Quantifying the spatial ripple effect of the Bohai Sea ice disaster in the winter of 2009/2010 in 31 provinces of China

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ABSTRACT
The existence of multiple disaster-hit regions with spatially heterogeneous economic structures is vital to the investigation of the spatial ripple effects of disaster disturbances in the inter-regional supply-demand chain. We employed the inter-regional input-output (IRIO) model to modify the adaptive regional input-output model (ARIO) and reproduce indirect economic losses (IELs) after the Bohai Sea ice disaster event in the mainland of China. The results showed that the total IEL in China comprised 38% of the direct economic loss. The disaster area (the Bohai Rim region) lost 1460.55 million CNY, and other provinces were burdened with 49% of the total IEL. Agricultural services absorbed 44% of the total IEL in China. Furthermore, lingering effects of the disaster were detected in non-disaster areas 5–10 months after the removal of the spatial ripple effect compared with the disaster areas. Finally, the difference in total IEL in China caused by spatial heterogeneity in the supply-demand chain was ~46.8%. Our findings suggest that the spatial ripple effect and the spatial heterogeneity of economic structures play an important role in the extent of disaster impacts on inter-regional economic systems.

1. Introduction
Indirect economic losses (IELs) received minimal attention in disaster studies until the 1990s. Nevertheless, IELs are an important part of disaster losses and understanding them is an essential prerequisite in the design of restoration and rehabilitation strategies. IELs have been defined as extensive losses beyond the physical damage of disasters (Brookshire et al. 1997), which result from the ripple effect of disaster.
disturbances, spread into the economic system and reduce economic outputs due to product bottlenecks (Boisvert 1992); IELs should include all economic flow losses as a result of disaster-induced damage to production capital (Rose and Guha 2004). Because interest from economists regarding disaster disturbances to the economic system have heightened in recent years, the number of tools that reproduce disaster impacts on the economy have gradually increased (Hallegatte 2008; Gilbert and Ayyub 2016; Dixon et al. 2017; Ishikawa 2017).

Numerous studies have shown that there are four methods for measuring IEL. The first method employs econometric models to assess the IELs of natural disasters based on statistical data (Okuyama 2016). Although this method provides a relatively fast way to present the long-term economic impacts of disasters, the mechanism of disaster disturbance expansion in the economic system has not been investigated within this method (Noy and Nualsri 2007). The second method uses a social accounting matrix (SAM) to assess the multiorder impacts of disasters on socio-economic agents (Okiyama 2017; Seung 2017); however, capturing the differences between direct and multiorder effects is difficult (Rose 2004). The third method uses computable general equilibrium models (CGE) to describe non-linear recovery processes post-disaster (Kajitani and Tatano 2017). However, CGE models are difficult to operate due to their substantial reliance on parameters and hypotheses (Xu et al. 2015). Compared with the three methods mentioned above, the input–output (IO) model is generally capable of reflecting the ripple effect of disaster impacts on the socio-economic system, especially after integrating the IO model into the Adaptive Regional Input–Output model (ARIO) (Hallegatte 2008).

As one of the most widely used methods to quantify IELs from disasters, IO models can determine intraregional industrial relationships in demand-driven or supply-driven chains (Bierkandt et al. 2014; Ocampo et al. 2016) and assess short-term economic losses from disaster disturbances because they have the ability to describe the interdependencies of inter-sectors and the characteristics of simple structures using an easy calculation process (Baghersad and Zobel 2015; Tan et al. 2016). With IO models, (i) the propagation effect of supply or demand changes that expand in some sectors throughout the entire supply-demand system can be captured (Bierkandt et al. 2014); (ii) the degree of inoperability of an economic system post-disaster can be determined (Santos and Haines 2004); (iii) production bottlenecks can be described (Baghersad and Zobel 2015); and (iv) the adaptive behaviours of all agents, including the producer and the consumer, can be reproduced, especially following the construction of the ARIO model by Hallegatte (2008). The non-linear structure of the ARIO model has been widely used to estimate IELs from numerous disasters, including earthquakes, floods, storm surges, and droughts (Wu et al. 2012; Jenkins 2013; Koks et al. 2015; Zhang et al. 2017). Overall, in IO model frameworks, the dynamic reconstruction process of the entire disaster can be performed with flexibility and adaptability.

Furthermore, few studies have analysed the IEL derived from the spatial ripple effects of disasters in inter-regional areas. For example, Okiyama (2017) found that the magnitude of production losses was beyond 5.7 trillion yen in Japan when using an inter-regional SAM to detect the impacts of the Great East Japan Earthquake and
total IEL in unaffected disaster regions. Koks and Thissen (2016) reported spatial differences in the ripple effect of floods (three scenarios: 1/100-year, 1/1,000-year, and 1/10,000-year) on an economic system in Rotterdam and found that a majority of direct neighbouring regions strongly benefitted from the flood, while Germany suffered losses. Wu et al. (2017a) employed the inter-regional input–output (IRIO) model to detect the economic costs of counterpart assistance associated with the Wuchuan earthquake in mainland China and found that IELs occurred in every province of mainland China.

