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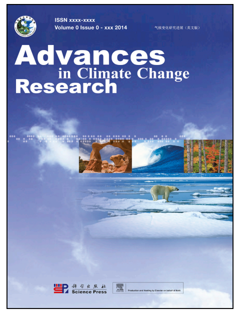

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Global climate damage in 2°C and 1.5°C scenarios based on BCC_SESM model in IAM framework

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Abstract

The quantitative functions for climate damages provide theoretical ground for the cost-benefit analysis in climate change economics, and they are also critical for linking climate module with economic module in the Integrated Assessment Models (IAMs). Nevertheless, it is necessary for IAMs to update sectoral climate impacts in order to catch up the advance in climate change studies. This study updates the sectoral climate damage function at global scale from climate Framework for Uncertainty, Negotiation and Distribution (FUND) model and develops the aggregate climate damage function in a bottom-up fashion. Besides conventional sectors such as agriculture, forestry, water resources, energy consumption and ecosystems, this study expands climate disaster types, assesses human health impacts caused by various air pollutants, and updates coastal damage by sea level rise. The Beijing Climate Center Simple Earth System Model (BCC_SESM) is used to project climate system based on Business-as-Usual (BAU) scenario, and the 2 °C and 1.5 °C scenarios based on RCPs and SSP2 databases. Sectoral results show that the agricultural sector is projected to suffer 63% of the total damage, followed by water resources (16%) and human health (12%) sectors in 2100. The regression results indicate that the aggregate climate damage function is in positive quadratic form. Under BAU scenario, the aggregate climate damage is projected to be 517.7 trillion USD during 2011–2100. Compared to that, the 2°C and 1.5°C scenarios are projected to respectively reduce climate damages by 215.6 trillion USD (approximately 41.6%) and 263.5 trillion USD (50.9%) in 2011–2100.

Keywords: Climate change; Climate impact; Climate damage function; Integrated Assessment Model (IAM); Earth System Model (ESM)

1. Introduction

Climate change has significant impacts on natural and human systems leading to severe economic losses (IPCC, 2012). Future climate is predicted to present intensified changes in climate extremes by the end of the 21st century (Zhou et al., 2014). Based on incomplete estimates, a 2 °C rise in global temperatures may directly result in a 0.2%–2% decline in gross world product (GWP) (IPCC, 2014), with total losses ranging from 1%–5% of GWP at 4 °C temperature rise under the baseline scenario (IPCC, 2007; Nordhaus and Sztorc, 2013). The climate damage function is useful for assessing various direct or indirect damages and systematic impacts caused by climate change, which describes the relationship between economic losses and various climate indicators, such as atmospheric temperatures, sea levels and climate extremes (Nordhaus, 2014).

The climate damage function is critical in Integrated Assessment Models (IAMs) which links climate modules and economic modules, and the IAMs community has already developed many methods for assessing the sectorial, regional and aggregate climate damages (Nordhaus, 2014). Among the various IAMs, the Regional Integrated model of Climate and the Economy (RICE)/Dynamic Integrated model of Climate and the Economy (DICE), Policy Analysis of the Greenhouse Effect (PAGE) and Climate Framework for Uncertainty, Negotiation and Distribution (FUND) are commonly used. These standard IAMs share a basic structure, however, they cover different sectors and use different climate damage functions. The DICE model is a simplified analytical and empirical model that describes the economics, policy, and scientific aspects of climate change, while RICE is a more detailed version that focuses on regional impacts. Sectors and fields include agriculture, other vulnerable markets, coastal sectors, health, non-market amenities, settlements (both human settlements and ecosystems) and catastrophic events, which usually express as functions of temperature increase. The total economic impacts of climate change are a quadratic function of temperature rise (Nordhaus, 2014), but this damage function dismisses several important factors (losses from biodiversity, sea level rise, catastrophic events, etc.) and uncertainty (Nordhaus and Sztorc, 2013). The PAGE model includes four impact categories: market sectors (agriculture, forestry, tourism, etc.), non-market sectors (e.g. mortality and ecosystem damages), sea level rise (i.e. coastal flooding), and stochastic discontinuity (Hope, 2012; Moore et al., 2018). Climate damages assessed by the PAGE model are proportional to the 1st–3rd power of temperature rise (Hope, 2006; Stern, 2007). The FUND model covers a more comprehensive range of sectors likely to be impacted by climate change, including agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, human health (diarrhea, vector-borne diseases, cardiovascular and respiratory mortality), and extreme weather (tropical storms and extratropical storms). Damages in each sector are calculated with specific functions, and parameters for these functions vary in 16 geographic regions in the world (Anthoff and Tol, 2010, 2013). There is not a simplified aggregate damage function of all sectors for the FUND model, but previous studies have provided detailed calculations of climate impacts on each sector (Tol, 2002b). Other IAMs like the Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE) and the Multi-Regional Integrated Model of Climate and Economy with GDP Spillovers (MERICES) also use a quadratic function of temperature rise to calculate climate damages. Very few studies (i.e. CETA-M, Carbon Emissions Trajectory Assessment) build a function between climate impacts and temperature increase rate.

Sectoral climate damage functions in FUND are referred to in this study due to their accessibility and integrity, but they need to be updated or expanded. The impact evaluation of extreme events currently focuses on the economic damages and mortality due to an increase of the frequency and intensity of tropical storms (Narita et al., 2009a) and extratropical storms (Narita et al., 2009b). However, other disasters, such as floods, extreme temperatures, droughts, landslides and wildfires, also make profound impacts on the total climate disaster damage (CRED, 2015). Air-pollution-related health impacts, neglected in FUND, are also influenced by climate change, which can decrease the boundary layer height (Hong et al., 2019) and increase the concentration of air pollutants. Higher temperatures, along with greater ultraviolet (UV) radiation, enhance photochemical reactions and increase the concentration of ground level ozone (Bell et al., 2007). Exposure to ozone influences asthma and lung diseases. Change in humidity, precipitations and biogenic emissions due to climate change can also influence the formation and growth of fine-particulate matter ($PM_{2.5}$), which may lead to cardiopulmonary diseases (Giorgini et al., 2017). The relationship between climate change, air pollution and human health is still a hot topic and remains largely uncertain.

The FUND model lacks an aggregate damage function, which makes it difficult to compare economic impacts across different climate change scenarios or to compare results from different IAMs. Moreover, most studies in China dealing with this subject focus on the sectoral or local damages caused by one single climate disaster (Zhang et al., 2018). Very few assess aggregate climate damages at the global level. If an aggregate climate damage function can be developed, it is not only a meaningful supplement for FUND model, but is also useful for IAM modeling and policy simulation in China. Meanwhile, the monetized value of climate impacts are very sensitive to different discount rates due to the long-term estimation (Liu, 2012). However, few literatures studied the impacts of discounting on the monetized value of climate impacts in various climate scenarios (Nordhaus and Sztorc, 2013).

Studies on global climate damages, especially in the IAM community, are all based on foreign climate system models, while none of them are based on Chinese climate system models (Deng and Dan, 2018; Duan et al., 2014; Wei et al., 2013; Zhang et al., 2018). The climate system model provides the climate variables as the input of climate damage functions. Popular climate models such as the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) (Wigley, 2008) and traditional Climate System Model (CSM) are either 'black boxes' or too complex for IAMs. The Beijing Climate Center Simple Earth System Model (BCC_SESM) is an simplified model based on the Beijing Climate Center

Climate System Model (BCC_CSM1.1) (Wu et al., 2013) and it is designed and coupled in the IAM model called C^3IAM (China's Climate Change Integrated Assessment Model) (Wei et al., 2018). BCC_SESM has the advantages of being parsimonious, transparent and robust in climate prediction (Liu et al., 2019). This BCC_SESM model can be used to project the future climate system and provide predicted results of various climate variables for the calculation of climate damages. The development and validation of the BCC_SESM model has been discussed in Liu et al., 2019. Regarding the data, previous studies are based on old dataset such as IS92 or SRES scenarios for key input variables such as the economy and population growth, rather than the latest IPCC RCPs and SSPs database, causing difficulties in inter-comparison for climate damage results from different models (Nordhaus and Sztorc, 2013; Tol, 2014b).

