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ORIGINAL ARTICLE

Human settlement and regional development in the context of climate change: a spatial analysis of low elevation coastal zones in China

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Abstract Low elevation coastal zone (LECZ) in China is densely populated and economically developed, which is exposed to increasing risks of hazards related to climate change and sea level rise. To mitigate risks and achieve sustainable development, we need to better understand LECZ. As the first step, in this paper we define the extent of the LECZ in China, and analyze the spatial distribution of LECZ and its population, using a geographic information system software (ArcGIS) to combine elevation models and population data sets. Our findings show that, overall, this zone covers 2.0 % of China's land area but contains 12.3 % of the total population, which is the largest population living in LECZ in the world. There are large regional variations in the distribution of both LECZ and LECZ population, with half of the LECZ within 30 km from the coastline, and Jiangsu Province having the largest LECZ area and population. The LECZ is also concentrated in three major

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economic zones in China, which accounts for 54 % of LECZ and three quarters of all LECZ population in China. The impact of future climate change on China's LECZ is exacerbated by rapid economic and population growth, urbanization and environmental degradation. Coordinating development in coastal and inland China, enhancing adaptive capacity and implementing integrated risk management for LECZ are needed to reduce the risks related to climate change and to achieve sustainable development.

Keywords Population distribution · Climate change · Hazard risk · Low elevation coastal zone · China

1 Introduction

Low elevation coastal zone (LECZ), or coastal low-lying area, is defined as the contiguous area along the coast that is less than 10 m above the sea level (McGranahan et al. 2007). Overall, the LECZ accounts for around 2 % of the world's land area. Yet it hosts 10 % of the world's population and 13 % of the world's urban population (McGranahan et al. 2007; Vafeidis et al. 2011). Globally, there are 3,351 cities located in the LECZ, and 13 of the 20 megacities are located in coastal zones (UN-HABITAT 2008). LECZ is generally densely populated and economically developed, yet is also prone to natural hazards, and experiencing the adverse consequences of hazards related to climate change and sea level rise. In recent decades, there have been more frequent and powerful storms and consequent flooding in LECZ, demonstrating its increasing risk. Many millions more people are projected to be flooded every year due to sea-level rise by the 2080s, and the numbers affected will be largest in the mega-deltas of Asia and Africa (Nicholls et al. 2007; Nicholls and Czenave 2010). Despite its utter importance in our society and increasing exposure and risk in the context of climate change, we know little about LECZ, especially those in populous developing countries, such as China. This paper aims to study LECZ in China and its relationship with population distribution and economic development. In addition to contributing to the literature on LECZ, this paper can provide a baseline for future research on LECZ, and facilitate policy design and implementation in China.

In recent years, there has been an increasing interest in climate change and LECZ among scholars, and there is an emerging body of literature. At continental and regional scales, numerous long-term changes in climate have been observed, and the changes will continue or even accelerate over 21st century and beyond. The anticipated climate-related changes include: an accelerated rise in sea level, a further rise in land and sea surface temperature, an intensification of tropical and extra-tropical cyclone, larger extreme waves and storm surges, altered precipitation/run-off, and ocean acidification (Elsner et al. 2008; Finkl 2013; Meehl et al. 2007; Nicholls et al. 2007). The impacts are virtually certain to be overwhelmingly negative with considerable variations at regional and local scales (e.g., Anthoff et al. 2010; Dasgupta et al. 2009, 2011; Kebede and Nicholls 2011; Nicholls and Czenave 2010; Williams 2013).

Those densely-populated LECZ, where adaptive capacity is relatively low and which already face other challenges such as tropical storms or local coastal subsidence, are especially at risk (Nicholls et al. 2007). With rapid population, urbanization and economic growth, utilization of the low-lying coastal areas increased dramatically and the trend will certainly continues through the 21st century. These non-climate drivers impose stresses on natural systems, and lead to the damage and loss of biodiversity and ecological functions, environmental pollution and degradation in LECZ, particularly that in developing countries (Adger et al. 2005). LECZ is environmentally fragile with disproportionately more environmental hot spots, which makes it even more difficult to avert the risks of climate change (Finkl 2013; McGranahan et al. 2007; Newton et al. 2012; Nicholls et al. 2007, 2008a; O'Brien et al. 2008). Therefore, it is important to explore new challenges and difficulties of human settlement and regional development facing the climate change in LECZ, and to put forward the measures or proposed policies to handle, mitigate and adapt the adverse consequences and serious challenges caused by climate change.

With 18,000 km coastlines and 14,000 km island shorelines, China has a huge LECZ, and the largest population living in LECZ in the world (McGranahan et al. 2007; Vafeidis et al. 2011). Since 1978 when China launched its economic reform and open door policy, the government has adopted a development strategy that is biased towards the coastal area. As a result, the coastal area has experienced rapid economic growth and urbanization, which in turn has attracted massive migrants from inland China to the coastal zone (Cai et al. 2009). The most populous and economically most developed cities such as Shanghai, Tianjin, Guangzhou, Shenzhen and Hong Kong are all located in LECZ. LECZ in China is also prone to natural disasters such as typhoon, rising sea level, storm surge, flood and saltwater encroachment. This coast-biased development has significantly increased China's exposure to natural disasters (UNDP 2004), which may potentially lead to colossal economic and population losses. Meanwhile, the environment and ecological systems in LECZ are rapidly deteriorating due to pollutions caused by rapid industrialization and urbanization on the one hand, and natural disasters on the other hand. This has significantly reduced LECZ's capability to reduce risks associated with natural disasters and future climate change.

According to the Bulletin of Sea-level in China Seas 2012 issued by the State Oceanic Administration, China's coastal sea-level is rising at a rate of 2.9 mm a^{-1} between 1980 and 2012, much higher than the world average. The rising sea-level exacerbates many coastal zone hazards including storm surge, coastal erosion, saltwater encroachment, lowlands submerge, floods, and worsening pollution (Nicholls and Czenave 2010). For example, by 2050, it will make the once-every-100-year storm tide occurs once every 5~20 years in the Yangtze River delta, Pearl River delta, western coast of the Bohai Sea (The Second National Assessment Report on Climate Change Editorial Committee 2011). Natural disasters and environmental problems occur frequently in LECZ, and climate change will further increase the risks of both in China. Thus, there is an urgent need to study LECZ especially in the context of future climate change.

