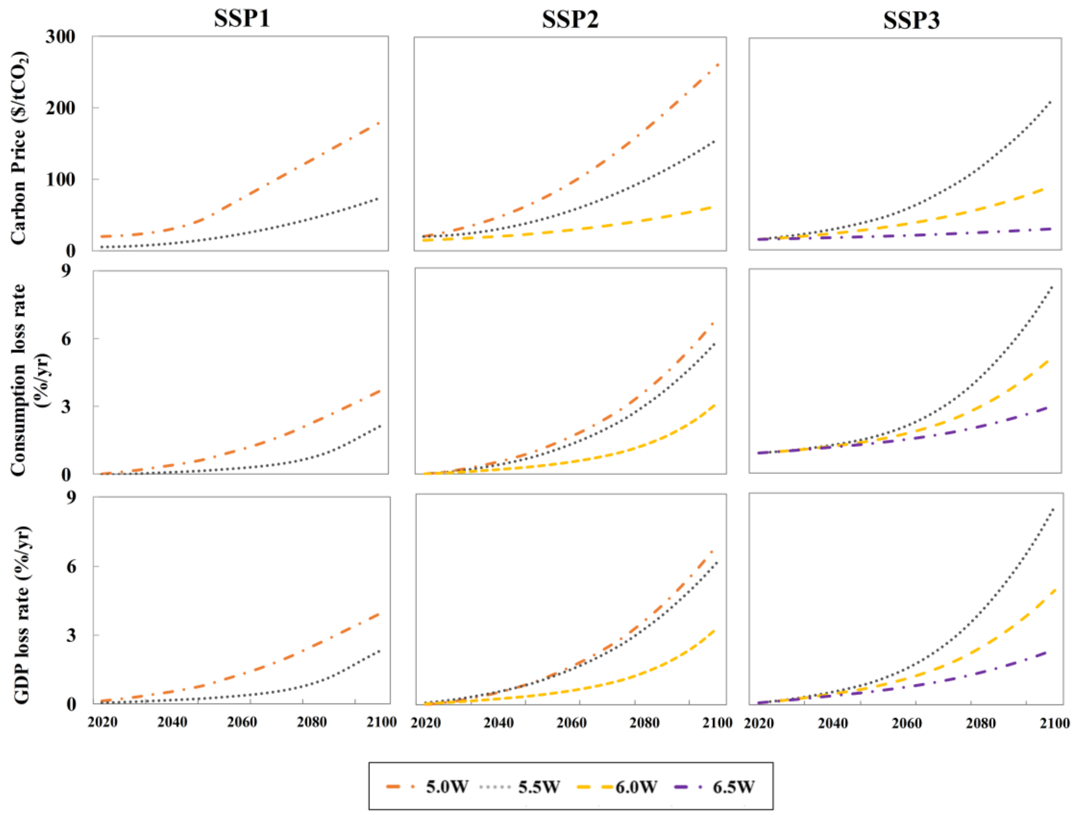

Fig.16. Mitigation costs (carbon price, GDP loss, and consumption loss) related to six mitigation cases for SSP1, SSP2, and SSP3. The macroeconomic losses are represented by the percentage change from the BAU scenarios.

3.2 How will the world's energy, economy and climate systems change under INDCs?

In this section, we explore how the world's energy, economy and climate systems change would be like over the period 2011 to 2100 under SSP1, SSP2 and SSP3 world with the specific consideration of INDCs. The results will be explained from the following aspects: primary energy supply, GHG emissions, temperature change, mitigation cost, and carbon income.

3.2.1 The scale and structure of primary energy supply under INDCs

There is no evident change of total primary energy supply and its structure, which directly leads to the small amount of responding CO_2 emissions change (as shown in Fig.17). In INDCs scenario, the total primary energy supply under SSP2 reaches 1183

EJ/year in 2100, with the same trend of SSP3. On the contrary, SSP1 has a stark difference compared with the other SSPs, reaching 882 EJ/year in 2100. It is noteworthy that, the total energy supply of SSP2 is 171 EJ/year higher than that of SSP3, which is contrary to results without consideration of INDCs. This is mainly because under INDC emission targets, the total amount of renewables in SSP3 is too low compared with SSP2, which directly leads to the anomalism. As shown in the right of Fig.17, in SSP2 and SSP3, the proportions of renewables are about 8% and 2%, respectively. However, the proportions of fossil fuel in SSP2 and SSP3 are 88% and 98%, which are still in consistent with narratives.

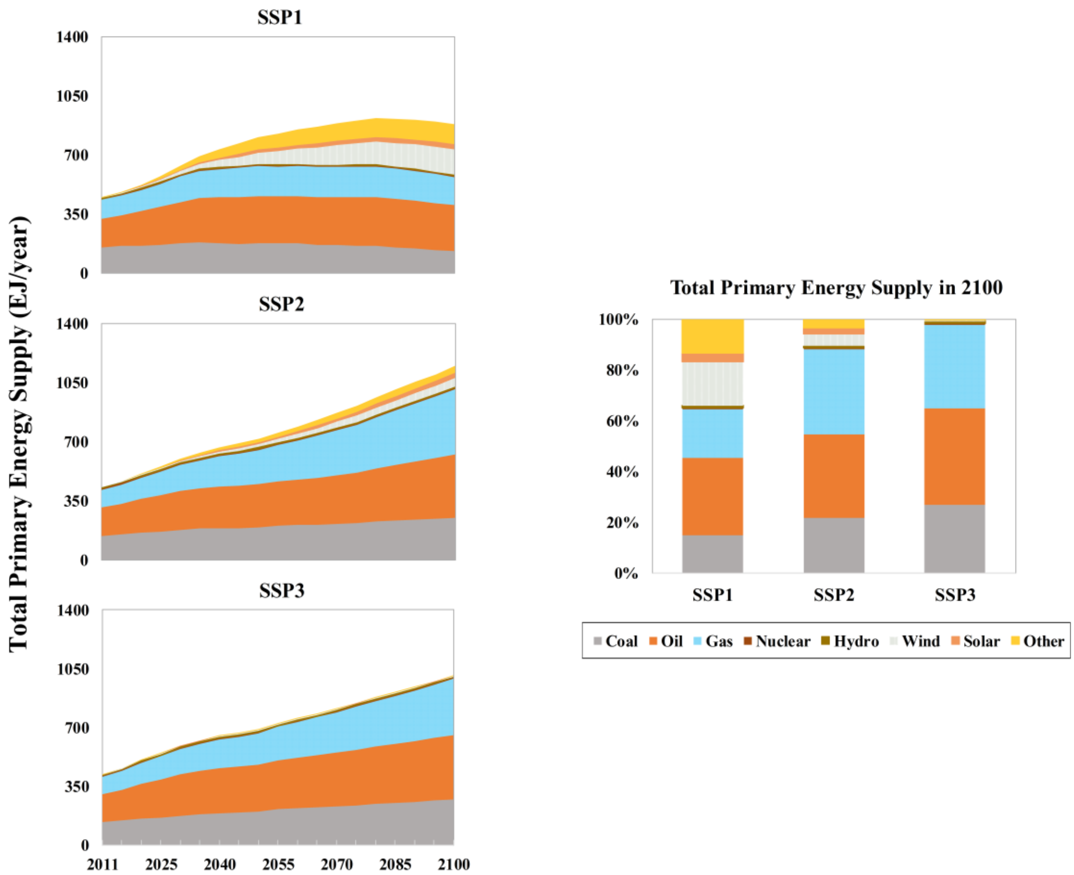

Fig.17. Global primary energy supply toward 2100 under INDCs for SSP1, SSP2 and SSP3.

