Hindawi
Discrete Dynamics in Nature and Society
Volume 2021, Article ID 5540452, 14 pages
https://doi.org/10.1155/2021/5540452

Research Article

Climate Change Vulnerability and Key Adaptation Trajectory of the Regional Economic System

Pengbang Wei, Yufang Peng, and Weidong Chen

College of Management and Economics, Tianjin University, Tianjin 300072, China

Correspondence should be addressed to Weidong Chen; chenweidong@tju.edu.cn

Received 5 January 2021; Accepted 11 May 2021; Published 24 May 2021

Academic Editor: Victor Shi

From the microperspective, climate change restricts human life in many aspects, and it affects the regional economic system from the macroperspective. The paper presents an inoperability input-output model (IIM) that is an extension approach of the Leontief input-output model. The IIM is able to provide a feasible methodology for measuring the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. The IIM is applied in Tianjin to explore its dilemmas facing the increased demand for electricity, water, and public health service sectors under the RCP2.5, RCP4.5, and RCP8.5 climate scenarios. The results indicated that the inoperability ranking of all economic sectors is the same under the three climate scenarios. The key adaptation trajectory in Tianjin is S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. The costs required by the key adaptation trajectory to adapt to climate change account for more than 90% of that required by the whole economic system. These results can be helpful for policy-makers to prioritize sectors in terms of climate adaptation and understand the efficacy of climate change risk mitigation strategies.

1. Introduction

Due to the considerable inertia of greenhouse gases, even if the current greenhouse gas emissions are not increasing, global warming is expected to continue in the coming decades, which may bring significant risks related to climate warming to present and future generations [1, 2]. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, a list of abbreviations and symbols for the manuscript is shown in Table 1) [3], global climate warming is likely to accelerate and cause more frequent extreme climate events, making human beings and regional economic systems more vulnerable to climate change. Failure to effectively adapt to climate change could lead to serious short-term and long-term problems, which could result in huge costs to regional development [4].

A significant feature of climate change is that its impact is no longer within fixed sector boundaries [5]. Similarly, when climate change adaptation strategies primarily focus on individual sectors, it can be useless or only be valuable on a smaller scale. When some individual economic sectors in the regional economic system are affected by climate change, the sectors cannot operate normally and cannot recover quickly by themselves, which may further lead to many other sectors unable to operate as planned, and even threaten the security of the regional economic system. Therefore, more and more scholars are calling for a more holistic understanding of climate vulnerability and key adaptation trajectory of the regional economic system to coordinate the efforts of various sectors to improve the regional capacity to adapt to the inevitable climate change [6].

These climate change impact and risk may also restrict human life in many aspects [7]. Climate change adaptation aims to reduce or manage the impact of climate change on people's lives, which is bound to increase regional demand for electricity [8], water [9, 10], and health services [11, 12]. The best climate change adaptation practice in a region depends on the reasonable combination of available resource endowment and its optimal allocation [13]. Due to the limitation of social wealth accumulation, the cost of adaptation to climate change cannot be afforded by the individual vulnerable sectors [14]. Therefore, it is of great significance

Table 1: List of symbols for the manuscript.

Symbol	Description
IIM	Inoperability input-output model
IPCC	Intergovernmental panel on climate change
AR5	IPCC's fifth assessment report
RCPs	Representative concentration pathways proposed in IPCC's AR5
x_i	The output of sector i
x_{ij}	Intermediate demand of sector j from sector i
y_i	Final demand of sector i
a_{ij}	Direct-input coefficient
X	Sector outputs vector
A	Technological coefficient matrix
Y	Final demand vector
L	The Leontief inverse matrix
x_j^s	Production capacity of sector j
$b_{ij}^{(s)}$	Direct-output coefficient
v_j	Value-added component
$(X^s)^T$	Row vector of sector supply
$B^{(s)}$	Direct-output coefficient matrix
V^T	Row vector of value-added items
G	The output inverse matrix
x_k^d	Total regional demand for the products of sector k
x_k^s	Product supply of sector k
$V^{(d)}$	The value-added vector required by the economic system when the social final demand have changed
q	The sector inoperability vector of the economic system
V	The current value-added vector of the economic system
$\mathrm{diag}(V)$	a resulting diagonal matrix constructed from the given vector V
K	The sector resilience coefficient matrix
T	Temperature anomaly in period t
Elec_t	Electricity demand in period t
$\overline{\mathrm{Elec}_t}$	Electricity demand in period t without climate warming
Wate_t	Water demand in period t
$\overline{\mathrm{Wate}_t}$	Water demand in period t without climate warming
Heal_t	Regional demand for health service in period t
$\overline{\mathrm{Heal}_t}$	Regional demand for health service in period t without climate warming

to identify the key adaptation trajectory in the economic system and to further promote the efficiency of the regional economic system to adapt to climate change.

In the field of climate vulnerability and climate adaptation study, current research on the economic system climate adaptation indicates that theoretical explanations for regional economic system climate vulnerability and the key adaptation sectors are not very clear [15]. To this motivation, the paper tries to cast light on the regional economic system climate vulnerability and the key adaptation trajectory by integrating insights on the increasing demand required by adaptation to climate change, and the regional supply capacity constraint.

The remainder of this paper is organized as follows: Section 2 reviews the related literature about climate change vulnerability and climate adaptation. Section 3 elaborates the methodological framework. Section 4 presents an empirical analysis, followed by some conclusions and policy implications of the paper in Section 5.

2. Literature Review

How to adapt to climate change is a complex issue, which involves many aspects of knowledge in many fields. In this section, we introduced a series of studies related to adaptation to climate change. We conduct a systematic literature review on the driving factors and obstacles of climate change adaptation, which economic sectors are vulnerable to climate change, and key points for adapting to climate change in different regions. The existing kinds of literature are of great help to further study the climate change vulnerability and key adaptation trajectory of the regional economic system in this research.

The terminology of climate change adaptation was first proposed by the Assessment Reports of the IPCC [16], and it was dominated by general and ambiguous terms when climate change vulnerability assessment was the major field of adaption research. The diverse aspects involved together with the lack of a holistic understanding of them constitute many barriers to collaboration across disciplines in climate change adaptation studies [17].

In the last decades, more and more studies tried to find out the driving factors and obstacles of regional adaptation to climate warming, especially after the emergence of the Private Proactive Adaptation to Climate Change model proposed by Grothmann and Patt [18]. Due to the lack of systematic tools to study climate change adaptation, most research mainly focuses on qualitative research and metaanalysis of adaptation case studies. More effort is needed to better understand climate change vulnerability and facilitate the region to formulate practical strategies for climate change adaptation, especially on its aspects related to the economic conditions.

Scholars try to open the door to climate change adaptation research by studying which economic sectors are more vulnerable. The electricity sector is the first sector that attracts the attention of scholars. The literature has extensively studied how climatic variables, especially temperature, influence electricity consumption. This relationship has received increased attention in light of potential climate change because social electricity demand is increasing due to climate change. Eskeland and Mideksa explored the relationship between electricity consumption and outdoor temperature in thirty-one European countries, and their results illustrated that temperature has a statistically significant effect on electricity demand [19]. Deschênes and Greenstone suggested that the net effect of climate warming over the 21st century is likely to increase electricity demand substantially [20]. Auffhammer and Aroonruengsawat simulated the impact of warming temperatures caused by climate change on residential electricity consumption in California, and they suggested that holding the population constant, the total electricity fee for the households may increase by up to 55% by the end of the century [21]. In addition to the increasing effect, Auffhammer et al. thought the impact of climate change on the frequency and intensity of peak load will be greater [22]. Li et al. explored how electricity demand would change in Shanghai (China) in the context of climate change, and they found that a 1°C increase in daily temperatures may lead to around a 14.5% increase in electricity demand [23].