The total land area and population of LECZ in China have been reported previously (McGranahan et al. 2007; Vafeidis et al. 2011). However, LECZ, population and their exposure and vulnerabilities to sea level rise and other climate changes have significant regional variations (Nicholls et al. 2007, 2008a; Ramieri et al. 2011). For the purpose of improved understanding of LECZ, in this paper, we analyze the spatial pattern of LECZ and its population in China; discuss the regional development strategy as a key driving forcing for migration to LECZ, rapid urbanization and economic growth, accompanied by coastal ecosystem degradation over the last three decades; we further discuss the increasing hazard risks result from climate change, non-climatic environmental change and socio-economic dimensions, and the necessity of integrated disaster risk management and climate change adaptation in China's LECZ. By doing so, we hope to better understand the land and population exposure to risks related to climate change, to identify the critical zones which may be of most potential impacts caused by climate change, and to provide a reference for China to combat natural disasters and climate changes, and to achieve sustainable development in the LECZ.

2 Data and methodology

This study utilizes various datasets from different sources, including the advanced space borne thermal emission and reflection radiometer global digital elevation model version 1 (ASTER GDEMv1) (http://www.gdem.aster.ersdac.or.jp), LandScan 2011 global population database (ORNL 2013) (http://www.ornl.gov/sci/landscan/), gridded population of the world, version 3 (GPWv3) (Balk and Yetman 2004; CIESIN 2005), China's population statistics, and the ESRI (Environmental Systems Research Institute, Inc.) vector data of Chinese administrative divisions. The data above were imported into ArcGIS 9.3 (a geographic information system software) and processed by using spatial analysis methods.

2.1 ASTER GDEM

ASTER GDEM is jointly developed by the Ministry of Economy, Trade and Industry (METI) of Japan and the National Aeronautics and Space Administration (NASA). The ASTER Global DEM version 1 (GDEMv1) was released to the public on June 29, 2009, and can be freely downloaded from the Earth Remote Sensing Data Analysis Center (ERSDAC) and the United States NASA's Land Processes Distributed Active Archive Center (LP DAAC). The ASTER GDEM is based on optical imagery collected in space with the METI ASTER imaging device that was operated on NASA's Terra satellite. The approach used for constructing the GDEM is correlation of stereoscopic image pairs (e.g., Shapiro and Stockman 2001). The complete ASTER GDEM covers land surfaces between 83° South and 83° North. The overall vertical accuracy of ASTER elevations is specified to vary between 10 m and 25 m (ASTER Validation Team 2009). ASTER refers to the World Geodetic System 1984 (WGS84), with the heights transformed via the Earth Gravitational Model 1996 (EGM96) to a physical height. ASTER has the highest formal spatial resolution (1″ or ~30 m) and best available coverage to date (Hirt et al. 2010).

2.2 Gridded population data

LandScan global population database (LandScan), developed by Oak Ridge National Laboratory (ORNL), is the finest resolution global population distribution data available and represents an ambient population (average over 24 h). The LandScan uses a multi-layered, dasymetric, spatial modeling approach to allocate the total population to each cell within an administrative boundary. The resultant population count is an ambient or average day/night population count. A worldwide 1998 population database for estimating ambient population at risk was produced at first (Dobson et al. 2000), then the database is updated annually by incorporating new spatial data and imagery analysis. The dataset has a spatial resolution of 30 arc-seconds, representing approximately 1 km^2 near the equator. Because of this ambient nature, care should be taken with direct comparisons of LandScan data with other population distribution surfaces. Manual verification and modification processes are applied to improve the spatial precision and relative magnitude of the population distribution, and the database is regarded as the community standard for global population distribution (Bhaduri et al. 2007; ORNL 2013). LandScan 2011 of China (the 13th version of LandScan), used in this study, was bought from East View Information Services, Inc.

2.3 Administrative division data

The dataset for China's administrative divisions is in a scale of 1: 1 million (Environmental Systems Research Institute, Inc. (ESRI) Shapefile format). This data includes the province-level (the first-level) administrative units such as provinces, municipalities, autonomous regions and special administrative regions (SAR), as well as the county-level (the second-level) administrative units.

2.4 Definition of China's LECZ

Generally, the coastal area of China refers to the provincial level administrative units along the coast, which include, from north to south, Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong Provinces and municipalities, Taiwan, Hong Kong and Macao SAR, Guangxi Zhuang Autonomous Region, and Hainan Province (Fig. 1). In this paper, LECZ is defined as the coastal continuous zone with the elevation less than 10 m in the above mentioned provincial level administrative units.

To define the extent of LECZ, we used ArcGIS 9.3 to splice the ASTER GDEM raster data into a digital elevation model (DEM) which covers China's coastal areas. The procedures are as follows: (1) Using Contour function to generate a set of 10 m contour lines to be used in step 4; (2) Extracting all areas where elevation is less than 10 m; (3) Taking the vector data of coastal provincial level administrative units as a mask to remove the low-lying areas (with elevation less than 10 m) outside of the coastal provincial level units; (4) The west side of the raster data obtained after steps (2) and (3) still have many discrete patches, but LECZ is defined as a contiguous area along the coast. Therefore, the above raster data need further processing. The continuous 10 m contour lines of each coastal region was picked out on the basis of the 10 m contour lines generated in step (1); then the selected contour lines were connected to generate a polygon as a mask; finally, the scattered patches outside the mask were removed to obtain the study area—the coastal low-lying areas or LECZ in China (Fig. 1).

2.5 Supplement of the population data

The LandScan 2011 of China doesn't include Taiwan region, Hong Kong and Macao Special Administrative Regions. The GPWv3, compiled by the Center for International Earth Science Information Network (CIESIN) of Columbia University (http://sedac.ciesin.columbia.edu/gpw/index.jsp), was used to fill up these regions. GPWv3 includes the world population data of 1990, 1995 and 2000, as well as the future estimates of world population for 2005, 2010 and 2015. The horizontal resolution of GPWv3 is 2.5 arc minutes, which is approximately equivalent to a 21.4 km^2 square at the equator. GPWv3 is also used in the study of population patterns over the LECZs (e.g., McGranahan et al. 2007; Vafeidis et al. 2011). The GPWv3 population data of 2000 is updated by using population data from the sixth national census in 2010 since the population data of GPWv3 after 2005 are estimated data. China's demographic data include the 2000 and 2010 population statistics of the province-level and county-level administrative units. They are from the National Bureau of Statistics of China (http://www.stats.gov.cn) and statistical yearbooks of each province-level administrative units. We first calculated population growth rate between 2000 and 2010 for each county level division in China's LECZ using existing demographic data. We then calculated the centroids of those county-level units using ArcGIS, used the inverse distance weighting method to interpolate the growth rates onto a raster with 1 km cell size, which was multiplied by GPWv3 population data of 2000 over the LECZ to estimate the grided population density data of 2010.

