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Effects of sea level rise on economic development and regional disparity in China

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ABSTRACT

Among the climate change-induced threats to coastal regions, sea level rise is considered as the most serious one. Most large and prosperous cities in China are located along coastal regions and are thus likely to suffer huge economic impacts when a sea level rise occurs. The effects on coastal regions can also be transmitted to inland regions through movement of labor and trade, thus affecting regional disparity. To strengthen evidence-based policies of abatement and adaptation, it is essential to assess the economic impacts of sea level rise in addition to the physical impacts already investigated in the literature. Based on data from GIS analysis of flooded areas, this study uses a state-of-the-art technique (TERM-China, a multiregional general equilibrium model of China) to evaluate the economic impacts of sea level rise. The simulation results suggest that if the sea level rise coincides with sudden-onset extreme storm surges, the coastal regions' GDP loss would reach 11% in 2050, wherein Tianjin, Shanghai, and Jiangsu would have the most severe losses with over a 20% decline in their individual GDP in 2050. At the sectoral level, high capital-intensive sectors have more significant output losses. Our results also indicate that sea level rise could cause more unemployment in developed coastal regions, drive people to other developing inland regions, and even convert some mega-cities into middle-scale cities.

1. Introduction

Sea level rise is considered the most serious threat caused by climate change to coastal regions of China. In the past century, China has experienced a persistent trend of rising sea levels with around 20–30 cm total rise and 2.5 mm annual average rise in sea levels. Even faster rise in sea levels, with annual average of 2.6 mm, was witnessed from 1978 to 2008 (SOA, 2008). More importantly, large parts of coastal provinces are in low-altitude regions which are vulnerable to land erosion caused by sea water and storm surges. For example, the average elevation of Shanghai, the biggest and wealthiest city in China, is reportedly only around 4 m (SOA, 2008).

China's coastal regions comprise a large part of the economy and population and are thus likely to suffer huge economic impacts when sea level rise occurs. While China's 11 coastal provinces cover only 13.5% of the land, they account for 57.4% of the national GDP and over 42.2% of the population as of 2016 (NBSC, 2017). Meanwhile, 60% of mega-cities (those with a population of >5 million) in China are located in these areas, including metropolitans like Shanghai, Guangzhou, Tianjin, and Nanjing (Fig. 1). Coastal regions are also intensively industrialized areas, producing over 80% of information technology (IT) equipment, automobiles, and aircrafts in China (NBSC, 2017). Given the huge social and economic importance of the coastal cities, it is imperative to study the impacts of any climate change induced disasters, especially those of sea level rise on economic development on these urban centers.

Moreover, the effects on coastal regions can be transmitted to the inland regions through labor migration and trade, thus affecting regional disparity in China. According to the "Chinese Floating Poeple's Development Report 2016," laborers from other regions account for 74.7% of the total labors in eastern China (NHFPC, 2016). The extreme amount of traffic around Chinese New Year also illustrates the large movement of labor between different regions in

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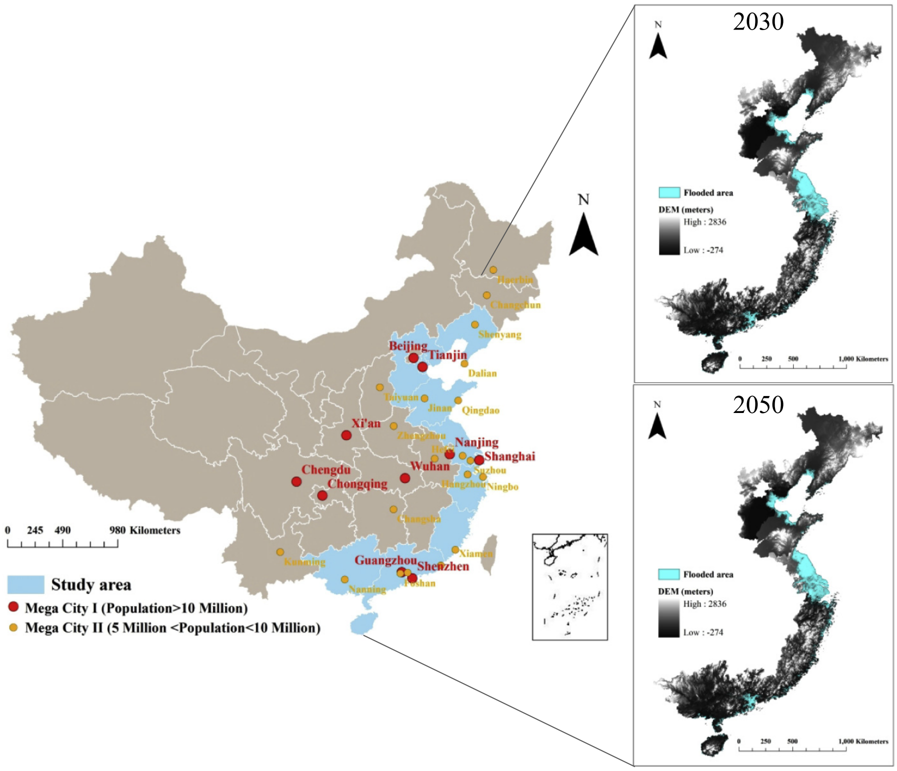

Fig. 1. Coastal regions in China (11 provinces) and flooded areas under the worst scenario with slow-onset sea level rise superimposed on sudden extreme storms in 2030 and 2050 (Note: the possible mega-cities are projected after 2020 by Fang (2014); the percentage of flooded areas under only the slow-onset sea level rise scenario are listed in Tables A.2 and A.3).

China. Sea level rise will likely drive people to go back to inland regions due to closed business, reduced wages and flooded land in the coastal regions. Meanwhile, the Term-China database suggests that exports from coastal regions to other regions of China account for 15% of China's production in 2012. As for the close interactions between regions of labor and trade, it is possible that the impacts of sea level rise will transmit to the whole country and further change the regional disparity.