The water sector is also one of the most vulnerable sectors, which has attracted many scholars' attention. Trærup and Stephan studied the role of the water sector in the context of climate change in Lebanon, and they thought that the regional demand for water is inevitably increasing in order to adapt to climate change and water-saving technologies would be necessary in the future [24]. Harrison et al. explored cross-sectoral impact of climate change in Europe and they believed that the water sector was the key sector for regional climate change adaptation strategies [25]. Lengoasa studied the impact of climate change on water availability and considered that water security is critical for climate change adaptation [26]. Kundzewicz et al. conducted a brief assessment of climate change and associated impact on the water sector in Poland, and they suggested that ensuring the supply for various types of water is the basis of regional climate change adaptation strategies [27]. Verbist et al. conducted a vulnerability test for climate change impact on water security using climate risk-informed decision analysis, and the results emphasized the vulnerability of water sector to climate change [28].

As the threat of climate change to human health is becoming more and more obvious, the health sector has been increasingly concerned by many scholars. Both epidemiology and economics literature pointed out the detrimental effects of climate warming on mortality, prenatal health, and human health in recent years [29]. Numerous recent studies have investigated the impact of climate change on the health care and social welfare sector, both in developed and in developing countries [30, 31]. The Lancet suggested that human health has been now recognized as one of the most serious influenced areas of climate change and therefore should be a global research priority [32]. Gökçeku and Al-othman showed the health impact of climate change with projected trends in climate-related health, and they thought that climate change may affect human health in many ways: through the influences on disease environment and through changes in the daily temperature [30]. Ye et al. considered climate change is affecting human health in a profound manner, and it contributes to the regional burden of disease, which increases the demand for the health sector and makes health services scarce, especially in developing countries [11].

There are also some studies conducted on how regions and/or countries have adapted to climate change, especially in vulnerable areas. Hinkel et al. assessed the sea-level rise impact on Africa at continental and national scales as well as the benefits of applying climate adaptation measures, and they thought that in 2100, 16–27 million people would expect to be flooded per year, and annual damage costs range between US$ 5 and US$ 9 billion if no adaptation takes place [33]. Costa et al. estimated the costs of climate adaptation in developing regions by an empirical approach, and they suggested that the investments associated with the understanding and planning of climate adaptation be more significant when compared with implementing infrastructure [15]. Canosa et al. (2020) thought that climate adaptation is a priority for Arctic regions that suffer more from climate change globally, and they suggested that adaptation should be a central component of climate policy [34]. Petzold et al. studied the role of indigenous knowledge on climate change adaptation through a global evidence map of academic literature, and their results showed that there are adaptation knowledge gaps in northern and central Africa, South America, northern Asia, Australia, and urban areas [35]. Ledda et al. found out that the current climate adaptation plan in many regions could not fully work because of failing to include key adaptation sectors and actions [36]. To design effective regional climate adaptation plan, decision-makers need a state-of-the-art, regional, and sector-specific knowledge [37].

When reviewing the literature on climate change adaptation, we find that most of them focused on a single aspect of the economic system or focused on specific adaptation measures. It is necessary to scale-up insights from a single sector study to multisector economic system research on climate change adaptation. The shift toward economic system research methods requires complementing previous work on climate change vulnerability and climate adaptation with some comprehensive social science perspective. Climate change vulnerability and climate adaptation research is a typical transdisciplinary study field involving various methods originating from both natural and social science disciplines [38].

Climate change adaptation has become a practical necessity, which has been progressing from around fields concerning adaptation costs and benefits to a much wider array of aspects, related to the economic institution, development, and equity, as highlighted by the emerging climate adaptation science [39]. Hence, the array of methods applied needs to expand considerably and especially in the domain of social sciences. The input-output model and its extension approaches are particularly valuable in analyzing such dilemmas as they are adept in investigating how economic conditions give rise to certain types of regional dilemma [40]. The input-output approaches provide a possible method for regional climate adaptation research to deepen understanding of economic system climate vulnerability and key adaptation trajectory, and then formulate targeted solutions.

The aim of this study is to provide a feasible methodology for measuring the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. While climate change directly affects many sectors, the paper can only partially select some of the most vulnerable sectors as original inducing sectors due to the lack of quantifying functions applied in measuring how climate change directly affects their demands. Nevertheless, we hope that the study can advance the disclosure of this significant and complex field of climate change vulnerability and climate adaptation in a relatively clear and structured manner.

3. Methodology

The input-output model was proposed by W. W. Leontief and has been adopted and developed by many scholars [41]. With the help of the input-output technique, we attempt to explore the response of the whole regional economic system and the key climate adaptation trajectory when some vulnerable sectors are directly affected by climate change. In our modelling framework, we take into account sector supply capacities because of the constraints of production resources.

3.1. Input-Output Model Background. The basic Leontief input-output model is mainly constructed from the observed economic data for a specific geographic area (nation, city, county, etc.). The model is elaborating on the activity of a set of industries that both produce goods (outputs) and also consume goods from other industries (inputs) in the process of producing each industry's own products. The model exhibits the economic activity among regional sectors, concerned with exploring the interdependency of a region's producing and demanding units based on their cross transactions. Its based data are the product/service flows from each of the sectors (as a producer) to each of the sectors (as a purchaser), where the interindustry flows are measured for a particular time period (usually in one year) and in monetary terms. The Leontief input-output model helps itself well to showing the interdependencies of the economic system. It is usually being used to analyze multisector modelling for policy analysis from the whole regional perspective. An economy system can be expressed by the Leontief input-output model as shown in Figure 1.

As shown in Figure 1, consider n sectors in the economic system, and the row balance equation is given as

$$x_i = \sum_{j=1}^{n} x_{ij} + y_i \Leftrightarrow x_i = \sum_{j=1}^{N} a_{ij}x_j + y_i, \quad i, j = 1, 2, \ldots, n, \tag{1}$$

where x_i is the output of sector i, x_{ij} is the intermediate demand of sector j from sector i, y_i is the final demand of sector i, and a_{ij} is the direct-input coefficient ($a_{ij} = x_{ij}/x_j$). Let

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}, \quad Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}. \tag{2}$$

The Leontief input-output model can be described in the following matrix form:

$$X = AX + Y, \tag{3}$$

where X is the sector outputs vector, A is the technological coefficients matrix, and Y is the final demand vector. Here, equation (3) is parallel to equation (1), which is generally used to denote a set of linear equations. Equation (3) is just a standard form in input-output analysis, and the difference between equations (3) and (1) is purely notational.

Let I be the $n \times n$ identity matrix, that is, ones on the main diagonal and zeros elsewhere:

$$I = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}, \tag{4}$$

then

$$(I - A) = \begin{bmatrix} (1 - a_{11}) & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & (1 - a_{22}) & \cdots & -a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{n1} & -a_{n2} & \cdots & (1 - a_{nn}) \end{bmatrix}. \tag{5}$$

And then the $n \times n$ economic system shown in equation (3) can be expressed as follows:

	Industry		
Industry	Intermediate transaction $\{x_{ij}\}\ \forall\ i, j$	Final demand (Y)	Total output (X)
	Value added (V^T)		
	Total input (X^T)		

Figure 1: The Leontief input-output model.

$$(I - A)X = Y. \tag{6}$$

As for a given Y, the sector output X is given by (for a given set of Y, whether there is a unique solution of X or not depends on whether $(I - A)$ is singular or not. As in other studies, the paper also assumes that $|I - A| \neq 0$ here, so we can get $(I - A)^{-1}$)

$$X = (I - A)^{-1} Y = LY, \tag{7}$$

where L is a mnemonic for "$(I - A)^{-1}$," which is also known as the Leontief inverse. Based on equation (7), we can see that an increase in Y induces an associated increase in X.

From the economic system form depicted by the Leontief input-output model, we can see that it is a demand-driven input-output model, where the Leontief inverse connects sector gross outputs with the amount of final demand, that is, the amount of products leaving the interindustry system and directly consumed by the society. The sector output defined in the Leontief input-output model is the total output required by the economic system to meet the gross intermediate demand and final demand of the society. The basic assumption of the Leontief input-output model is the direct-input coefficients (a_{ij}) are fixed in the economic system.