LandScan 2011, supplemented with the updated GPWv3 population data of 2010 in Taiwan, Hongkong and Hong Kong and Macao (Fig. 2), is used in this study. Population in the LECZ was then calculated by overlaying the population data with the layer of the LECZ areas.

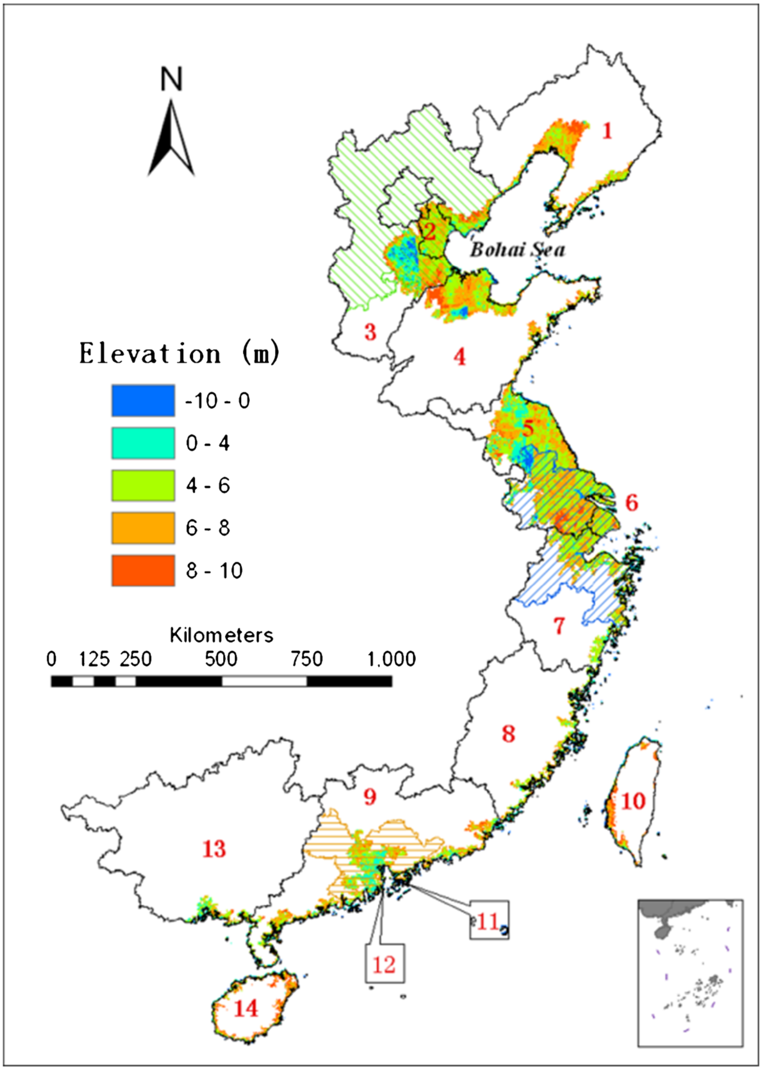

Fig. 1 Distribution of LECZ in China. *Numbers 1~14* represent Liaoning, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Taiwan, Hong Kong and Macao, Guangxi and Hainan, respectively. The area covered by *green lines* represents Beijing-Tianjin-Hebei zone, the area covered by *blue lines*, the Yangtze River delta zone, and the area covered by *orange lines*, the Pearl River delta zone

3 The spatial distribution of LECZ in China

The distribution pattern of LECZ is a fundamental element to assess and understand potential risks associated with climate changes and natural disasters, and to develop strategies to reduce risks and cope with natural disasters in coastal lowlands. In this section, we aim to provide a detailed picture of the distribution of LECZ in China, physically, administratively, and economically.

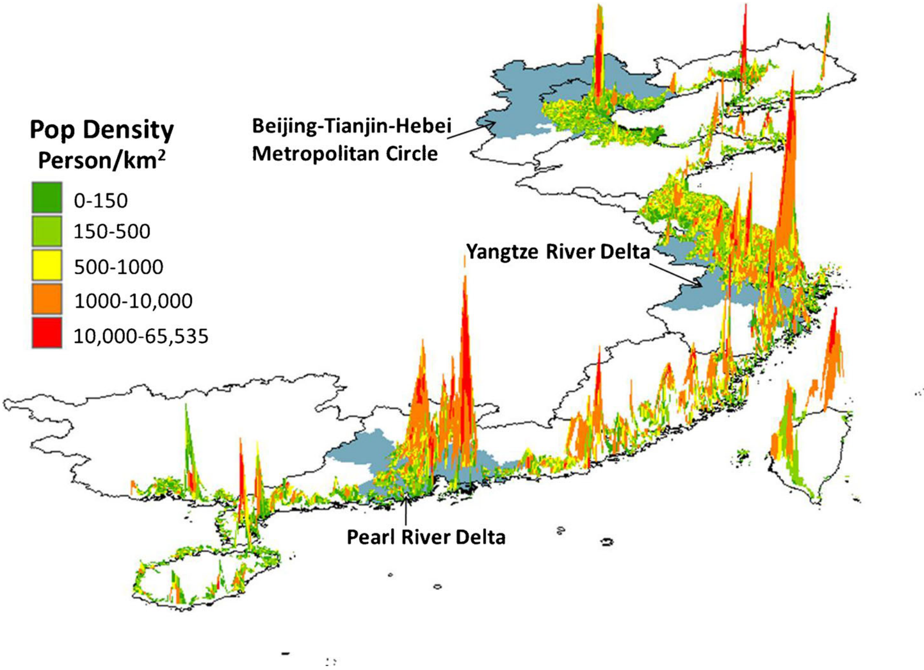

Fig. 2 Population density distribution in China's LECZ

3.1 Spatial distribution of LECZ among administrative units

The total area of LECZ in China is 194,045 km^2, which accounts for 2 % of China's land area, and 14.6 % of all land area in China's coastal provincial level units (Table 1). LECZ are most widely distributed in the Bohai Rim, North Jiangsu Plain, Yangtze River delta, and Pearl River delta (Fig. 1).

