A global perspective on climate-induced versus relative sea-level rise: implication for risk and adaptation

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ARTICLES

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A global analysis of subsidence, relative sea-level change and coastal flood exposure

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Climate-induced sea-level rise and vertical land movements, including natural and human-induced subsidence in sedimentary coastal lowlands, combine to change relative sea levels around the world's coasts. Although this affects local rates of sea-level rise, assessments of the coastal impacts of subsidence are lacking on a global scale. Here, we quantify global-mean relative sea-level rise to be 2.5 mm yr^{-1} over the past two decades. However, as coastal inhabitants are preferentially located in subsiding locations, they experience an average relative sea-level rise up to four times faster at 7.8 to 9.9 mm yr^{-1}. These results indicate that the impacts and adaptation needs are much higher than reported global sea-level rise measurements suggest. In particular, human-induced subsidence in and surrounding coastal cities can be rapidly reduced with appropriate policy for groundwater utilization and drainage. Such policy would offer substantial and rapid benefits to reduce growth of coastal flood exposure due to relative sea-level rise.

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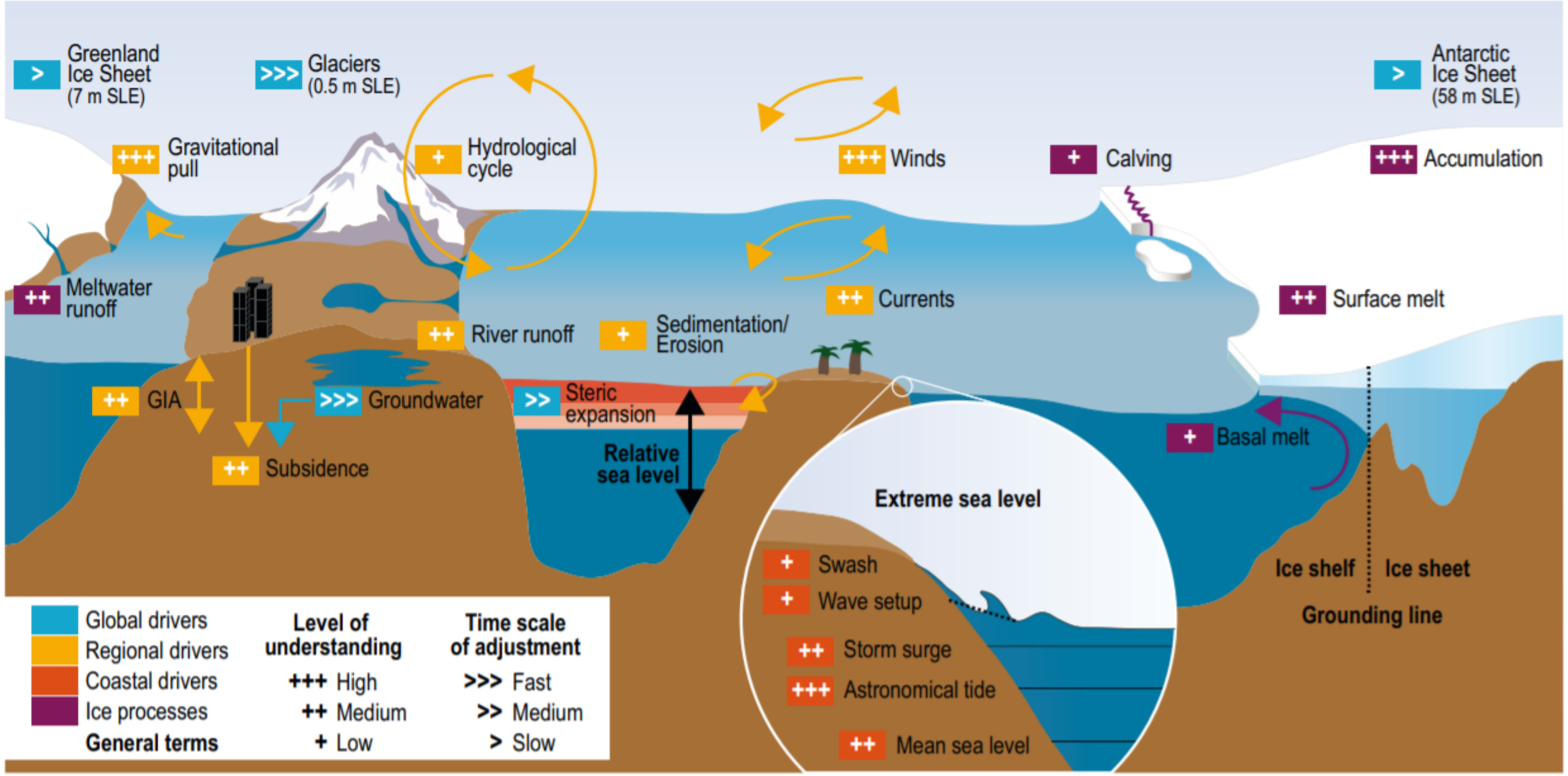
Relative Sea-Level Components