3.2. Supply-Side Input-Output Model. The supply-side input-output model was presented by Miller and Blair [42]. It is an alternative input-output model based on the same economic data set that underpins the Leontief input-output model in Section 3.1. The supply-side input-output model emphasizes that the production factors in some situations may become the determinant in an economic system, when the demands are increasing or when there is a general limitation of resources. Due to the constraints of human resources, capital, and other resources, the supply capacity of the regional economic system may not be able to meet the increasing demand caused by climate change. The supply-side input-output model defines the balanced equation for the economy from the perspective of the value formation of the output of each sector. Referring to the interindustry output formation matrix given in Figure 2, we can see that the total sector output can be derived alternatively by aggregating the total value flow in the sector.

The columns in Figure 2 describe the compositions required by a particular industry output (supply). Through transposing the vertical (column) view of the interindustry system to a horizontal (row) equation, the supply-side input-output model balance equation can be given as

$$x_j^s = \sum_{i=1}^{n} x_{ij} + v_j \Leftrightarrow x_j^s = \sum_{i=1}^{n} b_{ij}^{(s)} x_i + v_j, \quad \forall j = 1, 2, \ldots, n, \tag{8}$$

where x_j^s represents the production capacity of sector j, x_{ij} represents the intermediate input from sector i to sector j to maintain the productive capacity of sector j, $b_{ij}^{(s)}$ is the direct-output coefficient ($b_{ij}^{(s)} = x_{ij}/x_i$), and v_j represents the value-added component used by sector j in order to maintain the productive capacity. The value-added component contains wages, fixed capital consumption, income, rental, and net interest, among others.

The supply-side input-output model can be described in the following matrix form:

$$\left(X^s\right)^T = \left(X^{)}\right)^T B^{(s)} + V^T, \tag{9}$$

where $(X^s)^T = [x_1^s, x_2^s, \ldots, x_n^s]$ represents the row vector of sector supply in the region, $B^{(s)} = [b_{ij}^{(s)}]_{n\times n}$ is the direct-output coefficients matrix derived from the regional economic input-output data, and $V^T = [v_1, v_2, \ldots, v_n]$ is the row vector of value-added items.

From equation (9), we can get (as in other studies, we also assume that $|I - A^{(s)}| \neq 0$ here, so we can get $(-A^{(s)})^{-1}$)

$$\left(X^s\right)^T = V^T (I-)^{-1} = V^T G, \tag{10}$$

where G is a mnemonic for "$(I - B^{(s)})^{-1}$," which is also called the output inverse matrix. It can be interpreted as measuring the total production that can be supplied by the economic system based on a certain amount of primary value-added.

A change in V^T can induce an associated supply (output) change as

$$\Delta\left(X^s\right)^T = \left(\Delta V^T\right) G. \tag{11}$$

The supply-side input-output model can relate sector gross production with the primary inputs, that is, the amount of value-added entering the interindustry system at the starting of the process. The basic assumption of the supply-side input-output model is the direct-output coefficients $(b_{ij}^{(s)})$ are fixed in the economic system.

3.3. Inoperability Input-Output Model. As the Leontief input-output model can relate the economic system to the social final demand and the supply-side input-output model can relate the economic system to the initial value-added entering the interindustry system, this subsection attempts to integrate the two models to investigate the impact of increases in final demand of some vulnerable sectors caused by climate change on the economic system and the initial value-added required by the society. Combining the demand side and the supply side of the economic system is a potential method for measuring the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. Therefore, we present the inoperability input-output (IIM) model which is a combination of the Leontief input-output model

	Industry	Producers as consumers (intermediate demand)						Final demand	Total demand
		Sector 1	Sector 2	$\cdots$	Sector j	$\cdots$	Sector n		
Producers	Sector 1	x_{11}	x_{12}	$\cdots$	x_{1j}	$\cdots$	x_{1n}	y_1	x_1
	Sector 2	x_{21}	x_{22}	$\cdots$	x_{2j}	$\cdots$	x_{2n}	y_2	x_2
	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$	$\vdots$
	Sector j	x_{j1}	x_{j2}	$\cdots$	x_{jj}	$\cdots$	x_{jn}	y_j	x_j
	$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$	$\vdots$
	Sector n	x_{n1}	x_{n2}	$\cdots$	x_{nj}	$\cdots$	x_{nn}	y_n	x_n
	Value added	v_1	v_2	$\cdots$	v_j	$\cdots$	v_n		
	Total supply	x_1	x_2	$\cdots$	x_j	$\cdots$	x_n		

Figure 2: The supply-side input-output framework.

and supply-side input-output model (here, the direct-input coefficients and direct-output coefficients in the inoperability input-output model are assumed to be fixed simultaneously. Although this assumption is not completely strict, it is relatively reasonable under the condition that the technological level and social circumstances are stable). The IIM can relate the economic system to both the social final demand leaving the interindustry system and the initial value-added entering the interindustry system.

3.3.1. Static IIM. Supposing that the demand for sector k has increased due to climate change, the balance equations of sector k can be expressed from both the demand side and supply side as the following two equations:

$$x_k^d = \sum_{j=1}^{n} x_{kj} + y_k, \tag{12}$$

$$x_k^s = \sum_{i=1}^{n} x_{ik} + v_k, \tag{13}$$

where x_k^d is the total regional demand for the products of sector k and x_k^s is the product supply of sector k in the region. We illustrate equations (12) and (13) in the following intuitive form:

$$\begin{cases} x_{11} + x_{12} + \cdots + x_{1k} + \cdots + x_{1n} + y_1 = x_1^d, \\ x_{21} + x_{22} + \cdots + x_{2k} + \cdots + x_{2n} + y_2 = x_2^d, \\ \vdots \\ x_{k1} + x_{k2} + \cdots + x_{kk} + \cdots + x_{kn} + y_k = x_k^d, \\ \vdots \\ x_{n1} + x_{n2} + \cdots + x_{nk} + \cdots + x_{nn} + y_n = x_n^d, \end{cases} \tag{14}$$

$$\begin{cases} x_{11} + x_{21} + \cdots + x_{k1} + \cdots + x_{n1} + v_1 = x_1^s, \\ x_{12} + x_{22} + \cdots + x_{k2} + \cdots + x_{n2} + v_2 = x_2^s, \\ \vdots \\ x_{1k} + x_{2k} + \cdots + x_{kk} + \cdots + x_{nk} + v_k = x_k^s, \\ \vdots \\ x_{1n} + x_{2n} + \cdots + x_{kn} + \cdots + x_{nn} + v_n = x_n^s, \end{cases} \tag{15}$$

where each specific equation in equation (14) describes the distribution of demand for a specific sector, and each specific equation in equation (15) describes the distribution of inputs required by a specific sector to maintain its supply. We express equations (14) and (15) in matrix form as follows:

$$X^d = AX^d + Y, \tag{16}$$

$$X^s = \left(B^{(s)}\right)^T X^s + V, \tag{17}$$

where the variables in equation (16) are consistent with those corresponding to equation (3) and the variable in equation (17) is the transposed matrix of the corresponding variable in equation (9).

From equations (16) and (17), we have

$$X^d = (I - A)^{-1} Y, \tag{18}$$

$$X^s = \left[I - \left(B^{(s)}\right)^T\right]^{-1} V. \tag{19}$$

Combining equations (18) and (19), we can see that an increase in final demand (Y) will induce a higher output (X^d), which needed a corresponding supply (X^s) that requires sufficient regional value-added (V) to maintain the needed high supply capacity. Regrettably, the available regional value-added is not unlimited usually; thus, we need to consider the issue of value-added shortage caused by climate change. Based on equations (18) and (19), the formulation relationship between the final demand and the initial added value required by the economic system is given as follows:

$$V^{(d)} = \left[I - \left(B^{(s)}\right)^T\right](I - A)^{-1} Y = G^{-1} L Y, \tag{20}$$

where $V^{(d)}$ is the value-added vector required by the economic system when the social final demand vector is Y, and the other variables are the same as above in this paper.

