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Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways

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ABSTRACT

Existing quantifications of the Shared Socioeconomic Pathways (SSP) used for climate impact assessment do not account for subnational population dynamics such as coastward-migration that can be critical for coastal impact assessment. This paper extends the SSPs by developing spatial projections of global coastal population distribution for the five basic SSPs. Based on a series of coastal migration drivers we develop coastal narratives for each SSP. These narratives account for differences in coastal and inland population developments in urban and rural areas. To spatially distribute population, we use the International Institute for Applied Systems Analysis (IIASA) national population and urbanisation projections and employ country-specific growth rates, which differ for coastal and inland as well as for urban and rural regions, to project coastal population for each SSP. These rates are derived from spatial analysis of historical population data and adjusted for each SSP based on the coastal narratives. Our results show that, compared to the year 2000 (638 million), the population living in the Low Elevated Coastal Zone (LECZ) increases by 58% to 71% until 2050 and exceeds one billion in all SSPs. By the end of the 21st century, global coastal population declines to 830–907 million in all SSPs except for SSP3, where coastal population growth continues and reaches 1.184 billion. Overall, the population living in the LECZ is higher by 85 to 239 million compared to the original IIASA projections. Asia expects the highest absolute growth (238–303 million), Africa the highest relative growth (153% to 218%). Our results highlight regions where high coastal population growth is expected and will therefore face an increased exposure to coastal flooding.

1. Introduction

In coastal areas, flood impact assessments are of high relevance because flooding from extreme water levels is considered to be the major climate change related hazard in terms of damage (Wong et al., 2014). In addition, the frequency and intensity of flooding are expected to increase due to climate-change induced sea-level rise (Hunter, 2010), thus leading to higher damages (Hinkel et al., 2014). In order to assess future impacts, it is essential to understand the spatial distribution of future population exposure for a range of plausible future conditions. Therefore, socioeconomic scenarios for the coastal zone, which consider that population in coastal and inland areas develops in different patterns (McGranahan et al., 2007), are needed. The SSPs provide a suitable framework for this exercise. As central components of the latest scenario framework developed by the climate change research community, Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) are flexible tools to create scenarios that account for a wide range of possible climatic and socio-economic futures (Moss et al., 2010; van Vuuren et al., 2011; O'Neill et al. 2014; Ebi et al., 2014). Scenarios are used in impact assessment to account for uncertainties in assessing exposure of population and assets to natural hazards (Fang et al., 2014). They have been designed to replace the SRES scenarios as a standard in climate change IAV research and will increase the comparability of studies (Ebi et al., 2014; O'Neill et al., 2014).

Five basic SSPs have been established by the research community, providing possible pathways for society and society-influenced systems to develop in the course of the 21st century (O'Neill et al., 2014). They have been developed on global to regional scales based on socio-economic challenges for mitigation and adaptation. SSP1 describes a sustainable world with low challenges for mitigation and adaptation, SSP2 is a 'Middle of the Road' pathway with intermediate challenges, whereas SSP3 assumes regional rivalry, resulting in high challenges for both, mitigation and adaptation. In SSP4, which is characterised by inequality, challenges are high for adaptation and low for mitigation. SSP5, the pathway of fossil-fuelled development, has low challenges for adaptation and high challenges for mitigation (O'Neill et al., 2015). Furthermore, the research community has devised and agreed upon four RCPs which assume different levels of radiative forcing owing to the emission of greenhouse gases: RCP2.6, RCP4.5, RCP6 and RCP8.5

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(van Vuuren et al., 2011). Within the new scenario framework, individual SSPs can be combined with different RCPs in order to construct climate change scenarios for the 21st century (van Vuuren et al., 2014).

Each SSP consists of a qualitative narrative and quantifications for e.g. population and income projections. The narratives describe socio-economic developments in a broad enough fashion as to guarantee their utilisation in a wide range of studies (O'Neill et al., 2015). Several quantitative projections of population, urbanisation and gross domestic product (GDP) have been developed and published (see KC and Lutz, 2014 for population; Jiang and O'Neill, 2015 for urbanisation; and Crespo Cuaresma, 2015; Leimbach et al., 2015; Dellink et al., 2015 for GDP and income). The data are available in the public database of the International Institute for Applied Systems Analysis (IIASA, 2015).

So far the basic SSPs have been developed on global to national scales without accounting for differential subnational population dynamics (e.g., different growth rates of coastal and inland populations). Due to the lack of this spatial explicitness, their usefulness for regional scale analyses of population and asset exposure is limited and previous research has called for regional and sectoral extensions of the basic SSPs, at high spatial resolution (Ebi et al., 2014; van Ruijven et al., 2014; O'Neill et al., 2014, 2015). For coastal Impact, Adaptation and Vulnerability (IAV) research on global to regional scales, gridded population projections are of high interest to assess exposure to natural hazards (Moss et al., 2010; Jones et al., 2015).

This paper addresses this gap by extending the SSP narratives to the coastal zone and by downscaling national population projections to subnational gridded population projections. In these projections, we employ historical observations of differences between coastal and inland population development for each country. So far, studies have combined observations of specific areas (e.g. China and Bangladesh) with expert judgement and generally assumed future population in coastal areas to grow faster than in inland areas (Nicholls et al., 2008; Neumann et al., 2015). However, our approach also accounts for cases with faster growth of inland areas compared to coastal areas and additionally differentiates between urban and rural areas. Based on our coastal narratives, we adjust the observed historical patterns to account for different pathways of coastal development across the SSPs.

The remaining of the paper is structured as follows. In Section 2 we describe the data and methods employed for developing the coastal SSP narratives and the population projections. In the results section we provide the coastal SSP narratives along with an explanation of how we quantify them for each SSP and show the spatial projections of coastal population on global and continental scale for the 21st century. In order to test the sensitivity of the results, we compare the world's future coastal population projections of our approach to alternative approaches and discuss the differences.

2. Material and methods

2.1. Coastal SSP narratives

The first step in our approach is the development of coastal SSP narratives. Therefore, we determine factors of coastal migration based on literature review (Table 1). These factors promote settlement at the coast as compared to inland areas. We additionally differentiate coastal migration factors for urban versus rural areas. We do not include urbanisation as a separate coastal migration factor and adopt the basic urbanisation assumptions from O'Neill et al. (2015), since urbanisation processes are already accounted for by differentiating between urban and rural migration factors.