This study aims to assess various sectoral climate damages and develop a global aggregate climate damage function that is in line with the latest climate scenarios and databases, which can be applied in the IAM community for cost-benefit analysis of climate change. The difficulty in developing global aggregate and sectoral climate damage functions lies in integrating various modules, scenarios and data in a transparent and consistent fashion. In this study, global sectoral and aggregate climate damages are estimated based on the FUND model, including impacts from climate extremes and air-pollution-related health impacts. Data on climate variables are from the BCC_SESM model. The energy and climate scenarios are based on the Global Energy Interconnection (GEI) 2 °C and 1.5 °C scenarios (hereinafter referred as 2 °C and 1.5 °C scenarios), which emphasize clean energy transition to achieve the temperature targets in the Paris Agreement (specified in Section 2.1). The impacts of discounting on the climate damages are also investigated.

2. Methodology and data

2.1 Models, scenarios, and data

Sectoral and aggregate climate damages are calculated based on four modules, including climate, energy, emission, and socio-economy. Carbon emission pathways are from the Model for Energy Supply Strategy Alternatives and their General Environmental Impact-GLObal

BIOsphere Model (MESSAGEix-GLOBIOM) (Fig. A1), which are the input for the climate module (Fig. A2a). The climate module BCC_SESM provides climate-related data (e.g. temperature rise, GHGs concentrations) that based on the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) which are in line with the Coupled Model Intercomparison Project 5 (CMIP5) (Liu et al., 2019). The BCC_SESM is a simple earth system model at the global level developed based on the BCC_CSM1.1 as the precursor complex climate model and using the climate module setting in DICE model as the prototype (Nordhaus and Sztorc, 2013), in order to establish the relationship among emissions, carbon cycle, radiative forcing and temperature. More information on BCC_SESM can be found in the Appendix A. Fig. A2b–g illustrates these variables, such as the carbon cycle in the atmosphere, ocean and land, changes in radiative forcing, and changes in atmospheric/ocean temperatures. The energy and emission scenarios are results from the MESSAGEix-GLOBIOM IAM model (McCollum et al., 2018). Socio-economic data, such as population statistics and GDP figures are obtained from the various SSPs (Fricko et al., 2016), which are exogenous to MESSAGEix-GLOBIOM. Sectoral climate damages are assessed using data from these four modules, which are further aggregated and fitted into the aggregate climate function.

Three energy and emission scenarios are set: the Business-as-Usual (BAU), 2 °C and 1.5 °C scenarios. The 2 °C and 1.5 °C scenarios are based on the Global Energy Interconnection (GEI) roadmap (Liu, 2015). With clean energy production, large-scale allocation of clean power, and high electrification rate, GEI provides a feasible way to achieve the 2°C or even 1.5°C target outlined in the Paris Agreement (Hou et al., 2020). Energy and emissions data are from the 1.5°C and 2°Cscenarios (Hou et al., 2020; Tan et al., 2019; Zhang et al., 2020; Zhou et al., 2018) and the BAU scenario is based on the national polices (NPi_V4) developed by International Institute for Applied Systems Analysis (IIASA) (McCollum et al., 2018), which are in line with RCP1.9, RCP2.6 and RCP8.5 scenarios respectively. Modelling processes and input-output data are illustrated in Fig. 1.

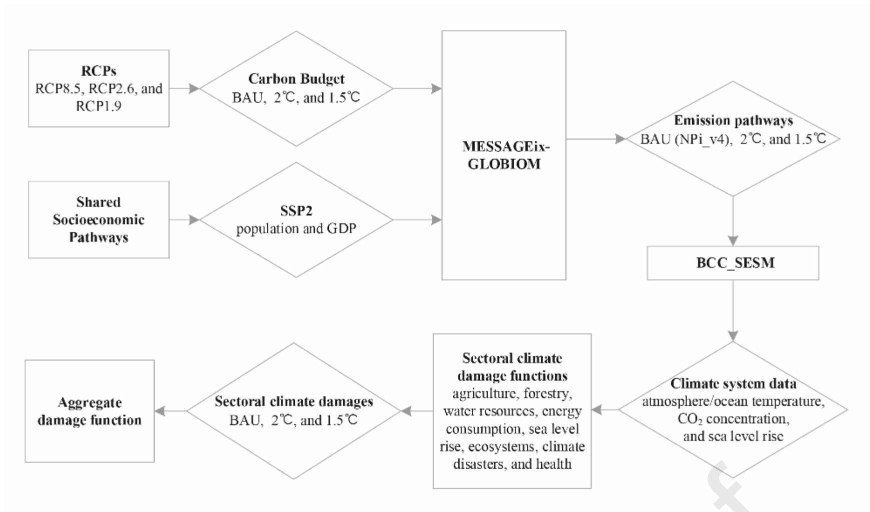

Fig.1 Modelling processes (indicate in the rectangles) and input-output data (indicated in the diamonds).

2.2 Calculation of sectoral and aggregate climate damages

Besides conventional sectors, an aggregate damage function was developed. Firstly, the human health losses caused by climate change is considered. Apart from diarrhea, vector-borne diseases and cardiovascular and respiratory diseases, human health losses from air pollution ($PM_{2.5}$ and ozone) are considered in climate damage functions. Secondly, with regard to the climate disaster, we include not only the tropical and extratropical storms as considered in the FUND model but also other climate disasters, including earthquake, flood, extreme temperature, drought, mass movement, volcanoes, and wildfires. Thirdly, with regard to the coastal sector, we add the impact of seal level rise on dry land and wet land areas. Since the scope for the three above sectors have been expanded, we have adjusted the relevant parameters and re-calibrated their formulae. In other sectors such as the agriculture, forestry, water resources, energy consumption, ecosystems sector, we apply the established sectoral formulas (Tol and Anthoff, 2014b) to calculate sectoral impacts in different scenarios. The calculation to methodology is in Appendix A, the sectoral damage functions and parameters are based on calibration of historical and predicted future results, which are obtained from Tol and Anthoff (2014a) as shown in Table A1.

Three steps are taken to develop sectoral and aggregate climate damage functions. The first step is to quantify the impacts for each sector using climate variables, such as the temperature, CO_2 concentration, sea level rise, and temperature of the hottest month. Then impacts in each sector need to be monetized and added up to obtain aggregate damages. Finally, the aggregate damage function is obtained through econometric regression methods.

Agriculture. The impacts of climate change on the agriculture are connected with the rate and level of climate change, and the effects of CO_2 fertilization (Tol and Anthoff, 2014b). The parameters were calibrated using the procedure described in Tol (2002a) consistent with other literature (Fischer et al., 1996; Kane et al., 1992; Morita et al., 1994; Reilly et al., 1994; Tsigas et al., 1996).

Forestry. The impact of climate change on commercial forestry is based on the effect of international trade, coupling with detailed models of forest growth and timber markets (Perez‐Garcia et al., 1997; Tol, 2002a). The damages in this sector are represented as a share of total income in the consumer and producer surplus model, as a function of global mean temperature and atmospheric CO_2 concentration.

Water resources. Downing et al. (1996) found the impact of climate change on water resources changes both water supply and demand. The water supply is modified from the Thornthwaite equation, and the water demand is calculated based on water deficits, per capita incomes and water prices (Tol, 2002a).

Energy consumption. Energy consumption here consists of space heating and space cooling. The lower heating costs and higher cooling costs due to climate change relates to degree days, per capita income and energy efficiency. The parameters are obtained from Tol and Anthoff (2014a) as Table A1, which were calibrated based on the results of Downing et al. (1996).

Sea level rise. Coastal vulnerability (*CV*) during climate change is regarded as a global process by Nordhaus and Boyer (2000), assuming as a power function according to Yohe and Schlesinger (1998). In addition to this, the economic loss due to sea level rise constituted of the damage from drylands and wetlands, according to the function in Darwin and Tol (2001) and Tol (2007). The loss of dryland and wetlands due to rises in sea level triggered by climate change is associated with coastal area protection (Darwin and Tol, 2001). Consistent with the methodology of Tol and Anthoff (2014b) and Tol (2007), the level of protection for coastal area ($Level_P$) is expressed as the fraction according to the cost-benefit analysis (Fankhauser, 1994). Major losses come from cumulative drylands damage, which is expressed as a function of sea level rise, assuming without coastal area protection. The unit monetized value of dryland per square kilometer is under the hypothesis of being linear in income density according to Tol and Anthoff (2014b). The wetland loss is expressed as a linear function of sea level rise, effected by the fraction coastal area protection and increase with income and population density.

$$CV_t = \beta(\frac{T_t}{2.5})^{1.5} \quad (1)$$

$$Level_{P,t} = \max[0,1 - \frac{1}{2}\left(\frac{VP_t + VW_t}{VD_t}\right)] \quad (2)$$

Where t denotes time; the parameter $\beta = 0.12$ denotes the estimated damage coefficient in Nordhaus and Boyer (2000); *VP* refers to the net present value of the protection assuming all coast areas are protected; *VW* refers to the net present value of the wetland lost due to coastal squeeze assuming all coast areas are protected; *VD* refers to the net present value of the dryland lost without any protection for coastal area. Data on rising sea levels are from IPCC (2013). Other parameters are obtained from Tol and Anthoff (2014a) as in Table A1.