3.2.2 GHG emissions and temperature variations toward 2100 under INDCs

The changes in GHG emissions described above drive changes in atmospheric CO_2 concentrations, radiative forcing, and temperature in SSP1-3. As discussed in section 3.1.3, GHG emissions without INDCs in 2100 under SSP1-3 are 67, 105, 117 $GtCO_2eq$, respectively. SSP1 would peaks at 70 $GtCO_2eq$ in 2075 while SSP2 and SSP3 keep increasing through the century. Fig.18 presents that GHG emissions under INDCs steadily increase during this century and almost have the same trend with SSPs without INDCs targets. In 2100, GHG emissions under SSP1-3 are 57, 96, 97 $GtCO_2eq$, respectively. This result indicates that, compared with the BAU scenario in SSP1, SSP2 and SSP3, current INDCs put forward by every country in the Paris Agreement, in general, have a very small restriction for their future CO_2 emissions.

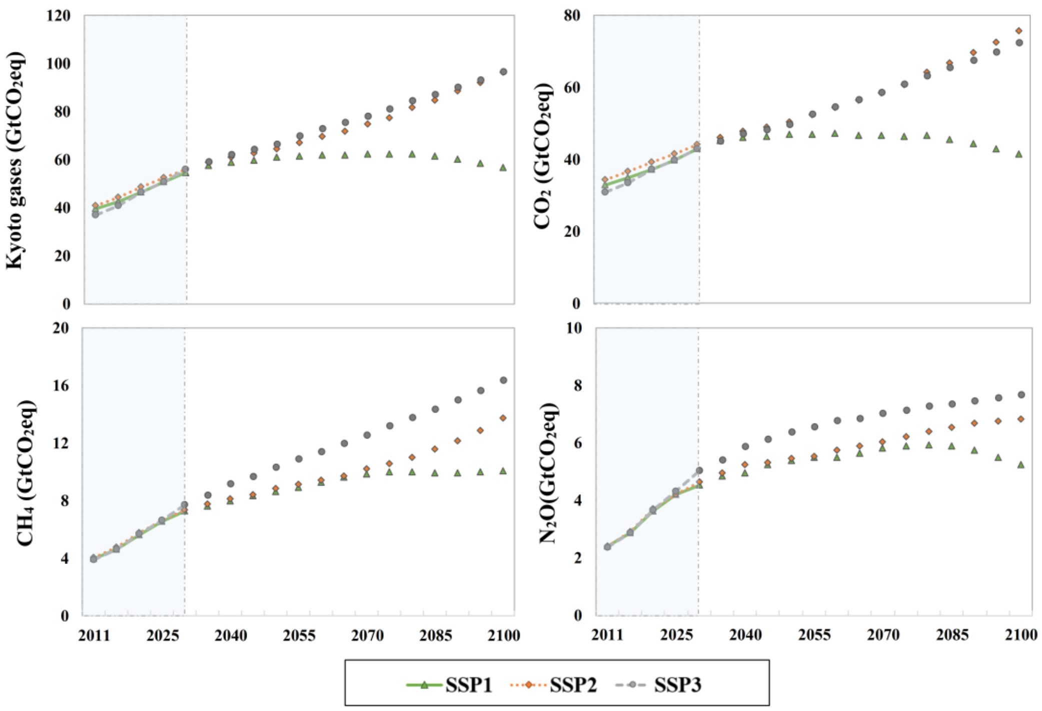

Fig.18. Global GHG (Kyoto gases), CO_2, CH_4, and N_2O emissions under INDCs for SSP1, SSP2, and SSP3.

Fig.19 illustrates the temperature variations from 2000 to 2100. Global mean surface temperature change rises almost linearly throughout the century, reaching 3.20°C, 3.48°C and 3.59°C in SSP1-3, respectively. This result is lower than the temperature rise in the case without the consideration of INDCs, which are 3.21°C under SSP1, 3.54°C under SSP2 and 3.79°C under SSP3. The estimated global mean temperature rise of the BAU scenarios highlights the need for climate change mitigation. Even in SSP1, a world reigned by a green-growth paradigm, temperature further increases by 1.2°C compared with 2°C target. In summary, we find that current INDCs are not in line with the 2°C goal, which indicates increasing effort is still needed if we are to keep open the possibility of limiting the rise in global mean temperature to 2°C.

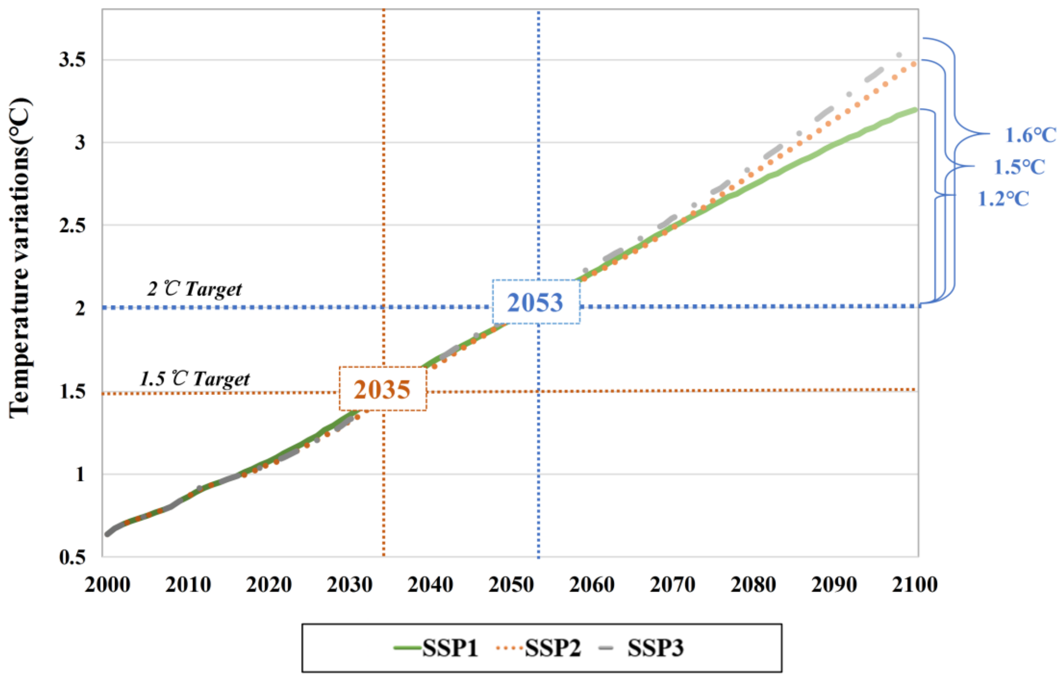

Fig.19. Global temperature variations under INDCs for SSP1, SSP2 and SSP3.