Table 1
Factors of coastal migration.

Coastal migration factors		
Urban	Rural	Reference
Shipping		Balk et al. (2009), Hugo (2011)
Large-scale fisheries	Small-scale fisheries	FAO (2014)
Coastal Tourism		Scott et al. (2012)
Lifestyle		Benson and O'Reilly (2009)
Coastal management		Balk et al. (2009), Nicholls et al. (2008), UN (2015), Seto (2011)

We then select a number of basic SSP key elements from O'Neill et al. (2015) which we use in two ways. First, we select the basic SSP key elements urbanisation, economic growth and technology as a general frame for our coastal SSP narratives and adopt the assumptions for these key elements from the narratives of the five SSPs. Second, we choose elements which are explanatory variables for the coastal migration factors (Fig. 1). Based on these elements, we interpret the characteristics of the coastal migration factors for each coastal SSP. In this step, we transform the coastal migration factors into our coastal SSP elements. Specifically, we assume that high international trade and globalisation lead to high importance of shipping (Balk et al., 2009; Hugo, 2011). We further expect that inequality leads to an increase in small-scale fisheries, because small-scale fisheries currently secure the livelihoods of millions of people, in particular in developing countries (FAO, 2014). High meat consumption, including seafood, also implies growing importance of fisheries (FAO, 2014). High agricultural productivity, however, leads to a decrease in small-scale fisheries. Tourism is another driver of coastward migration, both to rural and urban locations. Since coastal tourism is globally the largest tourism segment (Scott et al., 2012), we conclude that tourism in the coastal zone is high if the sector's contribution to the GDP is high. Further, we assume that lifestyle migration to the coast due to its natural attractiveness is high if economic growth is high and inequality is low (Benson and O'Reilly, 2009). Additionally, we expect coastal zone management to be effective if international cooperation and institutions are effective (Balk et al., 2009; UN, 2015). Coastal management also depends on the policy orientation. If policies are oriented towards sustainability, ecosystems are protected and land use change is restricted (Nicholls et al., 2008). If policies focus on economic growth, economic activities at the coast expand since the importance of shipping increases (Seto, 2011).

2.2. Coastal population projections

The population projections are produced in three subsequent steps. First, we utilise GRUMP (Global Urban Rural Mapping Project) population count grids (CIESIN et al., 2011a; Balk et al., 2006) to analyse the current state of the spatial population distribution. GRUMP uses night-time light satellite data to identify urban areas and reallocates census count data within administrative boundaries. The datasets have a spatial resolution of 30 arc sec (approximately 1 km at the equator) and represent the population adjusted to UN-national totals for the years 1990, 1995 and 2000. Furthermore, we use Urban Extents Grid (CIESIN et al., 2011b; Balk et al., 2006) to distinguish between urban and rural areas.

Second, we identify the Low Elevation Coastal Zone (LECZ), which includes all land areas up to 10 m elevation connected to the ocean (McGranahan et al., 2007), using the CGIAR-CSI SRTM v4.1 elevation data (Jarvis et al., 2008) with a spatial resolution of 3 arc sec (approximately 90 m at the equator) and GTOPO30 elevation data (USGS, 1996) for high latitudes, not covered by SRTM. We apply an elevation threshold of 10 m to reclassify the elevation data and perform a connectivity analysis with eight neighbouring cells to ensure hydrological connectivity to the ocean (Poulter and Halpin, 2008; Lichter et al., 2011; Neumann et al., 2015). Pixels below or equal to the threshold with a hydrological connection to the ocean are classified as coastal areas. Pixels above the threshold or below the threshold with no connection to the ocean are classified as inland areas. Finally, we resample the data to a resolution of 30 arc sec to match the spatial resolution of the population datasets.

Third, we calculate urban and rural population until 2100 by employing the population numbers and projections from the SSP

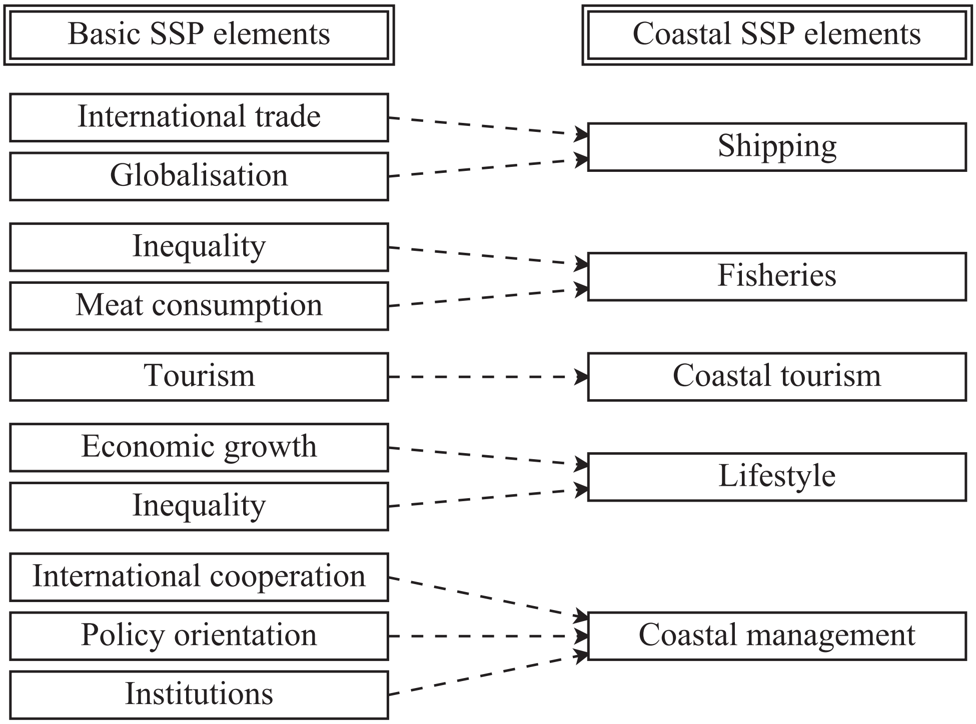

Fig. 1. Basic SSP elements selected from O'Neill et al., 2015 as explanatory variables for the coastal SSP elements.

database provided by the IIASA (IIASA, 2015). The SSP database contains population projections for 193 countries in 5-year increments from 2015 to 2100 for each SSP (KC and Lutz, 2014). Additionally, we incorporate the urbanisation rates of the National Center of Atmospheric Research (NCAR). This dataset, which is also available from the SSP database, contains projections for 151 countries with a population of >1 million in 2010 and an area of at least 1000 km^2 in 10 year time steps, from 2020 to 2100 (Jiang and O'Neill, 2015). For small countries with no population or urbanisation projections, we assumed the year 2000 data to be constant over time. For the spatial delineation of countries and regions we use the Global Administrative Areas (GADM) dataset version 2.0 (http://www.gadm.org/).