1. **<u>Global components –</u>** increasing ocean volume linked to climate change
2. **<u>Regional components –</u>** climate variability such as El-Nino, geological trends (uplift/subsidence)
3. **<u>Local components</u>** – often human-induced subsidence due to fluid withdrawal and drainage (oxidation of organic soils)
4. Extremes – tides, surges, waves
5. Here we examine mean relative sea-level rise (the first three components)



Source: IPCC SROCC Report 2019

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Global Analysis of Contemporary Relative Sea-Level Rise

We combine data on four components of relative sea-level change:

1. Satellite observations of sea-level change from 1993 to 2015;
2. Glacial-isostatic adjustment (GIA), derived from the model of Peltier et al (2015);
3. Deltaic subsidence – natural and anthropogenic subsidence in 117 deltas worldwide, building on the earlier work of Ericson et al (2006);
4. City subsidence – the additional subsidence beyond deltaic subsidence that susceptible coastal cities (> one million people) on deltaic and alluvial plains experience (following Nicholls et al., 2008).

These four components are assumed to be independent and hence can simply be summed.

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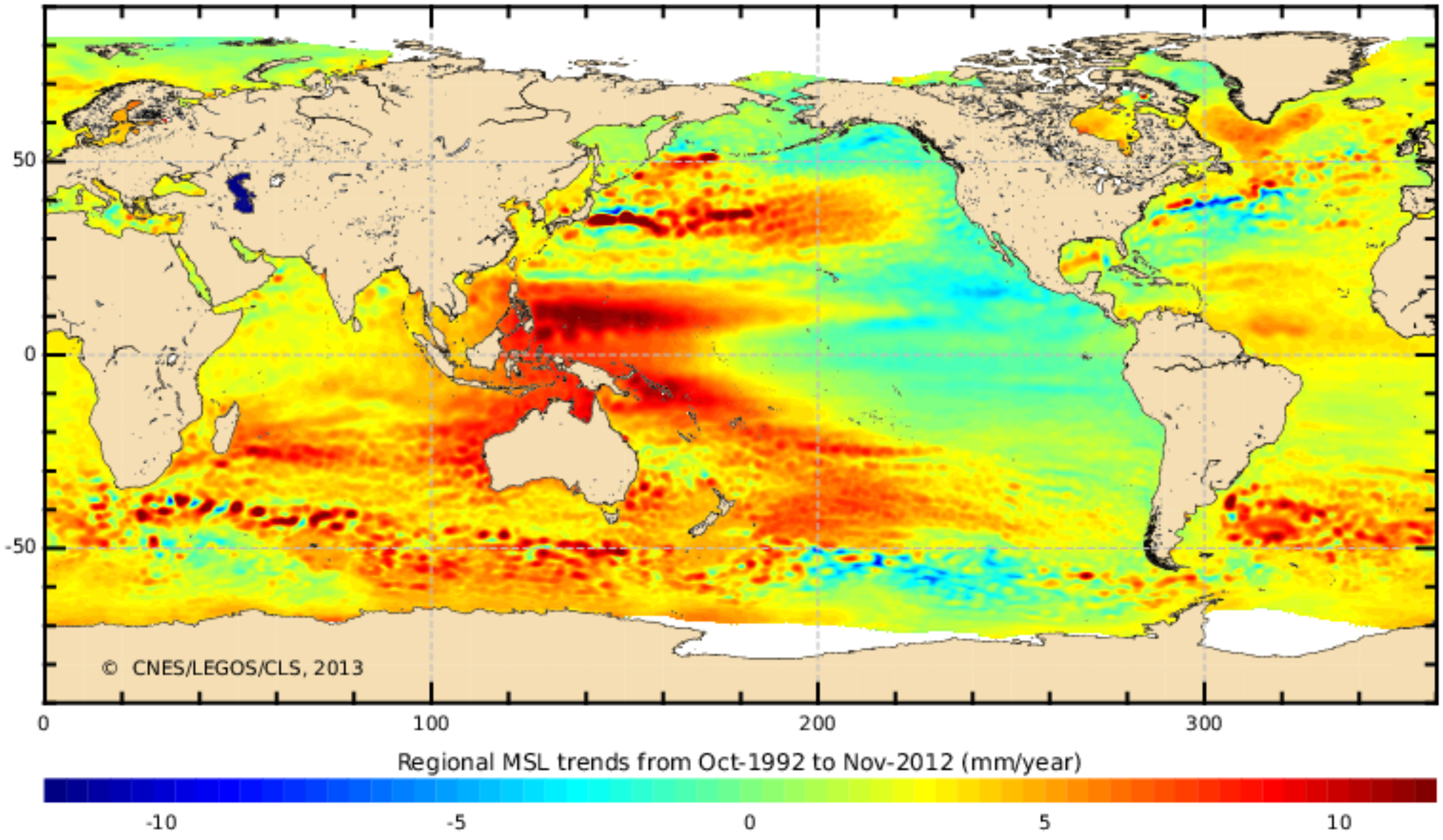
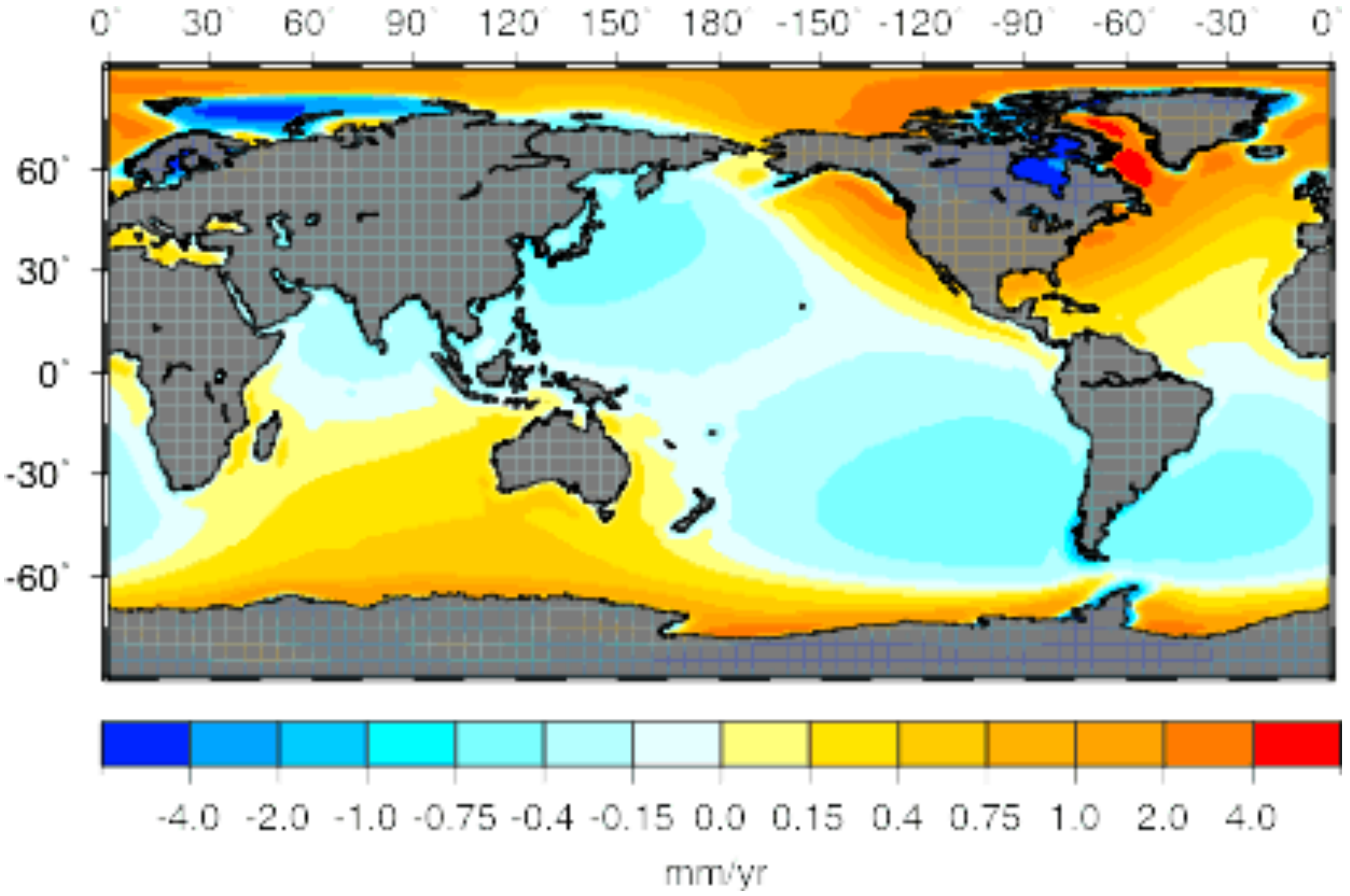
Component 1: Satellite-based sea-level observations