It is known that sea level rise negatively impacts coastal economies through several physical shocks. For example, the increase in global mean temperature causes the thermal expansion of ocean water, which coupled with the melting of land-based icebergs and mountain glaciers results in a rise in sea levels (Deke et al., 2001). In addition, climate change also increases the speed of sea level rise by changing both the probability and severity of extreme weather events, such as storms and floods (Wu, 2016). Retreating coastlines cause the inundation of land and fixed physical assets, which are difficult to recover. As a result, inundated cropland, construction land, and assets severely threaten the economy (McInnes et al., 2003; Nicholls and Tol, 2006; Hallegatte et al., 2011).

The existing research mainly focuses on the physical impacts of sea level rise on China, with very few studies estimating economic and social impacts on China's coastal regions. An early study has shown that if sea levels rose by 1 m, over 92,000 km^2 of the four large coastal plains would be vulnerable to inundation or more frequent coastal flooding (Han et al., 1995). Dong et al. (2010) suggested that major urban agglomerations in coastal regions of China were severely threatened by floods, land inundation, erosion, water pollution, and destruction of ports and riverways. A study on Shanghai found that storm surge flooding at the maximum possible tide level could cause nearly total inundation of the landscape and put approximately 24 million people at direct risk resulting from consequences of flooding (Yin et al., 2011).

To strengthen evidence-based policies of abatement and adaptation, it is necessary to evaluate the physical impacts and then assess the corresponding economic losses of sea level rise. Thus, for policy makers and the public, if they can see the effects on economic growth and leading industries, which are in accordance with their own macroeconomic forecasts, they will be better able to choose the most effective emission reduction measures (Leiserowitz, 2006; Krosnick et al., 2006; Lorenzoni et al., 2007; Dong, 2017). For microenterprises or households, these developed areas abound with many large cities; and thus when inundation threatens and labor demand reduces, people will have no other options but to migrate to more advantageous inland regions (Barnett, 2003; Curtis and Schneider, 2011). When industries and the masses see these disastrous effects, even some large cities being converted into medium-scale or even small-scale cities, they will more effectively adopt private measures against sea level rise. Keeping in view the importance of assessing the effects of sea level rise on coastal regions of China, this study attempts to answer the following questions:

- How large will the effects of sea level rise on economic growth of the coastal areas be?
- How large will the effects of sea level rise on output of the leading industries be?
- How large will the effects of sea level rise on wage disparity of coastal and other regions be?
- Will residents of inundated regions migrate to other regions because of loss in wage advantage? Will some of the coastal mega-cities become middle- or small-scale cities?

The purpose of this paper is to examine the economic development and regional disparity impacts of sea level rise in the future, taking consideration of both slow-onset sea level rise and sudden-onset storm surges. Thus, based on data from GIS analysis of flooded areas, we use a state-of-the-art economic technique (TERM-China, a multisector and multiregional general equilibrium model of China) and design alternative scenarios based on sea level rise projections to simulate the economic implications for coastal provinces in 2030 and 2050. Our approach offers two key advantages: first, based on TERM-China, our economic impacts on coastal provinces not only portray the reduced capital supply shock, but also include influences from interactions among different sectors. So, we can evaluate not only the impacts on economic growth but also on the industrial structure. Second, we analyze the interregional economic impacts from the coastal provinces to the rest of China to see the spillover effects of sea level rise on developed coastal regions. Thus, we can assess the impact on movement of labor and regional disparity.

The rest of the paper proceeds as follows. Section 2 quantifies the physical impacts of sea level rise. Section 3 introduces our multi-regional computable general equilibrium (CGE) model and explains the scenario design based on sea level rise projections. Section 4 reports the impacts of sea level rise on economic development, industry output, and regional disparity due to employment change. Section 5 concludes this paper with a discussion.

2. Quantification of the physical impacts of sea level rise

Measuring the physical damage from sea level rise is essential to simulate the ensuing economic impacts. Previous research has only simulated the flood inundation areas in the coastal region as a whole or in some more vulnerable regions (Han et al., 1995; Dong et al., 2010; Yin et al., 2011). The interregional labor flow and the relocation of factories and industries caused by sea-level rise can not be captured by using the model at national level. To assess the dynamics of sea level impacts, we need to estimate the flood inundation areas at a more detailed level. Sea level rise induces physical impacts through the following channels: (1) increased inundation probability and submergence; (2) increased erosion; (3) coastal wetland loss; and (4) change in salinization. In this study we only consider the channel with the largest impact on the coastal regions i.e., increased inundation probability and submergence.

The sea level rise and storms can cause economic damages by inundating both construction land and cropland. Previous studies have used different methods to quantify the physical impacts of sea level rise. For example, some damages can be easily quantified in terms of physical units, such as amount of land or physical assets lost and number of people displaced (Bosello et al., 2012; Ma et al., 2015). However, other damages are more difficult to quantify, for example, the increasing vulnerability of coastal areas. Considering the difficulty of measuring the damage from sea level rise in monetary units, this is often quantified in terms of physical units (Deke et al., 2001), such as acres and percentages of land lost. Therefore, this study quantifies the physical damage caused by climate change as the percentage loss of construction land and cropland in coastal regions.

To investigate the impacts of sea-level rise at provincial level, we derive the percentage loss in construction land and cropland through an integrated GIS analysis of future rise in sea level and the Digital Elevation Model (DEM) status added to land use data in each coastal province, as follows:

- For slow-onset sea level rise, we use the data for sea level rise in meters in 11 coastal provinces in the next 30 years from China's State Oceanic Administration (China Sea Level Communique, 2016). Then, combining with current sea level altitudes of each province (with a 60–70 cm difference from northern to southern provinces),[1] the sea level altitudes are projected for 2030 and 2050. We employ the uncertainty expression in predicting the range of sea level rise with the best and worst scenarios. For sudden-onset extreme storms, the sea level rise (in meters) in a once-in-a-hundred-year event is calculated from the statistical data record by more than 30 long-term coastal tide stations in the 11 provinces (Zuo et al., 2013). Then, combining the future sea level altitude caused by only slow-onset sea level rise, we estimate the sea level altitude in 2030 and 2050 with simultaneous occurrence of extreme storms (Both types of rise in sea level are shown in Appendix Table A.1).
- Flooded areas of different land use types in 11 provinces are estimated based on the assumption that “when sea level rises x meters, the coastal regions with DEM elevation below x meters are submerged.” The data for DEM is at 90 m resolution and comes from ASTER GDEM's products.[2] The land use data, at a resolution of 300 m, comes from GlobCover.[3] For assessing the impact on coastal developed cities, the land use data of study area is divided into three categories: construction land, agricultural land, and open spaces. We upscale the land use data resolution from 300 m to 90 m to match with DEM data.