We adopt the “United Nations Method”, which is defined as the difference between urban and rural growth rates (UN, 2015; Jiang and O'Neill, 2015), to differentiate the growth rates of coastal urban and inland urban regions (GD^U) and coastal rural and inland rural regions (GD^R). A value >0 corresponds to a higher growth rate of the coastal region whereas a value <0 with a higher growth rate of the inland region. Our analysis of 177 countries and regions with urban areas both inside and outside the LECZ shows that 91 regions (51%) have a GD^U < 0 and 86 (44%) out of 197 countries and region that had rural areas inside and outside the LECZ have a GD^R < 0. These values indicate that neither the coast nor the inland grows faster across all countries if urbanisation patterns are treated separately (Fig. 2). We then implement the observed growth differences on country level to develop spatially explicit population projections.

In order to downscale future population to a subnational level, we split each country into four zones: coastal-urban (*CU*), coastal-rural (*CR*), inland-urban (*IU*) and inland-rural (*IR*) (Fig. 3). Landlocked countries have a maximum of two zones (*IU* and *IR*).

Based on GRUMP population count data, we calculate the population in each of the four zones on a country level for the 1990, 1995 and 2000 observations. The population living in these zones sums up to the total population of a country (P^T).

$$P^T = P^{CU} + P^{CR} + P^{IU} + P^{IR} \tag{1}$$

Subsequently, we calculate the growth rate (gr) between the years 1990 to 1995 and 1995 to 2000 in each zone:

$$gr_t^z = \frac{P_{t+1}^z - P_t^z}{P_t^z} \tag{2}$$

with P representing the population count in zone z and t the time. In a next step, we use the mean of the calculated observed growth difference (GD_{obs}) between coastal and inland zones for the 1990 to 1995 and 1995 to 2000 periods. We focus on the growth difference between the coastal urban and the inland urban zone (GD_{obs}^U) as well as the coastal rural and the inland rural zone (GD_{obs}^R).

$$GD_{obs}^U = 0.5*\left(gr_{1990}^{CU} - gr_{1990}^{IU} + gr_{1995}^{CU} - gr_{1995}^{IU}\right) \tag{3}$$

$$GD_{obs}^R = 0.5*\left(gr_{1990}^{CR} - gr_{1990}^{IR} + gr_{1995}^{CR} - gr_{1995}^{IR}\right) \tag{4}$$

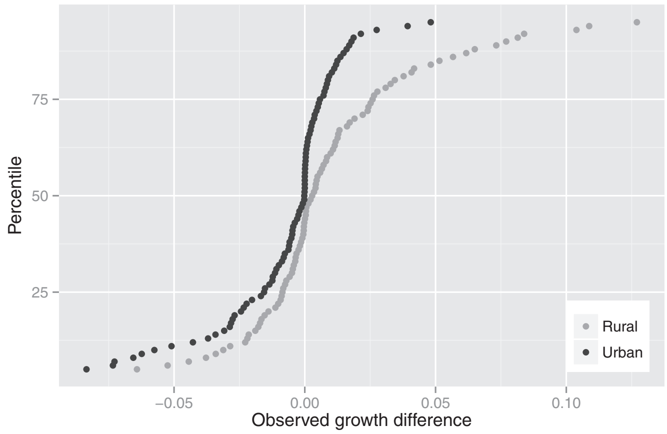

Fig. 2. 5th to 95th percentiles of observed urban and rural growth difference.

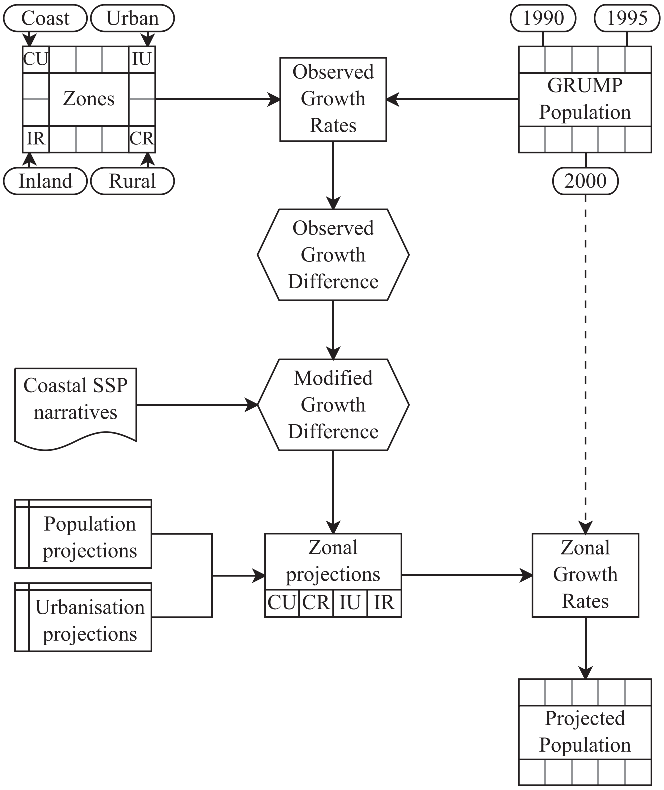

Fig. 3. Flow chart describing the approach used to produce gridded population projections.