(1992 to 2012)



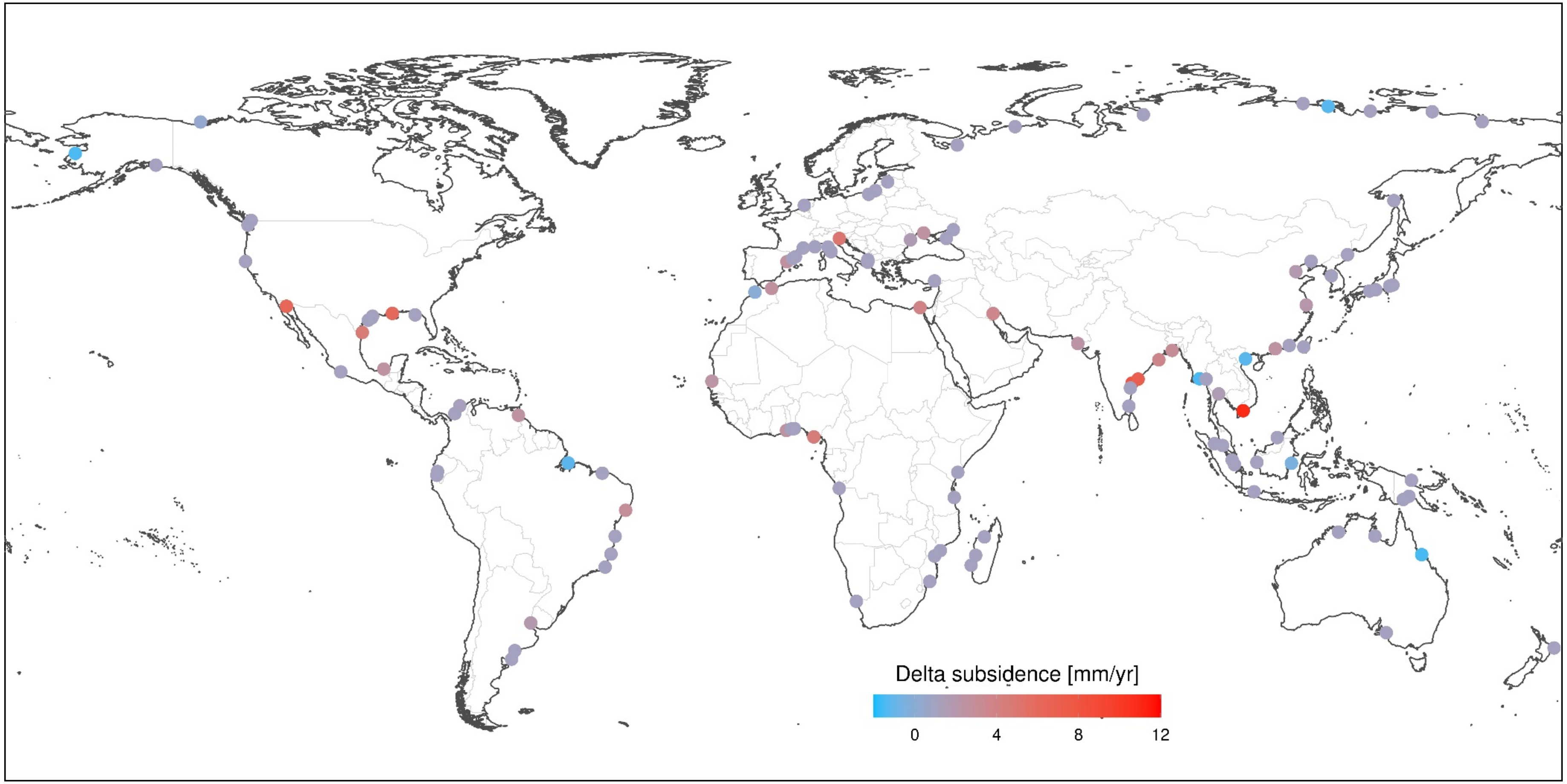
Component 2: Glacial Isostatic Adjustment (GIA)

