



# Parameter uncertainties in evaluating climate policies with dynamic integrated climate-economy model

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## Abstract

Climate change is a complex issue with significant scientific and socio-economic uncertainties, making it difficult to assess the effectiveness of climate policies. Dynamic Integrated Climate-Economy Models (DICE models) have been widely used to evaluate the impact of different climate policies. However, since climate change, long-term economic development, and their interactions are highly uncertain, an accurate assessment of investments in climate change mitigation requires appropriate consideration of climatic and economic uncertainties. Moreover, the results of these models are highly dependent on input parameters and assumptions, which can have significant uncertainties. To accurately assess the impact of climate policies, it is crucial to incorporate uncertainties into these models. In this paper, we explore the impact of parameter uncertainties on the evaluation of climate policies using DICE models. Our goal is to understand whether uncertainty significantly affects decision-making, particularly in global warming policy decisions. By integrating climatic and economic uncertainties into the DICE model, we seek to identify the cumulative impact of uncertainty on climate change. Overall, this paper aims to contribute to a better understanding of the challenges associated with evaluating climate policies using DICE models, and to inform the development of more effective policy measures to address the urgent challenge of climate change.

**Keywords** Dynamic integrated climate-economy model · Long-term decisions models · Global warming · Information theory · Partial preference information · Uncertainty

## 1 Introduction

Human activities, primarily the burning of fossil fuels and tropical deforestation, have increased the natural greenhouse effect, causing global warming. With the inception of the Industrial Revolution, the amount of CO<sub>2</sub> in the atmosphere is increasing. Measurements of CO<sub>2</sub> show that CO<sub>2</sub> concentration in the atmosphere has increased from about 313-ppm in 1960 to about 389-ppm in 2010, and reached the 418-ppm milestone by 2022, up from around 280-ppm ongoing rise in the CO<sub>2</sub> concentration before the Industrial Revolution (EPA 2022; NASA 2023). That is a huge increase (around 49%) and may lead to catastrophic global warming and climate change. The effects of global warming are far-reaching, gradually increasing, and encompass everything such as

falling crop yields, rising sea level, increasing air pollution, decreasing in water availability, increasing in heavy precipitation events, and rising number of species face extinction.

Climate change is one of the most pressing issues of our time, and effective policy measures are needed to mitigate its impact. Dynamic Integrated Climate-Economy Models (DICE models) have been widely used to evaluate the effectiveness of various climate policies. However, the results of these models are highly dependent on input parameters and assumptions, which can have significant uncertainties. This paper aims to explore the impact of parameter uncertainties on the evaluation of climate policies using DICE models. Specifically, we focus on the uncertainties in input parameters such as the discount rate, climate sensitivity parameter, and damage function parameter. We review several studies that have investigated the impact of parameter uncertainties on the evaluation of climate policies using DICE models, and discuss the implications of these findings for policy decision-making. This paper underscores the importance of carefully considering the uncertainties in input parameters when evaluating climate policies using DICE models, and

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highlights the need for robust policy measures that are less dependent on parameter assumptions. Ultimately, our goal is to contribute to a better understanding of the challenges associated with evaluating climate policies using DICE models, and to inform the development of more effective policy measures to address the urgent challenge of climate change.

Climate change is a major global challenge, and the development of effective policies to mitigate its impact is critical. Dynamic Integrated Climate-Economy Models (DICE models) have been widely used to evaluate the effectiveness of various climate policies. However, the results of these models are highly dependent on the input parameters and assumptions, which can have significant uncertainties.

Several studies have investigated the impact of parameter uncertainties on the evaluation of climate policies using DICE models. For instance, Borgonovo et al. (2022) conducted a sensitivity analysis of the DICE model and found that the discount rate and the climate sensitivity parameter have a significant impact on the optimal level of carbon tax. The study also found that the uncertainty in the damage function parameter can affect the optimal carbon tax rate. Similarly, Tavoni and Valenta (2022) analyzed the robustness of the optimal carbon tax policy to parameter uncertainties using a stochastic version of the DICE model. The study found that the optimal carbon tax rate is highly sensitive to the discount rate and the climate sensitivity parameter, and that the optimal policy may be quite different under different parameter assumptions. Also, several journal papers (Kunreuther et al. 2013; Stern 2008), academic books (Nordhaus 2008, and 2013), and environmental agencies like Intergovernmental Panel on Climate Change (IPCC), United States Environmental Protection Agency (EPA), World Nature Organization (WNO), European Environment Agency (EEA) point out the potential impacts of climate change and

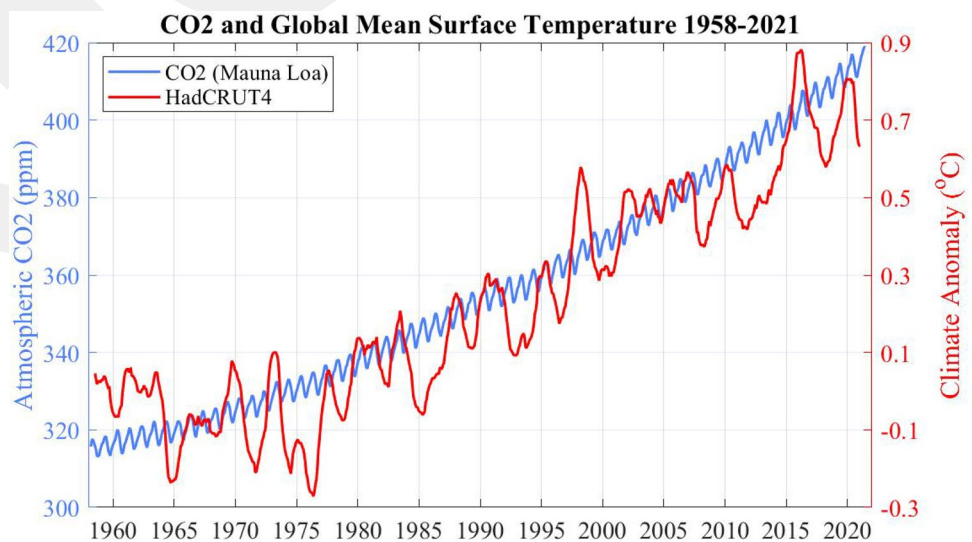
global warming on water resources, food production, health, economy and the environment. There is a large and growing volume of literature on global warming and climate change, most of the existing studies model alternative scenarios of global warming by using integrated assessment models. There are three main integrated assessment models used by the EPA (United States Environmental Protection Agency); DICE (Dynamic Integrated Climate-Economy), FUND (Climate Framework for Uncertainty, Negotiation and Distribution), and PAGE (Policy Analysis of the Greenhouse Effect).

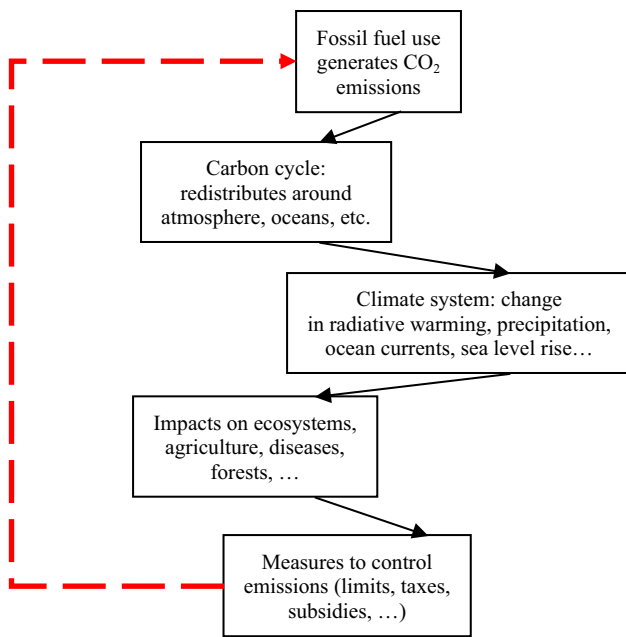
Global average temperature is one of the most-cited indicators of global climate change. The earth's global temperature increases in direct proportion to rising carbon dioxide level and global average temperature shows an increase of approximately 0.778 °C since the early 20th Century (EPA 2022). Figure 1 shows the relationship between CO<sub>2</sub> concentration and surface air temperature. Red line in Fig. 1 indicates surface air temperatures from 1958 to 2021 in Celsius degree. The blue line shows atmospheric carbon dioxide concentration in parts per million (ppm).