Table 1
Comparison of flood inundation ratios estimated by this study with the previous research (the sea level rise and extreme storm scenario in 2050).

	This study	Zuo et al. (2013)
The Coastal Region	10.1%	9.4%
Bohai Sea Zone	4.2%	3.0%
Yangtze River Delta	30.4%	30.4%
Pearl River Delta	2.9%	2.8%

The inundation ratios of construction land and cropland depend on scenarios of sea level rise and storm surges caused by climate change and the DEM status in coastal provinces (Fig. 1). It is noted that our estimations do not consider the impacts of any future protection measures. For slow-onset sea level rise, Guangdong and Hainan have the most inundated construction land at over 10% in 2050, followed by Jiangsu Province with 8.27–10.24% in 2050. For other coastal provinces, less than 2% of the construction land is inundated in 2050 due to slow-onset sea level rise (Table A.2). Under the same scenario, Jiangsu and Guangdong Provinces would have the greatest losses in cropland with around 6% in 2050 (Table A.3). Other provinces have slight cropland inundation (<2%) in 2050. In case of sea level rise with superimposed storm surges, the indentation ratio of construction land and cropland are much higher than situations with only slow-onset disaster. Though Tianjin, Shandong, Shanghai, and Zhejiang have slight inundation of construction land owing to slow-onset sea level rise, they have very serious inundation of construction land due to sea level rise with superimposed storm surges-ranging between 40% and 52%. The situation for loss of cropland in most provinces is similar to that of construction land, except Shandong has significant inundation of construction land but insignificant cropland loss.

The ratios of flooded areas estimated in this study are very close to the results of previous literature (Table 1). For instance, due to both sea level rise and extreme storm surges, we estimate that 10.1% of the coastal areas are submerged as compared to 9.4% found in the previous research (Zuo et al., 2013).

[1] http://www.psmsl.org/data/obtaining/stations/933.php.
[2] http://gdem.ersdac.jspacesystems.or.jp/.
[3] http://due.esrin.esa.int/globcover/.

3. Methodology and scenarios

3.1. TERM-China model

In this study, the economic impacts of sea level rise are evaluated based on a state-of-the-art multiregional CGE model, TERM-China, which is the modified version of TERM (The Enormous Regional Model). Compared with other national CGE models, such as the ORANI-G model (Horridge, 2014), TERM-China has a high degree of regional details, which makes it a more useful tool for examining the regional impacts of shocks (especially supply-side shocks) on provincial economies. TERM-China also has a particularly detailed treatment of all industrial sectors and is therefore better suited for simulating the impacts on sectors and the intersectoral relationships. Overall, TERM-China provides a unique opportunity to analyze the regional and industrial impacts of sea level rise.

Specifically, TERM-China has a "bottom-up" structure which treats each province in China as a separate economy and links regional economies to each other through commodity trade and movement of endowment (e.g., labor). Unlike many other multiregional CGE models, TERM-China allows commodity re-exports between regions based on the hypothesis that one region may leave some of its direct imports unused, which could be reexported to other regions. Similarly, exports from one region are not necessarily produced there and may come from other regions. Therefore, TERM-China has the capability to not only evaluate the direct impacts of sea level rise on coastal economies but also to capture the indirect impacts through interregional linkages.

In our model, a closure with fixed regional capital stock is chosen, which can incorporate the physical impacts of sea level rise caused by climate change on different sectors. Thus, the rate of capital return may differ among coastal regions. TERM-China model identifies five types of labor force, three of which are in rural and two are in urban areas. We assume that national employment is independent of the real wage (full employment), while allowing the labor of the same type to move between regions according to regional wage gaps. Other assumptions in this paper follow the standard closure of the standard TERM model, which has been extensively used in literature (Giesecke et al., 2010).

The basic database of TERM-China used in this paper comes from the 2012 provincial input–output tables published by the National Bureau of Statistics, containing 30 provinces (excluding Tibet, Hong Kong, Macao, and Taiwan) and 42 industries (NBSC, 2016). In addition, the data on international trade and tariffs are collected from China Customs with 2012 as the base year. To simulate the economic impacts of sea level rise in coastal regions, the regions of TERM-China are aggregated into 12 regions, including 11 coastal provinces[4] and one noncoastal region. The industries in TERM-China encompass 42 industries with 1 agricultural sector, 27 manufacturing sectors, and 14 services sectors (Appendix, Table B.1).

Under climate change, we incorporate the direct physical damages of sea level into TERM-China to evaluate the economic impacts of sea level rise. Following Eboli et al. (2010), the physical damages due to sea level rise in TERM-China are modeled as the shock to industry capital stock in each coastal province. Specifically, we first calculate the percentage loss of cropland and construction land in each coastal region. We also assume that the assets adhering to a piece of land will be lost if the land is inundated as a result of sea level rise.

3.2. Scenarios

Our study simulates the economic effects of sea level rise (projected for 2030 and 2050) on the current economic conditions as of 2012. This analysis would be the equivalent of having the future climate change applied to today's economy. This approach has the advantage of minimizing the assumptions on future economic evolution and easily explaining the results originating from climate change shocks and is adopted by several studies (e.g., Halsnæs et al., 2007; Ciscara et al., 2011).