In order to quantitatively measure the climate change vulnerability of an economic sector, we introduce a new variable, inoperability [43]. In the paper, the sector inoperability is defined as the percentage of the needed increasing amount of value-added caused by climate change relative to the current amount of value-added. Formally, climate change induced inoperability of the economic sector is formulated as

$$q = \left[(\mathrm{diag}(V))^{-1} \left(V^{(d)} - V \right) \right], \tag{21}$$

where $q = [q_1, q_2, \ldots, q_n]^T$ is the sector inoperability vector of the economic system; $V^{(d)} = [v_1^d, v_2^d, \ldots, v_n^d]^T$ is the value-added vector required by the economic system when the social final demand is increasing induced by climate change; $V = [v_1, v_2, \ldots, v_n]^T$ is the current value-added vector of the economic system; $\mathrm{diag}(V)$ is a resulting diagonal matrix constructed from the given vector V; and $\mathrm{diag}(V)$ is illustrated as

$$\mathrm{diag}(V) = \mathrm{diag}\left([v_1, v_2, \ldots, v_n]^T \right) = \begin{bmatrix} v_1 & 0 & \cdots & 0 \\ 0 & v_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & v_n \end{bmatrix}. \tag{22}$$

By introducing sector inoperability, the paper can quantitatively measure the climate change vulnerability of an economic sector. With the help of the regional input-output table, we can use the IIM to investigate the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. The IIM implicitly assumed that if an industry's supply cannot satisfy its demand, the intermediate demands needed by other sectors are served in priority. It means that, in the case of shortage, social final demands are the last demands to be met compared with intermediate demands needed by other sectors. The priority given to intermediate demands is justified by several facts [44]. When climate change needs additional final demands for some sectors, it is beneficial for local society only if intermediate demand can be met priority.

3.3.2. Dynamic IIM. In the above IIM, the inoperability levels of each sector are static. In this section, we take sector resilience factors into the dynamic IIM to model its dynamic evolution over time. Note that the concepts and definitions in the above static IIM are all applicable to the dynamic IIM, which expands the static IIM with farther dynamic and stochastic factors. Referring to one of the most widely used dynamic Leontief input-output model forms [45–47], the dynamic IIM is given as

$$q_{(t)} = \left[\left(\mathrm{diag}\left(V_{(t)} \right) \right)^{-1} G^{-1} L \left(Y_{(t)}^{(d)} - Y_{(t)} \right) \right]. \tag{23}$$

Let $(\mathrm{diag}(V_{(t)}))^{-1} (Y_{(t)}^{(d)} - Y_{(t)}) = V_{(t)}^*$ and $G^{-1}L = B^*$, and by introducing sector resilience component, the dynamic IIM can be formally shown as

$$q_{(t+1)} = q_{(t)} + K \left[B^* V_{(t)}^* - q_{(t)} \right], \tag{24}$$

where the diagonal matrix K is the sector resilience coefficient matrix, and its ith nonnegative diagonal element k_i represents the ability of the industry to recover from an inoperability level caused by climate change. A greater k_i indicates a faster response of the economic system to an imbalance in supply and demand [48].

The value of k_i is determined from the initial inoperability of sector i and the time $q_i(T_i)$ required by the sector to recovery to a predefined inoperability level from the initial level of inoperability $q_i(0)$. The formulation of k_i can be given as

$$k_i = \frac{\ln \left(q_i(0) / q_i(T_i) \right)}{T_i \left(1 - b_{ii}^* \right)}. \tag{25}$$

where the term in the numerator measures the recovery rate and the denominator represents the reliance of the sector on itself, and the notion b_{ii}^* represents the ith diagonal element in the matrix B^*.

It should be pointed out that the economic data used in both the theoretical IIM and the following empirical analysis are given in monetary units. In order to avoid the price effects on the results, we assume that the prices of all products/services during the study period are constant.

4. Empirical Applications and Discussion

In this section, the IIM elaborated in Section 3 is applied in Tianjin to explore its climate change dilemmas. Tianjin is one of the four municipalities in China, which is located in the northeast part of North China Plain (38°34′–40°15′ N, 116°43′–118°04′ E) [49]. Tianjin is a megacity with a population of over 15 million, and it is representative of the surrounding areas. Therefore, in this paper, Tianjin is chosen as an interesting case to provide experience for the North China.

4.1. Data Source and Processing

4.1.1. Input-Output Table of Tianjin. The empirical study is based on the 2012 input-output table of Tianjin in monetary units, and the input-output table consists of 42 sectors, whose names and codes are shown in Table 2. We process the input-output table as follows. The subdividing final demand and value-added inputs are combined into a single final demand and total value-added, respectively, and we have removed the effects of regional inflows and regional outflows in order to accurately grasp the impact of vulnerable economic factors on the whole economic system and identify the key adaptation trajectory of the economic system.

4.1.2. Climate Data. Additionally, the future prediction data of climate change by the end of the century from the IPCC's Fifth Assessment Report [50–52] are also used in the study. The IPCC's Fifth Assessment Report has proposed four representative concentration pathway scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), and the projected temperature changes of Eastern Asia are shown in Figure 3 [53].

In this paper, we chose RCP2.6, RCP4.5, and RCP8.5 to, respectively, represent the low climate change scenario, medium climate change scenario, and high climate change scenario to study the Tianjin case. Based on the temperature change projections of Eastern Asia simulated in the RCP scenarios, the paper assumes future predictions of temperature change in Tianjin as listed in Table 3.

Table 2: Sector code and name in the Tianjin input-output table.

Code	Sector name
S1	Farming, forestry, husbandry, and fishery
S2	Mining and wasting of coal
S3	Extraction of petroleum and natural gas
S4	Mining of metal ores
S5	Mining and processing of nonmetal ores
S6	Manufacture of foods and tobacco
S7	Manufacture of textile
S8	Manufacture of textile wearing apparel
S9	Manufacture of timbers and furniture
S10	Papermaking and manufacture of articles
S11	Processing of petroleum, and coking
S12	Chemical industry
S13	Manufacture of nonmetallic mineral
S14	Smelting and rolling of metals products
S15	Manufacture of metal products
S16	Manufacture of general purpose machinery
S17	Manufacture of special-purpose machinery
S18	Manufacture of transport equipment
S19	Manufacture of electrical machinery
S20	Manufacture of communication equipment
S21	Manufacture of measuring instrument
S22	Other manufacture
S23	Scrap and waste processing
S24	Repair services of machinery and equipment
S25	Electric power and thermal power
S26	Production and distribution of gas
S27	Water production and distribution
S28	Construction
S29	Wholesale and retail trade
S30	Transportation, storage, and post
S31	Hotel and restaurants
S32	Information transmission and computer
S33	Finance
S34	Real estate trade
S35	Tenancy and commercial service
S36	Scientific research and technical service
S37	Environment and municipal conservancy
S38	Resident services and repair services
S39	Education
S40	Health care and social work
S41	Culture, art, sports, and recreation
S42	Public management and social service

4.2. Vulnerable Sector and Climate Adaptation Function. Through reviewing the literature about climate change research of the last 20 years, we find that electricity, water, and health sector are the first three most vulnerable sectors to climate change. Its microfoundations are the increasing demand for electricity, water, and health services needed by people to maintain their lives in the context of climate change. In this empirical analysis of Tianjin, the paper selects electricity, water, and health sector as original inducing sectors to investigate the impact of the three climate-vulnerable sectors on the whole economic system and identifying the key adaptation trajectory of Tianjin's economic system. Here, we introduce the climate adaptation function of the three vulnerable sectors, which is a function of sector demand changes with respect to future climate changes. While this certain quantitative relationship is difficult to assess, we refer to a number of the empirical literature and examine the functions used in the current climate-economy models, and then we have defined the form and parameters of climate adaptation function of electricity, water, and health service sector, respectively.