However, an important characteristic of disasters must be considered when assessing the spatial ripple effect, namely, that disaster events may occur across multiple administrative regions. Multiple disaster-hit regions are a common phenomenon in single geological or meteorological disaster events due to the zonal distribution of earthquakes and climate (Wise 2016; Wu et al. 2017b). For example, 3, 17, and 5 provinces were struck in the 2008 Wenchuan earthquake, the 2008 snowstorm in southern China, and the drought in southwestern China from summer 2009 to spring 2010, respectively (Lu et al. 2011; Wu et al. 2012; Hu et al. 2014), while the spatial ripple effect was only derived for the disaster area in Jonkman et al. (2008), Okiyama (2017), Wu et al. (2017a), respectively. However, the economic cost of counterpart assistance was only provided for the Sichuan Province after the Wenchuan earthquake (Wu et al. 2017a). In other words, the spatial ripple effect that derived from other disaster areas (i.e. the Gansu and Shaanxi provinces) was not considered when assessing the IEL of the Wenchuan earthquake. Furthermore, different disaster regions have heterogeneous economic relationships with other regions (Sakamoto 2011; He, Huang, et al. 2014), and the regional heterogeneity of economies in disaster areas also yields different economic influences (Fang et al. 2005). For example, the economic contact among regions in eastern coastal cities is substantially greater than that among the western areas of China (Liu et al. 2005). The great 2008 Chinese ice storm swept across 17 provinces in the east-central/western regions of southern China (Xie et al. 2014). Every province that the ice storm hit had different economic connections (either intra-regional or inter-regional), which led to different IELs. Consequently, estimating the spatial ripple effect of a disaster on a single region does not provide an accurate picture of that disaster’s impact; therefore, additional attention must be paid to the spatial ripple effect of disasters on multiple disaster-hit regions and their impact on spatially heterogeneous economic structures.

Sea ice is one of special hazard types threatening offshore aquaculture, marine navigation and ocean engineering (Ogilvie and Jónsdóttir 2000; Song et al. 2010; Chen et al. 2011; Liu et al. 2012), and sea ice disasters mainly occur within 10 km of the coastline in northern China (Gu et al. 2013). The loss statistics associated with sea ice disasters improved after the large-scale sea ice event that occurred in the winter of 2009/2010 (Sun et al. 2011). Zhang et al. (2009) found that a minor sea ice event resulted in more than 4 million CNY in shellfish losses in Laizhou Bay in the winter of 2005/2006; and Zhang et al. (2013) further estimated that the IEL of this event was beyond 1 million CNY; however, it is unclear how they estimated this figure. For the Bohai sea ice event in 2010, Pan et al. (2017) estimated that the IELs in Shandong Province exceeded 4.5 billion CNY given a 2.8 billion CNY of direct economic loss.
(DEL) using a static IO model; however, they did not consider the dynamic processes and inter-regional ripple effects of sea ice impacts in their calculation. Overall, the IEL of sea ice disasters has rarely been estimated. Meanwhile, the impact of the marine economy in China is increasing, and total mariculture production has increased approximately 100-fold from 0.15 million tons in 1954 to 15.5 million tons in 2011 (Shen and Heino 2014). The coastal GDP of marine-related industries increased 60% from 1978 to 2010 (He, Bertness, et al. 2014). As such, considering the increase in sea ice disasters (Zhang et al. 2006; Yan et al. 2017) and in the exposed marine economy in the coastal regions of China, estimating the economic losses (especially IEL) of sea ice disasters is vital to supporting adaptation strategies within this sector.

To close these gaps, we employed the ARIO model, which models adaptive behaviours and non-linear processes and which we modified by introducing the inter-regional supply-demand structure from the IRIO model to reproduce the spatial ripple effect of the Bohai Sea ice disaster in the winter of 2009/2010 in China. The influence of spatially heterogeneous economic systems was revealed by comparing four scenarios. The results provide a specific reference for understanding how disaster disturbances are felt in different regions.

2. Materials and methods

2.1. Bohai Sea ice disasters

Bohai Sea ice usually appears in late November, reaches its maximum extent in February of the following year, and gradually melts in March (Wang et al. 2011). Marine fisheries, ocean transportation and ocean engineering are usually affected by sea ice (Gu et al. 2013). For marine fisheries, floating ice may damage offshore aquaculture equipment, resulting in fish and shrimp die-offs due to lack of dissolved oxygen; and fishing activities are restricted by sea ice, which leads to direct economic losses to the fishery (Song et al. 2010). For ocean transportation, large-range sea ice may blocks the sea channel and delays freight shipments or forces its transportation via other means; and ocean transport capacity is decreased by damage to ships (Liu et al. 2012). For ocean engineering, sea ice strikes or pushes against marine structures such as drilling platforms and results in damage (Chen et al. 2011). Economic losses from the above incidents spread throughout the economic system via the supply-demand chain based on inter-regional economic relationships (Pan et al. 2017).