We design two climate change scenarios to investigate two types of sea-level rises caused by climate change. Follow the previous studies (Nicholls and Tol, 2006; Gasper et al., 2011; James et al., 2014), the first scenario (Scenario S1) only considers the slow-onset sea level rise caused by climate change. For Scenario S1, both the high and low projections of sea level rise are used respectively. The second scenario (Scenario S2) simulates the economic impacts of the sudden-onset storm surges on top of slow-onset sea level rise caused by climate change (Perch-Nielsen et al., 2008; Karim and Mimura, 2008; Hallegatte et al., 2011). For Scenario S2, the slow-onset sea level rise is first averaged by the high and low projections used in Scenario S1, then is superimposed by the storm surges.

4. Estimates of the economic impacts

The following section describes simulated impacts of sea level rise in 2030 and 2050 on economic growth and industry production in developed coastal regions and the spillover effect to the rest of China by employing TERM-China. To this end, percentage changes indicated in the text refer to differences in simulation results with respect to the base data of TERM-China in 2012.

4.1. Economic impacts of sea level rise

Sea level rise would result in land inundation, reduced industrial capital, and decline in GDP of coastal regions. Under Scenario S1, the total real GDP of coastal regions would decline by 1.97%–2.39% in 2050. Real GDP would decline by around 11% in 2050 under Scenario S2, considering the additional damage caused by extreme storm disasters.

The impacts of sea level rise caused by climate change on real GDP differ among coastal regions depending on the percentage of inundated cropland and construction land. Under Scenario S1, the real GDP of Guangdong, Jiangsu, and Hainan are most severely impacted by sea level rise, decreasing by over 5% in 2050. The GDP of other coastal regions decrease slightly by around 0.5% in 2030 and less than 1% in 2050 (Fig. 2a). The negative impacts of sea level rise on real GDP are consistent with the inundation of cropland and construction land. These provinces also experience the severest loss of cropland and construction land from slow-onset sea level rise, as shown in Tables A.2 and A.3. Compared with Scenario S1, the impacts of sea level rise on provincial GDP are more significant under Scenario S2, which considers the damage caused by sudden-onset storms in addition to the slow-onset sea level rise (Fig. 2b). Among the coastal provinces, Tianjin, Jiangsu, and Shanghai would have the most severe damage to GDP with declines of around 20% in 2050, followed by Guangdong, and Zhejiang with GDP losses over 10% in 2050. Interestingly, Tianjin and Shanghai have slight GDP decreases attributed to the slow-onset sea level rise, but they are expected to experience significant GDP losses from extreme storms. Under Scenario S2, nearly 50% and 75% of construction land is inundated in Tianjin and Shanghai in 2050 (Table A.2), leading to around 20% loss in their respective GDPs.

Though all coastal provinces experience inundation of cropland

[4] From north to south: Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan.

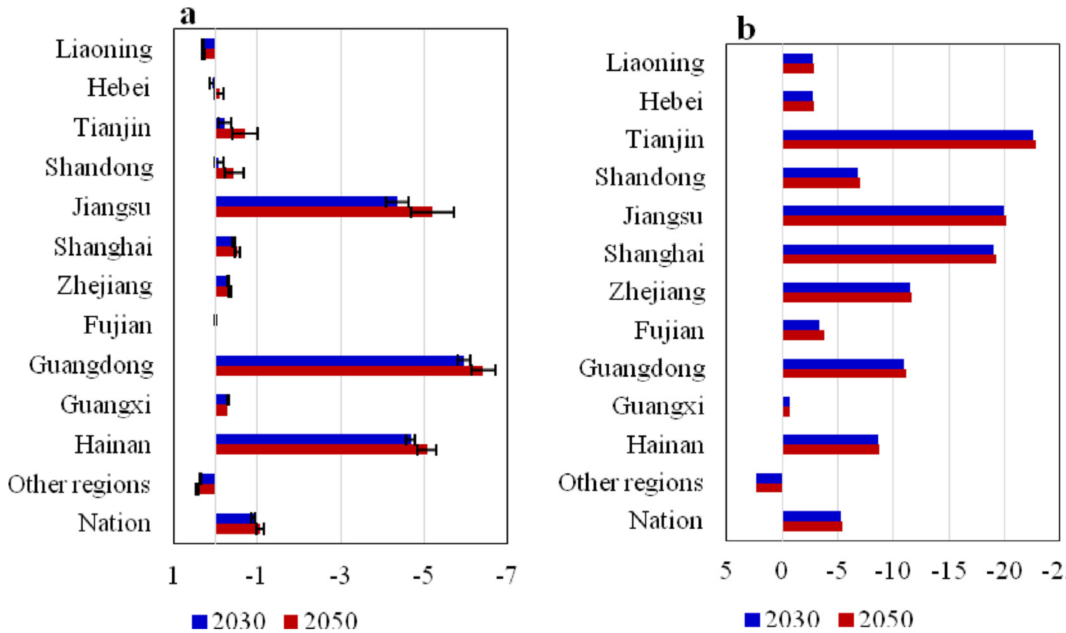

Fig. 2. Impacts of sea-level rise on China's provincial GDP under Scenario S1(Fig. 2a) and Scenario S2(Fig. 2b)(%).

and construction land due to sea level rise, under Scenario S1, the provincial GDP of Liaoning, Fujian, and Hebei also see positive impacts of slow-onset sea level rise (left panel, Fig. 2). Compared with other provinces, these provinces generally have less inundation of cropland and construction land (Tables A.2 and A.3). While their production capital also suffers, the sea level rise provides two opportunities to expand their production. On one hand, the coastal provinces with less damage from sea level rise would cease the opportunity to expand their production to make up for the loss of production in the provinces that experience severe damage. On the other hand, given the fixed national employment, the coastal provinces with severe damage would have a greater reduction in real wages, which consequently results in movement of labor to provinces with less damages (discussed at length below). Thus, the provinces with less inundation of cropland and construction land would see increases in real GDP. Even under Scenario S2, these provinces would have a relatively lower decrease in GDP of less than 3% in 2050 (right, Fig. 2).