The issue of global warming has proven one of the most controversial and difficult problem involving significant scientific and socio-economic uncertainties. Over the last several decades, the issue has discussed in academic and scientific journals, conference proceedings and meetings.

Most of the literature on quantitative methods on climate change focused integrated assessment models (IAM) to solve the economic impacts of global warming and reduce the emission to slow climate change. The advantage of IAMs models is that they can deal with important issues such as the efficient allocation of abatement problems and accepted damages, by specifying the costs and benefits of various abatement policies, using a detailed description of both economic and environmental improvements. Most of these models in the literature are purely deterministic approaches

**Fig. 1** Global annual average Surface Air Temperature and Carbon Dioxide Concentration





**Fig. 2** Schematic flow chart of a full IAM for climate change science, economics, and policy

like DICE model which was one of the economic models of climate change model that analyze the problem of global warming from an economic point of view. However, accurate evaluation of investments in climate change mitigation must take proper consideration of climatic and economic uncertainties because climate change, long-term economic development, and their interactions are highly uncertain. Therefore, it is important to incorporate uncertainty into the usual cost–benefit climate change models.

Uncertainty is an important factor and it should not be ignored or avoided. Ignoring uncertainty in scientific calculations may lead to underestimate or overestimation of results. Hence proper modeling of uncertainty is an important aspect in science. In this paper, we have attempted to study the effect of uncertainty in global warming policy decisions and integrate climatic and economic uncertainties into the DICE model to find out what will be the cumulative impact of integrating uncertainty on climate change by applying Cumulative Residual Entropy into the DICE model. DICE model is an integrated economic and geophysical model of the economics of climate change developed by Nordhaus and colleagues (Nordhaus 1977a, 1977b).

Carbon emission and their impacts on the environment would be directly observable, and the equivalent monetary values of these impacts would be very expensive. A reasonable value for global warming damages is determined approximately \$18 per ton of CO<sub>2</sub> increasing by about 2.1% per year to \$50 in 2055 (Rennert et al. 2022). Therefore, it is

crucial to take actions for slowing global warming carefully. However, the future of global warming is uncertain due to the several parameters such as population, CO<sub>2</sub> emission and discount rate. Therefore, it is important to analyze the environmental policies under uncertainty. There are several studies effort to incorporate uncertainty into the models with some assumptions such as independence among uncertain parameters or variables to deal with global environmental change (Schmidt et al. 2011; Funke and Paetz 2011; Babonneau et al. 2012; Haurie et al. 2012; Keppo and van der Zwann, 2012; Brock and Xepapadeas 2021). Also, some models focus on forecasting with extended models and also integrate uncertainty (Agliardi and Xepapadeas 2022; Sutcu 2022; Barnett et al. 2022; Barnett 2023; Plaga and Bertsch 2023). There are a few studies have tried to incorporate uncertainty into DICE model to evaluate climate change policies. Webster et al. (2012) used Monte Carlo simulation methods and estimated climate uncertainty conditional on different policy scenarios.

In this paper, our main aim is to incorporate climatic and economic uncertainties into the DICE model to find out what will be the cumulative impact of integrating uncertainty on climate change. We primarily examine the original version of the DICE model, namely the deterministic case. Then, we integrate the uncertainty situations into the model. In this case, we first consider that the variables in the model are independent. Then we solve the model again with integrating dependency among model variables into model. As the last case, we compare the results in these three cases and analyze the results of the study to show the effect of integrating uncertainty and dependency into model.

The reminder of this paper is divided into six sections. Section 2 introduces the DICE model and explains the global warming policies used in the DICE model. Section 3 discusses theoretical models used to integrate uncertainty and dependency into the model. In Sect. 4, we study the uncertain parameters used in the model and discuss how to use them in our analysis. In Sect. 5, we run simulation experiments for five different policies, and discuss the results of the analysis. Section 6 contains the concluding remarks and future work.

## 2 Dynamic integrated climate-economy model

In this section, we first discuss about the Nordhaus’ Dynamic Integrated Climate-Economy model and in the second subsection, we are going to give background information about five different environmental policies that are used in our analysis.

**Table 1** Marginal distributions of uncertain variables of DICE model

Variable	Definition of the variable	Mean	St dev	Unit
Ga0	Rate of growth of total factor productivity	0.079	0.004	Per year
dsig	Rate of De-carbonization	−0.001	0.002	Per year
T2xCO2	Equilibrium temperature-sensitivity coefficient	2.900	1.110	Celsius per CO2 doubling
a2	Damage parameter	0.003	0.001	Fraction of global output
pback	Price of backstop technology	344	138	\$ Per ton of carbon replaced
propasym	Asymptotic global population	10,500	1892	Millions
B12	Transfer coefficient in carbon cycle	0.088	0.017	Per decade
Fossilim	Total resources of fossil fuels	6000	1200	Billions of tons of carbon

## 2.1 DICE as an integrated assessment model

The Dynamic Integrated Climate-Economy model, referred to as the DICE model, is an integrated assessment model of climate change developed by William Nordhaus and colleagues that integrates both the economic costs and benefits of greenhouse gas controls with an aggregate model linking economic growth with climate change to reduce emission and slow greenhouse warming. The DICE model is a simplified analytical and empirical model that represents the economics, policy, and scientific aspects of climate change.

DICE model attempts to quantify how the atmospheric concentration of CO<sub>2</sub> negatively affects economic output through its impact on global average surface temperature. The model appears to have first been proposed in a discussion paper for the Cowles Foundation in 1992, and the final version of the model is published with updated discussion of the model in 2013. Figure 2 shows a schematic flow chart of a full integrated assessment model for climate change science, economics, and policy of the DICE model.

DICE model is a policy optimization model that has an economic objective function which is a measure of economic welfare. DICE model includes the estimates of both the costs of reducing carbon dioxide emissions and the long-term future climate impacts from climate change. This allowed for a balancing of the benefits and costs of carbon dioxide emissions to help determine the optimal level of near-term controls. So, main goal of the DICE model is to maximize the welfare function to evaluate alternative policies.

The DICE Model seeks to choose a policy which maximize the social welfare function,  $W$ , that is the discounted sum of the population-weighted utility of per capita consumption. The objective function that DICE seeks to maximize is

$$\max \sum_{t=1}^{T \max} U[c(t), L(t)]R(t) \quad (1)$$

where  $c(t)$  is per capita consumption,  $L(t)$  is total population,  $R(t)$  is the discount factor and  $U[c(t), L(t)]$  is the total worldwide utility of consumption.

**Table 2** Low, base and high percentiles of uncertain variables of DICE model

Variable	Percentiles		
	Low (10%)	Base (50%)	High (90%)
ga0	0.0739	0.0790	0.0841
dsig	−0.0036	−0.0010	0.0016
t2xCO2	1.4775	2.9000	4.3225
a2	0.0010	0.0027	0.0043
pback	168	344	520
Popasym	8075	10,500	12,925
b12	0.0662	0.0880	0.1098
Fossilim	4462	6000	7538

The utility function in equation-1 is defined as

$$U[c(t), L(t)] = L(t) \left[ \frac{[c(t)]^{1-\alpha}}{1-\alpha} \right] \quad (2)$$

where utility is equal to population multiplied by per-capita consumption. Per capita consumption is adjusted by an elasticity parameter ( $\alpha$ ) to account for disparities in equality. If  $\alpha$  is close to zero, then the consumptions are close substitutes, with low aversion to inequality; if  $\alpha$  is high, then the consumptions are highly differentiated, and this reflects high inequality aversion.