LECZ is distributed unevenly across space, with the absolute and relative values of LECZ areas dramatically different among provincial-level administrative units. Jiangsu Province has the largest LECZ of 67, 252 km^2, which accounts for 66.6 % of its territory and 34.7 % of all LECZ in China. Macau SAR has the smallest low-lying area of 18 km^2, but it accounts for 61 % of its territory. In terms of proportion, Shanghai and Tianjin have the largest proportions of its territory as LECZ, with 94 % and 82 %, respectively, while Guangxi Zhuang Autonomous Region has the smallest proportion of only 1 % (Table 1).

At the county or city level (second-level administrative unit), there are more than 350 counties/cities that has the LECZ (Fig. 3). Jiangsu Province has the most second-level regions that have LECZ (68), followed by Guangdong Province with 54. Among all counties/cities, Sheyang County in Jiangsu Province has the largest LECZ of 2,528 km^2, which accounts for 94 % of its territory. The distribution of LECZ shows that there are tremendously large spatial variations, with LECZ concentrated in a few provinces such as Jiangsu, Hebei and Guangdong province, and Shanghai and Tianjin are particularly exposed to natural disaster and climate change risks associated to LECZ.

Table 1 Land area statistics of the LECZ in the first-level administrative divisions of China

Administrative division	Territory (km^2)[a]	Area of the LECZ (km^2)	Percent (%)
Liaoning	145,558	12,879	8.8
Hebei	187,292	25,904	13.8
Tianjin	11,620	9,526	82.0
Shandong	154,227	23,266	15.1
Jiangsu	100,929	67,252	66.6
Shanghai	6,242	5,862	93.9
Zhejiang	101,953	16,525	16.2
Fujian	121,661	3,737	3.1
Taiwan	36,054	3,279	9.1
Guangdong	177,335	19,969	11.3
Guangxi	236,196	2,400	1.0
Hong Kong	1,101	220	20.0
Macao	29.5	18	61.0
Hainan	49,817	3,206	6.4
Total	1,330,015	194,045	14.6

[a] From China's administrative division data set in ESRI shapefile format

3.2 Distribution of the LECZ in relation to coastline

To better understand the distribution of LECZ in relation to risks associated with climate change and rising sea-level, we studied the distribution of LECZ by distance to the coastline. Multiple buffer rings at an interval of 10 km were generated along the coastline, which were then used to extract the areas of LECZ with different distances from the coastline in the continental portion (excluding islands), Taiwan and Hainan Islands. China's third largest island Chongming Island (its elevation is lower than 10 m) is located in the Yangtze estuary, and its maximum width is less than 20 km. Therefore, except Taiwan and Hainan Island, we assume that LECZ on all other islands are distributed within 10 km from the coastline. By doing so, we calculated areas of LECZ for every 10 km away from the coastline (Fig. 4). Not surprisingly, the area of LECZ decreases as distance from coastline increases. Nearly 90 % of LECZ in China are located within 100 km from the coastline. In particular, LECZ within 10 km from the coastline has the largest area, which accounts for more than a quarter of the total area of LECZ in China. LECZ within 30 km from the coastline is close to half of the total area. Beyond 20 km from the coastline, the areas of LECZ at an interval of 10 km do not exceed 10 % of the total area. In addition, more than 95 % of LECZ in China are located on the mainland, while only 4.7 % are on islands. Despite the large number of islands in China, only a very small proportion of LECZ in China are on islands, which might be a very different scenario from some other countries.

3.3 Distribution of LECZ in three major economic zones

Due to coast-biased development strategy in the reform era, three major economic zones—Yangtze River delta, Pearl River delta, and the Beijing-Tianjin-Hebei Metropolitan Circle have emerged and become the growth poles of China's economy. In 2010, the State Council approved and implemented the new Yangtze River delta Regional Planning, which

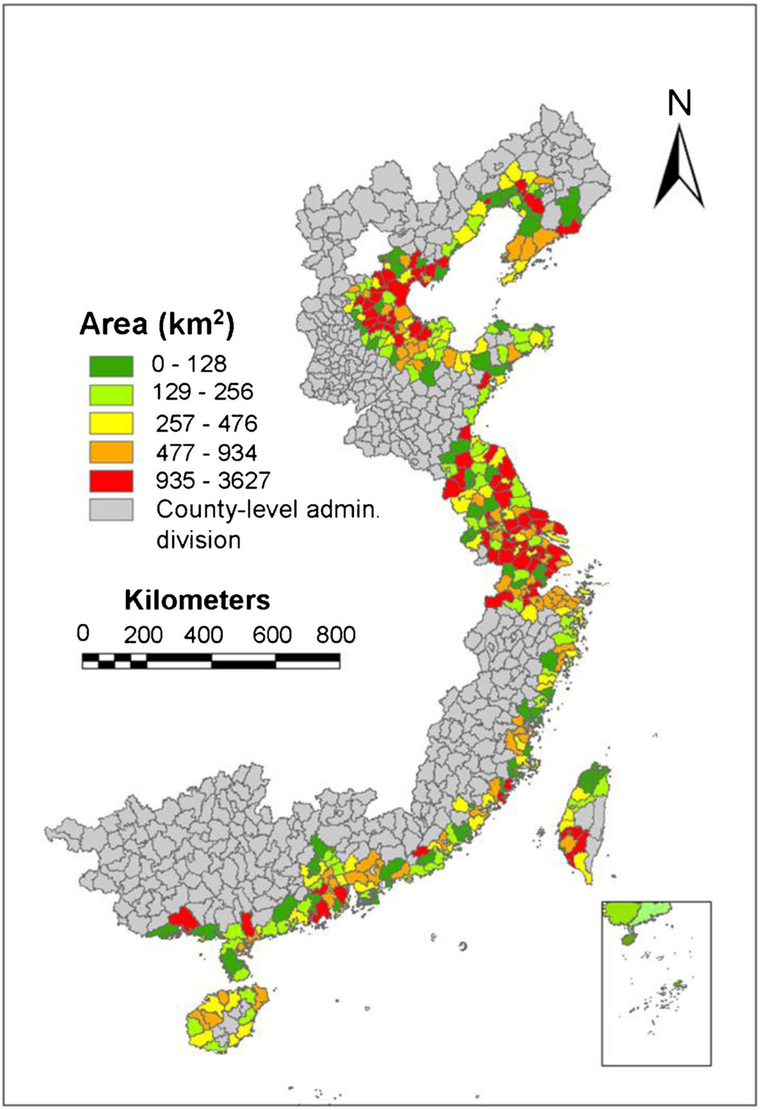

Fig. 3 Spatial distribution of the LECZ in the second-level administrative divisions