Meanwhile, real GDP will rise slightly in the inland regions by 0.40%–0.49% in 2050 under Scenario S1 (left, Fig. 2). TERM-China links provincial economies by interregional trade and movement of labor. Sea level rise reduces industrial production of coastal provinces and raises the local prices of commodities, which then stimulates the industrial production of China's inland regions. At the same time, the labor force moves from coastal to inland regions in response to wage gaps. Therefore, real GDP of inland provinces increases slightly under Scenario S1, and the impacts of sea level rise are found to be larger under Scenario S2 with an increase of 2.36% in 2050 (right, Fig. 2).

As a whole, sea level rise is projected to bring down the national GDP under both Scenarios S1 and S2 in 2030 and 2050 due to the damaged capital stock. Sea level rise brings China's real GDP down slightly without considering extreme storm damage (Scenario S1), however, the loss of real GDP becomes moderate due to the additional impacts of sea level rise from extreme storm damage (Scenario S2). Under Scenario S1, real GDP declines by 0.96%–1.16% in 2050, depending on different projections of sea level rise. However, real GDP would fall by 5.44% in 2050 under Scenario S2, considering the additional damages caused by sudden-onset storm disasters. Though extreme storms would not occur frequently (maybe once in a century), they could lead to more land indentation and greater GDP losses in the future if no protections measures are adopted.

4.2. Industrial impacts in coastal provinces

The output of different sectors in coastal regions would decline due to sea level rise.[5] Under Scenario S1 (slow-onset sea level rise), electronic products, including computers and cell phones, have the highest percentage decline (by 4.16%–4.88%) in 2050 among the industrial sectors, except the sector "other industry" (Fig. 3a). Following the electronic products, the chemical, machinery, services, and light manufacturing industries have similar output reductions in coastal regions, by around 2%–3%. Coincidently, most of these production units are located in the Yangtze River Delta, Pearl River Delta, and Bohai Sea Zone, which account for over 80% of electronic products and over 60% of machinery production of China (NBSC, 2017). Compared to the industrial sectors mentioned above, agriculture, mining, energy, and construction have relatively smaller output declines of less than 2%, and these sectors also account for a small ratio of the coastal economies.

Moreover, the impacts of sea level rise on industrial outputs are somewhat smaller than the inundated ratio of construction land in coastal regions. When the sea level rise causes indentation of construction land, industrial productions would decrease but the output prices would simultaneously increase. In response to the increase in output price, primary factors (i.e., labor and capital) will shift into these industries to expand production, which will at least partially mitigate the negative impacts of sea level rise on industrial output.

If the sudden-onset storm surges are superimposed by sea level rise (Scenario S2), the industry impacts of sea level rise in coastal regions will be much larger than those under Scenario S1. Particularly, electronic product output declines by over 17% in 2050, followed by over 10% decline in the output of chemical, metal,

[5] To save space, we present aggregated results of the original 42 sectors in TERM-China model into 9 sectors, as shown in Table B.1.

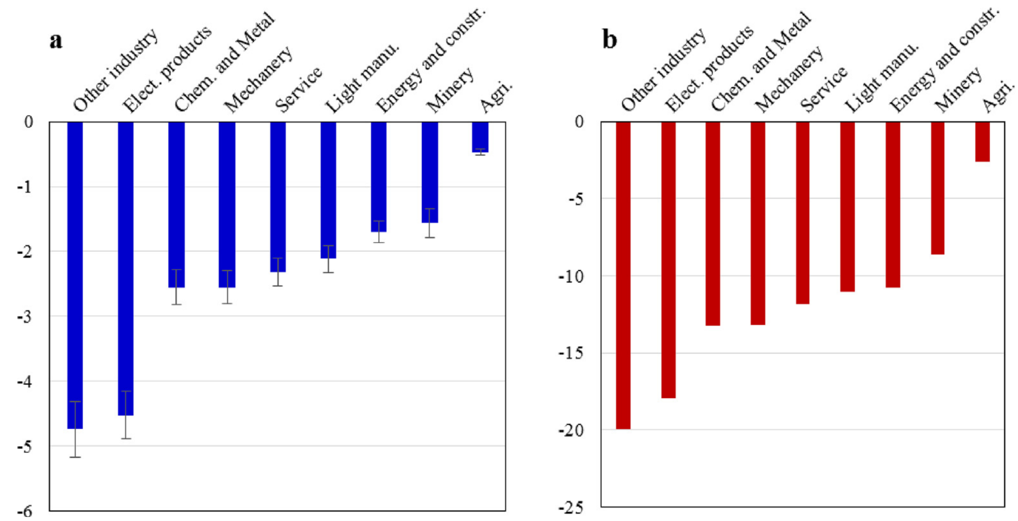

Fig. 3. Industrial impacts of climate change in coastal regions in 2050 for Scenario S1 (Fig. 3a) and S2 (Fig. 3b).

machinery, services, light manufacturing, and mining industries (Fig. 3b). Agriculture has the lowest output reduction in 2050 with less than 3% on average.

Our results indicate that the severest hazards occur mainly in developed urban agglomerations and strongly affect recently emerging industries. Thus, climate change could cause more unemployment in developed cities and drive people going back to other developing cities, and finally even slow down the growth of urban agglomerations in China.

4.3. The impacts of sea level rise on provincial real wages and employment

In addition to provincial GDP and industrial outputs, the sea level rise will significantly affect provincial real wages and employment.[6] Suffering from sea level rise, all coastal provinces would experience the spoilage of capital and land to different extents, depending on the inundation ratios of farmland and construction land. As a result, the industrial outputs in coastal provinces would decline, which in turn will lead to falling labor demand by the industries. Finally, provincial real wages would fall both in rural and urban areas of coastal regions.