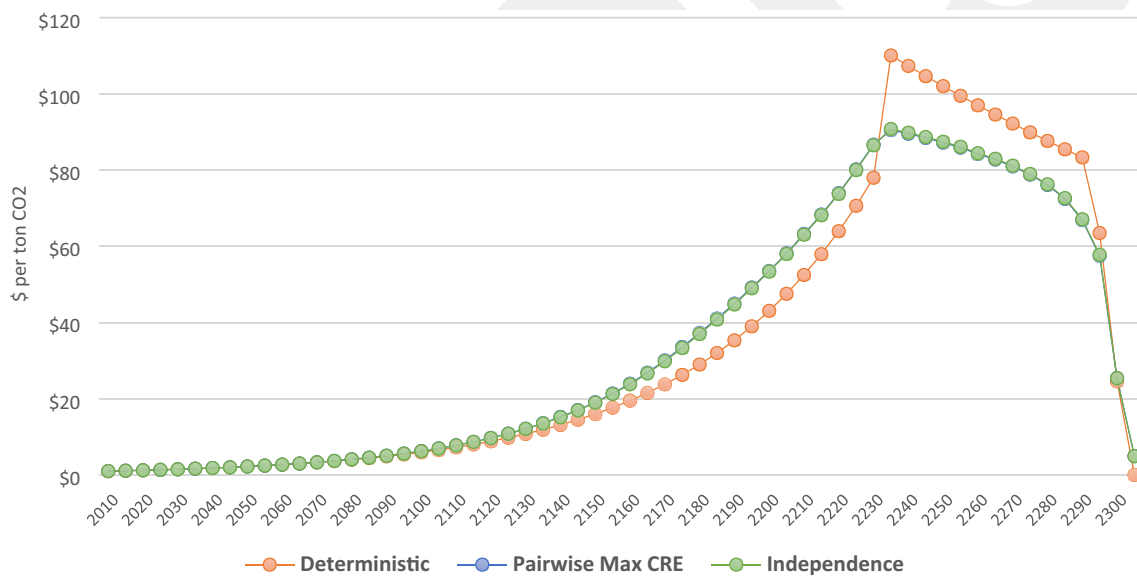
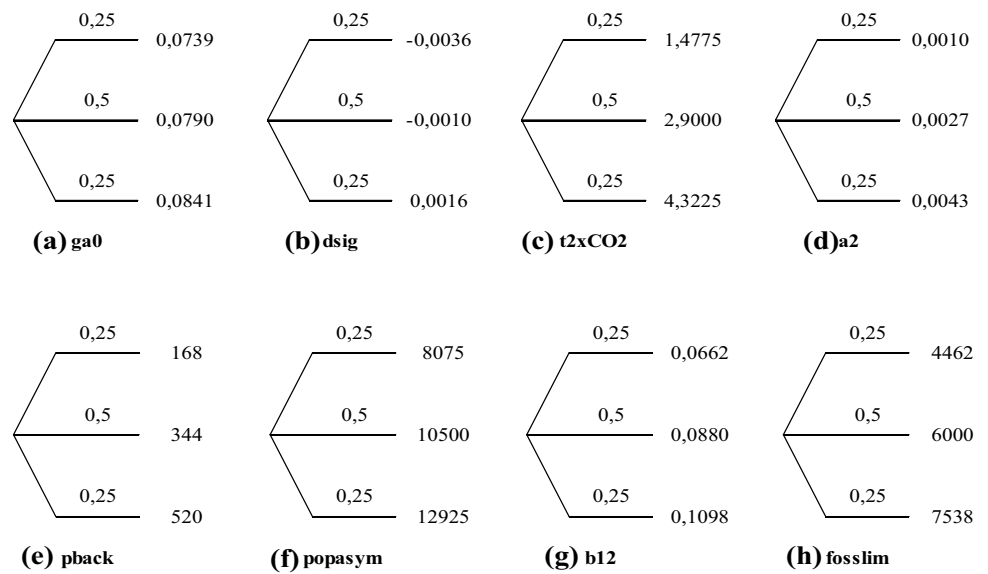
$R(t)$  in objective function is the discount factor and defined as

$$R(t) = (1 + \rho)^{-t} \quad (3)$$

where the pure rate of social time preference,  $\rho$ , is the discount rate which provides the welfare weights on the utilities of different generations. Equation 3 takes the total utility in each period and discounts it back to the present using the social discount rate ( $\rho$ ).

The objective function is non-linear in the DICE model and solved by non-linear optimization. Nordhaus divides the constraints into two groups; economic constraints and environmental constraints. The economic constraints of the

**Fig. 3** Decision trees of eight discretized variables of DICE model

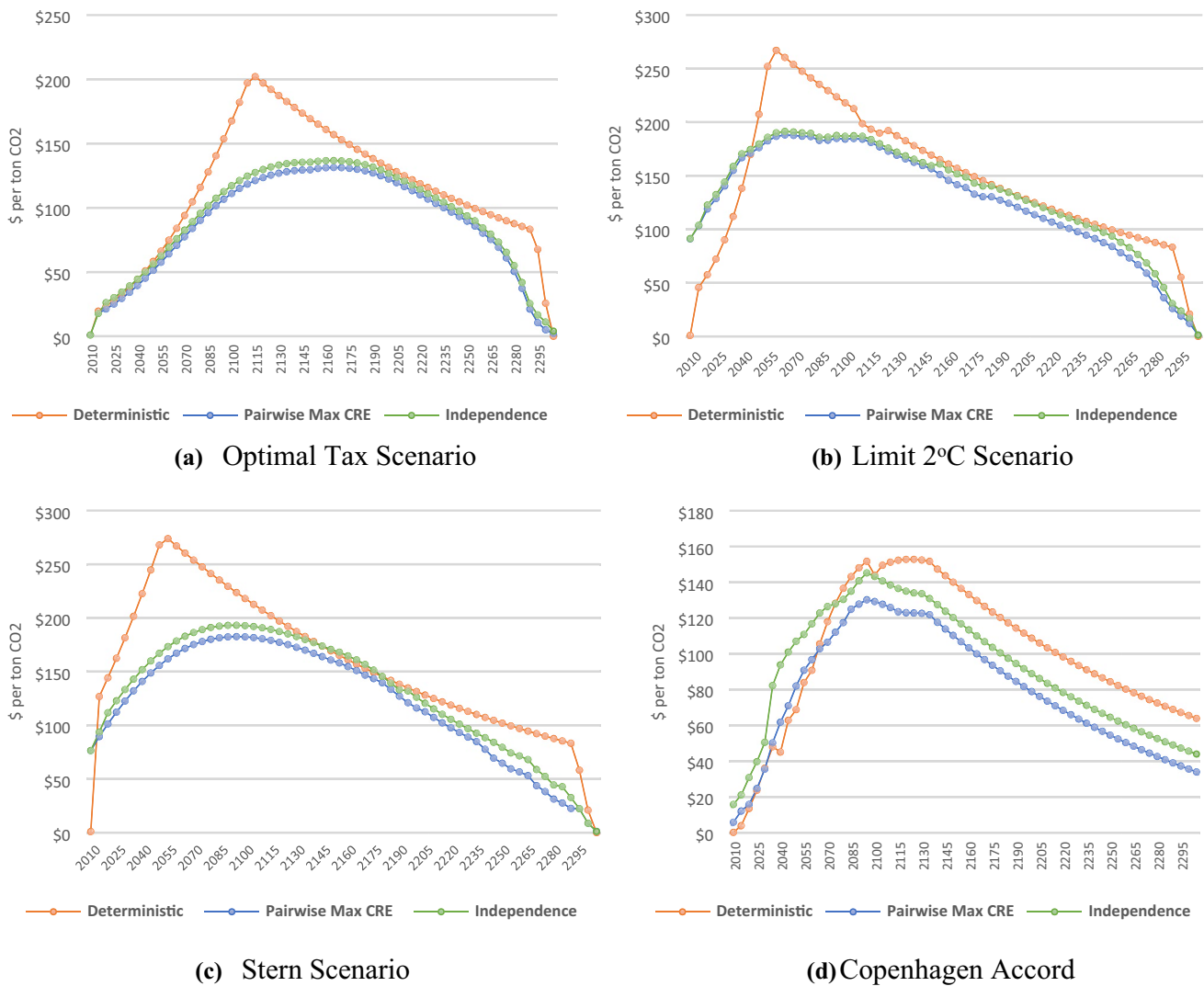


**Fig. 4** Carbon prices under no policy 2010–2300 for deterministic, independence, and dependence cases

DICE model are (i) output of the economy defined with Cobb–Douglas production function and (ii) the capital stock. Environmental constraints are (i) flow of emissions of greenhouse gases, (ii) concentration of GHGs in the atmosphere, (iii) change in temperature in atmosphere and shallow oceans, (iv) damage due to the temperature increase, and (v) economic cost of climate change policies.

### 2.2 Global warming policies used in DICE model

We now briefly explain the five different environmental policies that are used in our analysis. These policies are selected from the DICE-2013R model.



**Fig. 5** Carbon prices under alternative policies from 2010 to 2300 for deterministic, independence, and dependence cases

### 2.2.1 Baseline

The first policy is baseline policy which includes the existing policies as of 2010 and no new policies are taken to slow or reverse greenhouse warming. In this policy, several precautions or steps can be taken by individuals and companies to slow down climate change, but governments are assumed to take no steps to control or limit greenhouse-gas emissions.