Ecosystems. Because of their non-marketable nature, it is difficult to quantify damage to natural ecosystems in monetized terms. Tol (2002) assesses the impact of climate change on ecosystems, biodiversity, and landscapes based on the 'warm-glow' effect, which suggests that people's willingness to pay reflects their desire to contribute to a vaguely described 'good cause', rather than to a well-defined environmental good or service. The greater the decline in biodiversity, the greater the damage to ecosystems, as the value of biodiversity is inversely proportional to the number of species (Tol and Anthoff, 2014b). The ranking criterion and biodiversity index in the function are based on Weitzman (1992, 1993, 1998).

Climate disasters. According to Tol and Anthoff (2014b), the damage from the greater frequency and intensity of storms (*DS*) due to climate change consists of losses attributable to increased tropical storms (typhoons or hurricanes) and extratropical storms, each subdivided into economic damage (*TED* and *ETED*) and the mortality loss (*TML* and *ETML*). The economic damage and loss from mortality due to an increase in the frequency and intensity of tropical storms (Narita et al., 2009a) and extratropical storms (Narita et al., 2009b) are expressed as Tol and Anthoff (2014b).

$$DS_t = TED_t + TML_t + ETED_t + ETML_t$$

$$= \alpha_{\mathrm{TED}} Y_t \left(\frac{y_t}{y_{1990}}\right)^{\epsilon} \left[(1+\delta T_t)^{\gamma} - 1\right] + \alpha_{\mathrm{TML}} Y_t \left(\frac{y_t}{y_{1990}}\right)^{\epsilon} \phi \left[\left(\frac{C_{\mathrm{CO_2},t}}{275}\right)^{\gamma} - 1\right] +$$

$$\beta_{\mathrm{ETED}} P_t \left(\frac{y_t}{y_{1990}}\right)^{\eta} \left[(1+\delta T_t)^{\gamma} - 1\right] + \beta_{\mathrm{ETML}} P_t \left(\frac{y_t}{y_{1990}}\right)^{\varphi} \phi \left[\left(\frac{C_{\mathrm{CO_2},t}}{275}\right)^{\gamma} - 1\right] \qquad (3)$$

We use the same notation as Tol and Anthoff (2014b), t denotes time; P and y are the population and per capita income; T refers to the increase in global temperature over pre-industrial times; $C_{\mathrm{CO_2}}$ refers to the atmospheric average CO_2 concentration (CO_2 concentration in the pre-industrial era was 275×10^{-6}). α_{TED}, α_{TML}, β_{ETED}, β_{ETML}, ϵ, η, δ, γ, and ϕ are parameters obtained from Tol and Anthoff (2014a) as Table A1.

Most economic studies estimating the impacts of climate change have paid little attention to extreme weather and climate events. For example, in the FUND model, the analysis on agriculture sector examines the crop yield responses to baseline temperature rise and does not explicitly take into account the potential loss in productivity caused by extreme climate events (Tol, 2002a). The sum of climate damage from all extreme climate events is derived according to the proportion of storm damage in total climate disasters, considering economic damage and number of death affected by disaster types, based on the global statistical data from 1994 to 2013 (CRED, 2015). These climate disasters are based on CRED data include flood, extreme temperature, drought, landslide and wildfires etc.

Human health. Mortality is a popular health endpoint indicator in epidemiological studies. Premature deaths caused by air pollution ($PM_{2.5}$ and ozone), diarrhea, vector-borne disease and cardiovascular and respiratory diseases are investigated. The value of a statistical life (VSL) is assumed to be ten times of per capita GDP (Scovronick et al., 2019).

An all-cause all-age (≥ 30) dose response function is applied to calculate the relative risk (*RR*) based on $PM_{2.5}$ or ozone concentration (Scovronick et al., 2019), as shown in Eq. (4),

$$RR_i = \exp\left[\beta_{h,i}\left(C_i - C_{i,0}\right)\right] \tag{4}$$

where i = 1 or 2, indicating $PM_{2.5}$ or ozone, and $\beta_{h,i}$ is a constant, and C_i represents the exposure concentration of $PM_{2.5}$ or ozone, while $C_{i,0}$ is the safe level. The safe levels of $PM_{2.5}$ and ozone are respectively 7 μg m^{-3} and 19 μg m^{-3} (Lelieveld et al., 2015; Limaye et al., 2018). For each 10 μg m^{-3} change in $PM_{2.5}$ or ozone exposure, the relative risk is 1.030 or 1.003 at the global level (Anderson et al., 2004; Wagner et al., 2018), and $\beta_{h,i}$ can be calculated based on Eq. (4).

The attributable fraction (*AF*) of deaths from all causes can be calculated by Eq. (5) based on the definition of relative risk, i.e. death rates under hazardous levels of exposure compared to death rates under safe levels of exposure.

$$AF_i = \frac{RR_i - 1}{RR_i} \tag{5}$$

The number of premature deaths (D_i) is then obtained by

$$D_i = P \times r \times AF_i = P \times r \times \frac{RR_i - 1}{RR_i} = P \times r \times \{1 - \exp[-\beta_{h,i}(C_i - C_{i,0})]\} \tag{6}$$

where P refers to the population from SSP2 (Fricko et al., 2016), and r is the death rate projected by the World Population Prospects (UNPD, 2019).

Baseline air-pollution-related premature deaths can be calculated according to Eq. (6). Increases in $PM_{2.5}$ and ozone concentrations are assumed to be 0.36 μg m^{-3} and 4.0 μg m^{-3} for every 1°C rise in temperature (Bloomer et al., 2009; Orru et al., 2017; Tai et al., 2010). Future $PM_{2.5}$ and ozone concentrations are based on the RCP8.5 scenario (Silva et al., 2016). Increases in air pollutant concentrations and resulting premature deaths due to greater global temperatures can be estimated for three scenarios. Air-pollution-related deaths attributable to climate change are defined as the difference between baseline premature deaths and predicted premature deaths in each scenario. Although future $PM_{2.5}$ and ozone concentration cannot be accurately predicted in this study, the difference between baseline and predicted premature deaths is not sensitive to the $PM_{2.5}$ and ozone concentration and majorly determined by the increment of pollutant concentrations. We tested that if the ozone concentration increased by 10%, the additional deaths would increase by only 0.01%. Impacts of climate change on diarrheal diseases, vector-borne diseases, cardiovascular and respiratory disease are detailed in Appendix.

Aggregate climate damage. After calculating sectoral climate damages, we can aggregate all these sector damages into total damage, and apply econometric regressions analysis to establish the relationship between the total damage and increases in global atmospheric temperature. Based on previous studies (Nordhaus and Sztorc, 2013; Zhang et al., 2018), this relationship is in quadratic form :

$$D = c + aT + bT^2 \tag{7}$$

Where D denotes aggregate damage, i.e. the ratio of total damages to the GWP, c is a constant, while a and b are regressed parameters. Considering that the parameters are different for variant scenarios, we will specifically regress the parameters for each scenario in Appendix.

3. Results

3.1 Sectoral climate damages

Fig. 2 shows the absolute value of economic losses caused by climate change in different sectors from 2010 to 2100 in the BAU scenario. The climate damage in 2100 are 2.82% of GDP for the BAU scenarios, in accordance with the previous studies (Tol, 2009). The climate change related longer exposure is projected to cause worsening agricultural impacts, which will account for more than half of the total damage, from 1602 billion USD in 2010 (83% of total damage) to 7081 billion USD in 2100 (63% of total damage). The second one is the damage from water resource, increasing from 229 billion USD in 2010 to 1770 billion USD in 2100, the percentage of water resource damage increases from 12% in 2010 to 16% in 2100. Meanwhile, the human health related losses decrease from 97 billion USD in 2010 (5% of total damage) to 83 billion USD around 2020, then gradually rebound to 1142 billion USD till 2100 (10% of total damage). Whereas the forestry sector benefits from the increased temperature andCO_2 concentrations, showing negative value (less than 2% of the total damage) of loss through the end of the 21st century. The energy consumption shows benefits from climate change in 2010 due to the decreased expenditure on space heating. Then the increased expenditure on space cooling surpasses the decrease in expenditure on space heating around 2050–2055. The losses from energy consumption increase to 102 billion USD in 2100. The damages from climate disasters, sea level rise, and ecosystems are lower than other sectors, but they are continually increasing from 31 billion, 31 billion and 65 billion USD in 2010 to 246 billion, 793 billion, 244 billion USD in 2100, respectively.