The winter 2009/2010 Bohai Sea ice disaster swept across three provinces (Liaoning, Hebei and Shandong) and one municipality (Tianjin) and had a return period of 30 years (Su et al. 2012). Sea ice began to appear in early December 2009 and continued into the middle of March 2010 (Figure 1). The maximum sea ice extent exceeded 31,552.44 km², or 40.45% of the Bohai Sea, and severely affected fisheries and ocean transportation (Su and Wang 2012). This event led to DEL beyond 6,318.05 million CNY. However, the economic structures, and therefore impacts of the four administrative districts affected differed substantially. For example, the economic ratio of the three industries was 1:47:52 in Tianjin in 2015. In contrast, the primary industry in Hebei was 11% greater than that in Tianjin, but the tertiary industry was 12% less than that in Tianjin. For Liaoning and Shandong Provinces,
the ratios of the three industries were smaller (8:46:46 and 7:47:45 in 2015, respectively), as reported by the State Oceanic Administration of the People’s Republic of China. Given the above information, each administrative district exhibited significant spatial heterogeneities in economic structure. Thus, the spatial ripple effect of a sea ice disaster is likely to differ for each administrative district.

2.2. Data sources

To better investigate the IEL of the Bohai Sea ice disaster, four datasets were required. (i) The 2012 IRIO table, with 17 sectors in 31 provinces (excluding Hong Kong, the Macao Special Administrative Region and Taiwan) was obtained from the Institute of Policy and Management at the Chinese Academy of Sciences and used to reflect the supply-demand relationship between inter-sectors and inter-regions. The detailed sectors are given in Appendix A. (ii) The gross domestic product (GDP) of China in 2009 and 2012 was obtained from statistics released by the National Bureau of Statistics of the People’s Republic of China (http://www.stats.gov.cn/); these statistics were used to obtain a possible IRIO table for 31 provinces in China in 2009 using a ratio conversion of the GDP in 2009 and 2012. (iii) DEL records of the Bohai Sea ice disaster in winter of 2009/2010 were provided by the State Oceanic Administration of the People’s Republic of China (http://www.soagov.cn/) (Table 1) and used to present spatial differences in disaster impacts on the socio-economic system. (iv) A map of China’s administrative divisions was obtained from the Central People’s Government of the People’s Republic of China in 2013 (www.gov.cn) and used to present spatial differences in disaster impacts on the socio-economic system.
2.3. A modified ARIO model

The ARIO model, which is a hybrid modelling methodology, was developed by Hallegatte (2008) and based on the IO table. It is able to capture the IEL of disaster impacts using the supply-demand relationship of industrial sectors and has been widely used to reproduce dynamic economic losses after a disaster (Hu et al. 2014; Koks et al. 2015; Zhang et al. 2017). Basic assumptions of the ARIO are supply-demand equilibrium (i.e., the product of sector $i$ ($x_i$) is equal to the intermediate consumption ($a_{ij} \cdot x_i$)) and final demand ($f_i$),

$$x_i = \sum_{j=1}^{n} a_{ij} \cdot x_i + f_i$$  \hspace{1cm} (1)

where $i$ and $j$ represent sectors; $n$ represents the total number of sectors; and $a_{ij}$ is a square matrix ($n \times n$) of the intermediate coefficient, which is used to reflect the supply-demand relationship in the inter-sectors.

In a post-disaster event disturbance, new production can be assessed by the Leontief inverse matrix (i.e., assessing the IEL of the disaster that leads to an output change in every sector),

$$x_i = (I-a_{ij})^{-1} \cdot f_i$$  \hspace{1cm} (2)

With Equations (1) and (2), we find that the ripple effect estimated by the ARIO model is limited in a single area. In other words, when assessing IEL with the ARIO, the IEL is only captured in intra-disaster areas. Clearly, disaster areas are not closed and isolated; they are related by an inter-regional supply-demand chain. Thus, the ARIO model must be improved to reflect the spatial structure of supply-demand chains to better capture the spatial ripple effect of disaster impacts.

2.3.1. Importing the IRIO model to investigate the spatial ripple effect

The spatial spread of IELs is the result of an imbalance between supply and demand within a given inter-regional economic relationship. According to Isard (1951), each administrative region is linked by industrial sector supply-demand chains; when one or more areas are directly affected by a sea ice disaster and experiences a decrease in production, the linked areas may be affected because of their supply-demand chain relationships (ripple effects) (Figure 2). The severity of the IEL mainly depends on
the inter-regional supply-demand volume between disaster and non-disasters areas (Koks and Thissen 2016). To assess the IEL in non-disaster areas, we need to import the inter-regional supply-demand relationship at the provincial level to modify the ARIO model. The IRIO model describes these inter-regional economic relationships (Isard 1951). To capture the spatial ripple effect of a disaster, Equations (1) and (2) can be converted by introducing the equilibrium relationship from the IRIO model, which has a structure similar to that of the IO model.

\[
\begin{align*}
(a) \quad x_i^e & = \sum_{s} \sum_{j} x_{ij}^{rs} + \sum_{s} f_{i}^{rs, \text{exp}} \\
(b) \quad x_j^s & = \sum_{r} \sum_{i} x_{ij}^{rs} + \sum_{i} x_{ij}^{\text{imp},s} + \sum_{w, t, c} v_j^s
\end{align*}
\]