From Table 2, we can see that under Scenario S1 (slow-onset sea level), real wages in coastal regions would decline in 2050, with real wages of rural households decreasing more than those of urban households. For example, real wages in Guangdong Province decline by 4.53%–5.17% for rural households and 4.11%–4.61% for urban households in 2050 under Scenario S1. Following Guangdong Province, Jiangsu and Hainan are two other provinces where real wages fall by over 3%. Meanwhile, decreases in real wages are smaller in other coastal provinces because of smaller ratios of inundated cropland and construction land. As for inland regions, real wages decline by 1.70%–2.09% for rural households and 0.82%–0.98% for urban households. Due to decline in employment in all provinces, the national real wage would fall by 1.10%–1.23% for rural households and by 1.24%–1.51% for urban households in 2050 under Scenario S1. The impacts of sea level rise on real wages under Scenario S2 are larger (considering the sudden-onset storm surges superimposed on slow-onset sea level rise).

Table 2
Impacts of sea level rise on real wages in 2050 (%).

	S1				S2	
	Worst		Best			
	Rural	Urban	Rural	Urban	Rural	Urban
Liaoning	−2.15	−1.09	−1.71	−0.86	−12.28	−7.04
Hebei	−2.50	−1.43	−1.95	−1.09	−13.14	−7.46
Tianjin	−2.36	−1.71	−1.74	−1.21	−19.93	−16.44
Shandong	−2.51	−1.55	−1.91	−1.13	−13.69	−8.89
Jiangsu	−4.77	−4.17	−3.90	−3.43	−19.56	−15.88
Shanghai	−2.07	−1.48	−1.70	−1.21	−17.02	−14.64
Zhejiang	−2.18	−1.38	−1.78	−1.14	−15.15	−11.26
Fujian	−2.19	−1.21	−1.79	−1.02	−12.34	−7.39
Guangdong	−5.17	−4.61	−4.53	−4.11	−14.83	−11.01
Guangxi	−2.60	−1.38	−2.15	−1.19	−12.14	−5.71
Hainan	−4.36	−4.00	−3.72	−3.57	−15.21	−9.63
Other Regions	−2.09	−0.98	−1.70	−0.82	−10.22	−4.32

In response to changes in real wages, employment levels in coastal provinces would also change. In modeling approach, we assume full national employment and allow provincial employment to change in response to real wage gap. Parallel to GDP reduction in coastal provinces, provincial employment would have a large decrease in Jiangsu, Guangdong, and Hainan under Scenario S1 (the slow-onset sea level rise), which is consistent with the relative change in real wages (Fig. 4a). For example, rural

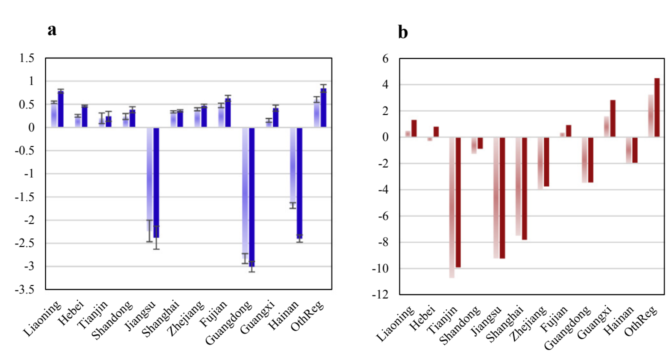

Fig. 4. The impacts of sea-level rise on employment in coastal regions in 2050 for Scenario S1 (Fig. 4a) and S2 (Fig. 4b) (%).

[6] To save space, we present aggregated results of the five types of labor in terms of two types: rural and urban.

employment in Guangdong Province declines by 2.72%–2.94% in 2050 in response to rural real wages decrease of 4.53%–5.17%. As mentioned above, these provinces have the largest share of inundated land, thus undergoing the most serious damage by sea level rise under Scenario S1. In contrast to coastal regions, employment in inland regions would increase slightly. Specifically, employment in inland regions would rise by 0.08%–0.84% for urban households and by 0.06%–0.60% for rural households in 2050. The impacts of sea level rise on provincial employment are more obvious under Scenario 2 (Fig. 4b). When employment falls in 7 of 11 coastal provinces in 2050, employment in inland regions would rise by 4.50% for urban households and 3.24% for rural households.

Considering that national employment is fixed, the changes in provincial employment suggest that labor must flow from the developed coastal regions to inland regions, which are less developed. Since most large cities are located in the developed coastal regions, the reversal of labor flow caused by sea level rise would significantly affect China's economy and urbanization path. Influenced by sea level rise, many factories and industries would have to relocate to inland regions in response to inundated construction land in coastal regions. Following this transition, many people would leave the coastal developed cities for inland regions to find jobs. We could expect that the growth of coastal agglomeration in term of both population and economy will slow down or even reverse. Finally, both the economic and population distributions in China would be significantly impacted by the sea level rise.

5. Conclusions and discussion

The economic impacts of sea level rise under climate change on China's developed coastal regions are evaluated in this paper. We estimate the ratios of inundated construction land and cropland due to slow-onset sea level rise and sudden-onset extreme storms in 2030 and 2050. Alternative scenarios are set up considering the high and low height of sea level rise, respectively. Then, we use the TERM-China model to assess the economic impacts of sea level rise on the coastal region's economic growth and industrial production. The simulation results suggest that the 11 coastal provinces collectively suffer economic impacts of sea level rise with GDP decrease by 1.97%–2.39% in 2050 due to the slow-onset sea level rise. Among those provinces, Guangdong, Jiangsu, and Hainan would severely suffer from sea level rise under the slow-onset sea level rise. If the sea level rise is superimposed upon by sudden-onset extreme storm surges, the GDP loss in coastal regions would reach 11.06% in 2050, with Tianjin, Jiangsu, and Shanghai receiving the severest damage, resulting in GDP declines of around 20% in these provinces in 2050. The impacts in coastal regions can transmit to the rest of China through trade and movement of labor, thus reducing China's GDP by around 0.96%–1.16% in 2050 due to slow-onset sea level rise and by about 5.44% due to both the slow-onset sea level rise and the sudden-onset extreme storms. In the coastal regions, high capital-intensive sectors have more significant output damage from sea level rise, including electronic products, chemicals and metals, machinery, and light manufacturing. It is therefore recommended that investments in adaptation measures should be directed to these regions and sectors on priority basis. Sea level rise would impact both the economic structure and population distribution in China, as labor would migrate from the developed coastal cities to inland regions. China might also need to reconsider its future urban planning and labor migration issues due to impact of sea level rise on mega cities in coastal regions. On the other hand, this could be a blessing in disguise, so as to reduce the income gaps between large and small cities and reversal of labor migration pressure on large cities.