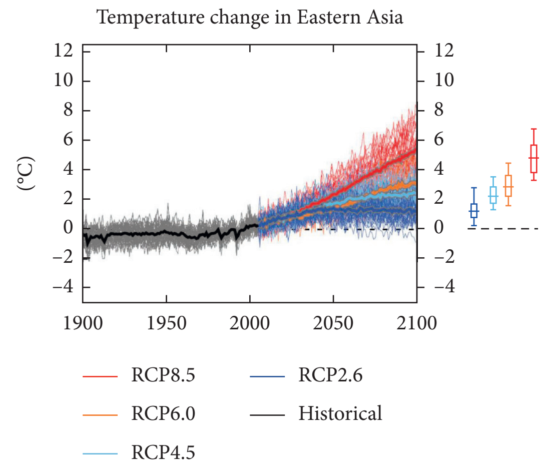

Figure 3: Time series of temperature change in Eastern Asia (20°N to 50°N, 100°E to 145°E). Note: thin lines represent one ensemble member per climate model and thick lines donate the multimodel mean. On the right-hand side, the 5th, 25th, 50th (median), 75th, and 95th percentiles of the distribution are illustrated in the four RCP scenarios. The temperature projection data in Figure 3 are sourced from IPCC's Fifth Assessment Report.

Table 3: Future predictions of temperature change in Tianjin under the three climate scenarios.

Scenarios	Projected change by 2100
RCP2.6	+1.2°C
RCP4.5	+3.1°C
RCP8.5	+4.8°C

Note: changes in temperature are based on the 2012 benchmark.

4.2.1. Electricity Sector. Through reviewing the broad empirical literature, we found that there is a U-shape relationship between electricity demand and temperature, and the net effect of climate change over the 21st century is likely to increase electricity demand substantially. When the temperature rises, the electricity demand may increase nonlinearly. Considering the nonlinear impact of climate change on electricity demand [25, 54, 55], the paper assumes that the effect of temperature rise on electricity demand is defined as

$$\mathrm{Elec}_t = \left(1 + 0.06\,T + 0.02T^2\right)\overline{\mathrm{Elec}_t}, \tag{26}$$

where $Elec_t$ represents the electricity demand in period t, T represents this period's temperature anomaly, and $\overline{\mathrm{Elec}_t}$ denotes the electricity demand in period t in the absence of climate warming.

4.2.2. Water Sector. Regional water demand is also sensitive to climate change [26–28]. It is generally suggested that climate change will trigger more water demand [7, 9, 10]. Through reviewing the related literature [24, 25], the paper assumes that the effect of temperature rise on water demand is defined as

$$\mathrm{Wate}_t = \left(1 + 0.05T + 0.01T^2\right)\overline{\mathrm{Wate}_t}, \tag{27}$$

where Wate_t represents the regional water demand in period t, T represents this period's climate anomaly, and $\overline{\mathrm{Wate}_t}$ denotes the regional water in period t in the absence of climate warming.

4.2.3. Health Sector. Both epidemiology and economics literature pointed out the detrimental effects of climate warming on mortality, prenatal health, and human health in recent years [29]. As the impact of climate change on human health is more and more significant, there is a growing demand for the health service sector [11, 12]. Through reviewing the related literature [30, 31], the paper assumes that the effect of temperature rise on health service demand is defined as

$$\mathrm{Heal}_t = \left(1 + 0.03\,T + 0.01T^2\right)\overline{\mathrm{Heal}_t}, \tag{28}$$

where $Heal_t$ represents the regional demand for health service in period t, T represents this period's climate anomaly, and $\overline{\mathrm{Heal}_t}$ denotes the regional demand for the health service sector in period t in the absence of climate warming.

4.3. Results Analysis and Discussion

4.3.1. RCP2.6 Scenario. In the IPCC's Fifth Assessment Report, the RCP2.6 scenario is a low climate change scenario, which supposed that the global temperature will rise within 2°C. Based on the 2012 input-output table of Tianjin, we apply the IIM elaborated in Section 3 to explore the impact of increased demand for electricity, water, and health service sectors caused by climate change on the whole economic system and identifying the key adaptation trajectory of the economic system. For simplicity of display, we illustrate the 15 sectors with the largest inoperability in Figure 4.

As shown in Figure 4, when the regional demand for the electricity sector (S25), water sector (S27), and health sector (S40) is increasing due to climate change in Tianjin, the most vulnerable 15 sectors are S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. In the RCP2.6 scenario, except for the original three inducing sectors (S25, S27, and S40), the inoperability of other sectors are all less than 0.006. The inoperability of the special equipment manufacturing sector (S17) is 0.0058, which should be the most important sector to be concerned about. Tianjin also needs to pay more attention to S17, S12, S02, S21, and S16 sectors when adapting to climate change, as the inoperability of those sectors are all bigger than 0.001. In the RCP2.6 scenario, except for S40, S27, S25, S17, S12, S02, S21, and S16 sector, the other 34 sectors' inoperability are all less than 0.001. On the whole, in the RCP2.6 scenario, climate

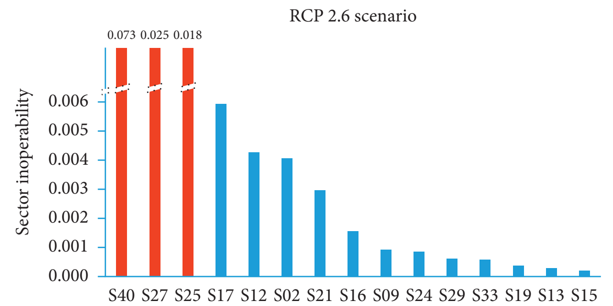

Figure 4: The 15 sectors with the largest inoperability in the RCP2.6 scenario. Note: the three red histograms represent the electricity, water, and health sector, respectively, which have been truncated because they are too high relative to other sectors. The sectors represented by the codes in the figure are shown in Table 2.

change has relatively modest impact on Tianjin's economic system, but certainly not negligible.

4.3.2. RCP4.5 Scenario. The RCP4.5 scenario is a medium climate change scenario, and Figure 5 illustrates the 15 sectors with the largest inoperability of Tianjin under the RCP4.5 scenario.

As shown in Figure 5, when the regional demand for the electricity sector (S25), water sector (S27), and health sector (S40) is increasing due to climate change, the most vulnerable 15 sectors are S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. In the RCP4.5 scenario, the inoperability of health sector (S40) is 0.275, which means that the initial value-added of health sector is facing a gap of 27.5% in meeting the increasing social demand. Except for the inducing sectors (S25, S27, and S40), the inoperability of the special equipment manufacturing sector (S17) is the highest, 0.022, which should be the most vulnerable sector to be concerned about. Tianjin also needs to pay more attention to S12, S02, S21, and S16 sectors when adapting to climate change, and these sectors' inoperability are all greater than 0.005. In the RCP4.5 scenario, climate change has obvious impact on Tianjin's economic system. Therefore, it is necessary to take measures to adjust production resources to reduce the inoperability of those vulnerable sectors, so as to avoid the imbalance of the whole economic system.

4.3.3. RCP8.5 Scenario. In the IPCC's Fifth Assessment Report, the RCP8.5 is a high climate change scenario, which supposed that the global temperature will rise around 5°C. Figure 6 illustrates the 15 sectors with the largest inoperability of Tianjin under the RCP8.5 scenario.

As shown in Figure 6, when the regional demand for the electricity sector (S25), water sector (S27), and health sector (S40) is increasing due to climate change, the most vulnerable 15 sectors are S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. In the RCP8.5 scenario, the inoperability of health sector (S40) is 0.544, which means that the initial value-added of health sector is facing a 54.4% gap in meeting the increasing social

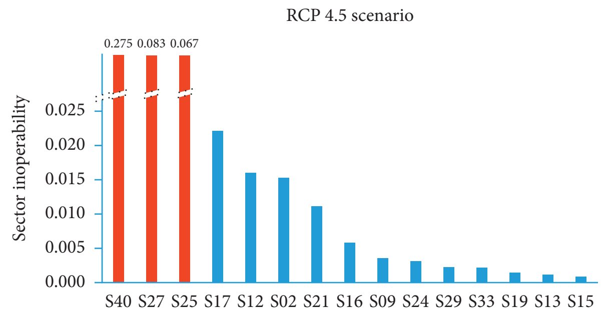

FIGURE 5: The 15 sectors with the largest inoperability in the RCP4.5 scenario. Note: the three red histograms have been truncated because they are too high relative to other sectors, and the sectors represented by the codes in the figure are shown in Table 2.