### 2.2.2 Optimal

Optimal policy involves a balancing of the present value of the costs of abatement and the present value of the benefits of reduced climate damages. In this policy, emissions are set to maximize the value of net economic consumption. This is the best possible policy for emissions reductions, given the

economic, technological, and geophysical constraints that we have estimated.

### 2.2.3 Temperature limited

The aim of this policy is to limit the global temperature to 2 °C from the 1900 average (pre-industrial level). The constraints are adapted not to exceed 2 °C.

### 2.2.4 Stern review

This policy is recommended by the Stern Review and this policy use very low discount rates for climate-change policy. This was implemented using a time discount rate of 0.1 percent per year and a consumption elasticity of 1. This leads to low

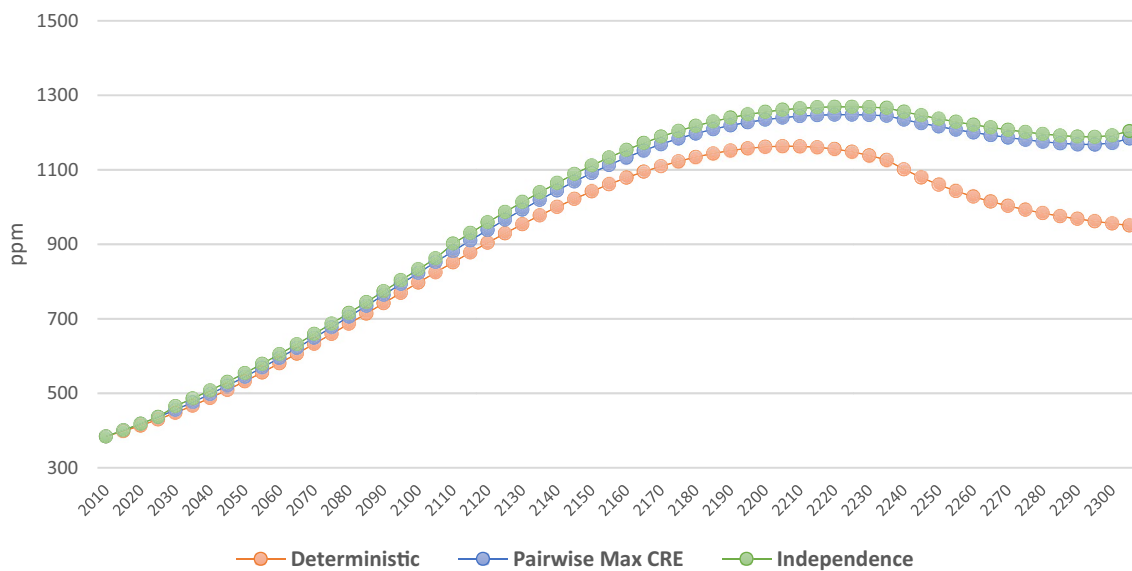


Fig. 6 Carbon concentration under no policy 2010–2300 for deterministic, independence, dependence cases

real interest rates and generally to higher carbon prices and emissions control rates.

### 2.2.5 Copenhagen accord

This policy is based on the Copenhagen Accord which is a continuation of the Kyoto Protocol. In this scenario, developed countries are assumed to implement deep emissions reductions over the next four decades, with developing countries following gradually.

## 3 Theoretical methodology

In this section, we discuss about the independence and dependence cases that we use in our analysis. First, we explain the independence case where this is the strong assumption in uncertain cases. Then, we discuss the dependence cases under uncertainty where Sutcu (2015) introduces maximum entropy with cumulative residual entropy and the maximum CRE model is used to integrate uncertainty into DICE model.

In independence case, if the marginal distributions of variables are known, then the joint probability distribution is equal to product of marginal distributions. For instance, if only marginal distributions of three variables,  $x, y, z$  are available, then the joint probability distribution as

$$p * (x, y, z) = p_x(x)p_y(y)p_z(z) \tag{4}$$

In the case of dependency, the core idea of Sutcu (2015)’s approach is to propose a method for approximating joint distributions from its lower order assessment using survival functions. If we want to incorporate dependence between variables into the maximum cumulative residual entropy formulation, we need to consider at least pairwise assessments between variables in addition to the marginal distributions of the variables. For instance, in the case of three variable decision problems, the available information should be marginal and/or pairwise assessments and the maximum cumulative residual entropy formulation of a three-variate joint distribution with the pairwise assessments is

$$\begin{aligned}
 S^*(x_{1i}, x_{2j}, x_{3k}) &= \arg \max - \sum_{x_{1i}, x_{2j}, x_{3k}} S(x_{1i}, x_{2j}, x_{3k}) \ln(S(x_{1i}, x_{2j}, x_{3k})) \\
 \text{s.t.} & \\
 \sum_{x_{3k}} S(x_{1i}, x_{2j}, x_{3k}) &= S(x_{1i}, x_{2j}) \\
 \sum_{x_{2j}} S(x_{1i}, x_{2j}, x_{3k}) &= S(x_{1i}, x_{3k}) \\
 \sum_{x_{1i}} S(x_{1i}, x_{2j}, x_{3k}) &= S(x_{2j}, x_{3k}) \\
 S(x_{1i}, x_{2j}, x_{3k}) &\geq 0
 \end{aligned}
 \tag{5}$$