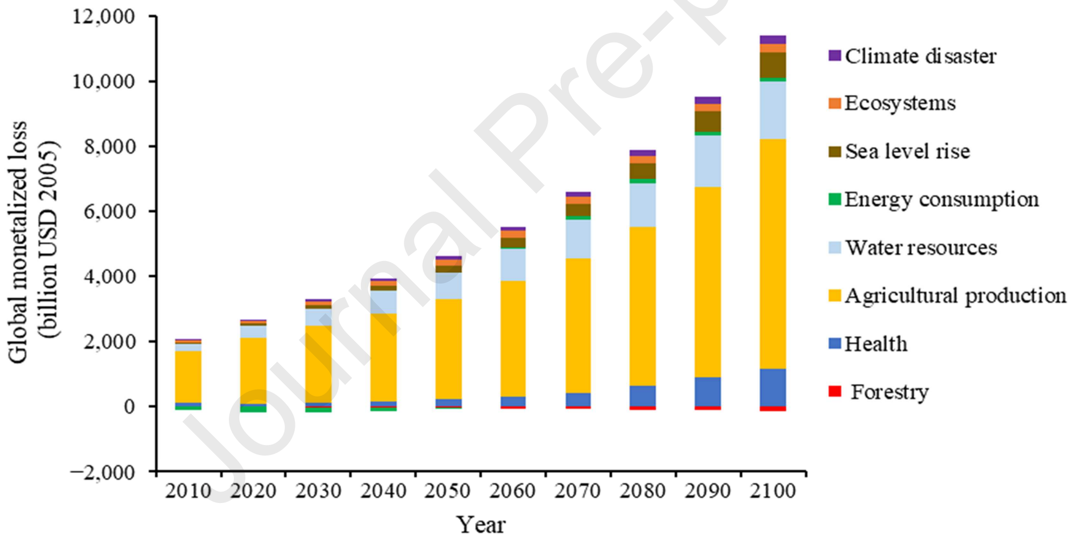

Fig. 2 The monetized value of climate damages in different sectors during 2011–2100 in the BAU scenario.

Fig. 3 illustrates the sectoral monetized losses evolving with time due to climate change in BAU, 2 °C and 1.5 °C scenarios. For the agriculture sector (Fig. 3a), greater CO_2 fertilization caused by climate change boosts agriculture production as crops will grow faster and use less water (Tol and Anthoff, 2014b). The magnitude of economic losses is always inversely proportional to the rate of climate change, meaning greater damages for faster climate change (Tol and Anthoff, 2014b). Although increased atmospheric CO_2 concentrations have accelerated the rate of CO_2 fertilization, benefits for agriculture production are overwhelmed by other negative effects of climate change. The agriculture production loss is projected to reach more than 7 trillion USD by the end of the 21st century in BAU scenario. The reduced GHG emissions in the 2°C and 1.5°C scenarios can effectively mitigate the rate and level of climate change. Agricultural production loss is projected to peak to 2607 billion and 2425 billion USD around 2045 and 2035 in the 2°C and 1.5°C scenarios, respectively, before steadily declining to 1396 billion and 1204 billion USD in 2100.

However, the forestry related activities (Fig. 3b) benefit from the increased temperature and CO_2 concentrations in these scenarios, meaning positive effects from climate change in forestry consumer and producer surplus. The benefits are higher in the 2°C scenario than the 1.5 °C scenario. The climate change related losses in sectors of water resource (Fig. 3c), sea level rise (Fig. 3e), and climate disasters (Fig. 3g) present similar trends, which shows increased damage from 2010 to 2100 and lower loss in the 1.5 °C scenario than the 2 °C scenario.

The energy consumption is constituted by the decrease in expenditure on space heating and increase in expenditure on space cooling (Fig. 3d). The decrease on space heating surpasses the increase in expenditure on space cooling causing economic benefits at the beginning. Then the increase in expenditure on space cooling gradually exceeds the decrease on space heating, and the economic costs is projected to exceed benefits around 2050–2055. The climate change triggered loss for energy consumption is modeled to peak at 118 billion USD around 2080–2090 in the BAU scenario. In 2°C and 1.5 °C scenarios, mitigations bring economic benefits, but the benefits decrease from 117 billion in 2010 to 3 billion and 13 billion USD, respectively in 2100. Space heating and cooling demands are linear to population. Energy efficiency improvements in space heating and cooling are assumed to be equal to the average energy efficiency improvements in the economy (Downing et al., 1996). With the technological progress in energy provision, there is less energy loss in energy consumption sector.

Based on the ‘warm-glow effect’, Tol (2002a) assesses the impact of climate change on the natural environment. For ecosystems (Fig. 3f), the loss in BAU scenario continually increases to 244 billion USD in 2100, due to the climate change impacts on the species. The differences of losses in these scenarios are not obvious at first. However, the economic damage in the 2 °C scenario peaks at 147 billion USD around 2055. Then it shows a decreasing trend since 2055, and the gain of 58 billion USD in 2100. The losses in the 1.5°C scenario start decreasing as early as 2035 because of more effective mitigation efforts to control temperature rise.

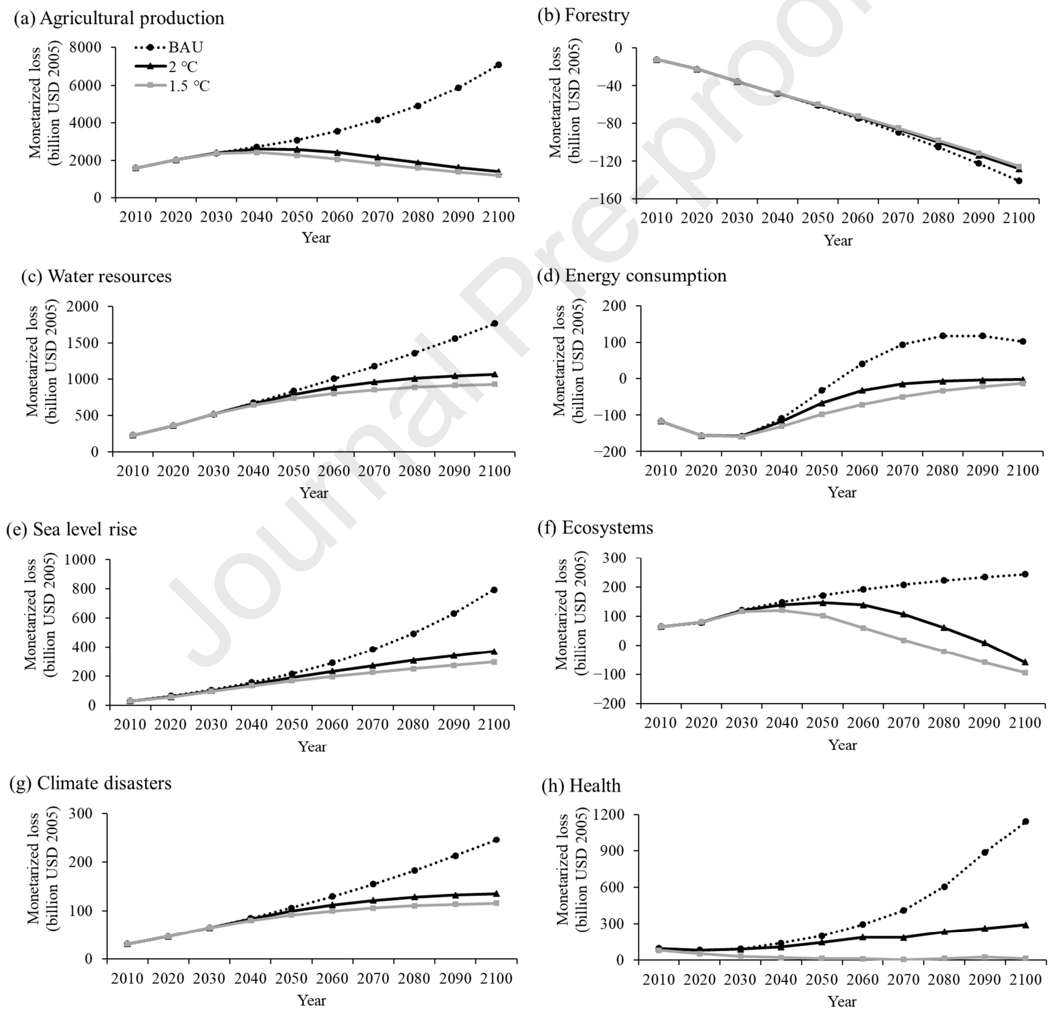

Fig. 3 Monetized climate damages in different sectors during 2011–2100.