The IRIO matrix formulation:

\[
\begin{bmatrix}
X^1 \\
X^2 \\
\vdots \\
X^m
\end{bmatrix}
= 
\begin{bmatrix}
A^{11} & A^{12} & \cdots & A^{1m} \\
A^{21} & A^{22} & \cdots & A^{2m} \\
\vdots & \vdots & \ddots & \vdots \\
A^{m1} & A^{m2} & \cdots & A^{mm}
\end{bmatrix} 
\begin{bmatrix}
X^1 \\
X^2 \\
\vdots \\
X^m
\end{bmatrix}
+ 
\begin{bmatrix}
F^1 \\
F^2 \\
\vdots \\
F^m
\end{bmatrix}
+ 
\begin{bmatrix}
F^{1, \text{exp}} \\
F^{2, \text{exp}} \\
\vdots \\
F^{m, \text{exp}}
\end{bmatrix}
\]
which is then transposed into:

$$
\begin{bmatrix}
X^1 \\
X^2 \\
\vdots \\
X^m
\end{bmatrix} = \left( I - \begin{bmatrix}
A^{11} & A^{12} & \cdots & A^{1m} \\
A^{21} & A^{22} & \cdots & A^{2m} \\
\vdots & \vdots & \ddots & \vdots \\
A^{m1} & A^{m2} & \cdots & A^{mm}
\end{bmatrix} \right)^{-1} \begin{bmatrix}
F^1 \\
F^2 \\
\vdots \\
F^m
\end{bmatrix} + \begin{bmatrix}
F^{1, \text{exp}} \\
F^{2, \text{exp}} \\
\vdots \\
F^{m, \text{exp}}
\end{bmatrix}
$$

Equations (4) and (5) are simplified as:

$$
\begin{align*}
X &= AX + F + F^r, \text{exp} \\
X &= (I - A)^{-1} \cdot (F + F^r, \text{exp})
\end{align*}
$$

From the above equations, $r$ and $s$ represent the provincial scale administrative regions in this study; $i$ and $j$ represent the industry sectors, which exist in every province; $\text{exp}$ and $\text{imp}$ represent the export and import products, respectively; $w$, $t$, and $c$ represent the wage bill, capital, and tax, respectively; and $x$ and $f$ represent the product and final demand, respectively, such that $x^i_j = x^j_i$. Furthermore, $A$ is a square matrix of $m \times m$ that represents the inter-regional intermediate consumption relationships, where every subset, $A^{rs}$, is a square matrix of $n \times n$, which is the inter-regional supply matrix (in coefficients) of sector $i$ in region $r$ and sector $j$ in region $s$.

2.3.2. Importing the disturbance of the sea ice disaster into the IRIO model

The IEL, or the expansive disaster loss, is generally prompted by the direct damage to capital and the reduction in products (Carrera et al. 2015). Thus, direct disaster damage is an indispensable driver of IEL related to that disaster in the ARIO model. For the winter 2009/2010 Bohai Sea ice disaster, two types of DEL occurred: (1) equipment losses, including agricultural equipment (fisheries) and transportation equipment; and (2) product losses (i.e. reductions in agricultural products).

According to the ARIO model (Hallegatte 2008), the loss of agricultural and transportation equipment must be repaired and distributed into additional demands ($F^{r, \text{indust}}$). Therefore, with the introduction of demand impacts, the equilibrium relationship of the IRIO model represented in Equation (6) is modified as:

$$
X = AX + F + F_{r, \text{exp}} + F_{r, \text{indust}}
$$

Losses in an agricultural product are categorized as output losses and restrict the supply that other intra- or inter-region sectors obtain. First, if the agricultural output is reduced to $\Delta x^r_i$ in the disaster area after the sea ice disaster, the agricultural product obtained in every sector of each province in disaster area $\Delta x^{rs}_{ij}$ is changed according to the equilibrium relationship of the IRIO model. The agricultural product obtained can then be generated using a proportional allocation in the row direction in the IRIO table (Equation (1)). Furthermore, based on the equilibrium relationship between supply and demand (i.e. the input is equal to the output) in the IRIO model, the sector outputs in each province, $\Delta x^c_i$, are also adjusted. This can be assessed using Equation (1) in the column direction of the IRIO table, which shows a first-order
cascade effect caused by direct product loss from a perturbed production site (Bierkandt et al. 2014). Clearly, $\Delta x^i_j$ is less than the initial output, $x^i_j$. The post-disaster agricultural supply, $\Delta x^i_{ij}$, does not recover to the initial agricultural product level, $x^i_{ij}$, which causes the entire supply-demand chain to suffer high-order cascading effects. Thus, an increase in product is required to cover shortages in inter-regional supplies and remove the propagation effects across the entire economic system, which can be interpreted as the ability to over-produce ($x^{\text{max}}$) in these sectors when product capacity is impaired (Hallegatte 2008). This study assumes that $x^{\text{max}}$ only exists in two economic sectors within the disaster area (agriculture and transport) for the winter 2009/2010 Bohai Sea ice disaster.

Finally, the adaptation characteristics of marketing agents in the ARIO after a disaster strikes are also extended from a single area into multiple regions, similar to the methods described in Equations (3)–(6). The detailed process is available in Hallegatte (2008), which will not be detailed in this study.

2.4. Estimating the influence of a spatially heterogeneous economic system on the IEL

To reflect the influence of spatial heterogeneity on inter-regional supply-demand structures and assess the spatial ripple effect of disaster impacts using the modified ARIO model, we analysed four scenarios; in other words, we hypothesized that four real disaster areas suffered the same amount of damage from the sea ice event and applied the modified ARIO to reproduce the IEL for each scenario. For these four scenarios, the DEL included agricultural product losses (6,046.00 million CNY), agricultural equipment damage (117.02 million CNY) and transportation equipment damage (155.03 million CNY) (Table 1). Finally, the influence of spatial heterogeneity of disaster impacts on the IEL was captured by comparing the resulting differences from the four scenarios analysed in this study.