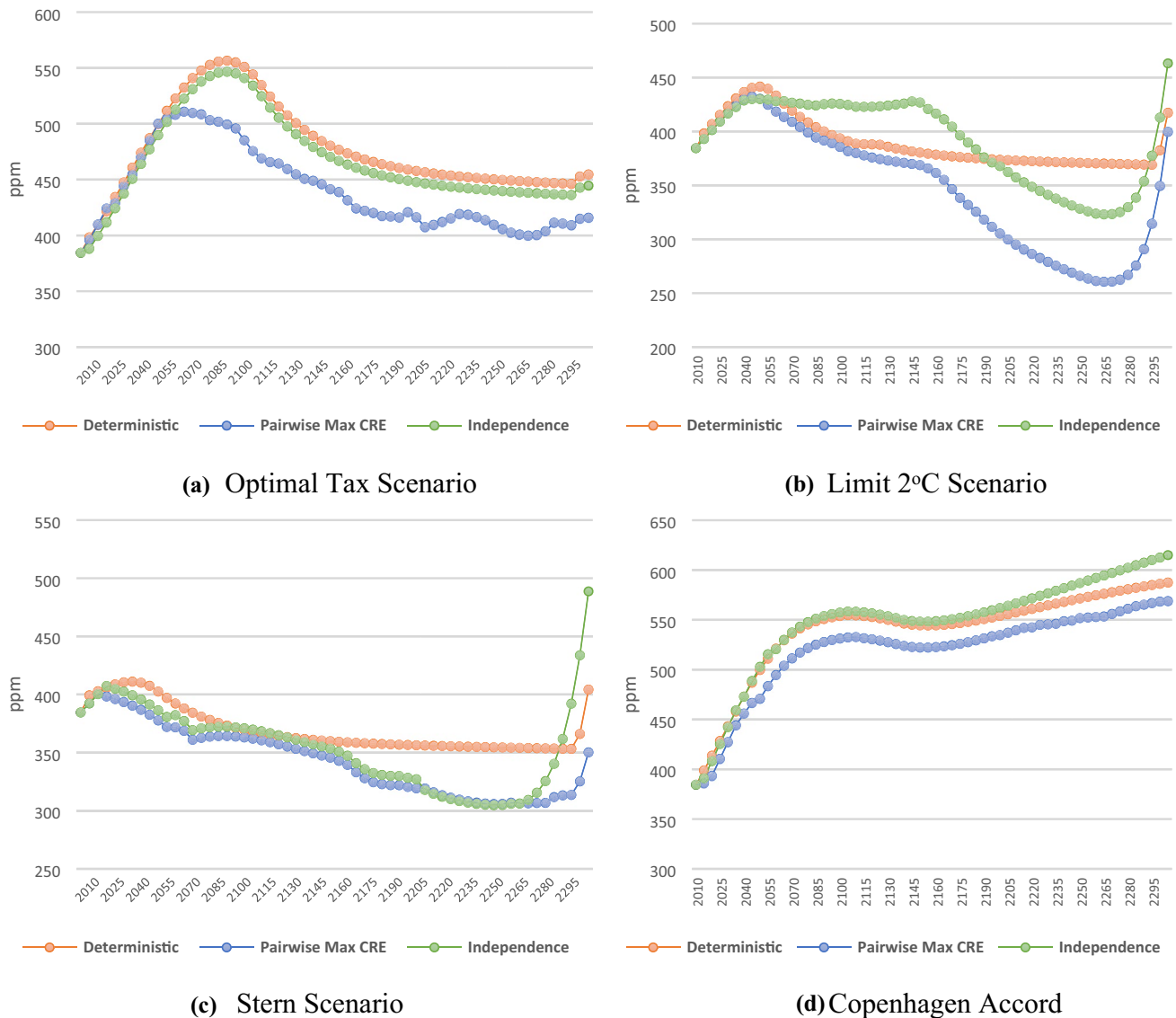
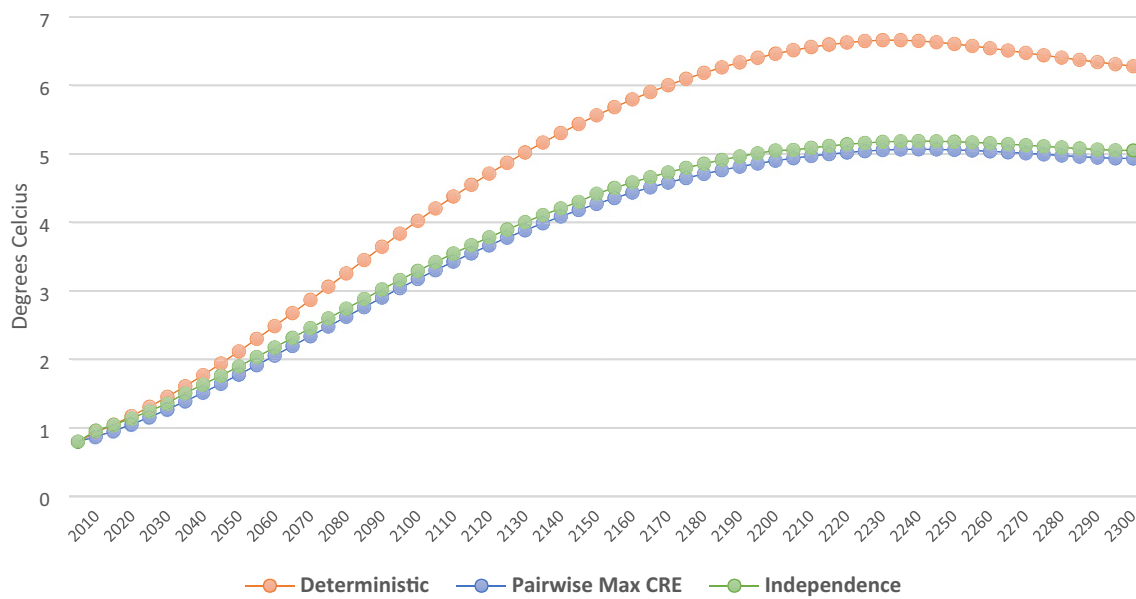


Fig. 7 Carbon concentration under alternative policies from 2010 to 2300 for deterministic, independence, and dependence cases

where  $x_{1i}$  refers to  $i$ th outcome of the first variable, and  $S(x_{1i}, x_{2j}, x_{3k})$  refers to the three variable joint survival function of the  $i$ th outcome of the first variable,  $j$ th outcome of the second variable,  $k$ th outcome of the third variable. The solution to the maximum cumulative residual entropy for three variables using pairwise assessments is  $S^*(x) = e^{-1 - \lambda_0 - \lambda_{ij} - \lambda_{i,k} - \lambda_{jk}}$ .

### 4 Analysis of the model

In this section, we discuss the uncertain variables and its parameters, the analysis of the model. Our purpose is to integrate climatic and economic uncertainties into the DICE model, and to find out what will be the cumulative impact of integrating uncertainty on climate change by applying CRE into the DICE model. The aim of the DICE model is to



**Fig. 8** Temperature increase under no policy 2010–2300 for deterministic, independence, dependence cases

maximize the present value of net welfare for the next sixty time periods where each period representing 5 years. We run the simulation for five different scenarios from 2010 to 2300. In the DICE model, there are eight different decision variables and each is discretized to three different values ( $3 \times 3 \times 3 \times 3 \times 3 \times 3 \times 3 \times 3$  joint distribution). We calculate our analysis for pairwise assessments of maximum entropy and maximum approximation CRE methods. We also calculate deterministic and independence cases.

Nordhaus pointed out eight critical uncertain parameters in the DICE model and we have selected these eight major parameters further study: uncertainties about the growth rate of total factor productivity ( $ga_0$ ), the rate of de-carbonization ( $dsig$ ), the asymptotic population growth ( $popasym$ ), the cost of the backstop technology ( $pback$ ), the damage-output coefficient ( $a_2$ ), the transfer coefficient of carbon dioxide ( $b_{12}$ ), the equilibrium temperature-sensitivity coefficient ( $t_{xCO_2}$ ), and the total availability of fossil fuels ( $fossilim$ ). Earlier studies have shown that these parameters have the largest impact on both outcomes and policies. The following table (Table 1) shows the marginal distributions of eight variables. We use the values given by Nordhaus in his books “A Question of Balance” (2008) and “DICE 2013R Manual” (2013) and assume that all the marginal distributions are from known families. All the variables in this analysis are normally distributed.

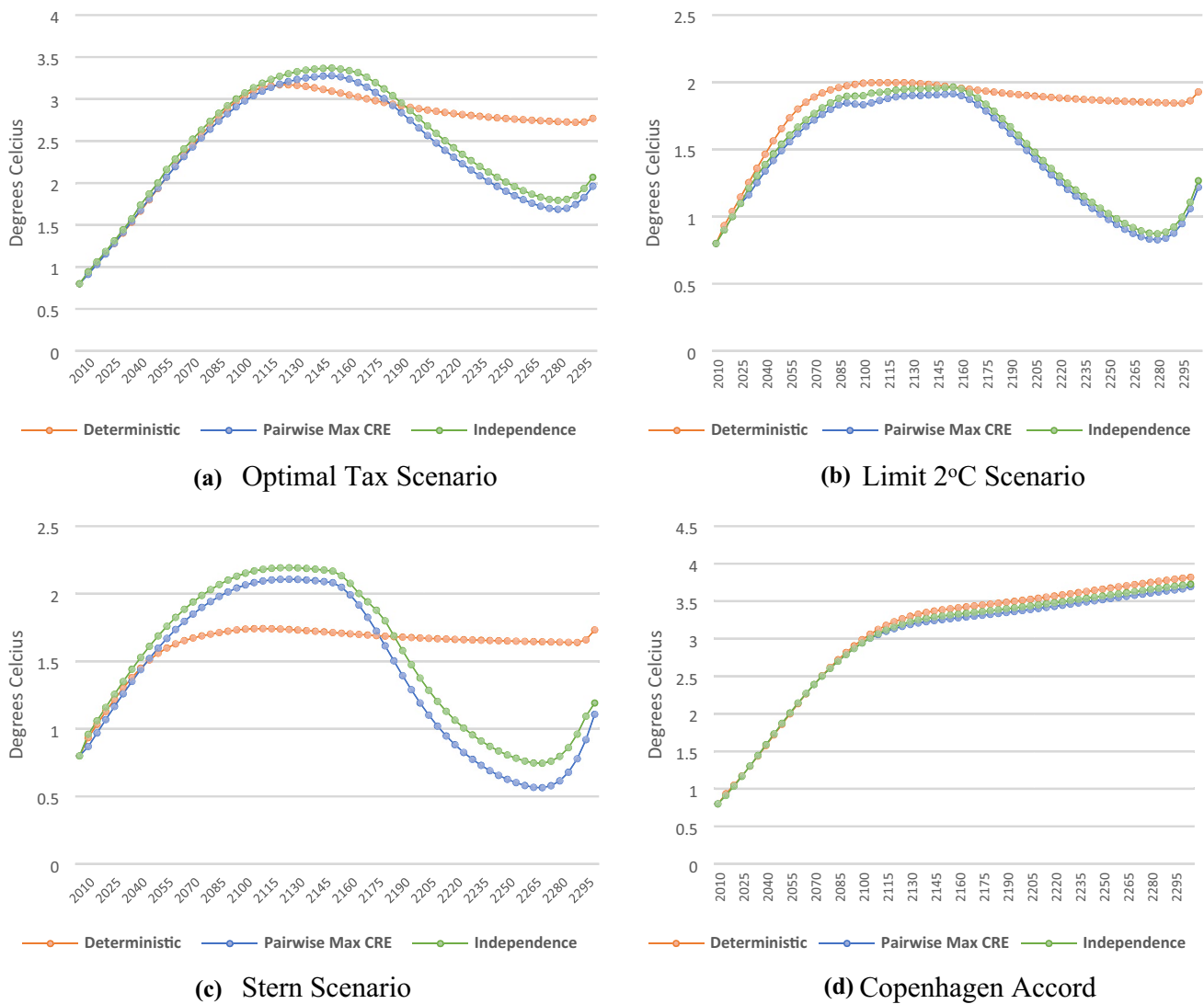
We discretized each variable by using the McNamee and Celona’s (1990) discretization method. We especially use