(after Peltier and others)



Deltas Considered (117 cases)

Component 3



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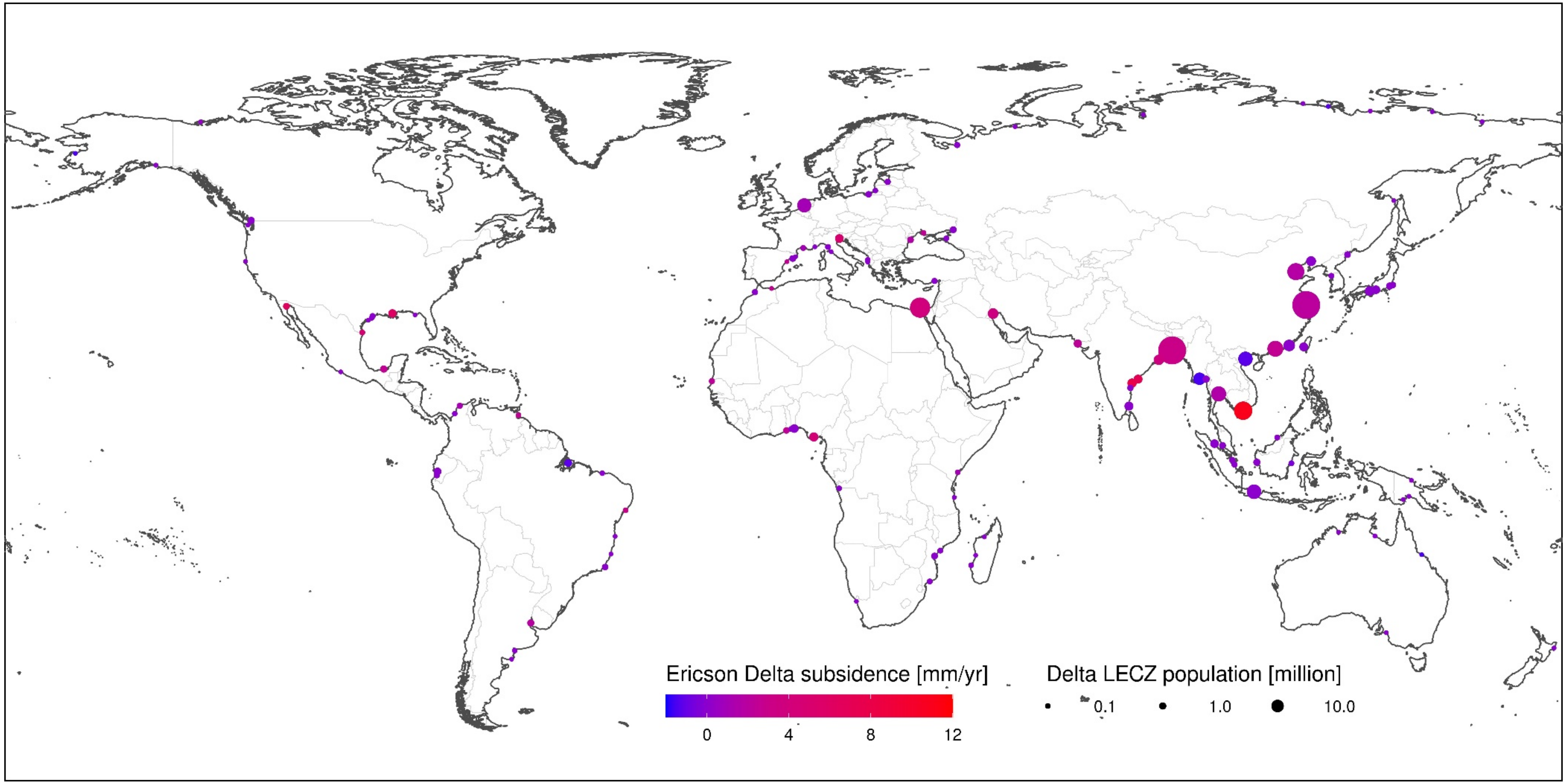
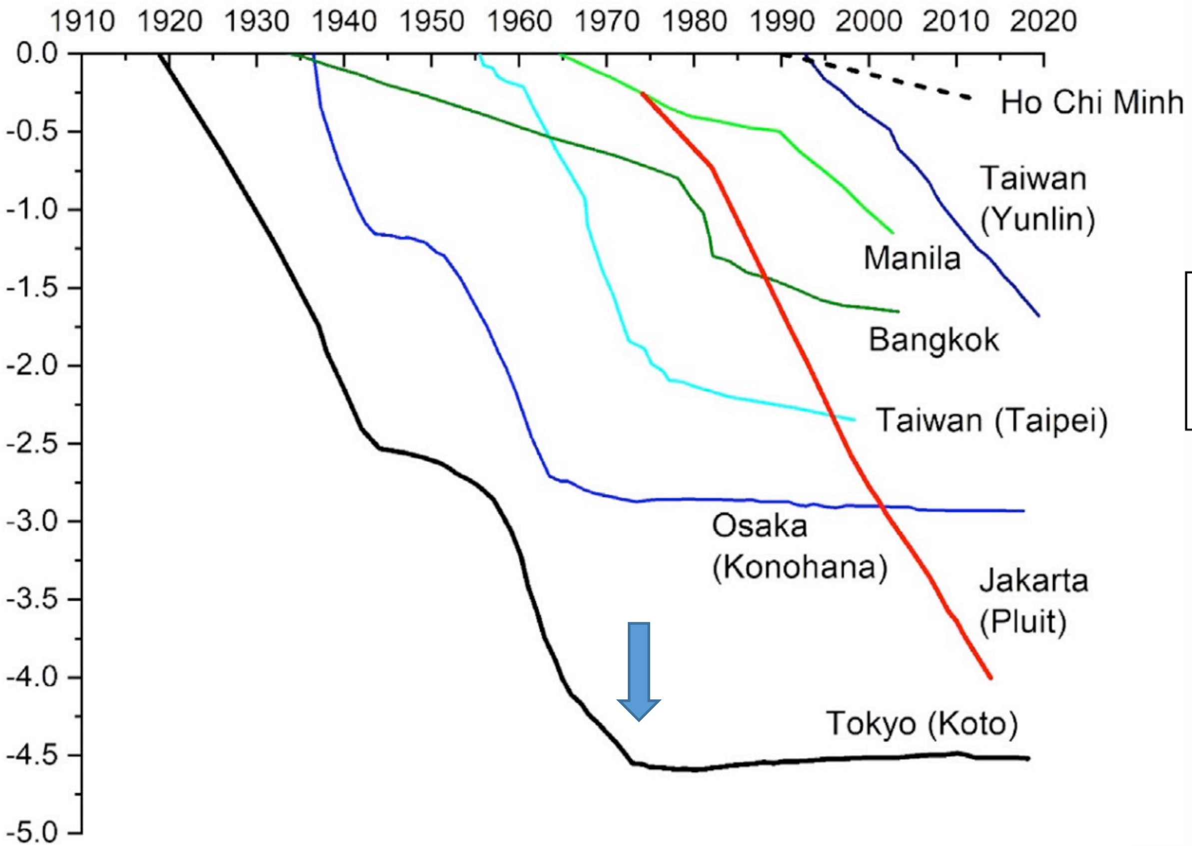
Deltas Considered (117 cases)