3. Results and discussion

3.1. IEL of the 2009/2010 sea ice event estimated by the modified ARIO model

As shown in Table 2, IEL caused by the spatial ripple effect of the sea ice disaster accounted for a large proportion of total economic losses. First, the total IEL reached 2,375.03 million CNY for the sea ice event in China, which was 38% of the total DEL (6,318.05 million CNY). As a result, the DEL estimation clearly underestimated the

| Disaster areas | Hebei | Liaoning | Shandong | Tianjin | Total | Nondisaster areas | Total |
|----------------|-------|----------|----------|---------|-------|-------------------|-------|
| Economic losses DEL | 154.77 | 3486.28 | 2676.00 | 1.00 | 6318.05 | 0 | 6318.05 |
| IEL | 46.08 | 743.78 | 652.57 | 18.12 | 1460.55 | 914.48 | 2375.03 |
| Ratio (Indirect/Direct) | 30% | 21% | 24% | 18| 12% | 23% | Null | 38% |

Note: The IEL was calculated using the change in value to avoid double-counting. The IEL (18.12 million CNY) in Tianjin included two categories: (i) industry-related loss of transportation equipment damaged in Tianjin (0.11 million CNY) and (ii) losses caused by the spatial ripple effect from other disaster areas (18.01 million CNY).
disaster’s impacts; therefore, this IEL assessment cannot be ignored. Moreover, the disaster areas withstood the greatest amount of IEL after the disaster occurred. The disaster areas lost 1,460.55 million CNY due to sea ice event impacts, which accounted for 61% of the total IEL. The Liaoning and Shandong Provinces suffered severe shock, which cost them 743.78 and 652.57 million CNY of the total IEL, respectively, because the DEL was greater in these two provinces. In addition, all non-disaster areas in China that were affected by the spatial ripple effect withstood 914.48 million CNY in IEL damage after the sea ice disaster. Although non-disaster areas did not suffer from direct damage, every province in China was closely linked by the inter-regional supply-demand chain. Abnormal disturbances in the disaster areas were inevitably diffused into non-disaster areas. Combined, non-disaster areas withstood 39% of the total IEL caused by the sea ice event due to this effect.

As shown in Figure 3(a), there were significant spatial differences in disaster disturbance at the provincial scale that were affected by the degree of the economic relation among provinces. First, disaster areas suffered major losses. The IEL was more than 600 million CNY in Liaoning and Shandong Provinces combined, which accounted for 59% of the total IEL in China. However, 2% of the IEL occurred solely in Hebei Province and the Tianjin municipality due to a small swath of damage that triggered a slight disturbance in the intra-region. Second, a plethora of developed provinces in non-disaster areas suffered large losses, e.g. Jiangsu, Guangdong, Henan, Sichuan, Hunan and Zhejiang. The remaining provinces suffered only minor economic losses after the sea ice disaster. For example, the IEL was so minimal as to be negligible in Qinghai and Tibet Provinces and was under 1 million CNY in Hainan and Ningxia Provinces.

In addition, as shown in Figure 3(b), the dynamic effects of IELs after the spatial ripple effect was considered were asynchronous. The higher-order economic effects on disaster areas caused by the sea ice event appeared earlier than those in non-disaster areas. The disaster’s disturbance to the supply-demand chain in disaster areas was delayed by 10 months after the sea ice strike, while the spatial ripple effect persisted for ~15 months in non-disaster areas.

Figure 3. Spatial distribution characteristics (a) and dynamic process (b) of the total IEL after the sea ice event in China at the provincial scale.
As shown in Figure 4, each industrial sector suffered from disaster impacts, with a significant difference in disaster areas and nondisaster areas. First, the IELs in the service industries suffered substantially both in disaster and nondisaster areas; industries affected included business and catering (sector 14, or sec14), finance and leasing services (sec15), and other services (sec17), including culture, sports, entertainment, and public administration. Certainly, agricultural IEL (sec1) was also larger due to fishery equipment damage, which reduced the overall agricultural product. Moreover, the heavy and manufacturing industries paid slight economic costs after the sea ice disaster (i.e. textiles and leather manufacture (sec4), timber and furniture manufacturers (sec5), petroleum and coke refineries (sec6), and non-metal (sec8) and energy (sec11) industries. In addition, the difference in IELs between disaster areas and non-disaster areas was greater than 25 million CNY, excluding the energy (sec11) and synthetic technique services (sec16). These abovementioned differences were caused by inter-regional spatial heterogeneities in the supply-demand chain.