the shortcut of the McNamee-Celona which is called equal areas method. This method divides the cumulative distribution function into intervals between the  $P_{100}$  and the  $P_{75}$ , the  $P_{75}$  and the  $P_{25}$ , and the  $P_{25}$  and the  $P_0$ . This produces a weighting of 0.25, 0.50, and 0.25, respectively. This method weights the 10th ( $P_{10}$ ), 50th ( $P_{50}$ ), and 90th ( $P_{90}$ ) percentiles of probability distribution by 0.25, 0.50, and 0.25, respectively. 10% (Low), 50% (Base) and 90% (High) percentiles for each uncertainty using equal areas method are given in Table 2.

We also show the variables in a decision tree format with their three different outcomes using the low, base and high percentiles of each variable in Fig. 3.

## 5 Results of the analysis

Nordhaus (2013) used the DICE model to evaluate and compare a number of different environmental policies including; (i) baseline scenario, (ii) optimal tax scenario, (iii) limit temperature increase to 2 Celsius degrees, (iv) Stern scenario, and (v) Copenhagen Accord scenario. There are eight uncertain parameters in the DICE model, however Nordhaus assume that there is no uncertainty in the DICE model and fix all the uncertain parameters their mean values. In this study, our aim is to integrate uncertainty into the DICE model to understand whether uncertainty has any significant effect on the performances of the policies. We take an



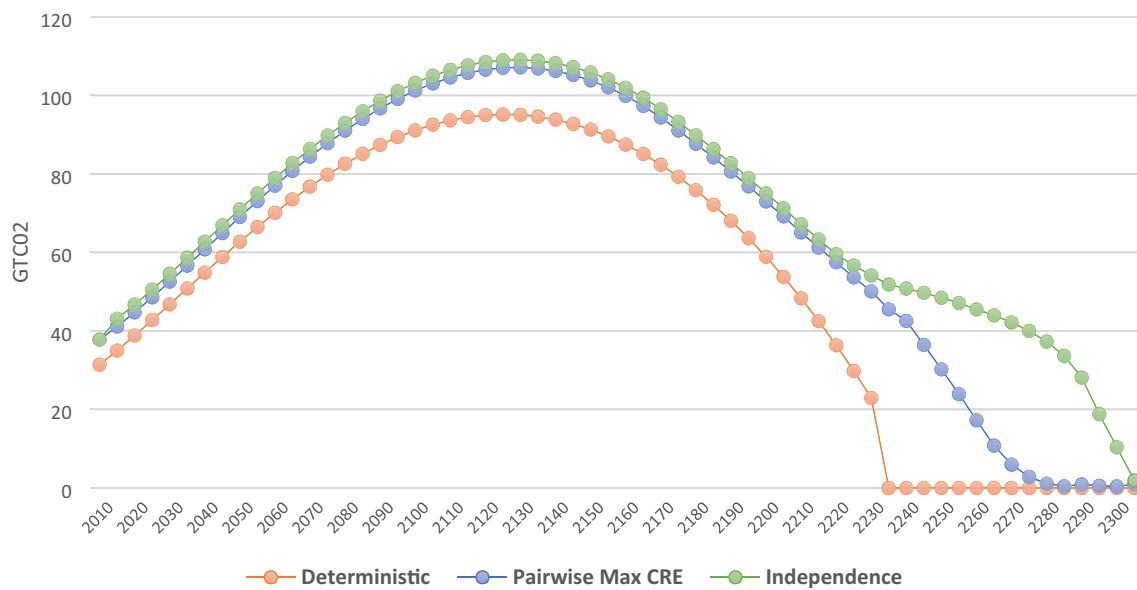
**Fig. 9** Temperature increase under alternative policies from 2010 to 2300 for deterministic, independence, and dependence cases

approach to handle the dependence between variables and uncertainty in the DICE model instead fixing the uncertain parameters to their mean values. We incorporate uncertainty into the DICE model by discretizing uncertain parameters. Then, we use the uncertain parameters in our analysis to generate joint probability distributions of eight uncertain parameters using our proposed methods to evaluate and compare the expected performances of different policies.

To understand whether uncertainty significantly affects decision-making and welfare consequences, three different optimizations are performed. We first assume that there is

no uncertainty in the model and fix the values of each uncertain parameter into their mean values same as the Nordhaus' analysis. Our second approach assumes that the parameters are uncertain but they are independent. Finally, we don't assume any independence among variables and take into consideration dependence among variables and integrate it into the DICE model.

In this study, we consider five different types of performance measures to compare and evaluate different global warming policies. We prefer to use performance measures often used in the literature. The performance measures are



**Fig. 10** Total carbon emission under no policy 2010–2300 for deterministic, independence, dependence cases

(i) carbon price or social cost of carbon which is optimized from the second period, (ii) carbon concentration in the atmosphere, (iii) average global temperature increase above preindustrial level, (iv) total carbon emission, and (v) net output of abatement cost and climate damages.

The following figures show the results of the analysis. Figures 4 and 5 show the results for the optimal carbon prices, Figs. 6 and 7 show the results of average carbon concentration in the atmosphere, Figs. 8 and 9 show the results of global temperature increase above preindustrial level, Figs. 10 and 11 show the results of total carbon emission, Figs. 12 and 13 show the results of net output of abatement cost and climate damages for five climate change policies.

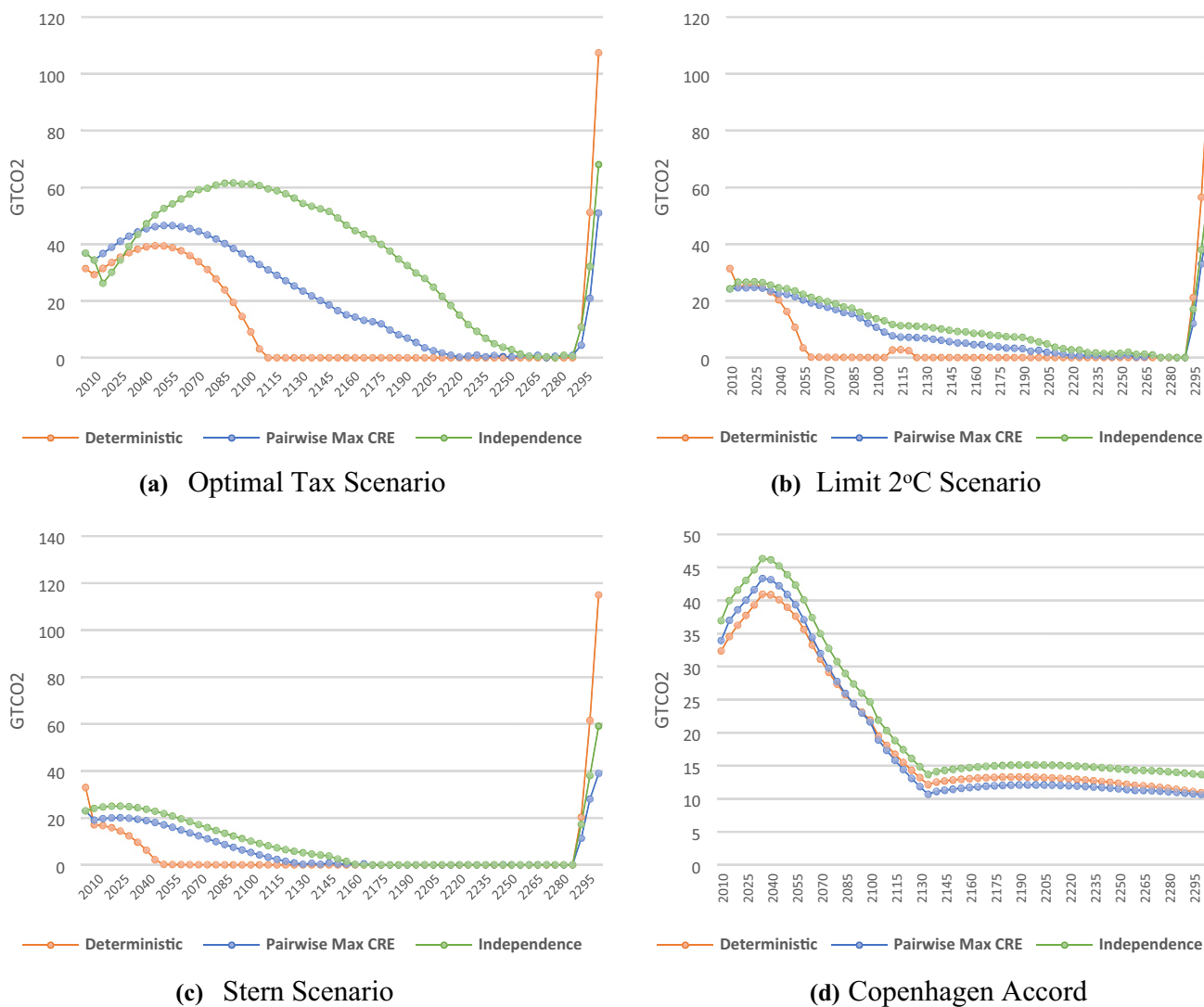
The results of the simulation experiments indicate that uncertainty does in fact matter and uncertainties about the future cannot be eliminated. Ignoring uncertainty could limit our capability to take corrective actions in the future, could result in poor policies, could lead to inefficient use of resources, and some of the important circumstances about global warming could have been avoided.