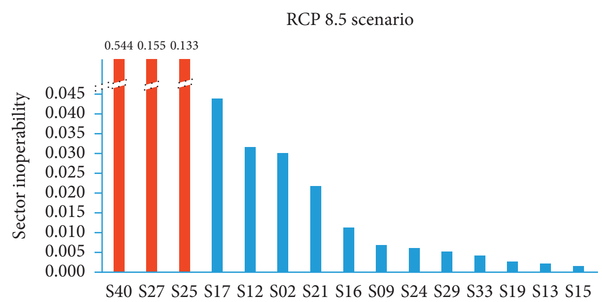

FIGURE 6: The 15 sectors with the largest inoperability in the RCP8.5 scenario. Note: the three red histograms have been truncated because they are too high relative to other sectors, and the sectors represented by the codes in the figure are shown in Table 2.

demand. Except for the inducing sectors (S25, S27, and S40), the inoperability of the special equipment manufacturing sector (S17) is 0.022, which should be paid more attention to. The inoperabilities of S17, S12, S02, S21, S16, S09, and S24 sectors are all bigger than 0.005. In the RCP8.5 scenario, climate change has significant impact on Tianjin's economic system. It is essential to take measures to reduce the inoperability of those vulnerable sectors, so as to avoid the paralysis of the whole economic system.

4.3.4. Inoperability Dynamics Analysis. In this subsection, the dynamic IIM is applied in Tianjin to analyze the inoperability trajectories. Taking the RCP4.5 scenario as an example, we simulate the inoperability dynamics of Tianjin's economic system. In the initial time, the sector inoperability of the electricity sector (S25), water sector (S27), and health sector (S40) is 0.067, 0.083, and 0.275, respectively, induced by climate change, and the sector inoperability of the other sector is zero. Assume that each sector can recovers to a level of 0.1% of the initial inoperability in each period, and Figure 7 displays the inoperability dynamics of the top 12 impacted sectors except for S25, S27, and S40.

From Figure 7, we can see that the most impacted 12 sectors are S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order, which is consistent with the

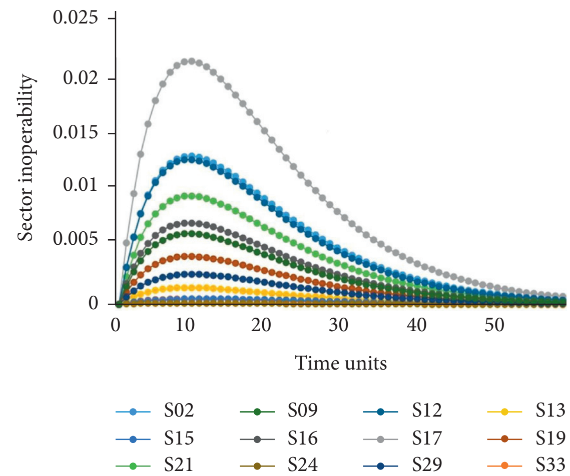

FIGURE 7: Inoperability dynamics of the top 12 impacted sectors in the RCP4.5 scenario.

static IIM analysis above. Mastering this key climate adaptation trajectory and allocating resources according to the sector inoperability is the practical basis of the climate adaptation scheme in Tianjin. Even if the initial state is not affected by climate change, the inoperability of the rest of the economic sectors will gradually increase affected by the electricity sector (S25), water sector (S27), and health sector (S40). From the dynamic analysis, we can also see that it may take almost 50 periods for the economic system to return to the original state when the recovery ability is 0.1% of the initial inoperability in each period. As shown, the difference in sector inoperability between the 12 sectors is relatively large. The results may be applied by policy-makers to prioritize sectors in terms of protection and understand the efficacy of climate risk mitigation strategies.

4.3.5. Comprehensive Results Analysis. In order to better understand the impact of increased demand for electricity, water, and health service sectors caused by climate change on the whole economic system and identifying the key adaptation trajectory of the economic system in Tianjin, we present the comprehensive results in multiple dimensions in this section.

In Table 4, we introduce a new variable, aggregate inoperability, which measures the proportion of the change in value-added required by the whole economic system due to climate change. As shown in Table 4, the impact of climate change on the health sector (S40) induced the most significant cascading influence on the whole economic system compared with the electricity sector (25) and water sector (27). Taking RCP4.5 scenario for example, the increasing proportion of regional demand for the electricity sector, water sector, and health sector is 0.3782, 0.2511, and 0.1892, respectively, but their inducing aggregate inoperability of the whole economic system is 0.00050, 0.00007, and 0.00578, respectively. It indicates that the health sector may play a critical role in adapting to climate change for the whole economic system. Our results also indicated that climate

Table 4: Aggregate results of RCP2.6, RCP4.5, and RCP8.5 scenarios.

Scenarios	Inducing sector	Changes in final demand	$X^{(d)}$ (million RMB yuan)	$\text{TVA}^{(d)}$ (million RMB yuan)	Aggregate inoperability
RCP2.6	Electricity (S25)	0.1008	5738307.2	2994429.9	0.00013
	Water (S27)	0.0744	5736547.1	2994096.9	0.00002
	Health (S40)	0.0504	5742545.3	2998643.7	0.00154
	Combined (S25, S27, and S40)		5744823.9	2999107.0	0.00170
RCP4.5	Electricity (S25)	0.3782	5743864.2	2995525.7	0.00050
	Water (S27)	0.2511	5737162.8	2994251.4	0.00007
	Health (S40)	0.1891	5759765.8	3011335.8	0.00578
	Combined (S25, S27, and S40)		5768217.1	3013049.3	0.00635
RCP8.5	Electricity (S25)	0.7488	5751288.3	2996989.5	0.00099
	Water (S27)	0.4704	5737926.9	2994443.3	0.00014
	Health (S40)	0.3744	5782772.0	3028292.1	0.01144
	Combined (S25, S27, and S40)		5799411.4	3031661.3	0.01257

Note: the column of changes in final demand represents change proportion of final demand for the corresponding sector in different climate scenarios, and the row of combined (S25, S27, and S40) represents corresponding results when the final demand for S25, S27, and S40 sector is affected by climate change at the same time, where $X^{(d)}$ and $\text{TVA}^{(d)}$ are the same variables defined in Section 3.

change also affects regional economic conditions and thus may exacerbate adaptation dilemma or create new ones, which is consistent with the studies by Hashemi [56] and Nguyen et al. [7].

4.4. Discussion. These results analyzed in the above subsection indicated that the impact of climate change on individual sectors varies substantially, which is indicative of a need for sector distinct strategies to adapt to climate change. The key climate adaptation sector trajectory of the economic system in Tianjin is stable, that is, S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector. The individualization adaptation strategy of each sector should be formulated based on this key climate adaptation sector trajectory. This sector heterogeneity in climate vulnerability would depend, of course, on the interconnection of the local economic system. In other words, sector differences are likely to persist in this form, although perhaps not in some ways we are anticipating.

It is worth noting that the overall impact of climate change adaptation on the economic system seems not obvious because the aggregate inoperability of the economic system has been smoothed by those sectors that are barely affected. This result implied that the overall impact found to date in the literature may not uncover its actual impact and unable to point out the direction of regional adaptation to climate change. For example, in Tianjin, while the aggregate inoperability is 0.0126 by the end of the century for RCP8.5 scenario, the sector inoperability of S40, S27, S25, S17, S12, S02, and S21 is 0.544, 0.155, 0.133, 0.044, 0.032, 0.030, and 0.022, respectively. To meet the total increased demand caused by climate change at current prices would cost around 37.6 billion RMB yuan in Tianjin under the RCP8.5 scenario, of which the abovementioned key sectors will need 34.3 billion yuan, accounting for 91.2% of the total. These key sectors might determine the security of the economic system facing climate change.