A value of 0 indicates that the population in both zones grows at the same rate. If the growth difference is positive (negative), the population at the coast grows faster (slower) than in the inland. For the projections, we assume the growth differences to be constant over time but to differ across the SSPs. However, the growth rates differ over time. In order to make our results consistent with previous work in the SSP framework, we use the projected population totals (P_t) produced by KC and Lutz (2014) and the projected urbanisation levels (u_t) created by Jiang and O'Neill (2015) to calculate future urban (P_t^U) and rural population (P_t^R) for each SSP.

$$P_t^U = P_t * u_t \tag{5}$$

$$P_t^R = P_t * (1 - u_t) \tag{6}$$

Based on the coastal SSP narratives, we modify the observed growth difference for each SSP (Table 2). The modification is based on percentiles of the observed growth difference. In order to obtain plausible results, we select percentiles with a small interpercentile range to the previous percentile and a high interpercentile range to the following.

Using the modified growth differences for each SSP (GD_{SSP}^U and GD_{SSP}^R), we subdivide these urban and rural totals into coastal and inland components:

$$P_t^{CU} = \frac{P_{t-1}^{CU}\left(P_t^U - P_{t-1}^{IU} * GD_{SSP}^U\right)}{P_{t-1}^U} \tag{7}$$

$$P_t^{IU} = P_t^U - P_t^{CU} \tag{8}$$

$$P_t^{CR} = \frac{P_{t-1}^{CR}\left(P_t^R - P_{t-1}^{IR} * GD_{SSP}^R\right)}{P_{t-1}^R} \tag{9}$$

$$P_t^{IR} = P_t^R - P_t^{CR} \tag{10}$$

Based on these regionalised population totals we calculate the growth rate for each zone and time step (r_t^z) by using the population numbers of 2000 as a base year.

$$r_t^z = \frac{P_t^z - P_{2000}^z}{P_{2000}^z} \tag{11}$$

Assuming that the growth rates are homogeneous within a zone, we multiply them by the GRUMP grid population counts representing the year 2000 population.

3. Results

3.1. Coastal SSP narratives

Table 2 gives an overview of the main elements of the five coastal SSP narratives developed. The following subsections then present each narrative in more detail. The first paragraph of each narrative thereby provides a short overview of the basic key elements of the socioeconomic pathway and its implications for the coastal SSP elements. The second paragraph then illustrates the differences of coastal population growth as compared to inland growth, as well as those between urban and rural areas.

SSP1 – Green Coast

The world's shift towards a more sustainable pathway results in well-managed coastal zones. Global institutions and environmental policies function effectively. Therefore, socioeconomic development is highly managed and focuses on the development of compact and

Table 2

Coastal SSP elements, quantifications for each SSP and modifications of observed urban (GD_{SSP}^U) and rural (GD_{SSP}^R) growth differences.

Coastal SSP element	SSP1 Green coast	SSP2 No wind of change	SSP3 Troubled waters	SSP4 Fragmented coast	SSP5 Coast rush
Shipping	Moderate	Moderate	Low	Moderate-high	High
Fisheries[a]	Low	Moderate	High	Very high	Low
Coastal tourism	Sustainable; low-impact, no mass tourism	Moderate; uneven	Very low; no international tourism	High for elites; low for majority of population	Very high; mass tourism
Lifestyle migration	Low	Moderate	Low	High for elites; low for majority of population	Very high
Coastal management	High; towards sustainability	Moderate	Weak	Towards elite's benefit; little interest in sustainability	High; towards economic growth
Urban growth difference (GD_{SSP}^U)	$= 0$	$= GD_{obs}^U$	$= GD_{obs}^U * 0.5$	$= GD_{obs}^U + (Q.66 - Q.50)$	$= GD_{obs}^U + (Q.83 - Q.50)$
Rural growth difference (GD_{SSP}^R)	$= GD_{obs}^R - (Q.50 - Q.25)$	$= GD_{obs}^R$	$= GD_{obs}^R * 0.5$	$= GD_{obs}^R + (Q.66 - Q.50)$	$= GD_{obs}^R + (Q.75 - Q.50)$

[a] In our coastal SSP narratives the term fisheries refers to small-scale fisheries since we do not explicitly account for large-scale fisheries as a coastal migration factor.

sustainable coastal cities without urban sprawl. Economic growth is medium to high and markets are globally connected, fostering rapid technological development and transfer. Due to more sustainable, regionalised production, international trade is on a moderate level. Therefore, shipping is moderately important. Tourism is practiced in a sustainable way. Lifestyle migration to the coast is limited. Reduced inequality, low-meat diets and improvements in farming productivity lead to decreasing importance of fisheries. The value of ecosystems and their protective function in the coastal zone are globally accepted and respected. Policies are oriented towards conservation and expansion of coastal ecosystems prevents settlement in the coastal zone.

The focus on sustainability leads to high urbanisation rates and compact cities. As coastal cities are regulated by environmental policies and since their economic importance does not differ from inland cities, population growth in coastal urban locations does not differ from inland urban ones. Coastal ecosystem protection and lower importance of fisheries lead to reduction of population growth in coastal rural areas compared to inland rural areas. Consequently, we use a growth difference of 0 for urban areas and reduce the observed growth difference for rural areas by the difference of the 50th and 25th-percentiles of the observed rural growth difference (see Table 2). In total, the coastal zone is less attractive for human settlement than the inland.

SSP2 – No Wind of Change

Under SSP2, socioeconomic development in the coastal zone does not deviate significantly from historical patterns. The management of socioeconomic development in the coastal zone is limited due to relatively weak international cooperation, uneven and moderately effective institutions, and rather slow implementation of environmental policies. Hence, the urbanisation rate is moderate with considerable spatial expansion of cities. Economic growth is, on average, medium and continues to be uneven across countries. Technological development is moderate and transfer slow. The semi-open global economy is characterised by moderate international trade, keeping the importance of shipping at a similar level. Tourism also continues at historical rates. Migration to the coast for lifestyle reasons is moderate. Fisheries remain important, owing to uneven reductions in inequality, material-intensive, medium meat consumption and slow improvements in productivity. Ecosystem protection is weak and leads to environmental degradation.