3.2.3 Mitigation costs and attainability

As the climate policies are implemented via a carbon price, the carbon price can be seen as an indication of the effort of reaching the forcing level. In C^3IAM, we assume that carbon tax stay the same after 2030, and carbon prices are 0.2, 5.6, 14.4 \$/tCO_2, respectively. Carbon prices are very low and they have insignificant positive changes in three SSPs (as shown in Fig.20). For example, in SSP1 that has smaller adaption and mitigation challenges, the carbon prices are decreasing with time and are lower than 3.2 $/tCO_2$ toward 2100. However, in SSP3 which has bigger adaptation and mitigation challenges, the carbon prices have an increasing tendency over time, from 9.3 $/tCO_2$ in 2011 to 14.4 $/tCO_2$ in 2030. Carbon prices in SSPs without INDCs, in contrast, are much higher than that in INDCs scenario. Specifically, in SSP2-5.0W, the increment of carbon price is more significant, reaching 260 $/tCO_2eq$, while in SSP1-5.0W the carbon price is around 178 $/tCO_2eq$. The lowest carbon price appears in SSP3-6.5W, which is about 30 $/tCO_2eq$ toward 2100.

As shown in Fig.21, both the global consumption and GDP show a rather small loss in three SSPs. The global GDP loss in SSP1, SSP2 and SSP3 is 0.026%, 0.104%, and 0.286%, respectively. Moreover, the global consumption loss has a lower value, which is 0.021%, 0.065%, and 0.174%, respectively.

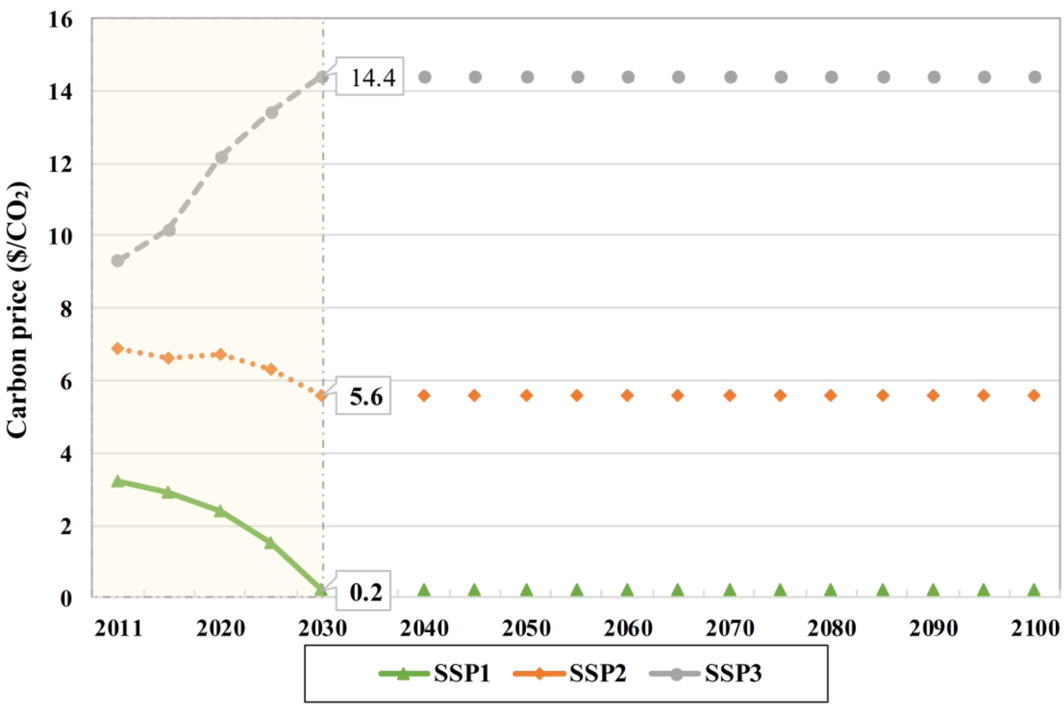

Fig.20. Mitigation costs (carbon price) under INDCs for SSP1, SSP2, and SSP3.

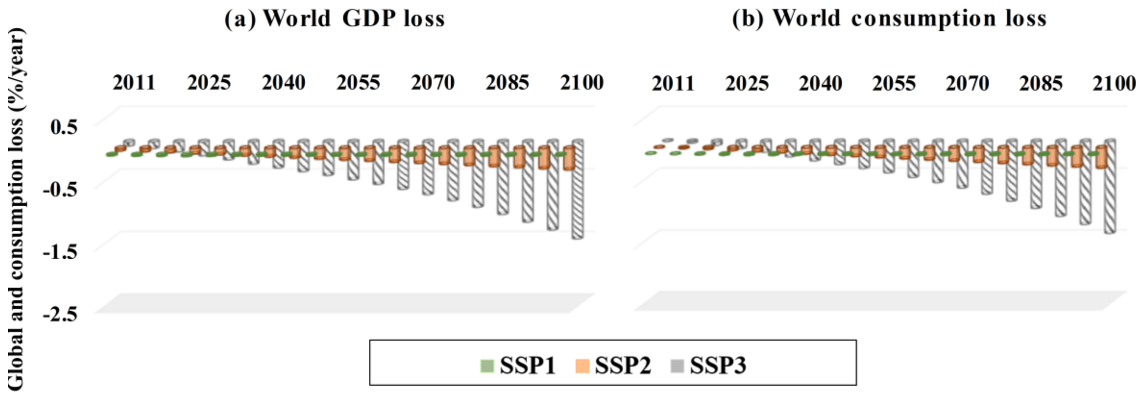

Fig.21. Mitigation costs (GDP and consumption loss) under INDCs for SSP1, SSP2 and SSP3.