As shown in Figure 5, the spatial heterogeneity of the disaster’s disturbance to the industrial sectors is well reflected by the four sectors with the highest IELs (for 31 provinces in China). First, IELs were most prominent in primary (sec1, agriculture) and tertiary industries (sec14, business and catering; sec15, finance and leasing services; and sec17, other services). The total IEL of these four sectors accounted for 44% of the total IEL in China. Second, of these four sectors, the IEL was greatest in Liaoning and Shandong Provinces (more than 50 million CNY). The sums of IELs in Liaoning and Shandong Provinces comprised 56, 60, 54, and 54% of the total IELs for sec1, sec14, sec15 and sec17, respectively. In other words, more than half of the IEL for these four sectors occurred in disaster areas. Third, the induced IEL among the sectors was not synchronized across the 31 provinces. For example, the

Figure 4. Total IEL for 17 industrial sectors in disaster and non-disaster areas of China caused by sea ice. Note: 'sec' stands for 'sector', and the number is the sequence number of the industrial sector in Appendix A.
agricultural IEL was less in Beijing, Shanghai, Tianjin, Zhejiang and Guangdong than in other provinces of China compared to the other three sectors. For these developed regions, agriculture represents a small proportion of the inter-regional economic system. Therefore, agriculture experienced only a minor impact from the disaster event in these areas. Fourth, the IELs from these four sectors were small in the developing provinces (<2 million CNY); for example, Tibet, Qinghai, Ningxia and Hainan (i.e. disaster areas) had weak economic relationships with these developing provinces.

### 3.2. Sensitivity analysis

A sensitivity analysis of important parameters was necessary due to the complex adaptive mechanisms of socio-economic agents for natural-hazard induced disasters and uncertainties associated with applying the ARIO model (Hallegatte 2008, 2014). In this study, over-production ($a_{\text{max}}$) and the time variables ($\tau_a$) associated with it are the key parameters in the modified ARIO model. Over-production is explained as the gradual increase in the supply of aquatic products by fisher folks to meet the balance between supply and demand. To evaluate the effect of the key parameters on the modified ARIO model, we modelled 12 paired combinations, which included six $a_{\text{max}}$ value {110, 120, 125, 130, 140, and 150%} and two $\tau_a$ values {3 months and 6 months}. For example, a combination with $a_{\text{max}}$ equal to 110% and $\tau_a$ equal to 3

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**Figure 5.** IELs for four sectors and the highest losses in every province of China. **Note:** The order of provinces is in descending order based on total IEL.
months means that over-production could reach to 110% times predisaster production after 3 months of ice melting. The simulation results are shown in Figure 6.

Although the model results are extremely sensitive to the change of $a^{\text{max}}$ from 100% (no overproduction) to 130%, the modified ARIO model is convergent for all paired parameters (Figure 6(a)). Meanwhile, the IEL sensitivity to $\tau_a$ gradually decreases with the increase in $a^{\text{max}}$. This is consistent with the reality that when production capacity is sufficiently high, the bottleneck effects associated with an imbalance in supply and demand will be reduced.

Figure 6(b, c) shows that the dynamic adaptation process in non-disaster areas is more sensitive than that in disaster areas. (i) The simulated convergence time for different paired parameters is similar in disaster areas—~11 months after sea ice melting—and in non-disaster areas—~16 months after sea ice melting. However, the IEL in non-disaster areas of China is more sensitive to the over-production parameters than that in the disaster areas. (ii) As $a^{\text{max}}$ increases and $\tau_a$ decreases in all areas of China, the convergent time of the model advances, and the IEL decreases, which further demonstrates that production supply is an important factor in counteracting the spatial ripple effect of disasters. These sensitive results are also an important reference for assessing the IEL associated with disasters.

### 3.3. Influence of spatially heterogeneous economic structures on IEL after a disaster

The total IEL modelled with the modified ARIO was substantially different across the four scenarios. The total IELs were 2095.60, 2541.00, 2960.10, and 3077.50 million CNY for the four scenarios, with 33.2, 40.2, 46.9, and 48.7% of the total DEL occurring in Hebei, Liaoning, Shandong and Tianjin, respectively (6318.05 million CNY). Because the same DEL amount occurred in Hebei and Tianjin, the total IEL of the 31 provinces in mainland China, which expanded from Tianjin into the entire economic system of China, was 46.8% ((3077.50–2095.60)/2095.60) more than that from Hebei.

Figure 7(a) shows the different influences of spatially heterogeneous economic structures after the expansion of disaster disturbance effects into the entire economic system by comparing deviation value results between the IEL of each scenario and the average IEL of the four scenarios (in non-disaster provinces). First, the IEL for
most provinces in the same scenario was similar to the average IEL, while abnormal IELs were also captured. The IELs in Beijing and Guangdong were larger than those in other provinces when the sea ice event struck Liaoning. In contrast, the IEL was smaller in Beijing when the sea ice event struck Tianjin. Moreover, the number of deviation values was substantially different between the inter-provinces in the four scenarios. For example, when the sea ice struck Shandong, the deviation reached 30 million CNY in Beijing, while the deviation was 5 million CNY in Hubei. This difference shows that Shandong was more closely economically related to Beijing than Hubei; in other words, Beijing suffered greater impacts than Hubei when post-disaster effects struck Shandong. The deviation was $-38$ and $27$ million CNY in Jiangsu when the disaster occurred in Hebei and Tianjin, respectively; this shows that defining different disaster areas caused different impacts in the same non-disaster regions. These differences originated from diversity in the inter-regional supply-demand structure.