This pathway shows a fragmented picture. Coastal zones remain as attractive for socioeconomic development as in the past, with rapid population growth in some coastal regions and slow growth or even declining population numbers in others. Urbanisation and urban sprawl continue in coastal as well as inland locations. Similarly, rural coastal and inland populations experience the same growth patterns as observed in the past. In total, historical patterns of coastal and inland population growth will continue at the same rates. Therefore, we use the observed urban and rural growth differences and do not modify them.

SSP3 – Troubled Waters

In this pathway, the focus on national and regional issues leads to converging population growth rates of coast and inland. International cooperation and global institutions are weak and uneven. National policies focus on security issues, resulting in poorly managed socioeconomic development. Therefore, urban areas are unattractive and urbanisation is slow. Due to a de-globalizing economy oriented towards security, international trade is strongly constrained and economic growth is slow. Therefore, technology development and transfer is limited. As a consequence, shipping experiences a marked decline. Likewise, international tourism hardly exists. Also, coastal lifestyle migration is low. Fisheries become more important because inequality is high, consumption is material-intensive and productivity is low. Further, food security needs to be guaranteed on a national level. This development in combination with the absence of environmental policies leads to serious environmental degradation.

Under SSP3 the coastal zone loses its importance as a focal point of international trade due to the orientation towards national and regional security. Since poorly managed inland urban areas also lose attractiveness, neither coastal nor inland urban areas are more attractive for human settlement. The same patterns apply to rural areas. Therefore, the population in both urban and rural locations changes at converging rates. We consider this convergence by reducing the observed growth differences for both urban and rural areas by half.

SSP4 –Fragmented Coast

SSP4 is characterised by high inequalities within and across countries. This applies to the coastal zone as well. International cooperation takes place among elites with effective institutions and policies in place for them. This leads to well-managed economic growth for the elites and leaves behind the rest of the population. Therefore, this pathway is characterised by highly fragmented socioeconomic development. Technology development is rapid, but transfer among population groups is low. Economic growth is uneven and international trade is moderate since only elites are connected globally. This makes urban areas, especially port cities, very attractive because they are regarded as economic engines with abundant job opportunities. Consequently, urbanisation is fast with considerable urban sprawl, including high unemployment rates and the formation of unplanned peri-urban slums. Tourism plays an important role for elites only. Similarly, lifestyle migration to the coast is high for elites. Consumption is high for elites and low for the rest of the population, increasing the importance of fisheries for poor population groups to secure their livelihoods. Extensive agricultural use and low productivity in rural areas leads to environmental degradation, since policies focus on the local environment surrounding the elites.

In this pathway, coastal areas experience fragmented population development, both socially and economically. Coastal urban areas are subject to higher population growth than inland urban areas because they are regarded as economic engines. Rural coastal areas are more attractive than rural inland areas due to the importance of fisheries. Also, the tourism industry fosters coastal development. Overall, the coastal zone experiences higher population growth than inland areas. Therefore, we increase the observed coastal to inland growth difference for urban and rural areas by the difference of the 66th and the 50th percentile.

SSP5 – Coast Rush

In this highly globalised world the coastal zone is of particular importance. International cooperation as well as institutions are effective. Policies focus on competitive, free markets and human well-being. This promotes socioeconomic development substantially. Global markets are highly interconnected with regional specialisation. This leads to high international trade and rapid economic growth, which promotes technological development and transfer. As a consequence, the importance of shipping increases markedly. That is why urbanisation is high and results in large cities with urban sprawl, which is managed more effectively over time. Also, international tourism plays an important role, resulting in extensive development in coastal areas. Similarly, lifestyle migration to the coast is very high. Consumption is characterised by materialism and meat-rich diets, leading to increased importance of fisheries. Inequality is strongly reduced and agricultural productivity is high. As a consequence, small-scale fisheries are replaced by large-scale fisheries. Environmental policies focus on the local environment which is extensively engineered to ensure people's well-being. Little attention is paid to global problems.

In this pathway, robust economic growth leads to high population growth in the coastal zone. This is due to the fact that in a globalised world port cities are centres of growth and urbanisation rates are high. Rural coastal areas also experience higher population growth than rural inland ones because coastal tourism is a major driver of rural economic growth. However, the difference between rural coastal and rural inland is not as high as between urban coastal and urban inland population growth. We account for these aspects by increasing the observed urban growth difference by the difference of the 83rd and the 50th percentile and by increasing the observed rural growth difference by the difference of the 75th and 50th percentile.

3.2. Coastal population projections

Fig. 4 shows the gridded population projections produced. Based on these projections we first present global patterns across the different