3.2.4 Carbon income under free trade of the certificate to achieve INDCs target

In Paris Agreement, a new mechanism named Sustainable Development Mechanism has established to "facilitate the mitigation of greenhouse gases and support sustainable development" (UNFCCC 2015). The new system is considered as the successor of the Clean Development Mechanism in Kyoto Protocol, but available to all parties rather than only Annex-B parties to participate. Under the new structure, we consider the free trade of the certificate to achieve the INDC targets. Fig.22 shows the carbon income under INDCs in all 12 regions. In detail, Japan, Other Branches of Umbrella Group (OBU) and European Union (EU) have set the strictest carbon targets among 12 regions examined by this study; therefore, when applying a unified carbon price around the world, these countries need to buy additional carbon quota in all SSPs in order to achieve the given INDCs target. On the contrary, India, Eastern European CIS excluding Russian Federation (EES), Asia and Middle East and Africa (MAF) these four regions show the least restrictive carbon targets, which is the reason why they can sell additional carbon quota to other regions in all SSPs. As for the remaining regions, the U.S., China and Russia have to purchase carbon quotas from other countries in SSP1 and SSP2 under unified carbon prices all over the world; both Other West European Developed Countries (OWE) and Latin America (LAM) need to purchase carbon quota only in SSP3.

Fig.22. Carbon income under INDCs in 12 regions for SSP1, SSP2 and SSP3.

3.3 Validity of C^{3}IAM

As discussed in section 2.3, there are four key points that should be evaluated in the context of consistency with the narrative that characterizes in the SSP1, SSP2 and SSP3: (1) population and economic developments, (2) mitigation challenge level, (3) regional development, and (4) technological development. This also provides insights for the validity of the developed C^{3}IAM on evaluating the future climate change.

Population and GDP illustrate the first point. As described in narratives, both the population and GDP in SSP2 are designed to situate in the middle of the pathway between SSP1 and SSP3.

Three factors, carbon price, GDP loss and consumption loss, are used to evaluate the second point. They are all higher in SSP3 than that in the other two SSPs no matter with or without INDCs.

For regional development, we apply trade dependency. Trade dependency in SSP3 is relatively small compared with the other two SSPs with or without INDCs, which is consistent with the scenario narratives.

Finally, we use energy and carbon intensity to illustrate the fourth point. As discussed in section 3.1.6, SSP3 has the lowest rate of energy and carbon intensity improvement. Based on the above discussion, all the main points are consistent with SSPs narratives.

4 Conclusions and policy implications

4.1 Conclusions

In this research, C^3IAM is used to establish a consistent framework that includes specific status of the world's energy, economic, land use and climate toward 2100 after applying INDC emission targets. In accordance with the other six IAMs communities, we applied five socioeconomic scenarios (SSP1-SSP5) associated with eight climate mitigation cases (5.0, 5.5, 6.0, 6.5, 7.0, 7.5 8.0 and 8.5 W/m^2). Scenarios matrix architecture is adopted for the quantification process and is applied to three socioeconomic scenarios (SSP1, SSP2 and SSP3). During this process, some major conclusions are drawn as follows.

(1) After considering INDCs, there is no evident change in total primary energy supply and its structure under all SSPs compared with the scenario without INDCs. Moreover, compared with the BAU scenario in SSP1-3, current INDCs put forward by each country in the Paris Agreement, in general, have a very small restriction for their future GHG emissions. In INDCs scenario, SSP2 reaches 1183 EJ/year in 2100, with the same trend of SSP3. On the contrary, SSP1 has a significant difference with the trend under the other SSPs, reaching 882 EJ/year in 2100. GHG emissions under INDCs steadily increase during this century and almost have the same trend with SSPs without INDCs targets. In 2100, GHG emissions of SSP1-3 under INDCs are 57, 96, 97 $GtCO_2eq$, respectively. GHG emissions without INDCs are 67, 105, 117 $GtCO_2eq$, respectively.

(2) A temperature rise occurs in all SSPs with consideration of INDCs, which is 3.20°C in SSP1, 3.48°C in SSP2, and 3.59°C in SSP3. Even in SSP1, a world reigned by a green-growth paradigm, the temperature would further increase by 1.2°C compared with 2°C target. The results indicate that the 2°C target is not achievable. Emissions should be drastically reduced after 2030 to achieve the 2°C target going through INDCs.

(3) From the perspective of quantitative terms, pathways in which SSP1, SSP2 and SSP3 have been unfolded over the period toward 2100. SSP3 is designed with a high level of challenges to mitigation, which is reflected in BAU scenario with a high level of GHG emissions than SSP2. The emission trajectories under different SSPs are observably different. BAU emissions in 2100 under SSP1-SSP3 are 67, 105, 117 $GtCO_2eq$, respectively. Moreover, high mitigation costs are observed in SSP3. In SSP3, carbon prices rise gradually over time. SSP2 shows the similar trend, but the magnitude in SSP3 increases significantly. As described in narratives, SSP3 has a higher challenge to mitigation than SSP2, which is reflected by carbon price. SSP3 has the largest GDP loss in all climate mitigation scenarios in 2100, which is 4.8% and 8.4% for SSP3-6.0W and SSP-5.5W, respectively. The corresponding GDP loss is lower in SSP2, with only 3.2% and 6.0%. Consumption loss shows a similar trend among all the three SSPs. Interestingly, it has smaller rate relative to GDP loss. Technological development is slower in SSP3 than in the other SSPs. In terms of the BAU case, energy and carbon intensity of SSP2 values are most similar to historical trends. On the contrary, SSP3 shows lower reduction rates in both dimensions (7% and 20%), and SSP1 shows higher rates (44% and 75%).

(4) Non-Annex B countries have played a more active role in the climate conference and announced ambitious commitment generally. However, the emission reduction targets of these countries (concentrated in EES, ASIA and MAF), compared with Annex B countries, there are more significant deviation from the emission trajectories under INDC scenario. Based on the results, India, Eastern European CIS excluding Russian Federation (EES), Asia and Middle East and Africa (MAF) these four regions show the least restrictive carbon targets, which is the reason why they can sell

additional carbon quota to other regions in all SSPs. Thus, there is a risk that the INDC targets of these countries could not be completed.

(5) We explore the main indicators of SSPs and confirm that the pictures of SSP1 to SSP3 is consistent with their narratives, which means that C^3IAM is valid in simulating the future climate change.

4.2 Policy implications

Based on the conclusions obtained above, some important policy implications can be drawn as follows.

(1) To make the mitigation policies more effective, decision makers should bring the climate agenda with their development goals and strategies together, at the domestic and international levels. Although climate change is a worldwide process, the climate damages would be undertake by each country. Therefore, the domestic benefit that countries gain when implement mitigation policies should be aware in the process of policymaking.

(2) There is long-term difficulties to keep warming well below 2°C and pursue efforts toward 1.5°C target even under INDCs. To avoid this, more ambitious reduction targets should be suggested when countries revise their INDCs targets after 2020. For example, India, Eastern European CIS excluding Russian Federation (EES), Asia and Middle East and Africa (MAF) these four regions should make more restrictive carbon targets.