In the short-run, the difference between the deterministic case, independence case, and uncertain case is very small. In the long-run, however, deterministic assumption in which all uncertainties are ignored leads to an underestimate of

average carbon prices between 2100 and 2200, and after 2200, deterministic case leads to an overestimate of carbon prices for the baseline scenario. For the other more aggressive scenarios, the carbon prices for deterministic case is much higher than the uncertain case after 2050.

The results for the carbon concentration in the atmosphere show a similar behavior to the carbon prices. In the twenty-first century, ignoring uncertainty overestimated carbon concentration in the atmosphere. By starting the twenty-second century, the rate of carbon concentration decreases significantly when uncertainty is considered. Uncertainty clearly has a dramatic effect on the future path of the carbon concentration and average carbon prices, but with a relatively small consequence for immediate decisions. Also, these results show that the carbon concentration in the atmosphere is negatively correlated to carbon prices. As the carbon prices increases, the carbon concentration decreases gradually.

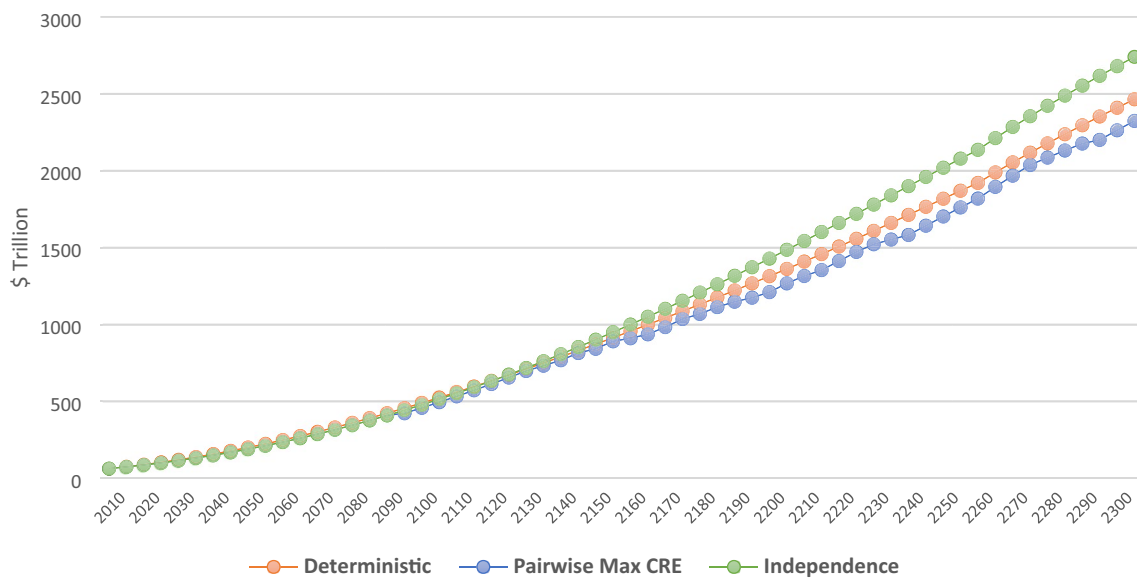
When we analyze the results for temperature increase performance measure, from Figs. 8 and 9, we can say that the results are very similar for deterministic and uncertain cases up to 2100, however after 2150, the temperature increase is overestimated by the deterministic method. The temperature goes almost constant under deterministic case after 2150 but



**Fig. 11** Total carbon emission under alternative policies from 2010 to 2300 for deterministic, independence, and dependence cases

decrease sharply in the case of uncertainty for optimal tax, limit 2 °C, and stern scenarios. Significantly, the expected change in mean global temperature associated with the Optimal tax, Stern, and Limit 2 °C scenarios are never greater than 3.5 °C above the pre-industrial norm, peaking in the year 2150 for three scenarios. For Baseline and Copenhagen Accord scenarios, the temperature is increasing gradually for all time periods and gives similar result under uncertain, independent, and deterministic conditions. Also, temperature increase is inversely proportion to carbon prices and directly proportion to carbon concentration. These results are reasonable because as the prices of carbon increases, people and companies prefer to use less carbon-based fuels which helps to decrease both carbon concentration and average temperature increase from the preindustrial level.

For total carbon emission, the results are very different compare to the other performance measures. The results are closer under uncertain and certain situations for baseline scenario however, in other four scenarios the total carbon emission decrease to zero around 2060 under deterministic condition which doesn't make sense. If we assume that all the values of uncertain parameters fix to their mean values, these results show that optimal tax, limit 2 °C, Stern, and Copenhagen scenarios are very powerful and achieve the desired goals in a short time. However, in reality, it takes a long time to reduce carbon emission and the damages due to the temperature increase near zero in the long run. If we compare the results with carbon concentration then we can also say that this is impossible in a short period of time. The results under uncertainty, however, make sense because the



**Fig. 12** Net output under no policy 2010–2300 for deterministic, independence, and dependence cases

carbon emission downs to zero after 2200 which means that after 200 years later the policies have an effect on people and companies to decrease carbon emission and temperature increase.

Ignoring uncertainty in the net output of abatement cost and climate damages initially very similar under uncertain and deterministic conditions, however deterministic case leads to an overestimation of costs and damages for all scenarios because carbon intensity may decrease at a faster rate under uncertainty, and abatement costs are assumed to be directly proportional to carbon intensity.

From Figs. 12 and 13, the estimate values of net values of abatement costs and climate damages under certainty is very similar to net values under uncertainty. Also, the graphs show very similar behavior as time periods increases. It seems like deterministic case is competitive to the uncertain case because net present values under deterministic and uncertain cases are very close. However, assuming certainty about the future while making global warming decisions is clearly not true in the majority of the policies and performance measures. Although the net present values under deterministic and uncertain cases are close, the average values of temperature increase, and carbon emission show that making decisions under certainty about the global warming may lead to catastrophic climate change.