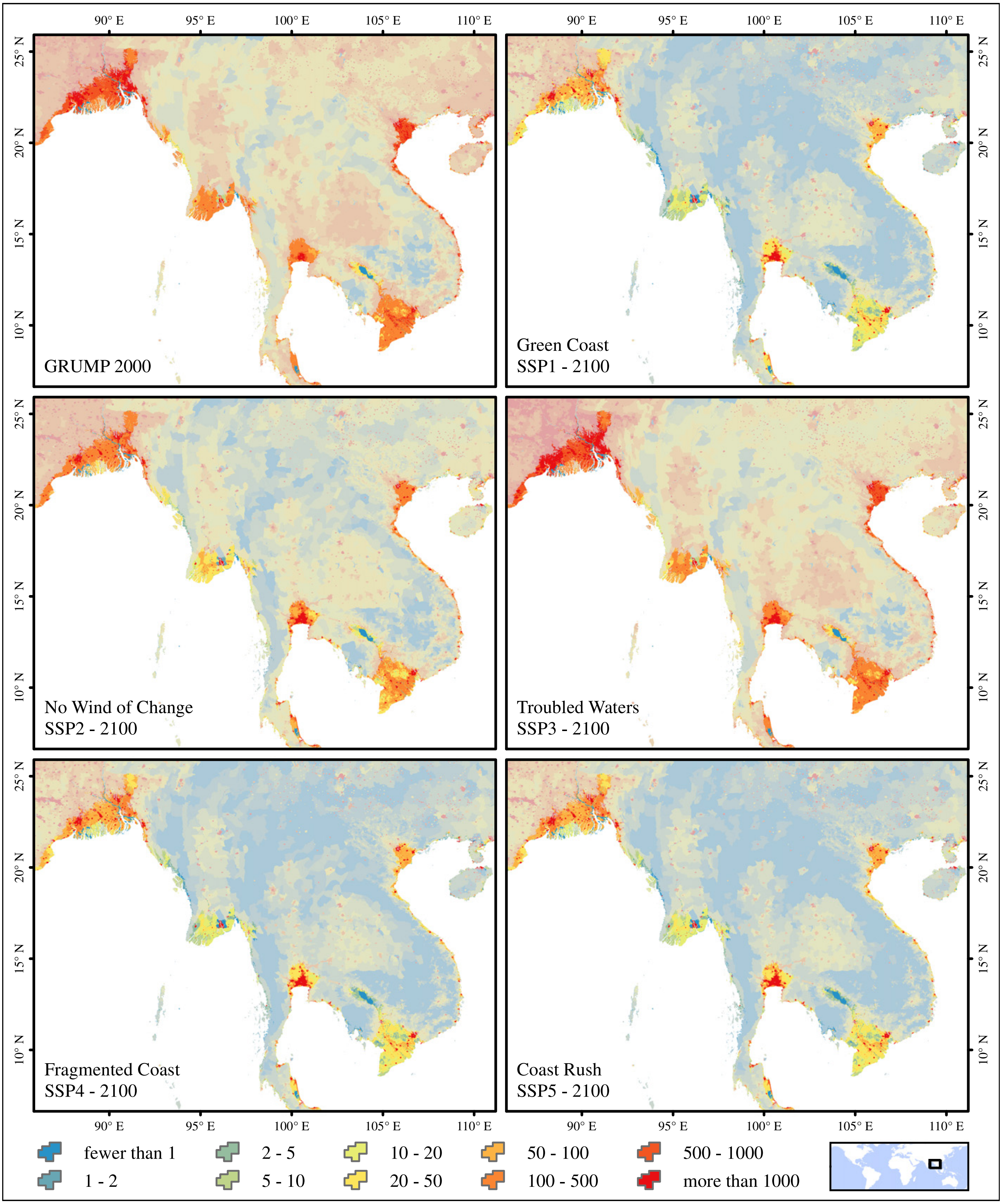

Fig. 4. Population projections of each SSP compared to the base year 2000 for Southeast Asia. Pixel size: 30 arc-seconds (~1 km^2 at the equator).

SSPs and then focus into regional patterns using the UN regions definition (UN, 2013).

3.2.1. Global

Our results show that the absolute coastal population will grow by 2050 across all SSPs (Table 3). SSP5 shows the highest LECZ population (1.091 billion), SSP2 the lowest LECZ population (1.005 billion). The share of coastal population is highest in SSP5 (12.8%) but lowest in SSP3 (10.5%). Compared to the year 2000, the population living in the LECZ increases between 58% (SSP2) and 71% (SSP5). Across all SSPs, the proportion of coastal population increases in the first half of the 21st century.

By end of the 21st century, the population living in the LECZ ranges from 0.830 billion (SSP4) to 1.184 billion in SSP3. The relative share of coastal population ranges from 9.0% in SSP4 to 12.3% in SSP1 and SSP5. Compared to the year 2000, the population grows by 30% (SSP4) to 86% (SSP3), whereas the other SSPs show a growth between 33% and 42%. Coastal growth exceeds inland growth in SSP1 and SSP5. Compared to 2050, coastal population rises solely in SSP3 (+13%). In the other SSPs, the coastal population declines by up to 0.2 billion (SSP1 and SSP4) in the second half of the 21st century. In line with the population projections of KC and Lutz (2014), the range of coastal population across the SSPs by end of the 21st century is wider (0.354 billion) than by mid of the century (0.086 billion).

3.2.2. Regional

On a continent scale, we expect the highest relative changes of coastal population in Africa. Compared to the base year 2000, Africa's coastal population grows between 1.4 times in SSP5 and 3.9 times in SSP3 by the end of the century. The absolute coastal population increases from 54 million in 2000 to 137 million (SSP5) and 172 million (SSP3) in 2050. By the end of the century, Africa's coastal population further increases to 265 million (SSP3). Only in SSP5 Africa's coastal population decreases from 2050 to 2100 to 130 million. The highest share of coastal population is in SSP1 (8%) and the lowest in SSP4 (6.1%). In SSP2 and SSP4 the inland population is growing faster than the coastal population over the 21st century, while in SSP1, SSP3 and SSP5 the coastal population is growing faster than the inland population.

In Asia, the coastal population by the end of the century grows between 3% in SSP4 and 66% in SSP3 compared to the year 2000 population. The absolute coastal population rises from 472 million in 2000 to a range from 710 million (SSP2) to 776 million (SSP5) in 2050. By the end of the century the coastal population will decrease from the 2050 peak to a number ranging from 487 million (SSP4) to 550 million (SSP1, SSP2 and SSP5). In SSP3, the absolute coastal population continues growing in the second half of the century leading to 784 million people living in coastal areas in 2100. SSP1 shows the highest relative share of coastal population (16.9%). In SSP2–4 the inland population is growing faster than the coastal population over the 21st century, while SSP1 and SSP5 indicate a higher growth rate of coastal regions.

For Europe, the scenarios show a wide range in the relative change of coastal population in the 21st century. In SSP1, SSP2 and SSP5 the population grows by up to 96% (SSP5) and declines in SSP3 (28%) and SSP4 (9%). By the mid of the century the absolute coastal population rises from 49 million in 2000 to a range of 49 million to 72 million (SSP3 and SSP5 respectively). In the second half of the century the coastal population decreases to a range from 35 million (SSP3) to 57 million (SSP2). Only in SSP5 the coastal population continues to grow to 96 million, which is the highest share across all pathways (10.5%). With the exception of SSP3 the coastal population grows faster than the inland population.

Latin America and the Caribbean face the highest relative coastal population growth in the 21st century in SSP3 (105%) and the lowest growth in SSP1 (1%). The absolute coastal population rises from 34 million in 2000 to a range of 48 million (SSP1 and SSP4) to 57 million (SSP3) by 2050. Solely in SSP3 the population continues to grow to 69 million by the end of the century while all other pathways show coastal population declining to a range between 34 million (SSP1) and 44 million (SSP2). SSP5 shows the highest share of coastal population (8.4%). In SSP1, SSP2 and SSP5 coastal population grows faster than inland population.