includes a group of 16 cities: Shanghai, 8 cities in Jiangsu and 7 cities in Zhejiang Province. In 2008, the State Council approved and carried out the Pearl River delta Regional Planning, which includes 9 cities in Guangdong Province such as Guangzhou and Shenzhen, which is referred as the Small Pearl River delta in this paper. The Greater Pearl River delta includes Hong Kong and Macau as well. Beijing-Tianjin-Hebei Metropolitan Circle is known as the third growth pole of Chinese economy, including Beijing, Tianjin and 8 cities in Hebei Province.

According to Table 2, three economic zones account for more than half (54 %) of LECZ in China, with 30 % in the Yangtze River delta, 18 % in Beijing-Tianjin-Hebei metropolitan circle and 6 % in the Greater Pearl River delta. The concentration of LECZ is striking given

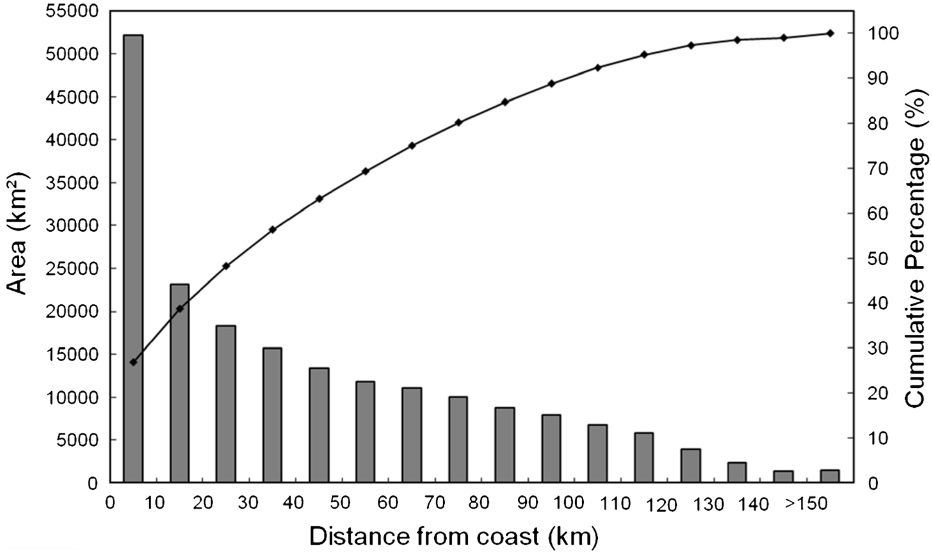

Fig. 4 Distribution of the LECZ vs the distance from coastline of China

the fact that the territory of these three economic zones accounts for only a quarter of the coastal region. This shows that the three zones are not only China's most important economic areas, but also regions with the most concentrated LECZ. There are also differences among these economic zones. The Yangtze River delta has the largest LECZ, with more than 57, 000 km^2, which accounts for more than half of its territory. In contrast, 19 % of the territory in Beijing-Tianjin-Hebei metropolitan circle, and 21 % of the Greater Pearl River delta are LECZ. In other words, the Yangtze River delta has the highest exposure to risks.

4 Population distribution in the LECZ

We analyze the distribution of population in LECZ by overlaying LandScan 2011 and the GPWv3 population data that was updated to 2010, together with administrative unit layers. The total population in the coast area is about 575 million, of which 163.9 million are living in the LECZ. LECZ population accounts for 28.7 % of the total population in coastal area, and 12.3 % of the nation's population (Table 3).

4.1 Population distribution in the LECZ among administrative units

There are large regional variations of population distribution in the LECZ over the first-level administrative divisions. Not surprisingly, Jiangsu Province stands out again, with the largest population of 50.3 million living in the LECZ, followed by Guangdong province with 30.5 million in the LECZ. In contrast, places like Macao SAR and Guangxi have small populations living in LECZ. Cities such as Shanghai and Tianjin have the highest proportion of population living in the LECZ, with 93.4 % and 79.3 %, respectively. In contrast, Guangxi and Fujian have the smallest proportion of only 3.1 % and 9.8 %, respectively, in LECZ. Regions with a large population in LECZ all concentrate along the southeast coast—Jiangsu,

Table 2 Land area and proportion of LECZ in three major economic zones of China

Zone	Area (km^2)	LECZ (km^2)	Percent of the territory (%)	Percent of China's LECZ (%)
Yangtze River delta	108,679	57,274	53	30
Beijing-Tianjin-Hebei metropolitan circle	183,426	35,062	19	18
Small Pearl River delta[a]	53,981	11,316	21	6
Greater Pearl River delta[b]	55,107	11,537	21	6
Total[c]	347,212	103,873	30	54

[a] Only includes 9 cities of Guangdong Province

[b] Includes Hong Kong and Macau as well

[c] Statistics for Yangtze River delta, the Beijing-Tianjin-Hebei metropolis circle and the Greater Pearl River delta combined

Guangdong, Shanghai, and Zhejiang. In addition to the fact that these regions are historically densely populated, the rapid economic development and urbanization in recent decades have attracted massive migration from the rest of the country to the southeast coast (Chan 2004; Huang 2011), which contributes to the large population and high population density in LECZ. This concentration of population in LECZ significantly increases the exposure to hazards, and the magnitude of impact on the population if disasters do occur.