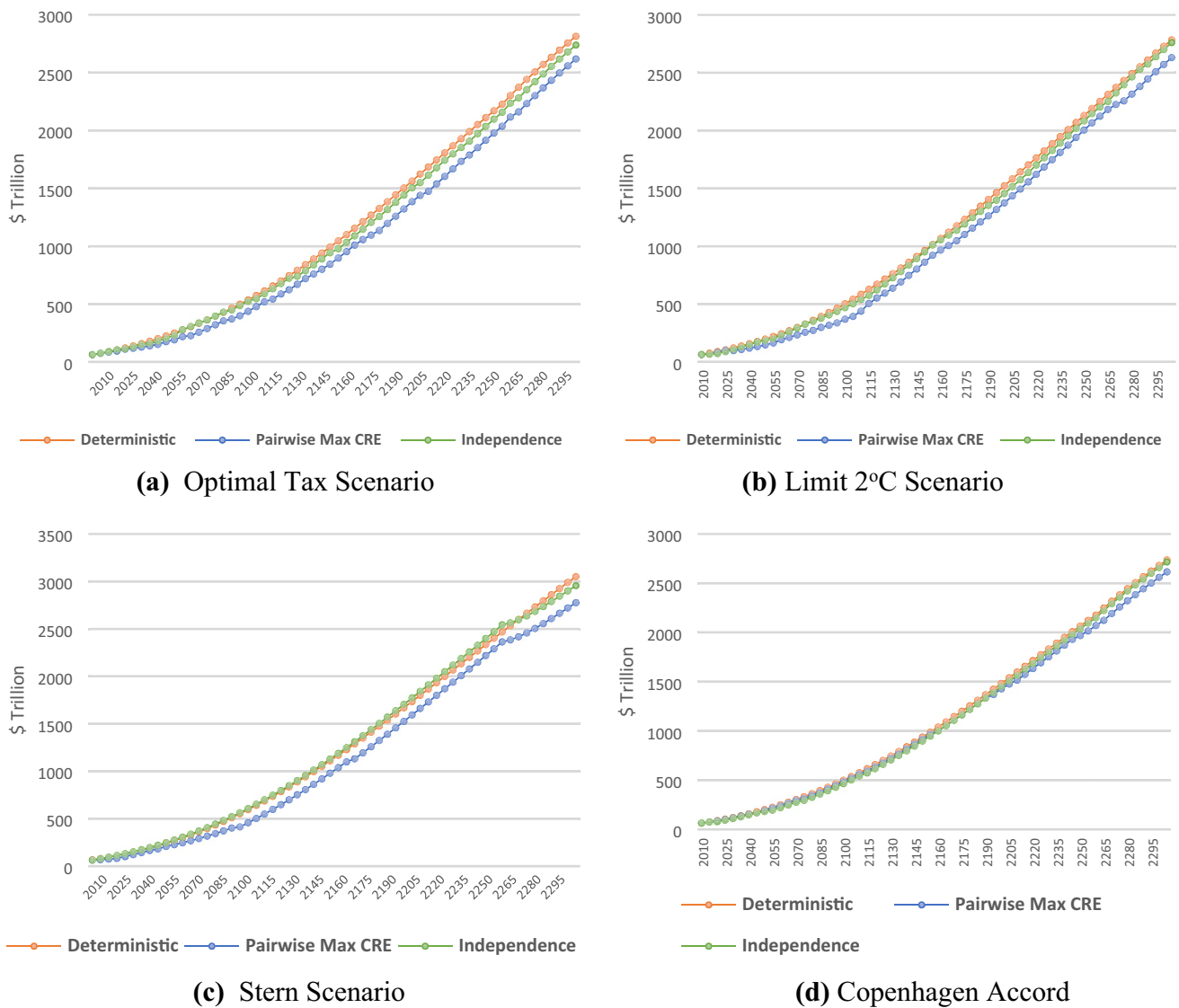
Ignoring uncertainty in temperature increase, net output of abatement cost and climate damages, and carbon price performance measures causes overestimation of the benefits

for all scenarios, but ignoring uncertainty causes slightly underestimation for total carbon emission and significant underestimation for carbon concentration. If there is not enough information to assume that the parameters are deterministic or independent, then dependence among variables and uncertainty should be considered into the global warming decisions as such dependence and uncertainty may have a significant impact on climate change and global warming decisions.

We also calculate the average values and standard deviations of each policy for all performance measures under deterministic and uncertain cases. The following table (Table 3) shows the mean and standard deviation values of five output variables from 2010 to 2300; the optimal carbon price, carbon concentration in the atmosphere, temperature increase from the preindustrial level, total carbon emission, and the net output of abatement cost and climate damages.

The results in Table 3 show that if uncertainty take into account, there is a significant impact on all performance measures and substantial change on the average values of all performance measures. However, the results under independence case are slightly different than pairwise assessment case. Then handle dependence among variable by using pairwise assessments may have very little impact on the average values of performance measures.

Also, if we analyze the results for carbon prices, we can easily say that deterministic case leads to an overestimate of carbon prices for the all scenarios. Moreover, the average



**Fig. 13** Net output under alternative policies from 2010 to 2300 for deterministic, independence, and dependence cases

value of global temperature increase associated with the Limit 2 °C and Stern scenarios is lower than 2 °C above the pre-industrial norm under deterministic and uncertain cases, however, there is a 0.4 °C difference, which is huge for our earth and for us, between the average temperature increase under deterministic case and the average temperature increase under uncertainty.

## 6 Conclusion

There are many important uncertain variables that affect global warming. However, these variables are generally accepted as deterministic when integrating them into economic and global warming models. In this paper, we

take into account the climatic and economic uncertainties because climate change, long-term economic development, and their interactions are highly uncertain. Climatic and economic uncertainties are integrated into the DICE model, and to find out what will be the cumulative impact of integrating uncertainty on climate change by applying CRE into the DICE model.

While uncertainty integrated into DICE model, we first assume that the variables are independent. However, if there is no ground for assuming independence, then dependence among those key uncertain parameters should be considered into the global warming modeling as such dependence may have a significant impact on global warming decision-making. We then integrate dependency among variables using maximum cumulative residual entropy method.

**Table 3** Mean and standard deviation of each performance measure under each policy 2010–2300 for deterministic, independence, and dependence cases

Scenarios	Method	Carbon price <sup>a</sup>		Carbon concentration <sup>b</sup>		Temperature <sup>c</sup>		Total carbon emission <sup>d</sup>		Net Output <sup>e</sup>	
		Mean	St. Dev	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev	Mean	St. Dev
Base	Deteministic	34.33	36.72	893.09	246.77	4.78	1.96	52.65	35.98	1040.83	731.69
	Pairwise Max CRE	34.00	32.77	967.87	289.95	3.71	1.43	64.69	35.43	985.12	689.34
	Independence	33.98	32.82	984.26	295.90	3.83	1.44	71.73	28.51	1123.18	829.76
Optimal	Deteministic	112.22	52.99	476.55	41.23	2.60	0.62	13.32	20.45	1171.02	860.20
	Pairwise Max CRE	86.76	41.15	440.35	36.72	2.35	0.70	21.12	17.77	1039.70	799.05
	Independence	91.66	41.75	466.72	40.87	2.44	0.71	35.92	21.55	1126.36	831.78
Limit 2C	Deteministic	143.83	64.95	389.67	22.08	1.81	0.27	6.63	16.95	1177.75	859.55
	Pairwise Max CRE	128.14	50.79	347.94	56.23	1.44	0.39	9.74	10.39	1066.94	823.19
	Independence	134.26	49.48	391.67	39.74	1.48	0.40	12.36	11.17	1145.03	848.00
Stern	Deteministic	155.64	65.65	370.25	19.24	1.61	0.20	5.42	17.49	1290.23	941.65
	Pairwise Max CRE	120.40	53.65	343.70	30.02	1.40	0.56	6.59	9.13	1167.55	889.50
	Independence	130.17	54.31	355.78	37.50	1.52	0.53	9.45	11.97	1302.19	937.06
Copenhagen	Deteministic	100.28	4.029	539.68	46.12	3.02	0.85	19.42	10.16	1151.36	836.98
	Pairwise Max CRE	79.21	34.79	519.21	44.53	2.94	0.79	19.19	11.34	1103.49	795.44
	Independence	91.97	35.39	547.35	52.19	2.97	0.81	22.20	11.34	1122.52	836.18

(a) \$ per ton

(b) ppm

(c) Degrees celcius

(d) GTCO2

(e) \$ trillion

The results show that if uncertainty considers, there is a significant impact on all performance measures and substantial change on the average values of all performance measures. However, the results under independence case are slightly different than deterministic case. Then, as a conclusion, we can say that handling dependence among variables may have very big impact on the average values of performance measures.

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**Data availability** The raw/processed data required to reproduce the above findings cannot be shared at this time due to legal/ ethical reasons. The dataset used to analyze are available from the corresponding author upon request.

**Declarations**

**Conflict of interest** Muhammed Sütçü declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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