Indicating low elevation coastal zone population (LECZ) i.e. below 10-m elevation

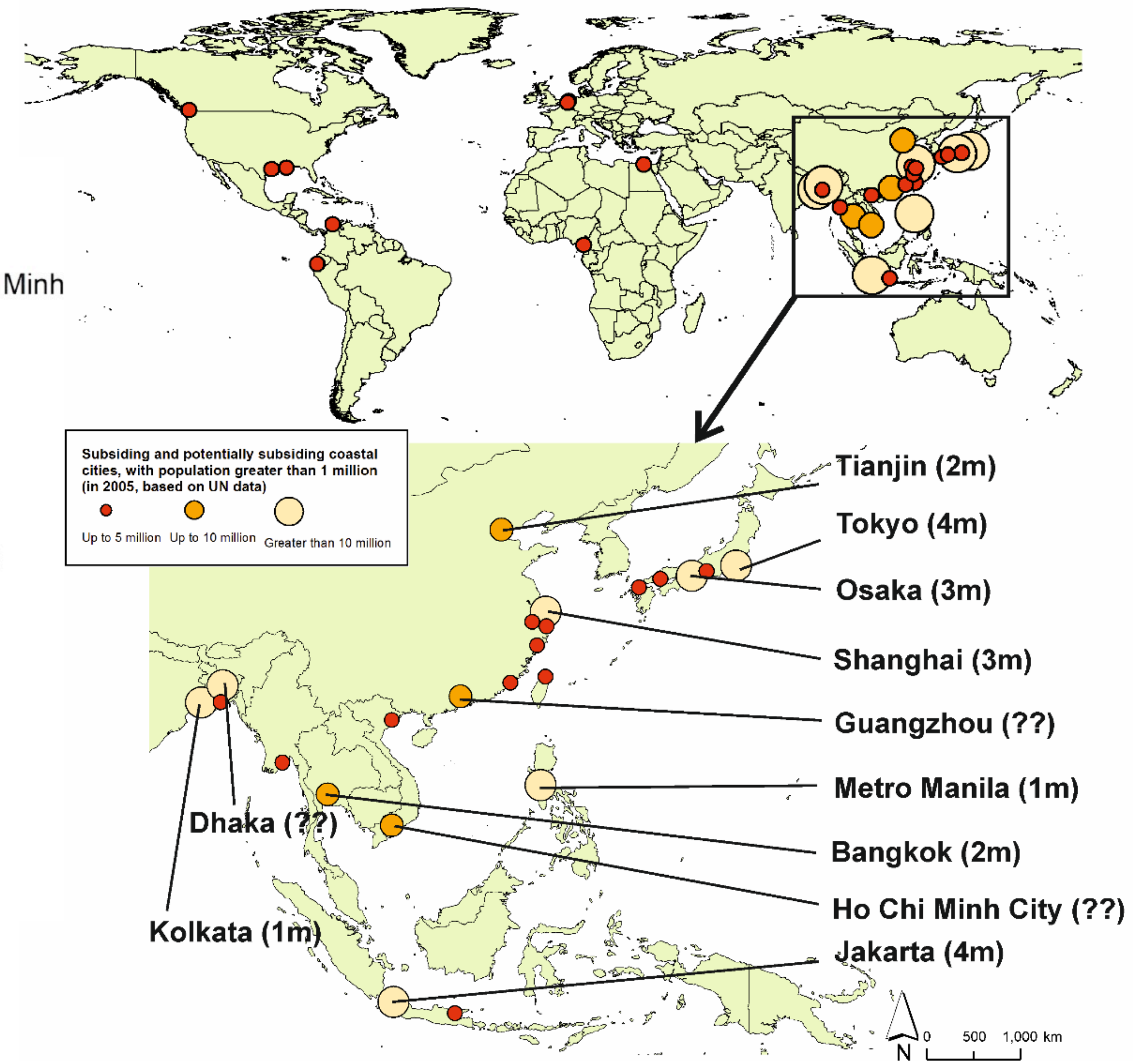


Subsiding Coastal Cities

population > 1 million in 2005,
including maximum observed subsidence during the 20th Century



Subsidence control
(reduced groundwater extraction)