As shown in Figure 7(b, c), in both disaster and non-disaster areas, the dynamic impact process was not synchronized. For the disaster areas, sea ice struck Hebei, Liaoning, Shandong and Tianjin; the IEL in Shandong was more than that in the other three disaster areas until 10–15 months after the disaster. The ripple effects were mostly absent from the four scenarios after 15 months. When analysing the same damage in the four scenarios, the IEL after the sea ice event was smallest in Hebei (Figure 6(b)). For non-disaster areas, the difference in dynamic impact processes was more obvious. The impacts on non-disaster areas when the event hit Hebei were less than those of the other three scenarios, while the impacts when the event hit Tianjin were clearly larger. The impacts from Hebei were reduced, while those from Tianjin increased 5 months after the disaster occurred (Figure 7(c)). When comparing the IEL between disaster and nondisaster areas, the disaster disturbance lingered in nondisaster areas. The lingering effects were most obvious and lasted ~10 months after the disaster hit Tianjin; in other words, the indirect economic impacts in Tianjin lasted 15 months after the event, while impacts lasted 25 months after the event in non-disaster areas (Figure 7(b, c)). In addition, the ratio of IEL to total economic losses was substantially different in non-disaster areas, although the total DEL
was identical in the four scenarios. For example, the IELs in non-disaster areas accounted for 38% of the total IEL (2095.60 million CNY); when the disaster occurred in Hebei, the IEL accounted for 55% of the total IEL (3077.50 million CNY). The ratios were 45% and 47% for Liaoning and Shandong, respectively.

3.4. Capturing the spatial ripple effect derived from multiple disaster-hit regions

This study investigated the spatial ripple effect derived from multiple disaster-hit regions using the modified ARIO model. Few studies have analysed the spatial ripple effect after a disaster using the inter-regional supply-demand chain. For example, Koks and Thissen (2016) developed a multiregional impact assessment model to detect ripple effects after national floods, which occurred in Rotterdam. When analysing the Great East Japan Earthquake, Ishikawa (2017) found that the economic impacts of population decline were negative in Fukushima until 2030, while positive effects were detected in the Kanto regions with the IRIO model; Yonemoto (2016) found that the ripple effect could optimize economic structures in non-disaster regions, while disaster regions, which suffer severe devastation, have benefitted less from reconstruction. However, there is a common characteristic among these techniques: all disaster areas are considered a single administrative area with the same supply-demand relationships, which ignores the influence of spatially heterogeneous economic structures on IELs after a disaster (i.e. differences in disaster regions). These issues have been resolved in our study. We found that the influence of spatially heterogeneous economic structures reaches 46.8% when assessing the spatial ripple effect of the 2009/2010 Bohai Sea ice event using four different scenarios (Section 3.2). The dynamic processes associated with IELs are also substantially different between disaster and non-disaster regions. Thus, all direct damages from a disaster across multiple administrative regions should be imported the same way into disaster impact assessment models to accurately reproduce the IEL of a disaster. Therefore, we further modified the ARIO model by introducing the IRIO model framework (Section 2.2) and assessed the estimated IELs of the 2009/2010 sea ice event (Section 3.1). In doing so, we considered the influence of spatially heterogeneous economic structures from multiple disaster-hit regions in our assessment of the spatial ripple effect of disasters (Section 3.1). Thus, the IELs reported in our study are closer to actual IELs than those derived from other models.

3.5. Limitations

Although we successfully captured the spatial ripple effect of the disaster event and differences caused by spatial heterogeneity in the economic system, some limitations are inevitable. First, some uncertainty may exist in the IEL estimation because of the IRIO data limitations. The estimated IELs in some coastal provinces of China, e.g. Zhejiang, Jiangsu and Guangdong, could be overestimated using the supply proportion of the whole agricultural sector as a substitute for the specific aquaculture as used in this study. Theoretically, the spatial ripple effect of a sea ice disaster on these
coastal provinces could be slight because of the high productivity in the aquaculture sector as mentioned above. In other words, the merging of economic sectors, which simplifies the heterogeneity in the inter-regional supply and demand relationship, will overestimate or underestimate the IELs for different sectors in different provinces. As such, the estimated absolute DELs should be taken with care.

Second, more adaptive behaviours need to be considered. The effectiveness and reliability of the ARIO model in reproducing the dynamic processes of disaster impacts has been tested by Hallegatte (2008). In addition, the ARIO model has been widely used to assess the indirect economic costs of disasters (e.g. earthquakes, floods, and typhoons) (Ranger et al. 2011; Wu et al. 2012; Jenkins 2013; Hallegatte 2014). However, the adaptive process is different for different types of disasters. For sea ice disasters, ocean transportation is often disrupted (Zhang et al. 2013), which leads to additional impacts; inventories also play an important role in the emergency management of gradual sea ice disasters (Hallegatte 2014). To increase insufficient supplies caused by fishery product reductions, fishermen pay more to purchase fish-seed and farming supplies, which creates a linkage effect in the inter-regional supply-demand chain. Thus, the results of this study could be more accurate if this adaptive behaviour is considered in the future.

4. Conclusions

This study expanded the estimation of environmental changes in sea ice to reproduce inter-regional cascade effects by investigating the macroeconomic effects of a specific disaster. We modified the ARIO model using the IRIO model to investigate the spatial ripple effect of disaster disturbances and the influence of spatially heterogeneous economic structures on IELs after a disaster. In addition, we applied the modified ARIO model to reproduce dynamic IELs after the winter 2009/2010 Bohai Sea ice disaster.