We caution that the paper is meant to illustrate the impact of vulnerable sectors on the whole economic system and analyze the key adaptation trajectory of the economic system in a business-as-usual setting. In other words, the IIM we estimate holds prices, economic growth, and current technology constant, used in many economic modelling contexts [22]. Constant prices and economic growth assumption means that the economic system in the current stable environment can ensure that all sectors in the economic system keep the balance of supply and demand without climate change. Changes in technology may mitigate the demand for electricity, water, and health service demand required by climate change, in the following ways. Efficient air conditioning technologies may reduce the electricity demand of society to adapt to climate change. Water-saving technology can also reduce the water demand required to adapt to climate change. Hierarchical diagnosis and treatment technology may also improve the efficiency of health services and better meet the needs of social health services to adapt to climate change. As technology factors may have great uncertainty in the future, so the paper does not consider them.

Despite the limitations, this study provides a more comprehensive view of the impact of vulnerable economic factors on the whole economic system and identifying the key adaptation trajectory of the economic system. Compared with the existing single sector climate vulnerability studies, this study provides a complementary perspective to understand the impact of climate change, which has more guiding significance for the study of regional adaptation to climate change. It may provide policy-makers with a significant indication of the climate adaptation efforts associated with economic activities that are foundational for the successful implementation of adaptation strategic decisions.

5. Conclusions and Future Work

This study presents a systematic approach to analyzing the impact of climate-vulnerable sectors on the whole economic system and the key adaptation trajectory of the economic system. The IIM elaborated in the paper is applied in Tianjin to explore its climate change dilemmas.

The results of RCP2.5, RCP4.5, and RCP8.5 scenarios indicated that the inoperability ranking of all economic sectors in Tianjin is the same under the three climate scenarios, which implies the key adaptation trajectory of Tianjin's economic system is stable. The key adaptation trajectory in Tianjin is S40, S27, S25, S17, S12, S02, S21, S16, S09, S24, S29, S33, S19, S13, and S15 sector in order. The costs required by the abovementioned key adaptation trajectory to adapt to climate change account for more than 90% of that required by the entire economic system. Mastering this key climate adaptation trajectory and allocating resources according to the sector inoperability is the practical basis of the climate adaptation scheme in Tianjin.

Our results also imply that it seems that the impact of climate change on the whole economic system seems to be not great, but it will have significant impact on some vulnerable sectors and their closely interconnected sectors. In particular, these sectors closely interconnected to the vulnerable sectors are easy to be ignored, which requires policymakers to focus on, in order to formulate appropriate climate adaptation policies to ensure regional economic system security.

The individualization adaptation strategy of each sector should be formulated based on its sector inoperability. Timely adjustment of resource allocation among sectors of the economic system according to sector inoperability may be the direction for the climate adaptation strategy of the whole economic system. This sector heterogeneity in climate vulnerability would depend on the interconnection of the local economic system, which is likely to persist in this form, although perhaps not in some ways we are anticipating. We can envision several strategies to mitigate the impact of the key climate adaptation trajectory we estimate. A hopeful effort is launching a climate change adaptation fund to improve the supply capacity of the key sectors and to finance their access to resources.

Future research might extend the proposed methodology to further correctly calibrate the climate adaptation function of the electricity, water, and health sector. Moreover, the IIM presented in this paper is on the assumption that direct-input coefficients and direct-output coefficients in the economic system are constant. This is probably not a very actual situation in much of the regional economic system. Although the IIM's assumptions on the characteristics of the economic system may not be realistic, we still believe that this is a meaningful attempt, and we hope it can advance the discourse of this complex issue in a relatively clear and structured manner. Another work may assess regionally available production resources and introduce them into the input-output table, so as to build optimization allocation models to better promote adaptation to climate change.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Pengbang Wei and Yufang Peng contributed equally to this work.

Acknowledgments

The authors sincerely acknowledge the financial support from the Major Project of the National Social Science Fund of China (no. 2014B-0130) and the National Natural Science Foundation of China (no. 71373173).

References

[1] W. Nordhaus, "Projections and uncertainties about climate change in an era of minimal climate policies," *American Economic Journal: Economic Policy*, vol. 10, no. 3, pp. 333–360, 2018.

[2] W. Nordhaus, "Evolution of assessments of the economics of global warming: changes in the DICE model," *Climatic Change*, vol. 148, no. 4, pp. 623–640, 2018.

[3] IPCC, *Climate Change 2014 Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects*, Cambridge University Press, Cambridge, UK, 2014.

[4] J. Hugo, C. du Plessis, and J. Hugo, "A quantitative analysis of interstitial spaces to improve climate change resilience in Southern African cities," *Climate and Development*, vol. 12, no. 7, pp. 591–599, 2019.

[5] W. Smith, B. Grant, Z. Qi et al., "Towards an improved methodology for modelling climate change impacts on cropping systems in cool climates," *Science of the Total Environment*, vol. 728, Article ID 138845, 2020.

[6] K. E. Mcnamara, L. Buggy, K. E. Mcnamara, and L. Buggy, "Community-based climate change adaptation: a review of academic literature," *Local Environment*, vol. 22, no. 4, pp. 443–460, 2017.

[7] Q. A. Nguyen, F. Miller, K. Bowen, and B. Tan Sinh, "Evaluating capacity for climate change adaptation in the health and water sectors in Vietnam: constraints and opportunities," *Climate and Development*, vol. 9, no. 3, pp. 258–273, 2017.

[8] A. T. D. Perera, V. M. Nik, D. Chen, J.-L. Scartezzini, and T. Hong, "Quantifying the impacts of climate change and extreme climate events on energy systems," *Nature Energy*, vol. 5, no. 2, pp. 150–159, 2020.

[9] C. Papadaskalopoulou, E. Katsou, K. Valta, K. Moustakas, D. Malamis, and M. Dodou, "Review and assessment of the adaptive capacity of the water sector in cyprus against climate change impacts on water availability," *Resources, Conservation and Recycling*, vol. 105, pp. 95–112, 2015.

[10] T. Gorman, A. Chaturvedi, and R. Arora, "Climate change impact chains in the water sector: observations from projects on the east India coast," *Journal of Water and Climate Change*, vol. 5, no. 2, pp. 216–232, 2014.

[11] B. Ye, X. Zhang, X. Zhang, and C. Zheng, "Climate change, environmental impact, and human health," *Environmental Geochemistry and Health*, vol. 42, no. 3, pp. 715–717, 2020.

[12] S. Wang, J. Jiang, Y. Zhou, J. Li, D. Zhao, and S. Lin, "Climate-change information, health-risk perception and residents' environmental complaint behavior: an empirical study in China," *Environmental Geochemistry and Health*, vol. 42, no. 3, pp. 719–732, 2020.

[13] C. D. Hewitt, R. C. Stone, and A. B. Tait, "Improving the use of climate information in decision-making," *Nature Climate Change*, vol. 7, no. 9, pp. 614–616, 2017.

[14] A. Conevska, J. Ford, and A. Lesnikowski, "Assessing the adaptation fund's responsiveness to developing country's needs," *Climate and Development*, vol. 12, no. 5, pp. 436–447, 2020.

[15] L. Filipe and J. P. Kropp, "Estimating investments in knowledge and planning activities for adaptation in developing countries: an empirical approach," *Climate and Development*, vol. 11, no. 9, pp. 755–764, 2019.

[16] IPCC, *AR4 Climate Change 2007: Impacts, Adaptation, and Vulnerability*, IPCC, Geneva, Switzerland, 2007.

[17] C. Göpfert, C. Wamsler, and W. Lang, "A framework for the joint institutionalization of climate change mitigation and adaptation in city administrations," *Mitigation and Adaptation Strategies for Global Change*, vol. 24, no. 1, pp. 1–21, 2019.

[18] T. Grothmann and A. Patt, "Adaptive capacity and human cognition: the process of individual adaptation to climate change," *Global Environmental Change*, vol. 15, no. 3, pp. 199–213, 2005.