The results come with a number of caveats. The economic impacts of sea level rise caused by climate change may be at least partially underestimated. We measure the physical impacts of sea level rise as inundated construction land and cropland of each coastal province, which are then transmitted into TERM-China. Thus, the economic implications are simulated at the provincial level assuming that the spatial distribution of capital stock is equal (due to lack of reliable data on the spatial distribution of the capital stock). But it is noted that we have different sea level rise altitude for each province and the area to be flooded according to the difference of sea level rise altitude and DEM data. However, industrial units and transport facilities are mostly located in coastal areas and ports in the coastal provinces at relatively lower altitudes. Consequently, the GDP loss caused by the future sea level rise is expected to be greater than the level reported in this paper. Nevertheless, our results could be considered as a relatively optimistic judgement of the economic implications of sea level rise.

Due to China's growing economy in the future, the economic damage of sea level rise may be greater than our estimation in terms of absolute value. The economic impacts of sea level rise are simulated based on a static multi-regional CGE model with base data driven from provincial input–output tables of China in 2012. China is anticipated to not only have a larger economy but also higher proportions of industrial output and urbanization rates in 2030 and 2050. Thus, the sea level rise superimposed upon by extreme storm surges will likely cause more severe damage to industrial output and GDP in terms of absolute value.

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Appendix A. Physical impacts results of sea level rise

Table A.1
Sea level rise altitude due to slow-onset sea level rise and sudden-onset storm.

	Slow-onset sea level rise (cm)				Sudden-onset storm (cm)
	Worst		Best		
	2030	2050	2030	2050	
Liaoning	9.6	18.6	4.9	9.3	300.6
Hebei	9.8	19.0	5.1	9.7	178.6
Tianjin	10.3	19.9	5.5	10.5	432.6
Shandong	10.6	20.6	5.9	11.3	250.4
Jiangsu	39.7	49.9	34.9	40.3	454.1
Shanghai	38.6	47.6	33.9	38.1	380.6
Zhejiang	38.6	47.6	34.1	38.5	555.6
Fujian	48.5	56.9	44.5	48.9	484.7
Guangdong	83.9	93.5	79.2	84.2	372.8
Guangxi	82.2	90.2	78.2	82.2	412.7
Hainan	84.5	94.9	79.9	85.5	367.7

Table A.2
Percent loss of construction land in coastal provinces caused by sea level rise.

	Slow-onset sea level rise				Slow-onset sea level rise + sudden-onset storm	
	Worst		Best			
	2030	2050	2030	2050	2030	2050
Liaoning	0.26	0.50	0.13	0.25	8.97	9.17
Hebei	0.54	1.06	0.29	0.54	7.92	8.21
Tianjin	1.21	2.35	0.65	1.24	50.88	51.73
Shandong	1.00	1.94	0.56	1.06	15.98	16.45
Jiangsu	8.16	10.24	7.17	8.27	43.25	43.97
Shanghai	1.30	1.60	1.14	1.28	40.44	41.02
Zhejiang	1.27	1.56	1.12	1.26	25.16	25.47
Fujian	0.64	0.75	0.58	0.64	9.28	10.00
Guangdong	11.20	12.49	10.58	11.25	24.05	24.52
Guangxi	1.16	1.27	1.10	1.16	5.26	5.33
Hainan	11.34	12.72	10.71	11.47	24.12	24.63

Table A.3
Percent loss of cropland in coastal provinces caused by sea level rise.

	Slow-onset sea level rise				Slow-onset sea level rise + sudden-onset storm	
	High		Low			
	2030	2050	2030	2050	2030	2050
Liaoning	0.07	0.13	0.04	0.07	3.75	3.84
Hebei	0.04	0.08	0.02	0.04	0.85	0.88
Tianjin	0.6	1.16	0.32	0.61	49.09	49.91
Shandong	0.09	0.17	0.05	0.09	2.37	2.44
Jiangsu	6.22	7.81	5.47	6.31	47.20	47.98
Shanghai	1.5	1.85	1.32	1.49	74.87	75.94
Zhejiang	0.26	0.32	0.23	0.26	22.35	22.62
Fujian	0.35	0.41	0.32	0.35	5.93	6.35
Guangdong	6.29	7.01	5.94	6.31	13.14	13.39
Guangxi	0.17	0.18	0.16	0.17	0.61	0.62
Hainan	1.65	1.85	1.56	1.67	5.70	5.81

Appendix B

An introduction to TERM-China model

In the TERM-China model, producers choose a cost-minimizing combination of intermediate and primary factor inputs. Two separate aggregates, of primary factors and of intermediate inputs, are modeled in proportion to industry output (Leontief assumption). The primary factor aggregate is a CES composite of capital, land, and a labor aggregate, and the last is a CES composite of five types of labor by skill group (three rural and two urban). The aggregate intermediate input is another CES composite of different composite commodities, which are, in turn, CES composites of commodities from different sources (i.e., imports vs. domestic). At the top of production nests, industrial outputs are transformed into commodity outputs via a CET mechanism. The CES equation of industry demand is shown as follows:

```
Variable
 (all,c,COM)(all,i,IND)(all,d,DST)
                                  xint_s(c,i,d) # Industry demands for dom/imp composite
Equation
 E_xint (all,c,COM)(all,s,SRC)(all,i,IND)(all,d,DST)
xint(c,s,i,d) = xint_s(c,i,d) - SIGMADOMIMP(c)*[ppur(c,s,i,d)-ppur_s(c,i,d)];
```

In the above equation, xint(c,s,i,d) is the percent change in the demand for domestic or imported commodity *c* of industry *i* in region *d*; xint_s(c,i,d) is the percent change of total demand commodity *c* of industry *i* in region *d*; SIGMADOMIMP represents the substitution elasticities of between domestic and imported commodities; ppur(c,s,i,d) is the percent change in price of domestic or imported commodity *c* of industry *i* in region *d*; and ppur_s(c,i,d) is the percent change in composite price of commodity *c* of industry *i* in region *d*. The CES equation above suggests that the industrial demand of domestic commodity *c* will increase only if domestic prices of commodity *c* decrease relative to the composite price of commodity *c*.