First, the modified ARIO model effectively captured the spatial ripple effect after a disaster disturbance. Regarding the sea ice disaster, IELs mainly occurred in the disaster areas, accounting for approximately 61% of the total IEL in China. The remaining 39% was distributed among the 27 provinces that were not directly struck by sea ice. The provinces neighbouring the disaster areas suffered great impacts and withstood greater IELs. Several remote and developed provinces (Sichuan, Guangdong and Hunan) were also severely hit. Economically less-developed areas (i.e. Tibet, Qinghai and Hainan) were impacted less.

Second, the spatial heterogeneity of the economic structure of China influenced the results of the disaster disturbance. Given the same direct disaster damages, the differences in IELs when the modified ARIO was applied were greater than 11% and reached upwards of 46.8% after the sea ice disaster. Therefore, understanding the intra- and inter-regional characteristics of supply and demand for each disaster area is vital to the effective evaluation of disaster impacts across multiple regions.

Third, the disaster disturbance to the supply-demand chain left clear lingering effects in non-disaster areas, and the lingering effects lasted ~5–10 months. Thus, even if high-order economic impacts in disaster areas were mostly removed, the effects would still last several months in nondisaster areas.

Overall, this study illustrates that a spatial ripple effect exists after disasters and that the differences in inter-regional industries directly affect the resulting disaster
impacts spread across the inter-regional economic system. The method used to estimate IEL in our study can be used for future disasters. Introducing the role of inventories and the impact of ocean transportation disruptions after a sea ice disaster event is necessary to further improve the ARIO model and reproduce a more reasonable and realistic dynamic spatial ripple effect in the future.

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### Appendix A. Sectors of Interregional input-output table of 31 provinces in China.

| No. | Sector                                      | Inclusion                  | Interpretation                                      |
|-----|---------------------------------------------|----------------------------|-----------------------------------------------------|
| 1   | Agriculture                                | Agri                       | Agriculture                                         |
| 2   | Miner                                       | CoalMineProc               | Coal                                                |
|     |                                             | CrudeOilGas                | Crude Oil and Gas                                   |
|     |                                             | MetalMine                  | Metal Minery                                        |
|     |                                             | NonMetalMine               | Nonmetal Minery                                     |
| 3   | Food manufacture                           | FoodTobcoPro               | Food and Tobacco                                    |
| 4   | Textiles and Leather manufacture           | Textiles                   | Textile products                                    |
|     |                                             | CthShoeLthr                | Cloth, Shoes and Leather                            |
| 5   | Timbers and Furniture manufacture          | SawmillFurnit              | Timbers and Furniture                               |
|     |                                             | PaprPrntCult               | Paper, Print and Cultural products                  |
| 6   | Petroleum Refine and Coke                  | PetrlRefCoke               | Petroleum Refine and Coke                           |
| 7   | Chemistry                                  | Chemical                   | Chemical Products                                   |
| 8   | Nonmetal                                   | NMetalProdt                | Nonmetal Products                                   |
| 9   | Metal                                       | MetalSmelt                 | Metals Melting                                      |
|     |                                             | MetalPrds                  | Metal Products                                      |
| 10  | Machinery                                  | GenerlEqp                  | General Machinery                                   |
|     |                                             | SplEqp                     | Special Machinery                                   |
|     |                                             | ComuTransEqp               | Transport Equipment                                 |
|     |                                             | ElecGasMach                | Electronic Machinery                                |
|     |                                             | ComuntComput               | Communication and Computer                          |
|     |                                             | MetrsOffcEqp               | Measurement Instruments                             |
|     |                                             | ArtsCrafts                 | Other Manufacture                                   |
|     |                                             | GenerlSplEqp               | Machinery Repair Service                            |
| 11  | Energy                                     | ElecSteam                  | Electricity and Steam Supply                         |
|     |                                             | GasSupply                  | Gas Supply                                           |
|     |                                             | WaterSupply                | Water Supply                                         |
| 12  | Construction                                | Construction               | Construction                                         |
| 13  | Transport                                  | TransWarehse               | Transportation, warehousing, and postal services    |
| 14  | Business and catering                      | Trade                      | Wholesale and retail trade                           |
|     |                                             | HotelsDining               | Hotel and Dining                                     |
| 15  | Finance, Real Estate and Leasing           | Finance                    | Finance                                             |
|     |                                             | RealEstate                 | Real Estate                                         |
|     |                                             | LeasCrdsrvc                | Leasing and Business Services                        |
| 16  | Synthetic technique service                | SynTechSrvc                | Scientific Research and Technique Services          |
|     |                                             | ComptTrsSrvc               | Information Service                                 |
| 17  | Other Service                              | WaterPubSrvc               | Public Service Facilities                            |
|     |                                             | ResidentSrvc               | Residential Services                                 |
|     |                                             | Education                  | Education                                            |
|     |                                             | HealthSocPub               | Health Care and Social Service                       |
|     |                                             | CultSpotReacr              | Culture, Sports and Entertainment                    |
|     |                                             | PublicAdmin                | Public Administration                                |
|     |                                             | Scrap                      | Scrap and Waste                                      |