(3) Low carbon technology and renewable energy always be treated as a way of actively capturing and removing GHG emissions. Therefore, in order to decrease the dependency on fossil fuel, development of low carbon technology and introduction of renewable energy should be given priority. Since development of these new low carbon technology and renewables are untested and could be controversial, policy makers should pay more attention on public acceptance when making related policies.

(4) Due to the dependency on fossil fuel, it is hard to achieve 2°C target under SSP3 even trying to transform develop road to SSP1. Therefore, a higher carbon price need to be set or low-carbon technologies need to be widely introduced.

5 Future research prospects

Although this study has contributed for answering some questions concerning the integrated assessment of INDCs under SSPs, some issues are still left to be done in the further work. Many studies have shown a significant and synergistic effect between climate policy and non-climate policy. Technical policy plays as a key complement to other mitigation policies. In order to evaluate the emissions reduction potential of different policies based on the industry's production technologies, the bottom-up energy technology selection model developed for China (C^3IAM/NET) will be given primary focus in our future work.

China is the largest emitter of carbon emissions in the world, which would have strong implications for the challenge of limiting temperature changes caused by GHG emissions to less than 2℃ from pre-industrial levels. However, past studies generally remains poorly in a more in-depth depiction of China. In order to reflect the regional and sectoral characteristics of China's energy consumption and emissions pattern, we will integrate C^3IAM/NET with C^3IAM/MR.CEEPA. Although the simulation results of the multiregional CGE model of China is not displayed in this paper, we will enrich and develop this part in future work.

Damage functions play an important role in quantifying, comparing, aggregating and communicating the many different economic risks that society faces from climate change, and serve to explore trade-offs between the welfares costs and benefits of investing in greenhouse-gas mitigation. Based on this motivation, we will enrich the C^3IAM/Loss model from the perspective of climate cumulative effect modeling, climate adaptability evaluation, dynamic vulnerability modelling，nonlinear effect modeling and regional heterogeneity study. Besides，we will try to explore the impact mechanisms related to growth and income level effect based on the perspective of macroeconomic and try our best to compensate some incidental defects. For example， monetize some non-market damage caused by climate change such as biodiversity loss. Above all， we hope to realize more and more accurate long-run projection of climate change impacts through the updated and calibrated global multiregional damage functions.

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Appendix A.

Table A.1 Classification of 175 countries in 12 regions in C^3IAM.

Region	Involved countries
USA	United States of America
CHN	China
JPN	Japan
RUS	Russian Federation
IDN	India
OBU (Other Branches of Umbrella Group)	Canada, Australia, New Zealand
EU (European Union)	Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom, Cyprus, Czech Republic, Estonia, Hungary, Malta, Poland, Slovakia, Slovenia, Bulgaria, Latvia, Lithuania, Romania, Croatia
OWE (Other West European Developed Countries)	Albania, Montenegro, Serbia, The former Yugoslav Republic of Macedonia, Turkey, Bosnia and Herzegovina, Guam, Iceland, Liechtnstein, Norway, Puerto Rico, Switzerland,
EES (Eastern European CIS excluding Russian Federation)	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
ASIA (Asia excluding China, India, Japan)	Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, Fiji, French Polynesia, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia (Fed. States of), Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Timor-Leste, Vanuatu, Viet Nam
MAF (Middle East and Africa)	Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Occupied Palestinian Territory, Oman, Qatar, Rwanda, Réunion, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe

LAM (Latin America)	Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, United States Virgin Islands, Uruguay, Venezuela (Bolivarian Republic of)

Table A.2 Classification of 27 sectors in C^3IAM/GEEPA.

		GEEPA 27 sectors	**GTAP 58 sectors**
			Description in GTAP database 9
1	pdr	pdr	Paddy rice
2	wht	wht	Wheat
3	gro	gro	Cereal grains, not elsewhere classified (n.e.c.)
4	v_f	v_f	Vegetables, fruit, nuts
5	osd	osd	Oil seeds
6	c_b	c_b	Sugar cane, sugar beet
7	pfb	pfb	Plant-based fibers
8	ocr	ocr	Crops n.e.c.
9	ctl	ctl	Cattle, sheep, goats, horses
10	petr	oap	Animal products n.e.c.
11	rmk	rmk	Raw milk
12	wol	wol	Wool, silk-worm cocoons
13	for	frs	Forestry
14	fsh	fsh	Fishing
15	col	Coal	Coal
16	oil	Oil	Oil
17	gas	Gas	Gas
18	omn	OtherMin	Minerals n.e.c.
19	cmt	OtherMnfc	Meat: cattle, sheep, goats, horse
20	omt		Meat products n.e.c.
21	vol		Vegetable oils and fats
22	mil		Dairy products
23	pcr		Processed rice
24	sgr		Sugar
25	ofd		Food products n.e.c.
26	b_t		Beverages and tobacco products
27	tex		Textiles
28	wap		Wearing apparel
29	lea		Leather products
30	lum		Wood products

31	ppp	EintMnfc	Paper products, publishing
32	p_c	Roil	Petroleum, coal products
33	crp		Chemical, rubber, plastic prods
34	nmm		Mineral products n.e.c.
35	i_s	EintMnfc	Ferrous metals
36	nfm		Metals n.e.c.
37	fmp		Metal products
38	mvh		Motor vehicles and parts
39	otn		Transport equipment n.e.c.
40	ele	OtherMnfc	Electronic equipment
41	ome		Machinery and equipment n.e.c.
42	omf		Manufactures n.e.c.
43	ely	Elec	Electricity
44	gdt	FuelGas	Gas manufacture, distribution
45	wtr	Water	Water
46	cns	Cons	Construction
47	trd	OthServices	Trade
48	otp		Transport n.e.c.
49	wtp	TransService	Sea transport
50	atp		Air transport
51	cmn		Communication
52	ofi		Financial services n.e.c.
53	isr		Insurance
54	obs	OthServices	Business services n.e.c.
55	ros		Recreation and other services
56	osg		PubAdmin/Defence/Health/Educat
57	dwe		Dwellings

Table A.3 Regions in C^{3}IAM/MR.CEEPA

No.	Regions	No.	Regions	No.	Regions
1	BeiJing	12	AnHui	23	SiChuan
2	TianJin	13	FuJian	24	GuiZhou
3	HeBei	14	JiangXi	25	YunNan
4	ShanXi	15	ShanDong	26	Tibet
5	Inner Mongolia	16	HeNan	27	ShaanXi
6	LiaoNing	17	HuBei	28	GanSu
7	JiLin	18	HuNan	29	QingHai
8	HeiLongJiang	19	GuangDong	30	NingXia
9	ShangHai	20	GuangXi	31	XinJiang
10	JiangSu	21	HaiNan		
11	ZheJiang	22	ChongQing		