Climate-change-related losses in health involve six diseases which are diarrhea, vector-borne diseases, cardiovascular and respiratory disease, $PM_{2.5}$-related and ozone-related diseases. In general, temperature rise has adverse impacts on these diseases, but it may be beneficial to some diseases (e.g. respiratory diseases) especially in cold areas. Climate change is estimated to cause 0.8–2.6 million additional deaths in 2050 and 2100 respectively in the BAU scenario. In 2100, 1.9 and 2.5 million deaths are projected to be avoided in 2 °C and 1.5 °C scenarios, respectively, compared to the BAU scenario, and the avoided losses is estimated be 850 billion and 1130 billion USD. Additional deaths caused by $PM_{2.5}$, ozone, and cardiovascular diseases is projected to increase as temperatures rise, while diarrhea and vector-borne diseases decrease probably because the increasing per capita GDP, one important indicator of climate adaptation, can help people to fight these two diseases better. Respiratory diseases are very sensitive to changes in temperature, and the mortality may increase with temperature rise when the temperature is above 16.5°C, while decreasing with temperature rise when below 16.5°C (Martens, 1998). With the global average temperature as the input parameter, global warming seems to reduce respiratory diseases, but this conclusion remains uncertain due to the sensitivity of respiratory diseases to temperature and also regional temperature differences. Moreover, the overlap between air-pollution-related mortality and cardiovascular or respiratory diseases also needs further investigation.

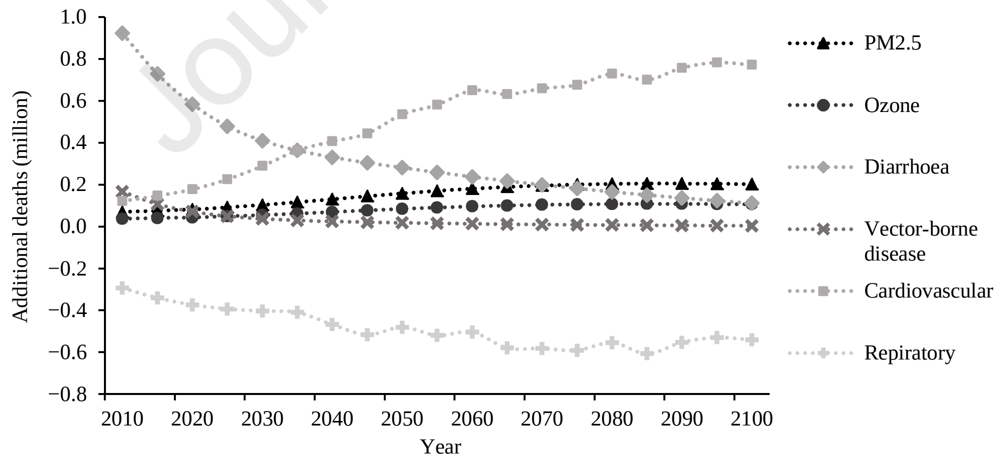

Fig. 4 Additional deaths caused by $PM_{2.5}$, ozone, diarrhea, vector-borne disease, cardiovascular, and respiratory diseases during 2011–2100 in the 2°C scenario.

3.2 Aggregate damage function

In absolute terms, the cumulative climate damage from 2011 to 2100 in the BAU scenario is predicted to be 517.7 trillion USD; equivalent figures for the 2°C and 1.5°C scenarios are respectively 302.1 trillion and 254.2 trillion USD. Compared to the BAU scenario, the 2°C and 1.5°C scenarios are predicted to reduce climate damages by 215.6 trillion and 263.5 trillion USD respectively (Table.1). In relative terms, the climate damage decreases from 2.4% of GWP in the BAU scenario to 1.4% and 1.2% of GWP in the 2°C and 1.5°C scenarios respectively. Here the climate damage is the percentage that the cumulative climate damage compared to the cumulative GWP during 2011–2100. The policy implication is that with higher and earlier mitigation efforts to achieve the 2°C and 1.5°C goals in the Paris Agreement, the climate damages are predicted to reduce 1.0 and 1.2 percents of GWP than the BAU scenario, which means the climate damages will reduce by 41.6% and 50.9% relative to BAU scenario.

We calibrate the aggregate climate damage function based on the results of three scenarios by employing econometric regression method. The aggregate climate damage function is:

$$D = 0.0002T^2 + 0.0062T \tag{8}$$

The aggregate climate damage function of this study is in positive quadratic form. We can compare the results of this study with other two studies, i.e., the Tol survey (Tol, 2009) and the DICE model (Nordhaus, 2009). The aggregate climate damage function of the DICE model and Tol survey are both in positive quadratic forms. Note that the aggregate climate damage function of Tol survey (Tol, 2009) is based on meta-analysis of existing literatures which illustrate large uncertainties both on temperature increases and climate damages, while the climate damage function in DICE model is based on Tol survey.

It is estimated by previous studies (Fankhauser, 1995; Hope, 2006; Maddison, 2003; Mendelsohn et al., 2000; Nordhaus, 2006; Nordhaus and Boyer, 2000; Nordhaus and Yang, 1996; Plambeck and Hope, 1996; Tol, 1995) that the climate damage is 0.7% of GWP on average with a standard deviation of 1.2% GWP for benchmarking 2.5°C scenario (Tol, 2009). The aggregate climate damage varies from 1% to 5% as of GWP at 4°C temperature increase in the IPCC fifth assessment report (IPCC, 2014). The climate damages in this study lie within the range of previous literatures.

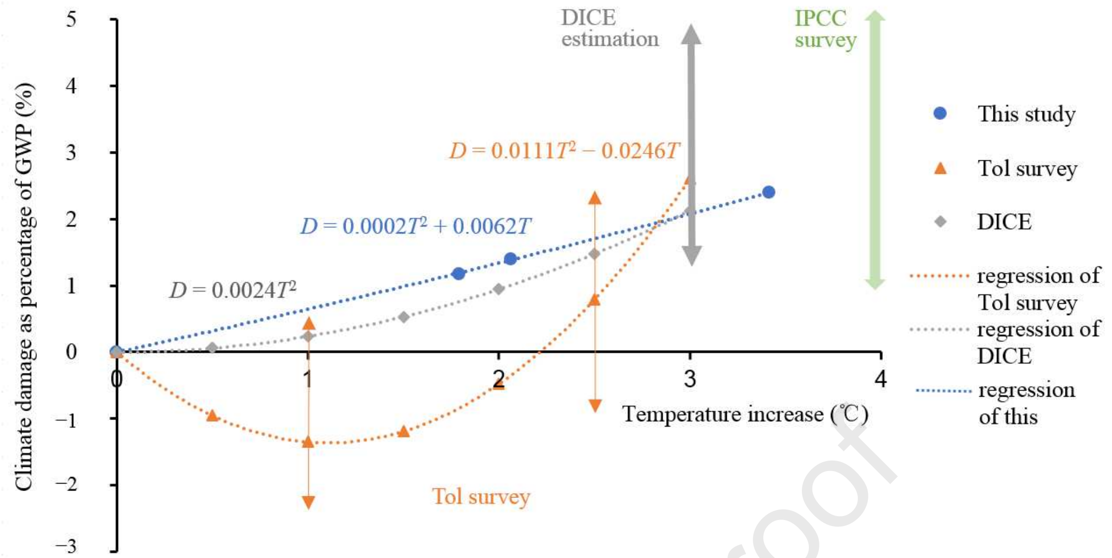

Fig. 5 Comparison of aggregate climate damage functions with different studies

The assumed discount rate has a huge impact on Net Present Value (NPV) of climate damages (Liu, 2012). Here we provide sensitivity analysis for the NPV of climate damages at different discount rates (see Table 1). With the assumption of 5% market discount rate (Nordhaus, 2014), the NPV values of climate damages are 60.7 trillion, 52.9 trillion and 49.2 trillion USD respectively under the BAU, 2 °C, and 1.5 °C scenarios. If we set the discount rate as 3%, the NPV of climate damages becomes 118.1 trillion, 91.5 trillion and 82.2 trillion USD respectively in the BAU, 2 °C, and 1.5 °C scenarios. If follow the Stern Report (Stern, 2007) and assume a discount rate of 1.4%, the NPV of climate damages are predicted to be respectively 204.0 trillion, 127.9 trillion and 107.8 trillion USD under the BAU, 2 °C, and 1.5 °C scenarios. Therefore, the smaller discount rates, the larger of the absolute climate damages of each scenario. The discounting factor alone has the largest impact on the NPV. Sensitivity analysis of the climate damage functions for different discount rates and for absolute values can be found in the Appendix.