Table 3 Population statistics in the LECZ of the first-level administrative divisions of China

Administrative region	Total population (person)	Population in LECZ (person)	Population density in LECZ (person/km^2)[a]	Percentage of population (%)
Liaoning	39,595,000	5,349,700	415	13.5
Hebei	65,610,100	12,589,100	486	19.2
Tianjin	9,604,800	7,613,600	799	79.3
Shandong	91,213,000	10,858,500	467	11.9
Jiangsu	77,233,400	50,253,700	747	65.1
Shanghai	17,577,400	16,408,900	2,799	93.4
Zhejiang	49,827,500	19,415,100	1,175	39.0
Fujian	37,865,300	3,726,900	997	9.8
Taiwan	23,296,200[b]	4,048,700	1,226	17.4
Guangdong	97,721,400	30,546,700	1,530	31.3
Guangxi	50,229,300	1,549,700	646	3.1
Hong Kong	6,520,200[b]	1,089,000	4,871	16.8
Macao	139,300[b]	100,900	5,471	73.4
Hainan	8,680,700	1,403,900	438	16.2
Total	575,113,600	164,954,400	850	28.7

[a] Due to the small land areas of Hong Kong and Macao, the data of population density extracted from GPWv3 may not be confident

[b] Calculated based on the density of population of 2000 from GPWv3, and then multiplied by the population growth rates between 2000 and 2011

4.2 Population distribution of LECZ in three economic zones

The concentration of population is even stronger in the three economic zones (Table 4, Fig. 2). Overall, there are more than 124 million people living in LECZ in three economic zones, which accounts for 46 % of their total population, and three fourths of all population in LECZ in China (75 %). Meanwhile, the territory of these three economic zones account for only 26 % of the coastal area. In other words, three fourths of all LECZ population in China live in about one quarter of the coastal area. Yet, there are large differences even among these economic zones. Yangtze River delta has the largest population in LECZ in terms of both absolute number and proportion. There are more than 65 million people living in LECZ in the Yangtze River delta, which accounts for 70 % of its total population, and 40 % of all LECZ population in China, a distant lead over the other two economic zones. Population density in LECZ in three economic zones is also much higher than the average density in these economic zones (1,194 vs. 769 person/km^2). The greater Pearl River delta has the highest population density in its LECZ (1,769 person/km^2, 10 times of the national population density in China), followed by Yangtze River delta (1,154 person/km^2) and Beijing-Tianjin-Hebei (555 person/km^2).

We also use SRTM (the shuttle radar topography mission) 90 m DEM (http://srtm.csi.cgiar.org/) (Farr et al. 2007) and the GPWv3 2000 data to extract the LECZ and population in China. Our results show that the total population in China's LECZ is 119, 498, 000, which accounts for 22.5 % of the total population in the coastal area and 9.3 % of the nation's population. This is somewhat smaller than the population proportion reported by McGranahan et al. (2007) (11 %). The main reason is that our definition for LECZ is only limited to the first-level administrative divisions along the coast, excluding areas below 10 m elsewhere such as those along both sides of Yangtze river that stretch into Anhui Province. The area of the LECZ derived by using SRTM 90 m DEM is also smaller than that by using ASTER GDEM (1.7 % vs. 2.0 % of all land area in China). This shows that results differ by using different DEMs. The overall vertical error of the ASTER GDEM was estimated to be approximately 20 m at 95 % confidence (ASTER validation team 2009). In addition, the data of population density extracted from GPWv3 in the LECZ of Hong Kong and Macao may not be confident due to the small land areas, so are the population in those LECZs. A few data of total population of the first-level administrative units in Table 3 are largely different from the ones of the resident population from the National Bureau of Statistics of China, for example, 17,577,400 persons of population in Shanghai was estimated from LandScan dataset (Table 3), in contrast, the resident population was up to 23 million though household registered population is over 14 million according to the sixth national census in 2010. Therefore, improved elevation models and population distribution datasets are needed for further detailed studies (Lichter et al. 2011).

5 LECZ, economic development, and hazards

5.1 Economic development and migration to LECZ

Historically, coastal China has always had larger and denser population, as well as more developed economy than inland due to its rich resource endowment and superior locations. However, the development strategy in recent decades has significantly accelerated the concentration of population and economy in its coastal area in general and in the LECZ in particular.

Table 4 Population and proportion in the LECZ in three economic zones of China

Economic zones	Population density (P/km^2)	Total population (P)	Population density in LECZ (P/km^2)	Population in LECZ (P)	Proportion of population in LECZ (%)	Population proportion of LECZ in China's LECZ (%)
Yangtze river delta	869	9,3438,500	1,154	65,239,700	70	40
Beijing-Tianjin-Hebei	381	6,9826,600	555	19,422,000	28	12
Small Pearl River delta[a]	922	4,9249,500	1,769	19,181,000	39	12
Greater Pearl River delta[b]	1,019	5,4439,500	1,864	20,208,000	37	12
Total[c]	769	266,954,100	1,194	124,050,700	46	75

[a] Only includes 9 cities of Guangdong Province

[b] Includes Hong Kong and Macau

[c] Total of the Yangtze River delta, the Pearl River delta and Beijing-Tianjin-Hebei Metropolitan Circle

Since 1978 when China launched the economic reform and open-door policy, the government has adopted a development strategy biased towards coastal China. After decades of isolation during the socialist era, the Chinese government decided to attract foreign investment and to experiment market economy and international trade gradually in a controlled environment. Four special economic zones (SEZs) (Shenzhen, Zhuhai, Xiamen, Shantou) were first established in 1979 along the southeast coast in proximity to Hong Kong and Taiwan to attract oversea Chinese investors. With preferential policies, massive foreign investment, and an influx of migrants from all over China working in newly established private/foreign economy, these SEZs had an instant success and grew rapidly. In 1984, another 14 coastal cities were opened as coastal economic development zones, and in 1985 open economic regions in the Yangtze River delta, Pearl River delta, Xiamen-Zhangzhou-Quanzhou Triangle region in southern Fujian, Liaodong Peninsula, Jiaodong Peninsula and districts around Bohai Sea were established. Hainan island and Pudong New District in Shanghai were added as the latest SEZs in 1988 and 1990, respectively (Fig. 5). Meanwhile the regional development strategy is so-called the ladder-step doctrine, meaning China would develop the Eastern region first, followed by the Central region, and then the Western China (Fig. 5) (Han 2008). As a result, coastal China grows much faster economically than the rest of China, and coastal population especially those of open cities also grow more rapidly due to massive migration from inland China (Cai et al. 2009). For example, urban population in Shenzhen and Zhuhai grew at 32 % and 29 % annually respectively and their industrial output grew at 95 % annually during 1978~1984 (Xu and Li 1990). The small Pearl River delta as a whole grew 7.7 % annually in its urban population and 16 % annually in its industrial output during 1978~1986 (Xu and Li 1990).