Table A.4 Sectors in C^3IAM/MR.CEEPA

No.	Sectors	Sectoral Description
1	AGRI	Agriculture
2	Coal	Mining and Washing of Coal
3	Oil	Extraction of Petroleum
4	NatGAS	Extraction of Natural Gas
5	OtherMin	Mining of Other Ores
6	FoodTob	Manufacture of Foods and Tobacco
7	Textile	Manufacture of Textile
8	WearApp	Manufacture of Textile, Wearing Apparel and Accessories, Leather, Fur, Feather and Related Products and Footwear
9	WoodProd	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products
10	PaperProd	Manufacture of Paper and Paper Products
11	Petr	Manufacture of refined petroleum products
12	Coking	Manufacture of coke
13	Chemistry	Manufacture of Raw Chemical Materials and Chemical Products
14	NonMetProd	Manufacture of Non-metallic Mineral Products
15	MetalSmelt	Smelting and Pressing of Ferrous Metals and Non-ferrous Metals
16	Metalware	Manufacture of Metal Products
17	Equipment	Manufacture of Machinery
18	ELEC	Production and Supply of Electricity and Heat
19	GasPandS	Production and Supply of Gas
20	WaterProSup	Production and Supply of Water
21	Construction	Construction
22	TraStorPost	Transport Service
23	OtherService	Other Service

Table A.5 Product types in C^3IAM/EcoLa model.

Crop types	Concrete products
Rice	rice
Wheat	wheat
CerealCrop	barley, buckwheat, canary seed, cereals, maize, millet, mixed grain, quinoa, rye, sorghum, triticale
VegCrop	almonds, apples, arecanuts, avocados, bambara beans, bananas, beans, berries, blueberries, brazil nuts, broad beans, horse beans, cabbages and other brassicas, carrots and turnips, cashew nuts, cashewapple, cassava, cauliflowers and broccoli, cherries, chestnuts, chick peas, chicory roots, chillies and peppers, citrus fruit, coconuts, cow peas, cranberries, cucumbers and gherkins, currants, dates, eggplants, figs, tropical fruit, garlic, gooseberries, grapefruit, grapes, hazelnuts, kiwi fruit, leeks, leguminous vegetables, lemons and limes, lentils, lettuce and chicory, lupins, mangoes, mushrooms and truffles, nuts, oats, okra, olives, onions, oranges, other melons, papayas, peaches and nectarines, pears, persimmons, pigeon peas, pineapples, pistachios, plantains, plums and sloes, pome fruit, potatoes, pulses, pumpkins, quinces, raspberries, roots and tubers, spinach, stone fruit, strawberries, string beans, sweet potatoes, tangerines, mandarins, taro, tomatoes, walnuts, watermelons, yams, yautia
OilCrop	castor oil seed, groundnuts, hempseed, jojoba seeds, kapokseed, karate nuts, linseed, melonseed, mustard seed, oilpalm, oilseeds, poppy seed, rapeseed, safflower seed, sesame, soybeans, sunflower, tallowtree Seeds, tung nuts
SugarCrop	sugar beet, sugar beet
FiberCrop	agave, fibrenes, hemp tow waste, jute, manila fibre, other bastfibres, ramie, sisal
OtherCrop	anise, apricots, artichokes, asparagus, carobs, cinnamon, cloves, cocoa, coffee, fonio, ginger, hops, kola nuts, maté, nutmeg, pepper, peppermint, pyrethrum, spices, tea, tobacco, vanilla, vetches
Livestock	cattle, goats, horses, sheep

Table A.6 List of assumptions of scenario parameters.

Element	SSP1	SSP2	SSP3
GDP	Based on Delink et al.(2017)		
Population	Based on Kc and Lutz.(2017)		
Autonomous energy efficiency improvement (AEEI)	High	Med	Low
Coal mining cost	High	Med	Low
Oil and gas extraction cost	High	Med	Low
Renewable energy cost	Low	Med	High
CCS cost	Low	Med	High
Air pollution control level	High	Med	Low
Livestock-oriented food consumption preference	Low	Med	High
Household preference for manufacturing goods	Low	Med	High
Service demand for transport	High	Med	Low
Renewable energy preference	High	Med	Low
Preference for fossil fuel-fired power plants	Low	Med	High
Fossil energy use preference	Low	Med	High
Energy use electricity preference or electrification speed	High	Med	Low

Appendix B. Supplementary Information

B1. Basic assumptions for each sub-module of C[3]IAM/GEEPA are shown as follows:

B.1.1. Production module

This module describes the production relationship among different regions, in which main assumptions include: 1) There are 27 sectors considered in this model and each sector produces one, and only one, distinct commodity; 2) When producing one commodity, labor, capital, energy and other intermediate inputs are all inputs needed; 3) Input in each sector assumes to follow a nested constant elasticity of substitute (CES) function, the basic form of which is shown in Eq. (1):

$$Y_{i,r} = \mathrm{CES}(X_{j,r};\rho) = A_i \cdot (\sum_j \alpha_{j,r} \cdot X_{j,r}{}^{\rho})^{\frac{1}{\rho}} \tag{1}$$

where $Y_{i,r}$ is the i th output in region r, $X_{j,r}$ is the j th input in region r, A_i is the shift parameter, α_j is the share parameter of $X_{j,r}$ in region r, ρ is the substitution parameter among different inputs.

Considering the production characteristics of different sectors, and referring to existing studies about this, this paper divides the sectors into four main sectors: including Generic economic sectors, Agriculture sector, Primary energy sector, Oil refining sector, Gas production and supply, Coking and Electricity sector.

(1) Generic economic sectors

For all sectors other than the ones listed below in (2)-(4), a five-level nested CES function is employed, as shown in Eqs. (2)-(6):

$$Z_{i,r} = \mathrm{CES}(RM_{j,i,\mathrm{r}}, KEL_{i,\mathrm{r}};\rho_{Z,i}) \tag{2}$$

$$KEL_{i,r} = \mathrm{CES}(KE_{i,r}, L_{i,r};\rho_{KEL,i}) \tag{3}$$

$$KE_{i,r} = \mathrm{CES}(K_{i,r}, Energy_{i,r};\rho_{KE,i}) \tag{4}$$

$$Energy_{i,r} = \text{CES}(Fossil_{i,r}, Electricity_{i,r}; \rho_{Energy,i}) \quad (5).$$

$$Fossil_{i,r} = \text{CES}(FoF_{fe,i,r}; \rho_{FoF,fe,i}) \quad (6).$$

In generic economic sectors, the process of production is followed by a five-level nested CES function.

At the top level, the total output is composed of different intermediate inputs and capital–energy–labor composition in (2), where $Z_{i,r}$ is the total output of sector i in region r, $RM_{j,i,r}$ is the intermediate input of commodity j in sector i in region r, $KEL_{i,r}$ is the composite capital-energy-labor input in sector i in region r.