Table.1 The NPV of climate damages for different discount rates.

Discount rate (%)	NPV (trillion USD)			NPV (as percentage of GWP)		
	BAU	2°C	1.5°C	BAU	2°C	1.5°C
5	60.7	52.9	49.2	2.1	1.8	1.7
3	118.1	91.5	82.2	2.2	1.7	1.5
1.4	204.0	127.9	107.8	1.9	1.2	1.0
0	517.7	302.1	254.2	2.4	1.4	1.2

4. Conclusions and discussion

This study assesses various sectoral climate damages and develops a global aggregate climate damage function by integrating BCC_SESM climate model, FUND damage module, and study three scenarios (BAU/2°C/1.5°C) based on IAM framework and standard RCPs/SSP2 database. It expands climate disaster types, assesses human health impacts caused by various air pollutants, and updates coastal damage by sea level rise beyond the conventional sectors in FUND model, and develop a global aggregate climate damage function which can be applied in the cost-benefit analysis in climate economics. This study overcomes the shortcomings of previous climate damage studies, which are either focused on sectoral damages without aggregate damage function (such as FUND model) or aggregate damage function without sectoral details (such as DICE model). And this study also applies the latest IPCC RCPs and SSP2 database, thus results can be used for model inter-comparison for climate damages from different IAM models.

Results show that in the BAU scenario, damages caused by climate change disproportionately impacts the agricultural sector, which is projected to suffer 63% of the total damage in 2100. The water resource sector has the second largest share of impact at the beginning of the period, the percentage of water resource damage increases from 12% in 2010 to 16% in 2100. Climate change is projected to initially cause a decline in energy consumption levels due to reduced demand for space heating, however, increased demand for space cooling will eventually offset these gains. In addition, the forestry sector is projected to benefit from higher temperatures and CO_2 concentrations.

Regression result indicates that the aggregate climate damage function is sensitive to the discount rates. The aggregate climate damage function is in positive quadratic form, with the assumption of zero discounting. However, for positive discount rates, the climate damage functions are in negative quadratic forms, and the concavity of the curves of climate damage functions increase with the discount rates. This finding is robust both for relative percent numbers and for absolute magnitude numbers of climate damages. In this study, the climate damage is 517.7 trillion USD during 2011–2100, which is approximately 2.4% of GWP.

Compared to the BAU scenario, the 2°C and 1.5°C scenarios are predicted to respectively reduce climate damages by 215.6 trillion USD (approximately 1% of GWP) and 263.5 trillion USD (1.2% of GWP) in 2011–2100. The policy implication is that with higher and earlier mitigation efforts to achieve the 2°C and 1.5°C goals in the Paris Agreement, the climate damages are predicted to reduce 41.6% and 50.9% than the BAU scenario.

There are factors contribute to the uncertainties of climate damage function in this study. First are the uncertainties from the input data mainly due to the complexity of natural science and climate system modeling, such as the future temperature increase, sea level rise, and extreme climate events. For example, the temperature increase in the 21st century varies from 3.2–5.4°C in the BAU scenario (IPCC, 2014). These uncertainties have been extensively discussed in the IPCC reports (IPCC, 2013) and CMIP experiments (Liu et al., 2019) which are out of the scope of this study. Second are the uncertainties from sectoral climate damages. The parameters are estimated base on empirical model data from previous studies or experts review. We studied the variations between different scenarios and compares different impacts. Third are the uncertainties of aggregate damage functions, equations and parameters, especially the impacts of different discount rates on the form of the damage functions, which have been discussed in section 3.2 and Appendix section 4.

Several caveats arise in this study and these questions need to be further studied. First is the region and nation level of climate damage studies. Considering that the climate impacts are idiosyncratic and vary significantly for different regions (IPCC, 2007), it is necessary to study the continental, regional and country-level climate damages. Second is model comparison. Although the specific sectors and aggregate climate damage have been studied in this paper, however, we need to compare results from different climate models, energy models and IAM models, and compare results based on different methodologies such as from the bottom-up and top-down models. Third is the fat-tail of climate damages. In essence, the uncertainty of climate damage is right-skewed and the damage probably been underestimated, especially in terms of failing to capture the fat-tail risks of climate change, for example, the climate catastrophic scenario with temperature increase higher than 5°C (Weitzman, 2010). Fourthly, during the study we find that there is significant divergence between the BAU scenario pathway versus the mitigation scenarios pathways such as 2 °C and 1.5 °C scenarios. Should models develop different climate damage functions for different scenarios in order to explore their temporal variations, this is also an interesting topic which needs to be further studied in the future. Lastly, the human adaptation to climate change, which has opposite impact on climate damages, should be considered in various scenarios (Gosling et al., 2017; Petkova et al., 2017).

Declaration of Competing Interest The authors declare no conflict of interest.

Supplementary Information Summary of parameters for sectoral climate disaster functions, modeling framework, and BCC_SESM results are illustrated in Appendix A.

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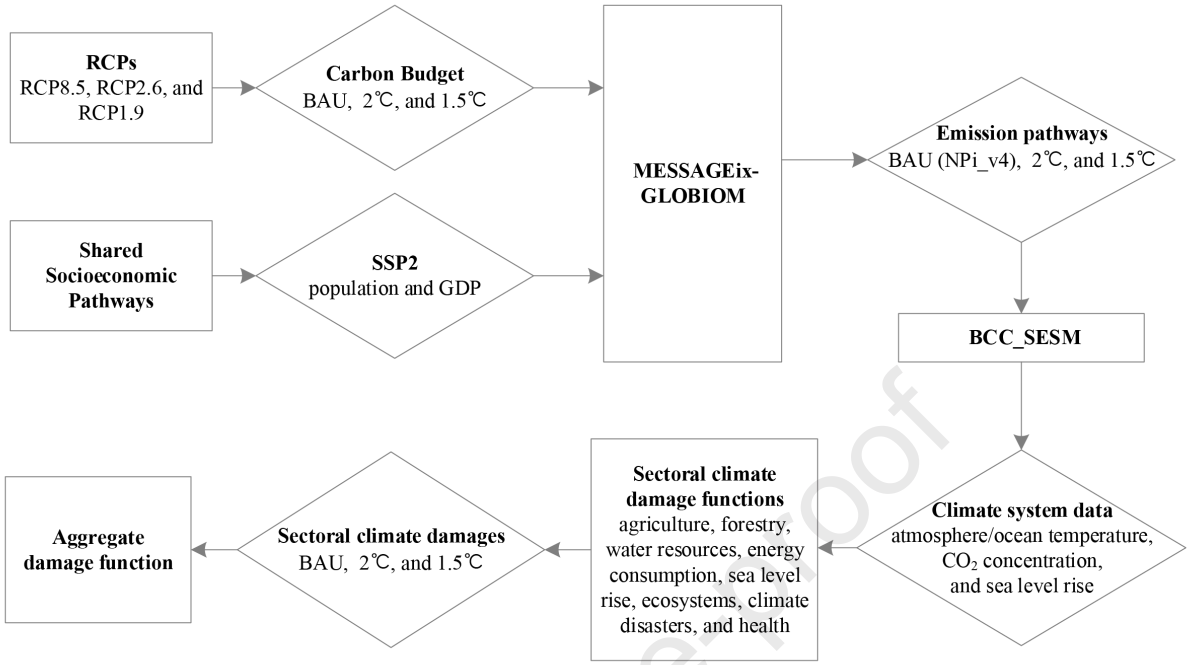
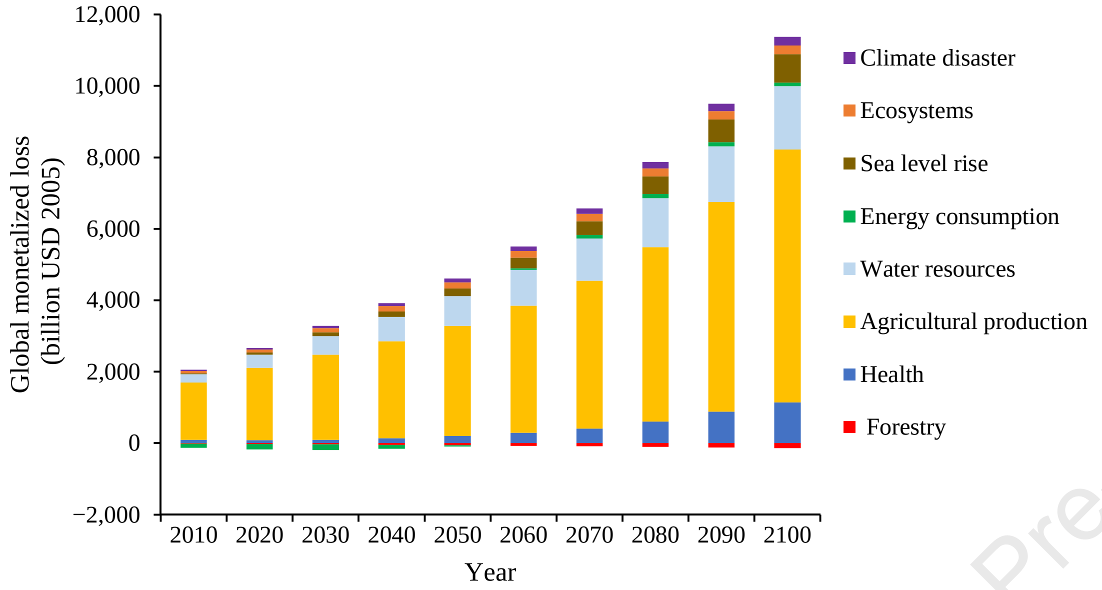