For North America, the relative change of coastal population in the 21st century ranges from a decrease of 2% (SSP3) to a growth of up to 228% (SSP5). Until 2050 the absolute coastal population grows from 25 million in 2000 to a range from 31 million (SSP3) to 49 million (SSP5). The coastal population continues to grow in the second half of

Table 3
Absolute and relative population living in the LECZ by UN-region and worldwide for the years 2000, 2050 and 2100.

		GRUMP	SSP1		SSP2		SSP3		SSP4		SSP5	
			Green Coast		No Wind of Change		Troubled Waters		Fragmented Coast		Coast Rush	
		2000	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Africa	Count	54	140	149	144	162	172	265	159	220	137	130
	Share	6.7%	7.9%	8.0%	7.1%	6.2%	7.4%	6.7%	7.1%	6.1%	7.9%	7.2%
	growth		159%	175%	165%	200%	218%	390%	194%	307%	153%	141%
Asia	Count	472	754	555	710	555	732	784	730	487	776	545
	Share	12.8%	15.9%	16.9%	13.8%	12.6%	13.0%	11.7%	14.7%	12.0%	16.4%	16.5%
	growth		60%	18%	51%	18%	55%	66%	55%	3%	64%	16%
Europe	Count	49	60	56	57	57	49	35	55	45	72	96
	Share	6.8%	7.7%	8.6%	7.5%	8.1%	7.2%	6.5%	7.7%	8.4%	8.5%	10.5%
	growth		21%	15%	16%	15%	0%	-28%	12%	-9%	46%	96%
Latin America and the Caribbean	Count	34	48	34	50	44	57	69	48	35	50	38
	Share	6.5%	7.1%	7.0%	6.7%	6.6%	6.7%	6.4%	6.8%	6.1%	7.6%	8.4%
	growth		42%	1%	49%	31%	69%	105%	42%	3%	48%	12%
Northern America	Count	25	38	44	37	43	31	25	36	36	49	82
	Share	8.0%	8.2%	8.5%	8.2%	8.4%	8.3%	8.5%	8.4%	8.8%	9.1%	10.3%
	growth		50%	76%	47%	72%	23%	-2%	41%	42%	93%	228%
Oceania	Count	3.4	6.6	7.3	7.0	8.9	5.7	5.4	7.0	8.1	9.1	15.4
	Share	11.0%	11.8%	12.4%	12.3%	13.7%	11.3%	10.9%	12.5%	13.3%	14.1%	17.7%
	growth		95%	115%	108%	162%	70%	60%	108%	141%	170%	355%
World	Count	637	1046	845	1005	870	1047	1184	1034	830	1091	907
	Share	10.5%	12.4%	12.3%	11.0%	9.7%	10.5%	9.4%	11.3%	9.0%	12.8%	12.3%
	growth		64%	33%	58%	37%	64%	86%	62%	30%	71%	42%

Count represents the LECZ population in million. Share is the share of LECZ population on total population in percent. Growth gives the relative growth of LECZ-population in percent compared to the year 2000 population as baseline.

the century and ranges from 36 million (SSP4) to 82 million (SSP5). Only in SSP3 the population living in the coastal zone declines to 25 million. Nevertheless, coastal population is growing faster than inland population across all SSPs, as in SSP3 the inland population is declining even more. This leads to a higher share of coastal population in all SSPs, with SSP5 showing the highest share (10.3%).

In Oceania, coastal population grows between 0.6 times (SSP3) and 3.6 times (SSP5) in the 21st century. The absolute coastal population rises from 3.4 million in 2000 to a range between 5.7 million (SSP3) and 9.1 million (SSP5) in 2050. Until the end of the 21st century the coastal population continues growing and ranges from 7.3 million (SSP1) to 15.4 million (SSP5). Only in SSP3 the coastal population declines from its 2050 peak to reach 5.4 million in 2100. SSP5 shows the highest share of coastal population (17.7%). With the exception of the second half of the century in SSP3, coastal population grows faster than inland population.

4. Discussion

Different from previous studies, this study uses historical data to account for differences in population growth between coastal and inland regions at subnational level. Previous studies have either employed a uniform global constant growth rate of coastal population (e.g. Nicholls et al., 2008) or have assumed coastal population to grow faster than inland population on a national level (e.g. Neumann et al., 2015). These studies also assumed coastal regions to grow up to two times faster than inland regions. These assumptions were based on the study of McGranahan et al. (2007), who found that coastal population in China and Bangladesh grew much faster than the inland population and that the fastest growth was located in urban coastal regions. In our study we determine the growth rate of coastal urban regions based on urbanisation and additional factors of coastal migration, for example shipping and tourism. These factors either increase or decrease the attractiveness of coastal regions compared to inland regions, thus leading to country-specific migration processes.

When comparing our results on historic growth rates with other studies, we find that contrary to McGranahan et al. (2007) and in line with the database of CIESIN (2013), our findings show no clear evidence of population to grow faster at the coast compared to inland (Table 4). Since a direct comparison of absolute population numbers between these studies was not possible due to the use of different input data, we compared the relative change of population in Bangladesh and China between 1990 and 2000. According to McGranahan et al. (2007), the population in the LECZ grew faster than the inland population for these two countries, with coastal urban areas showing the highest growth rates. This is not in agreement with the findings of CIESIN (2013) and our results, which show that in Bangladesh the inland grew faster than the coastal zone while in both Bangladesh and China inland urban areas grew faster than coastal urban areas. However due to the high concentration of urban areas in the coastal zone of China (Neumann et al., 2015), the growth rate of population in the LECZ was higher than in inland areas, despite the growth rates of coastal urban and coastal rural areas were smaller than their inland equivalents. This illustrates that urbanisation appears to be the dominant driver of population dynamics, independent of whether areas are coastal or inland. This demonstrates that our approach of using country-specific growth rates that also account for faster population growth in the inland instead of the general assumption of faster growing population in coastal regions is valid.

Next, we compare the results of our approach to other possible approaches: we (1) use an equal growth rate within each country, (2) consider urbanisation projections and use different growth rates for urban and rural areas within each country and (3) apply different growth rates for urban and rural areas within each country considering different patterns of coastal and inland development and following historical patterns. These approaches may lead to over- or underestimation of coastal population (Table 5).