At the second level, labor and capital-energy (E) constitute capital–energy–labor composition in (3), where $KE_{i,r}$ is the composite capital-energy input of sector i in region r, $L_{i,r}$ is the labor input of sector i in region r.

At the third level, capital–energy composition is constitutive of capital and energy composition shown in (4), where $K_{i,r}$ is the capital input of sector i in region r, $Energy_{i,r}$ the composite energy input of sector i in region r.

At the fourth level, the energy composition is constitutive of electricity input and fossil fuel composition and at the lowest level, fossil fuel composition is divided by the input of fossil fuel, which are shown in Eqs.(5)-(6). In (5)-(6), $Fossil_{i,r}$ is the composite fossil fuel input of sector i in region r, $Electricity_{i,r}$ is the electricity input of sector i in region r, $FoF_{fe,i,r}$ is the input of fossil fuel fe of sector i in region r.Among them, $\rho_{Z,i}$, $\rho_{KEL,i}$, $\rho_{KE,i}$, $\rho_{Energy,i}$ and $\rho_{FoF,fe,i}$ all represent the substitution parameters for different levels respectively.

(2) Agriculture sector, Primary energy sector

Besides the generic economic sectors, agriculture production and primary energy productions are both need land as the resource input. Therefore these two types of sectors follow a six-level nested CES function which is added the resource input at the first-level. The functions for the top two levels are shown in Eqs. (7) and (8) respectively.

$$Z_{i,r} = \text{CES}(R_{j,i,r}, KELM_{i,r}; \rho_{Z,i}) \quad (7).$$

$$KELM_{i,r} = \mathrm{CES}(KEL_{i,r}, RM_{j,i,r}; \rho_{KELM,i}) \quad (8).$$

where $R_{j,\mathrm{i},\mathrm{r}}$ is the resource input of sector i in region r, $KELM_{j,i,r}$ is the composite capital-energy-labor-material input in sector i in region r, $\rho_{KELM,i,r}$ is the substitution parameter of sector i between the composite capital-energy-labor input and various raw materials in region r.

Production functions for the other levels of these two types of sectors are the same with generic economic sectors.

(3) Oil refining sector, Gas production and supply, Coking

In particular, crude oil, natural gas and coal are all taken out from the fossil fuel composition and placed in the top level, because they are all the most important raw material in the production.

(4) Electricity sector

Here it is assumed that the output of electricity sector is a Leontief function composed of generation and transmission & distribution services. Electricity generation includes stable power supplies and intermittent power supplies. Stable power supplies include conventional fossil, nuclear, hydro and advanced generation technologies (eg. CCS technology) which are modeled as a homogeneous commodity. While intermittent power supplies include wind, solar power and other generation technology, which rely on special resource, fixed factor and value-added & intermediates.

B.1.2. Income and expenditure module

B.1.2.1. Household

In this module, household income mainly comes from labor income and capital returns. We assume that households receive various transfers from government and overseas as their disposable income, after paying household income tax and spend disposable income on saving and on the consumption of various goods. Household saving is obtained by multiplying household disposable income with saving rate, and which is described with an extended linear expenditure system (ELES) function household consumption is described as Eq. (9):

$$CDh_{i,h,r} = \frac{cles_{i,h,r} \cdot (1 - mps_{h,r}) \cdot YD_{h,r}}{PQ_{i,r}} \quad (9).$$

where $CDh_{i,h,r}$ and $cles_{i,h,r}$ respectively represents the consumption volume and consumption share of commodity i by household h in region r; $PQ_{i,r}$ is the composite price of commodity i (imports and domestic products) in region r; $YD_{h,r}$ and $mps_{h,r}$ respectively represents the disposable income and the saving rate of household h in region r.

B.1.2.2. Government

In this module, it assumes that government income is composed of tariff, indirect tax, household income tax and transfers from other countries/regions. Government spends its income on government consumption, transfers to households, and export rebate. In a given period, government saving is calculated by the difference between government income and expenditure.

B.1.3. Foreign trade module

Taking foreign trade into account, when ignoring the cost of transportation, the value of commodity i between from region s to region r and from region r to region s is homogeneous. C[3]IAM/GEEPA adopts Armington assumption, which assuming there is imperfect substitutability between imports and domestic output sold domestically. The commodity that supplied domestically is composed of domestic and imported commodities following a CES function. Furthermore, domestic commodity is used to meet domestic demands and for exports. In C[3]IAM/GEEPA, we uses a constant elasticity transformation (CET) function to allocate total domestic output between exports and domestic sales, shown in Eqs. (10) and (11).

$$X_{i,r} = A_{Ex,i,r} \cdot [\alpha_{Ex,i,r} \cdot E_i^{\rho_{Ex,i,r}} + (1 - \alpha_{Ex,i,r}) \cdot D_i^{\rho_{Ex,i,r}}]^{\frac{1}{\rho_{Ex,i,r}}} \quad (10).$$

$$\frac{E_{i,t,r}}{D_{i,t,r}} = \left[\frac{1 - \alpha_{EX,i,r}}{\alpha_{EX,i,r}} \cdot \frac{PE_{i,t,r}}{PD_{i,t,r}} \right]^{\sigma_{Ex,i}} \quad (11).$$

where $E_{i,r}$ and $D_{i,r}$ respectively represent exports and domestic sales of domestically produced good i in region r; $PE_{i,r}$ and $PD_{i,r}$ respectively represent export price and domestic sale price of domestically produced good i in region r; $A_{Ex,i}$ and $\alpha_{Ex,i}$ respectively represent the shift parameter and share parameter in transformation function; $\rho_{Ex,i}$ and $\sigma_{Ex,i}$ respectively represent the substitution parameter and substitution elasticity in CET function between export and domestic sales.

B.1.4. Investment module

Total investment is divided by inventory change and fixed capital investment. Inventory change in each sector is associated with a fixed ratio of the output in the sector respectively and fixed capital investment allocates among sectors according to fixed ratios. Key equations on describing investment module are as follows:

$$TotINV_r = HSav_r + GSav_r + ESav_r + FSav_r \cdot ER_r \tag{12}$$

$$FxdINV_r = TotINV_r - \sum_i DST_{i,r} \cdot P_{i,r} \tag{13}$$

$$DST_{i,r} = \vartheta_{i,r} \cdot Z_{i,r} \tag{14}$$

$$Dk_{i,r} \cdot PK_{i,r} = FxdINV_r \cdot \mu_{i,r} \tag{15}$$

where $TotINV_r$ represents total investment in region r; $HSav_r$, $GSav_r$, $ESav_r$ represents household and government saving in region r, respectively; $Fsav_r$ is foreign saving in foreign currency in region r; ER_r is exchange rate in region r; $FxdINV_r$ represents total fixed capital investment in region r; $DST_{i,r}$ represents inventory change in sector i in region r; $PK_{i,r}$ is the price of fixed capital input in sector i in region r; $P_{i,r}$ is the composite price of commodity i (imports and domestic products); $\vartheta_{i,r}$ is the share of inventory change to total output in sector in region r; $\mu_{i,r}$ is the share of sector i obtained in total fixed capital investment, which equals the share of sector i in region r in base year capital income (depreciation of capital plus earning surplus).