On the demand side of TERM-China model, a series of nests indicate the various substitution possibilities. Households choose each commodity between imported and domestic sources. A CES-Armington specification describes their choice guided by user-specific purchasers' prices (import vs. domestic).

The CES equation of household demand is shown as follows:

```
Variable
(all,c,COM)(all,d,DST) xhou_s(c,d) # Household demands for dom/imp composite #;
 E_xhou (all,c,COM)(all,s,SRC)(all,d,DST)
xhou(c,s,d) = xhou_s(c,d) - SIGMADOMIMP(c)*[ppur(c,s,"hou",d)-phou(c,d)];
```

In the above equation, xhou(c,s,d) is the percent change in household demand for domestic or imported commodity *c* in region *d*; xhou_s(c,d) is the percent change of total household demand for commodity *c* in region *d*; SIGMADOMIMP represents the substitution elasticities of commodities between domestic and imports; ppur(c,s,"hou",d) is the percent change in price of domestic or imported commodity *c* consumed in region *d*; and phou(c,d) is the percent change in composite price of commodity *c* in region *d*. The CES equation above suggests that the household demand of domestic commodity *c* will increase only if domestic prices of commodity *c* decrease relative to the composite price of commodity *c*.

Another mechanism in TERM-China is a sourcing mechanism for domestic commodities between origin regions. After determining the domestic uses of commodities using a CES-Armington specification, we must determine how to split the domestic uses to China's regions. In TERM-China, uses for the domestic commodities in one region are split through a CES mechanism between origin regions. The sourcing decision is made based on delivered prices, which include transport and other margin costs composited by a Leontief assumption. The equation representing the sourcing mechanism is as follows:

```
Equation E_xtrad # CES between goods from different regions #
 (all,c,COM)(all,s,SRC)(all,r,ORG)(all,d,DST)
 xtrad(c,s,r,d) - atrad(c,s,r,d) = xuse(c,s,d)
                  - SIGMADOMDOM(c)*[pdelivrd(c,s,r,d)+atrad(c,s,r,d)-puse(c,s,d)];
```

xtrad(c,s,r,d) represents the percent change in the use of commodity *c* in industry *i* in region *d* from region *r*; xuse(c,s,d) is the percent change in the use of composite commodity *c* of industry *i* in region *d*; pdelivrd(c,s,r,d) represents the price change for use of commodity *c* in region *d* from region *r*; puse(c,s,d) is the price change for use of the composite commodity *c* in region *d*; SIGMADOMDOM represents the substitution elasticities of commodities between origin regions; and atrad is a technology shifter. The CES equation above suggests that the use of commodity *c* from region *d* will increase only if the price of commodity *c* decreases from that of *d* relative to the composite price of commodity *c*.

The remaining features of TERM-China are common to most CGE models, such as the Global Trade Analysis Project (GTAP) model, a well-known global CGE model. The GTAP regions are countries or groups of countries, whilst in TERM-China they are regions/provinces within a single country. In the GTAP, the sum of global trade deficits must amount to zero whilst a national trade deficit is possible in TERM-China. There are also differences in data structures: the GTAP model has a far more detailed representation of bilateral trade taxes than does TERM-China, reflecting the freer trade that is usually possible within a nation. TERM-China can accommodate commodity tax rates that vary between regions but it does not allow for regional tax discrimination. Interregional movement of labor, a rarity in the GTAP model, are normal in TERM-China. Finally, TERM-China has a more detailed treatment of transport margins. While the GTAP model identifies how much each country contributes to world shipping supplies, the TERM-China data structure shows how much each region contributes to supply of transport between all separate pairs of source and destination regions.

Table B.1
Sectors of TERM-China model.

No.	Name	Aggregation
1	Agriculture	Agriculture
2	Coal	Mining
3	Crude oil and gas	Mining
4	Metal mining	Mining
5	Nonmetal mining	Mining
6	Food and tobacco	Light manufacture
7	Textile products	Light manufacture
8	Cloth, shoes, and leather	Light manufacture
9	Timbers and furniture	Light manufacture
10	Paper, print, and cultural products	Light manufacturing
11	Petroleum refinery and Coke	Chemical and metal
12	Chemical products	Chemical and metal
13	Nonmetal products	Chemical and metal
14	Metal-melting	Chemical and metal
15	Metal products	Chemical and metal
16	General machinery	Machinery
17	Special machinery	Machinery
18	Transport equipment	Machinery
19	Electronic machinery	Machinery
20	Communication and computer	Electronic products
21	Measurement instruments	Electronic products
22	Other manufacturing	Other industry
23	Scrap and waste	Other industry
24	Machinery repair services	Other industry
25	Electricity and steam supply	Energy and construction
26	Gas supply	Energy and construction
27	Water supply	Energy and construction
28	Construction	Energy and construction
29	Trade	Service
30	Transport and warehouse	Service
31	Hotel and dining	Service
32	Information services	Service
33	Finance	Service
34	Real estate	Service
35	Leasing and business services	Service
36	Scientific research and technical services	Service
37	Public service facilities	Service
38	Residential services	Service
39	Education	Service
40	Healthcare and social services	Service
41	Culture, sports, and entertainment	Service
42	Public administration	Service

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