[19] G. S. Eskeland and T. K. Mideksa, "Electricity demand in a changing climate," *Mitigation and Adaptation Strategies for Global Change*, vol. 15, no. 8, pp. 877–897, 2010.

[20] O. Deschênes and M. Greenstone, "Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US," *American Economic Journal: Applied Economics*, vol. 3, no. 4, pp. 152–185, 2011.

[21] M. Auffhammer and A. Aroonruengsawat, "Simulating the impacts of climate change, prices and population on California's residential electricity consumption," *Climatic Change*, vol. 109, no. S1, pp. 191–210, 2011.

[22] M. Auffhammer, P. Baylis, and C. H. Hausman, "Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States," *Proceedings of the National Academy of Sciences*, vol. 114, no. 8, pp. 1886–1891, 2017.

[23] Y. Li, W. A. Pizer, and L. Wu, "Climate change and residential electricity consumption in the Yangtze River Delta, China," *Proceedings of the National Academy of Sciences*, vol. 116, no. 2, pp. 472–477, 2019.

[24] S. Trærup and J. Stephan, "Technologies for adaptation to climate change examples from the agricultural and water sectors in Lebanon," *Climatic Change*, vol. 131, no. 3, pp. 435–449, 2015.

[25] P. A. Harrison, R. Dunford, C. Savin et al., "Cross-sectoral impacts of climate change and socio-economic change for multiple, European land- and water-based sectors," *Climatic Change*, vol. 128, no. 3-4, pp. 279–292, 2015.

[26] J. Lengoasa, "Climate variability and change: impacts on water availability†," *Irrigation and Drainage*, vol. 65, no. 2, pp. 149–156, 2016.

[27] Z. W. Kundzewicz, M. Piniewski, A. Mezghani et al., "Assessment of climate change and associated impact on selected sectors in Poland," *Acta Geophysica*, vol. 66, no. 6, pp. 1509–1523, 2018.

[28] K. M. J. Verbist, H. Maureira-cortés, P. Rojas, and S. Vicuña, "A stress test for climate change impacts on water security: a CRIDA case study," *Climate Risk Management*, vol. 28, Article ID 100222, 2020.

[29] O. Deschenes, "Temperature, human health, and adaptation: a review of the empirical literature," *Energy Economics*, vol. 46, no. 1, pp. 606–619, 2014.

[30] H. Gökçeku and D. Al-othman, "Impacts of climate change on human health," *International Journal of Innovative Technology and Exploring Engineering*, vol. 7, no. 10, pp. 5–8, 2018.

[31] A. Mcgushin and Y. Tcholakov, "Climate change and human health: health impacts of warming of 1.5°C and 2°C," *International Journal of Environmental Research & Public Health*, vol. 15, no. 6, pp. 11–14, 2020.

[32] A. Lancet, "Commission on climate change," *Lancet*, vol. 373, no. 9676, p. 1659, 2009.

[33] J. Hinkel, S. Brown, L. Exner, R. J. Nicholls, A. T. Vafeidis, and A. S. Kebede, "Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA," *Regional Environmental Change*, vol. 12, no. 1, pp. 207–224, 2012.

[34] I. V. Canosa, J. D. Ford, G. McDowell, J. Jones, and T. Pearce, "Progress in climate change adaptation in the Arctic," *Environmental Research Letters*, vol. 15, no. 9, Article ID 093009, 2020.

[35] J. Petzold, N. Andrews, J. D. Ford, C. Hedemann, and J. C. Postigo, "Indigenous knowledge on climate change adaptation: a global evidence map of academic literature," *Environmental Research Letters*, vol. 15, no. 11, Article ID 113007, 2020.

[36] A. Ledda, E. Di Cesare, G. Satta et al., "Adaptation to climate change and regional planning: a scrutiny of sectoral instruments," *Sustainability*, vol. 12, no. 9, p. 3804, 2020.

[37] B. Benedikt, H. Daniela, G. Torsten, P. Andrea, H. Tobias, and F. Herbert, "Towards better informed adaptation strategies: co-designing climate change impact maps for Austrian regions," *Climatic Change*, vol. 158, no. 3-4, pp. 393–411, 2020.

[38] J. Hinkel and A. Bisaro, "A review and classification of analytical methods for climate change adaptation," *Wiley Interdisciplinary Reviews: Climate Change*, vol. 6, no. 2, pp. 171–188, 2015.

[39] F. Meissner, A. Haas, J. Hinkel, and A. Bisaro, "A typology for analysing mitigation and adaptation win-win strategies," *Climatic Change*, vol. 160, no. 4, pp. 539–564, 2020.

[40] T. Arnold and D. Erik, "Global multiregional Input-Output frameworks: an introduction and outlook," *Economic Systems Research*, vol. 25, no. 1, pp. 1–19, 2013.

[41] T. J.. Blair, "A continuous Leontief dynamic input-output model," *Papers in Regional Science*, vol. 56, no. 1, pp. 177–188, 1985.

[42] R. E. Miller and P. D. Blair, *Input-Output Analysis: Foundations and Extensions*, Cambridge University Press, Cambridge, UK, 2nd edition, 2009.

[43] Y. Y. Haimes and P. Jiang, "Leontief-based model of risk in complex interconnected infrastructures," *Journal of Infrastructure Systems*, vol. 7, no. 1, pp. 1–12, 2001.

[44] S. Hallegatte, "An adaptive regional input-output model and its application to the assessment of the economic cost of katrina," *Risk Analysis*, vol. 28, no. 3, pp. 779–799, 2008.

[45] Y.-J. Yang, R.-F. Ma, J. Zhang, and F. Gu, "Global stability and dynamic analysis for a type of macroeconomic systems," *Discrete Dynamics in Nature and Society*, vol. 2020, Article ID 4904829, 10 pages, 2020.

[46] J. Colombi, M. Miller, E. Schneider, M. McGrogan, J. Long, and S. Plaga, “Model based systems engineering with department of defense architectural framework,” *Systems Engineering*, vol. 14, no. 3, pp. 305–326, 2012.

[47] M. Orsi and J. R. Santos, “Incorporating time-varying perturbations into the dynamic inoperability input-output model,” *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 40, no. 1, pp. 100–106, 2010.

[48] C. Lian and Y. Y. Haimes, “Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input-output model,” *Systems Engineering*, vol. 9, no. 3, pp. 241–258, 2006.

[49] S. Chen, Z. Li, F. Liu, S. Yang, and M. Li, “Risk evaluation of solar greenhouse cucumbers low temperature disaster based on GIS spatial analysis in Tianjin, China,” *Geomatics, Natural Hazards and Risk*, vol. 10, no. 1, pp. 576–598, 2019.

[50] IPCC, *Climate Change 2013:The Fifth Assessment Report*, Cambridge University Press, Cambridge, UK, 2013.

[51] Q. Sun, C. Miao, and Q. Duan, “Projected changes in temperature and precipitation in ten river basins over China in 21st century,” *International Journal of Climatology*, vol. 35, no. 5, pp. 1125–1141, 2015.

[52] Y. Tao and T. Yang, “Non-stationary bias correction of monthly CMIP5 temperature projections over China using a residual-based bagging tree model,” *International Journal of Climatology*, vol. 38, no. 4, pp. 467–482, 2017.

[53] IPCC, *Climate Change 2013: The Physical Science Basis*, Cambridge University Press, New York, NY, USA, 2013.

[54] T. Zachariadis and P. Hadjinicolaou, “The effect of climate change on electricity needs - a case study from Mediterranean Europe,” *Energy*, vol. 76, no. 1, pp. 899–910, 2014.

[55] E. Nnaemeka, C. Taha, and A. Rabiul, “The impact of climate change on electricity demand in Australia,” *Energy & Environment*, vol. 29, no. 7, pp. 1263–1297, 2018.

[56] H. Hashemi, “Climate change and the future of water management in Iran,” *Middle East Critique*, vol. 24, no. 3, pp. 307–323, 2015.