References

Adoption of the Paris Agreement Conference of the Parties, Twenty-first session FCCC/CP/2015/L.9 (United Nations Framework Convention on Climate Change, 2015); https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf.

Alcamo J, Koch J, Lapola DM (2011) An integrated approach to modelling land-use change on continental and global scales. Environmental Modelling & Software 26(8):1041-1051

Aldy J, Pizer W, Tavoni M (2016) Economic tools to promote transparency and comparability in the Paris Agreement. Nature Climate Change 6(11):1000-1004

Avetisyan M, Baldos U, Hertel T (2011) Development of the GTAP version 7 land use data base. GTAP Research Memorandum

Calvin K, Bond-Lamber B, Clarke L et al (2017) SSP4: A world of deepening inequality. Global Environ. Change 42:284-296

Damassa T (2015) Interpreting INDCs: Assessing Transparency of Post-2020 Greenhouse Gas Emissions Targets of 8 Top-Emitting Economics. World Resources Institute

Dellink R, Chateau J, Lanzi E, Magne B (2017) Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environ. Change 42:200-214

Emmerling J, Drouet L, Reis LA et al (2016) The WITCH 2016 Model-Documentation and Implementation of the Shared Socioeconomic Pathways.

Ewert F, Rounsevell MD, Reginster I, Metzger MJ, Leemans R (2005) Future scenarios of european agricultural land use. Agriculture Ecosystems & Environment 107(2): 101-116

Fawcett AA, Iyer GC, Clarke LE (2015) Can Paris pledges avert severe climate change? Science 350(6265):1168

Food, Agriculture Organization of the United Nations (2017) In: FAO (Ed.), FAOSTAT. Food and Agriculture Organization of the United Nations. Rome, Italy

Fricko O, Havlik P, Rogelj J et al (2017) The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environ. Change 42: 251-267

Fujimori S, Hasegawa T, Masui T et al (2017) SSP3: Aim implementation of shared socioeconomic pathways. Global Environ. Change 42: 268-283

Havlík P, Valin H, Herrero M (2014) Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences of the United States of America 111(10): 3709-14

Houghton RA (1999) The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. Tellus 51B: 298-313

IEA (International Energy Agency) (2015) World Energy Outlook. OECD/IEA. Paris

IIASA (2011) GAINS-Greenhouse Gas and Air Pollution Interactions and Synergies-Emissions dataset

IPCC (2014) Climate Change 2014: Synthesis report. Fifth assessment report of the intergovernmental panel on climate change. Tech. Rep.

Iyer GC, Edmonds JA, Fawcett AA (2015) The contribution of Paris to limit global warming to 2 °C. Environmental Research Letters 10(12):125002

KC S, Lutz W (2017) The human core of the Shared Socioeconomic Pathways: population scenarios by age, sex and level of education for all countries to 2100. Global Environ. Change 42:181-192

Kriegler E, O'Neill BC, Hallegatte S et al (2012) The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Global Environ. Change 22(4): 807-822

Kriegler E, Bauer N, Popp A et al (2017) Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Global Environ. Change 42:297-315

Kyle GP, Luckow P, Calvin K (2011) GCAM 3.0 agriculture and land use: data sources and methods. Office of Scientific & Technical Information Technical Reports

Magnan AK, Rodríguez T (2017) Global adaptation after Paris. Science 352(6291):1280-1282

Moss RH, Edmonds JA, Hibbard KA et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747-56

Nakicenovic N, Swart R (2000) Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

O'Neill BC, Kriegler E, Riahi K (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122(3): 387-400

O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, Levy M (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change 42:169-180

Popp A, Humpenöder, F, Weindl I., Bodirsky B L, Bonsch M, Lotzecampen H (2014) Land-use protection for climate change mitigation. Nature Climate Change 4(12): 1095–1098

Riahi K, van Vuuren DP, Kriegler E et al (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environ. Change 42:153-168

Rogelj J, Elzen MD, Höhne N (2016) Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534(7609):631

Rose SK, Richels R, Blanford G (2017) The Paris Agreement and next steps in limiting global warming. Climatic Change 142(1-2):255-270

UNFCCC (2015) Adoption of the Paris Agreement. I: Proposal by the President (Draft Decision), United Nations Office, Geneva (Switzerland) (s 32)

Schmitz C, Biewald A, Lotze-Campen H (2012) Trading more food: implications for land use, greenhouse gas emissions and the food system. Global Environmental Change 22(1): 189-209

Schmitz C (2013) The future of food supply in a constraining environment. Journal of the Royal Statistical Society 175(5): 799-811

Schwanitz VJ (2013) Evaluating integrated assessment models of global climate change. Environ. Model. Softw. 50:120-131

Sohngen B, Tennity C, Hnytka M (2008) Global forestry data for the economic modeling of land use. Gtap Working Papers

Souty F, Brunelle T, Dumas P (2012) The Nexus Land-Use model version 1.0, an approach articulating biophysical potentials and economic dynamics to model competition for land-use. Geoscientific Model Development 5:1298-1322

Tol RSJ (2013) Targets for global climate policy: An overview. J. Econ. Dyn. Control 37:911-928

van Vuuren DP, Carter TR (2014) Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old. Climatic Change 122(3):415-429

van Vuuren DP, Stehfest E, Gernaat DE et al (2017) Energy, Land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ. Change 42:237-250

Wei YM, Wang L, Liao H, Wang K, Murty T, Yan JY (2014) Responsibility accounting in carbon allocation: A global perspective. Applied Energy 130:122-133

Wei YM, Zou LL, Wang K, Yi WJ, Wang L (2013) Review of proposals for an Agreement on Future Climate Policy: Perspectives from the responsibilities for GHG reduction. Energy Strategy Reviews 2:161-168

Wei YM, Mi ZF, Huang ZM (2015) Climate policy modeling: An online SCI-E and SSCI based literature review. Omega 57:70-84

Wirsenius S, Azar C, Berndes G (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems 103(9):621-638

Wu TW, Li WP, Ji JJ et al (2013) Global carbon budgets simulated by the Beijing climate center climate system model for the last century. J. Geophys. Res. Atmos. 118:4326-4347

Wu TW, Song LC, Li WP et al (2014) An overview of BCC climate system model development and application for climate change studies. Journal of Meteorological Research 28(1): 34-56