RCPs
RCP8.5, RCP2.6, and RCP1.9
Carbon Budget
BAU, 2℃, and 1.5℃
Shared Socioeconomic Pathways
SSP2
population and GDP
MESSAGEix-GLOBIOM
Emission pathways
BAU (NPi_v4), 2℃, and 1.5℃
BCC_SESM
Climate system data
atmosphere/ocean temperature, CO_2 concentration, and sea level rise
Sectoral climate damage functions
agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, climate disasters, and health
Sectoral climate damages
BAU, 2℃, and 1.5℃
Aggregate damage function


Global monetalized loss
(billion USD 2005)
12,000
10,000
8,000
6,000
4,000
2,000
0
−2,000
2010
2020
2030
2040
2050
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2070
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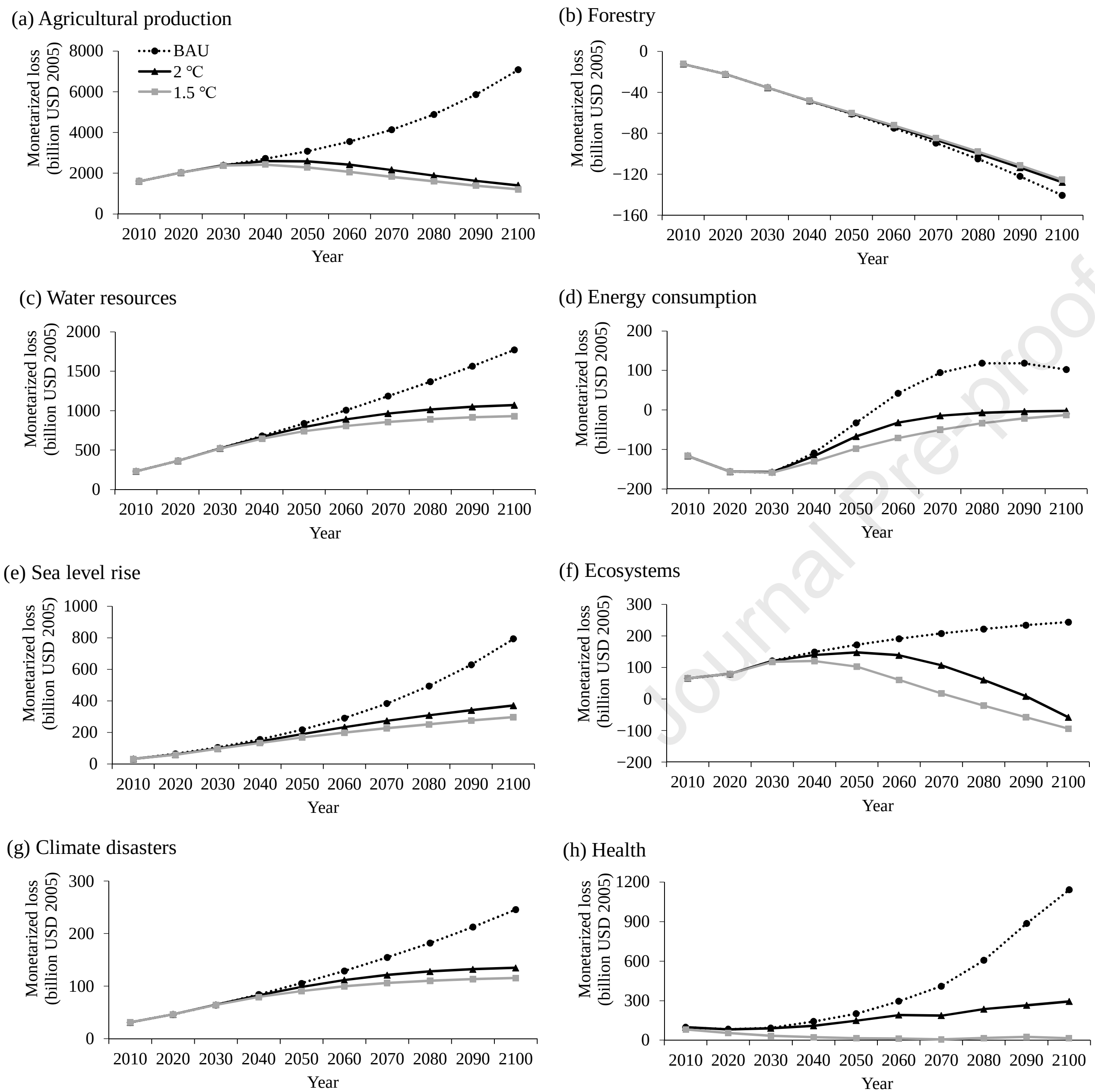
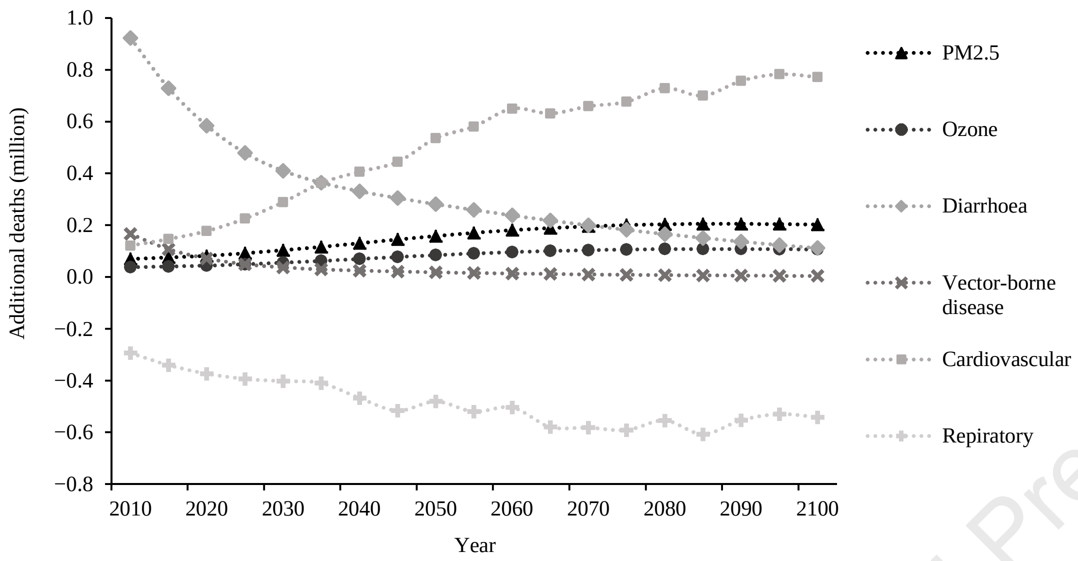
2100
Year
Climate disaster
Ecosystems
Sea level rise
Energy consumption
Water resources
Agricultural production
Health
Forestry