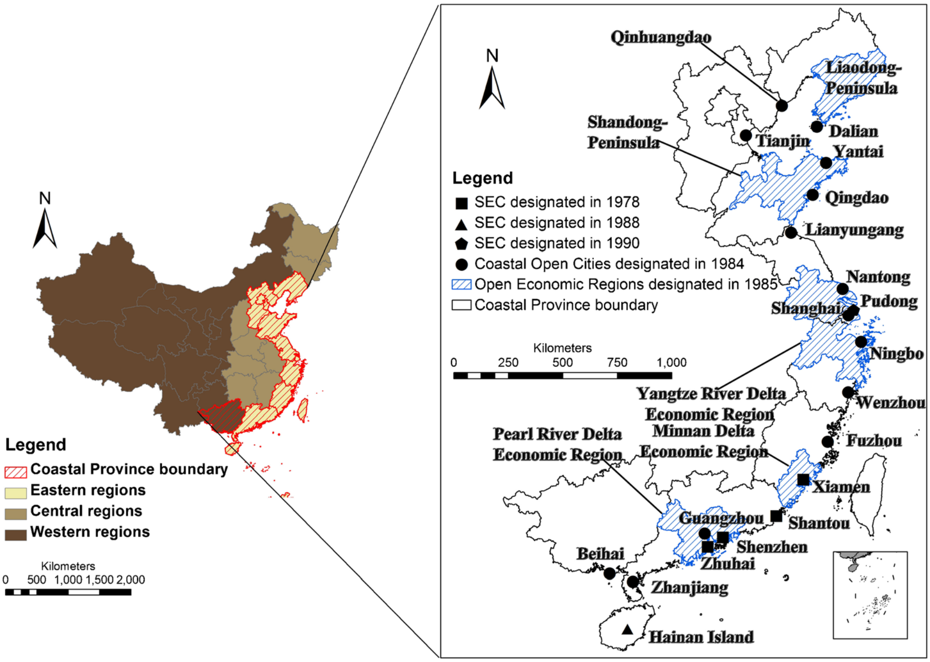

Fig. 5 Map showing the Eastern, Central and Western regions of China (*left*); the SEZs and Coastal Economic Development Zones established between 1979 and 1990 (*right*)

Realizing the severe regional unevenness, there is a brief attempt by the Chinese government to adjust its regional development strategy since the late 1990s. In 2000 it launched a Western Development campaign to encourage both foreign and domestic investment to go to Western China. Yet, it has not been very successful, and the large regional inequality remains and west-to-east migration continues. In fact regional inequality has increased and the eastward trend of migration has strengthened over time (Chan 2004; Wei 2003). Focusing on economic goals, the State Council recently issued a series of policies to support the development of newly developing regions along the coast of Tianjin (TBNA 2012) and Jiangsu Province (Xu 2011), and Hainan was designated as an International Tourism Island (Hainan Government 2009). In other words, the coast is favored again by the government for further economic development. Due to a combination of preferential policy, superior location and solid economic foundation, coastal China in general, and LECZ in particular have experienced the most rapid economic growth, the fastest rate of urbanization, and the largest influx of migration.

China not only has a large area of LECZ but also has a huge population living in the LECZ. Furthermore, the population in LECZ tends to concentrate in several hot spots in LECZ such as those in the Yangtze River delta and Pearl River delta. The three economic zones are the most important economic regions in China, but with an unusually high concentration of LECZ and population. Together these economic zones account for 54 % of all LECZ land area and 78 % of all population in the LECZ. In particular, the Yangtze River delta is the second largest LECZ in both land area and population among all delta regions in the world (Vafeidis et al. 2011). It accounts for more than 30 % of all LECZ land area in China and nearly 40 % of the LECZ population in China. In recent decades, these economic zones have experienced rapid urbanization and industrialization, with massive expansion of residential and industrial land use. Local governments' enthusiastic pursuit for high GDP growth rate has led to massive expansion of industrial parks which has in turn led to the rapid loss of high quality farmland (Liu et al. 2009). Rapid population growth and irrational economic development have led to ecosystem degradation and exacerbated environment problems and increased weather-related hazard risk. When confronting with future extreme weather events and sea level rise, the exposure, vulnerability and risk of cities such as Tianjin, Shanghai, Guangzhou and Shenzhen in the three economic zones are all ranked at the top among all port cities in the world, and this situation will become increasingly worse (Nicholls et al. 2008b).

Unfortunately, these risks and environmental concerns have not affected the development and settlement pattern in coastal China. Most scholars and policy makers still consider that the existing coast-biased development and coastward migration in China are reasonable and beneficial to the economic development in China. Therefore, in order to accelerate the development of the national economy, it has been suggested to maintain the current migration pattern in the future (Wang 2004; Wang et al. 2005; Wang and Xu 2010). This coastal biased policy and development will further increase the concentration of population and economy in LECZ, and thus further increase the already high risks China faces in relation to climate change and sea level rises.

5.2 Environmental problem and hazard risk in LECZ

Rapidly increasing human utilization of the LECZ has resulted in a series of environment problems in China. The rapid industrialization and extremely dense settlement have significantly increased the stress on the environment, and the LECZ is increasingly plagued with all kinds of pollutions. Among the most heavily polluted coastal areas are Liaodong Bay, Bohai bay, Yellow River estuary, Laizhou bay, Yangtze River estuary, Hangzhou bay and Pearl River estuary. Uncontrolled exploitation of resources and irrational economic activities such as excessive extraction of underground water, sand mining along the coast, and irrational land reclamation from intertidal mudflat also led to environmental degradation. About 78 % of the 18 regions under ecological monitoring along the coast were in a sub-state of ecological health or unhealthy, and major ecological problems included pollution, habitat loss, biological invasion and low biodiversity (Chen and Uitto 2003; State Oceanic Administration 2010). These have made the ecosystem in LECZ increasingly fragile and very sensitive to the coastal environmental change and natural disasters in the context of climate change.