Table 4
Relative change of population between 1990 and 2000 for Bangladesh and China.

	Bangladesh			China		
Values in %	McGranahan[1]	CIESIN[2]	This study[3]	McGranahan[1]	CIESIN[2]	This study[3]
National	12.6	23.9	23.9	10.9	10.8	10.4
Coastal	23.6	23.1	23.2	20.8	17.8	17.8
Inland	2.7	24.6	24.5	9.7	10	9.3
Coastal Urban	32	34.1	33.9	39.6	38.2	40.5
Coastal Rural	21.1	20.3	20.5	4.1	-10.4	-0.2
Inland Urban	0.2	34.3	35	23.2	43.6	41.8
Inland Rural	3.3	22.5	22.5	4.6	-9.6	-0.1

1) Population data: GRUMPalpha, LECZ: 10 m 2) Population data: GRUMPv1, LECZ: 20 m and 3) Population data: GRUMPv1, LECZ: 10 m.

The use of (1) a single growth rate per country is the most straightforward approach and applied in a number of studies (e.g. Hinkel et al., 2014). This approach tends to underestimate coastal population because it does not consider urbanisation.

Enhancing (2) this approach by urbanisation projections and applying different growth rates for urban and rural areas, coastal population tends to be overestimated, due to the fact that coastal areas show a higher population density than inland areas (Neumann et al., 2015). Urbanisation is not the only determining factor of coastal population development but is additionally influenced by processes that may reduce the attractiveness of coastal areas. For example, high population density in coastal regions can lead to higher land costs, thus rendering coastal areas less attractive. To account for these processes, the use of historical growth differences is appropriate.

Considering (3) urbanisation projections and historical growth differences between coastal and inland areas on national level leads to higher coastal population compared to the approach using a single growth rate and lower projections compared to the approach enhanced by urbanisation projections. The approach implementing observed growth differences can be used for a pathway where historical patterns continue in the future (as in SSP2 – no wind of change). Since we account for five different coastal SSPs and coastal migration factors differ across these pathways, we refine the approach by modifying the observed growth difference for each coastal SSP.

The population projections (Table 3) show a decrease of coastal population in some regions in the second half of the 21st century. The predominant reasons for this decrease are the general trends in the population projections that were used as input data. The projections of KC and Lutz (2014) show that the global population declines from 2050 to 2100 under SSP1, SSP2 and SSP5. On a regional scale this trend depends on the number of countries grouped into high fertility, low fertility and rich-OECD and can therefore differ from the global trends. For example, KC and Lutz (2014) assume natural population growth (high fertility, low mortality) and high migration to rich OECD-countries in SSP5, which leads to population growth in Europe, North America and Oceania in the second half of the 21st century. In addition, regional trends can be distorted by populous countries with a high positive or negative growth difference.

Finally, our study exhibits two limitations. First, we assume a static urban extent, which is suitable for urbanisation processes in SSP1, where urban sprawl is limited, but less suitable for SSP2 and SSP5, where urban sprawl and urbanisation levels are high. However, since urban sprawl affects both coastal and inland regions, the effect on the total number of coastal residents on regional and global scales is small. We defined the boundaries of urban areas according to the GRUMP Urban Extent data, which are based on a more generic definition of urban extent that is not limited to built-up areas but encompasses urban agglomerations and is therefore suitable for global and regional scale analyses. However, for local scale analyses, urban sprawl processes

Table 5
Absolute and relative global LECZ-population in 2100 calculated by different spatial approaches for the five SSPs.

	Single growth rate per country		Urbanisation projections		Historical patterns		Our approach	
	abs.	rel.	abs.	rel.	abs.	rel.	abs.	rel.
SSP1	619	9.0%	849	12.3%	712	10.4%	845	12.3%
SSP2	785	8.7%	1027	11.4%	870	9.7%	870	9.7%
SSP3	1067	8.5%	1287	10.2%	1118	8.9%	1183	9.4%
SSP4	688	7.4%	985	10.6%	800	8.6%	830	9.0%
SSP5	668	9.1%	899	12.2%	763	10.4%	907	12.3%

abs. represents the global LECZ population in million. rel. represents the relative share of LECZ population on total population in percent.

should be implemented. A second limitation of our approach is that the growth difference is based on a relatively short observational record (10 years) and is assumed to be constant over time. This is due to the absence of global gridded population data whose temporal and spatial resolution is high enough for use in coastal analysis. A longer observational record would lead to more robust estimates and enable the use of trends in growth difference on country level over the 21st century.

The population grids developed can be downloaded at (https://figshare.com/s/9a94ae958d6a45684382). They have been produced with a specific focus on the coastal zone in order to enable coast-related IAV assessments. This should be kept in mind when analysing the population projections outside the LECZ.

5. Conclusion

This study has developed spatially-explicit population projections for the five coastal SSPs by (i) defining SSP narratives for the coastal zone and (ii) producing gridded population projections for each coastal SSP at high temporal and spatial resolution. We combined the basic SSPs, which serve as boundary conditions, with coastal migration factors to account for differences in coastal and inland population growth across the coastal SSPs. These coastal SSPs span the range of plausible population development at the coast and project the population in a spatially explicit manner until 2100 by using a range of population growth rates at subnational level. The range accounts for potential growth but also possible decline of coastal population.

The population grids can be used in coastal IAV research to assess exposure of population to climate-change impacts and natural hazards on global to regional scale. Further, they can be summarised readily to policy-relevant administrative units for planning, decision-making or resource allocation. For studies on local scale, the produced grids are less suitable and results should be interpreted with caution. This is due to the fact that the population grids presented here are not demographic projections, but rather aim to account for uncertainties in the future distribution of the population living in the coastal zone under different scenarios.

Future work can extend the proposed coastal SSPs and regionalise them. In this context, further differentiation in coastal population development between countries could be useful for better representing regional development trends. At local to regional scales, further criteria other than fertility and income can be considered to cluster countries and differentiate between country groups. At subnational level, the gridded population projections can be further refined with dasymetric modelling approaches to account for changes in land cover and urban extents.

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