(a) Agricultural production
BAU
2 °C
1.5 °C
Monetarized loss (billion USD 2005)
0
2000
4000
6000
8000
Year
(b) Forestry
0
−40
−80
−120
−160
(c) Water resources
0
500
1000
1500
2000
(d) Energy consumption
200
100
0
−100
−200
(e) Sea level rise
0
200
400
600
800
1000
(f) Ecosystems
300
200
100
0
−100
−200
(g) Climate disasters
0
100
200
300
(h) Health
0
300
600
900
1200
2010 2020 2030 2040 2050 2060 2070 2080 2090 2100


1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
Additional deaths (million)
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
PM2.5
Ozone
Diarrhoea
Vector-borne disease
Cardiovascular
Repiratory

	GEI2D	GEI2D	GEI2D	GEI2D	能源系统投资（不包括能效和氢
2010	879.9417569	879.9417569	879.9417569	879.9417569	Investment|Energy Su
2020	1101.356198	1101.356198	1101.356198	1101.356198	
2030	1466.048652	1466.048652	1466.048652	1466.048652	
2040	1916.085908	1916.085908	1916.085908	1916.085908	
2050	2131.93901	2131.93901	2131.93901	2131.93901	
2060	2159.193967	2159.193967	2159.193967	2159.193967	
2070	2379.419809	2379.419809	2379.419809	2379.419809	
2080	2618.472081	2618.472081	2618.472081	2618.472081	
2090	2673.40611	2673.40611	2673.40611	2673.40611	
2100	3048.457855	3048.457855	3048.457855	3048.457855	
discount ra	1.05	1.03	1.014	1	
	28894	50991	94090	184101	
	28.9	51.0	94.1	184.1	
1.03					
1.014					
1	184101.2154				

	GEI15D	GEI15D	GEI15D	GEI15D
2010	879.9418	879.9418	879.9418	879.9418
2020	1101.356	1101.356	1101.356	1101.356
2030	2178.517	2178.517	2178.517	2178.517
2040	2266.026	2266.026	2266.026	2266.026
2050	2534.974	2534.974	2534.974	2534.974
2060	1987.796	1987.796	1987.796	1987.796
2070	2007.717	2007.717	2007.717	2007.717
2080	2067.941	2067.941	2067.941	2067.941
2090	2552.814	2552.814	2552.814	2552.814
2100	3435.117	3435.117	3435.117	3435.117
discount ra	1.05	1.03	1.014	1
billion USD	32431	55918	99710	188547
trillion USD	32.4	55.9	99.7	188.5

	BAU	BAU	BAU	BAU
2010	879.9418	879.9418	879.9418	879.9418
2020	1101.356	1101.356	1101.356	1101.356
2030	1563.728	1563.728	1563.728	1563.728
2040	2083.748	2083.748	2083.748	2083.748
2050	2533.687	2533.687	2533.687	2533.687
2060	2407.759	2407.759	2407.759	2407.759
2070	2447.172	2447.172	2447.172	2447.172
2080	2625.343	2625.343	2625.343	2625.343
2090	2724.394	2724.394	2724.394	2724.394
2100	2827.623	2827.623	2827.623	2827.623
discount ra	1.05	1.03	1.014	1
billion USD	30472	54115	99651	193410
trillion USD	30.5	54.1	99.7	193.4

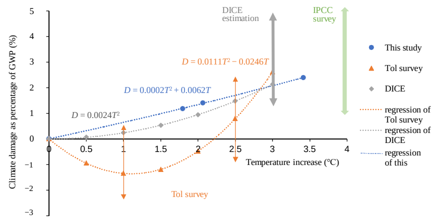
source: MESSAGEix-GLOBIOM_GEIDCO_V6_macro_calibration_merged.xlsx

	GDP	GDP	GDP	GDP
2010	65019.98	65019.98	65019.98	65019.98
2020	103470.1	103470.1	103470.1	103470.1
2030	149180.8	149180.8	149180.8	149180.8
2040	190185.9	190185.9	190185.9	190185.9
2050	227272	227272	227272	227272
2060	263317	263317	263317	263317
2070	298415.7	298415.7	298415.7	298415.7
2080	332292.5	332292.5	332292.5	332292.5
2090	365651.5	365651.5	365651.5	365651.5
2100	398562.4	398562.4	398562.4	398562.4
discount ra	1.05	1.03	1.014	1
billion USD	2882496	5411065	10549675	21615769
trillion USD	2882.5	5411.1	########	########

Tol 2009	Temperatu	% GDP (Tol	DICE
	0	0.00%	0.00%
	0.5	-0.95%	0.06%
	1	-1.35%	0.24%
	1.5	-1.19%	0.53%
	2	-0.48%	0.94%
	2.5	0.79%	1.48%
	3	2.61%	2.12%

	GDP （PPP, billion USD)
2010	65019.98
2015	82802.45
2020	103470.1
2025	126555
2030	149180.8
2035	170463.9
2040	190185.9
2045	208968.9
2050	227272
2055	245373.3
2060	263317
2065	281006.6
2070	298415.7
2075	315491.1
2080	332292.5
2085	348993.1
2090	365651.5
2095	382198.9
2100	398562.4

Fig.5



	(unit: trillic	**NPV of climate damages**				**NPV of energy investments**					
Temperatu	Discount ra	DR 5%	DR 3%	DR 1.4%	DR 0%	5%	3%	1.40%	0	Temperature rise	
3.414241	BAU	60.7	118.1	204	517.7	30.3	53.9	99.4	193.3	3.414241	
2.0624	GEI 2°C	52.9	91.5	127.9	302.1	28.9	51	94.1	184.1	2.0624	
1.79201	GEI 1.5°C	49.2	82.2	107.8	254.2	32.4	55.9	99.7	188.5	1.79201	
0		0	0	0	0					0	
Temperatu	占GDP比例	DR 5%	Default (DR 3%)	DR 1.4%	DR 0%					Temperature rise	
3.414241	BAU	0.02105814	0.021825648	0.019337089	0.023950108	0.010512	0.009961	0.009422	0.008943	3.414241	
2.0624	GEI 2°C	0.018352152	0.016909795	0.012123597	0.013975908	0.010026	0.009425	0.00892	0.008517	2.0624	
1.79201	GEI 1.5°C	0.017068542	0.015191095	0.010218325	0.011759933	0.01124	0.010331	0.009451	0.00872	1.79201	
0		0	0	0	0					0	
Temperatu	占GDP比例	DR 5%	Default (DR 3%)	DR 1.4%	DR 0%					Temperature rise	
3.414241	BAU	2.1%	2.2%	1.9%	2.4%	1.05%	1.00%	0.94%	0.89%	3.414241	
2.0624	GEI 2°C	1.8%	1.7%	1.2%	1.4%	1.00%	0.94%	0.89%	0.85%	2.0624	
1.79201	GEI 1.5°C	1.7%	1.5%	1.0%	1.2%	1.12%	1.03%	0.95%	0.87%	1.79201	
0		0	0	0	0					0	
	difference	**NPV of climate damages**				**NPV of energy investments**					
	Discount ra	5%	3%	1.40%	0	5%	3%	1.40%	0		
	BAU										
	GEI 2°C	7.8	26.6	76.1	215.6	1.4	2.9	5.3	9.2		9.172414
		9.2	**29.5**	**81.4**	**224.8**						
	GEI 1.5°C	11.5	35.9	96.2	263.5	-2.1	-2.00	-0.3	4.8		-17.95
					1.0%	0.416457					
	倍数				1.2%	0.508982					
	2度相比BA	5.6	9.2	14.4	23.4						
	1.5度相比I	-5.5	-18.0	-320.7	54.9						
	1.5度相比2	3.7	9.3	20.1	47.9	3.5	4.9	5.6	4.4		
		1.1	**1.9**	**3.6**	**10.9**						

Global Climate Damage in 2℃ and 1.5℃ Scenarios Based on BCC_SESM model in IAM framework

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Dear editors of ACCR,

We are glad to submit our research paper to ACCR. The title is "Global Climate Damage in 2℃ and 1.5℃ Scenarios Based on BCC_SESM model in IAM framework".

Declaration of Competing Interest The authors declare no conflict of interest.

Best regards

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