In particular, environmental changes and disasters related to climate change such as relative sea level rise, tropical cyclone, storm surge, and flood are the most destructive and can potentially lead to colossal losses in the LECZ. The United Nations Intergovernmental Panel on Climate Change estimated that by the end of this century, the sea level rise may reach up to 0.6 m (Meehl et al. 2007). However, recent research find that polar ice sheets are melting more quickly than before (Allison et al. 2009; Rignot et al. 2008, 2011; Velicogna 2009), which may cause the sea level rise reach or even exceed 1 m by 2100 (Pfeffer et al. 2008; Nicholls and Czenave 2010; Rahmstorf 2010). In China, the LECZ faces even higher risks associated with future sea level rise and related disasters because of significant ground subsidence in the Yangtze River delta, Pearl River delta and Bohai Rims on the one hand, and decreasing sediments in river deltas due to upstream hydroelectric development and construction of numerous dams (such as the Three Gorges on the Yangtze River, Longtan dam on the Pearl River, Xiaolangdi dam on the Yellow River) on the other hand (Dai et al. 2007). For example, the ground subsidence in Shanghai reached 3 m in the 20th century (Nicholls et al. 2008b), and the annual subsidence rate reaches up to 24.12 mm a^{-1} between 1980 and 2005 (Wang et al. 2012). These results in accelerated rates of relative sea-level rise and coastal erosion along the LECZ in the Yangtze River delta, Pearl River delta and Bohai Rims. In addition, the topography of the LECZ in China is such that the elevation in most of these places is about the same as the local mean high tide, and in some places it is even lower than the sea level, thus they mainly depend on the sub-standard levee for protection (Yang and Shi 1999). These problems and the risk of natural disasters in the LECZ are increasingly dire with climate change.

5.3 Risk management, adaptation and balanced development

In response to the growing risks of LECZ associated with coastal hazards and climate change, an integrated risk management (Aven and Renn 2010; Renn 2008; UNISDR 2004, 2011), which includes the natural disaster risk identification, risk analysis and risk assessment in the coastal lowlands, is needed to understand the consequences and their possibilities induced by climate change and natural disasters under different scenarios. Thus engineering and non-engineering measures should be designed and implemented to reduce risk, including prevention, preparedness, avoidance, transfer, mitigation, re-direction of migration and different regional development strategies.

Effective adaptation to climate change is also urgently required in the coastal systems and low-lying areas (Ayyub and Kearney 2011; IPCC 2012; Nicholls et al. 2007). Adaptation will provide immediate and long-term reduction in climate-related risks to the coastal systems, and enhancing adaptive capacity for reducing risks related to current climate extremes and variability as well as adapting to climate change are critical policy and management goals in China’s LECZ. Some proposals to strengthen adaptive capacity have been made including: raising design standard of storm defense; heightening and strengthening existing protection facilities and building new storm defense facilities; developing coastal shelter forest so as to effectively mitigate the impacts of such disasters as coast erosion, storm surges and floods; building ecological reserves of coastal wetlands, mangrove forest and coral reefs, and protecting ecological system of coastal zone; and building the warning system (The Second National Assessment Report on Climate Change Editorial Committee 2011). Furthermore, non-engineering measures that improve environmental management, enhance public awareness and participation, reduce poverty and increase the quality of life of vulnerable coastal groups are also important to strengthen adaptive capacity and coping mechanism.

Both defense and retreat are two baseline strategies for adapting to the climate change and sea level rise during 21rst century and beyond in China's LECZ. The rapidly growing population centres in low-lying coasts will face formidable challenges due to sea-level rise in the next century (Törnqvist and Meffert 2008). Though moving entire cities and their residents back to higher ground is hardly practical (Nature Geoscience Editorial 2009), adjusting the coast-biased development strategy is possible and necessary in China. Recently, the Chinese government developed a strategy to develop the Eastern, Central and Western China simultaneously (Li 2010; Wang 2010). This will correct the imbalance caused by the coast-biased open door policies, reduce coastward migration, promote economically coordinated development in eastern, central and western China, and reduce the increasingly severe regional inequality. It will not only mitigate existing economic and social problems but also significantly reduce China's risks and enhance China's ability to confront environmental problems related to climate change.

6 Conclusion

LECZ in China is most densely populated and economically developed region in China. Though LECZ in China accounts for 2.0 % of its total land area and 14.6 % of the total area in coastal provinces, the absolute amount of about 194,000 km^2 is still quite large. China has the largest population living in the LECZ in the world, with about 165 million people in 2011, which accounts for 28.7 % of the population in coastal provinces and 12.3 % of China's total population.

Moreover, the LECZ and its population in China vary considerably at regional and local scales. First, Jiangsu Province has the largest LECZ among all first-level administrative units, with two thirds of its land area as LECZ, and has the largest population living in the LECZ, with more than half of its population living in the LECZ and one third of China's total population in the LECZ. At second-level administrative unit, there are more than 350 counties/cities have LECZ in their territories, among which Jiangsu Province also has the most units. Second, the area of the LECZ distribution decreases as the distance from coastline increases. More than a quarter of the LECZ are located within 10 km from the coastline, about half of the LECZ are distributed within 30 km from the coastline, and 90 % are within 100 km from the coastline. Third, Yangtze River delta, Pearl River delta and Beijing-Tianjin-Hebei, the most important economic regions in China have large and densely populated LECZ. The three economic zones together account for 54 % of all LECZ in China, and their LECZ population accounts for 75 % of all LECZ population in China. Especially in Yangtze River delta region, the LECZ covers more than half of its total land area, which accounts for 30 % of the total LECZ in China, and its LECZ population accounts for 70 % of its total population, or two fifths of the total LECZ population in China.

LECZ in China are experiencing the adverse consequences of hazards related to climate and sea level, and rapidly increasing numbers of people and assets will be exposed to increasing risks over 21rst century and beyond due to climate change and sea-level rise, which imposes tremendous challenges for China. Measures including coordinating development in eastern, central and western China, enhancing adaptive capacity for climate change, integrated risk management for LECZ should be implemented in order to reduce the risks related to climate change and to achieve sustainable development.

This analysis should be considered as a first step towards a better understanding of issues related to human settlement, economic development, environment and hazard risks in China's LECZ. Currently, This work is focused on the spatial analysis of the LECZ in China and its population exposure from regional development and climate change perspectives. The climate-related hazard risk and vulnerability in the LEZC are reviewed based on a variety of important literatures, and in accordance with previous studies, we assume that climate change will lead to higher disaster risk in coastal lowlands. More integrated assessments of exposure, vulnerability and risk caused by the complicated interactions of climate change with other non-climate drivers are required, and improved datasets such as digital elevation models, population are needed for further detailed studies.

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