Source: Cao et al, 2021 (left); Nicholls, 2014 (above)

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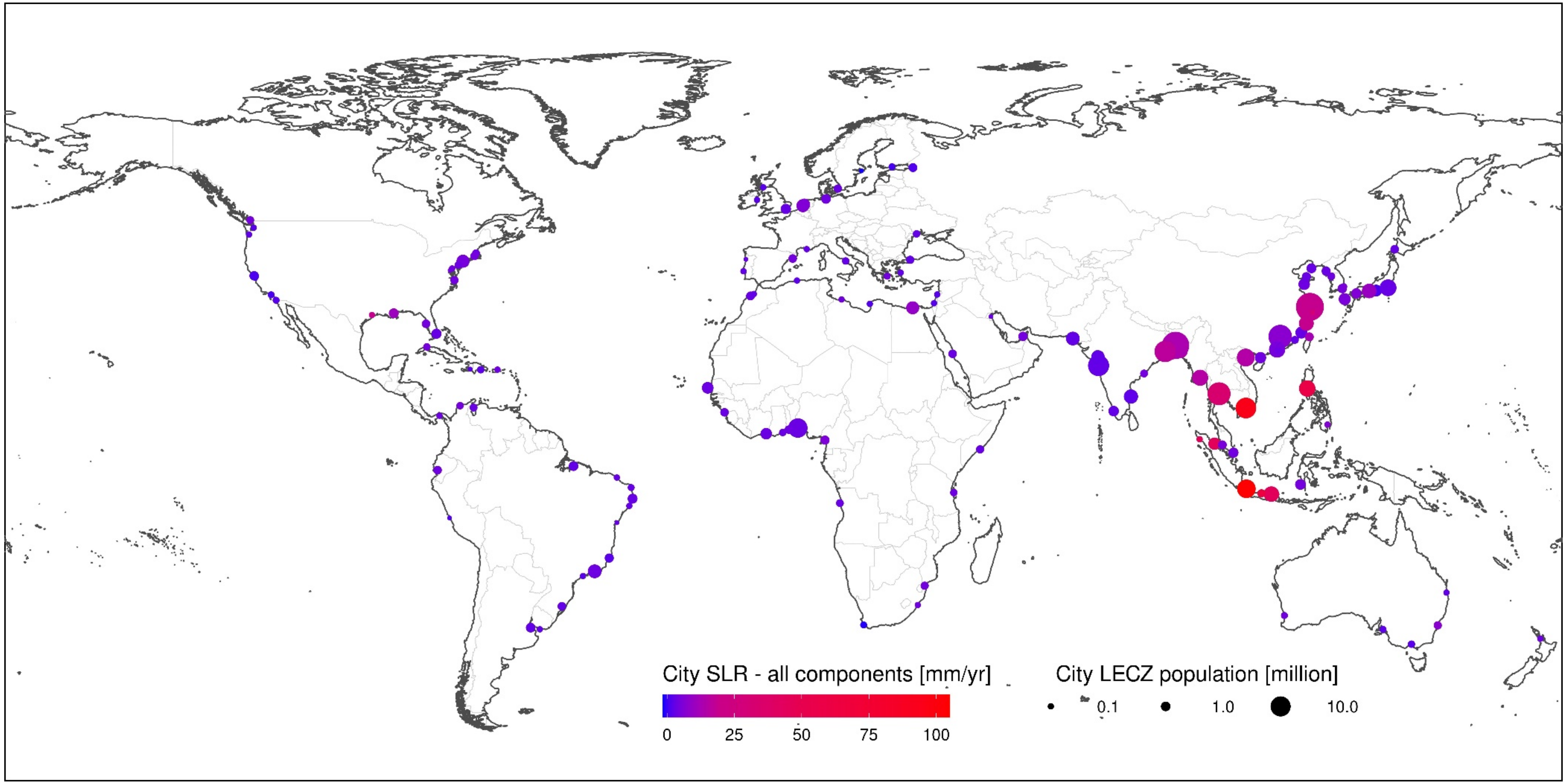
Subsiding Coastal Cities

Jakarta

(Photograph by Dr. Miguel Esteban, Waseda University, Tokyo, Japan, taken 28th March 2018)

Coastal Cities: Additional Subsidence

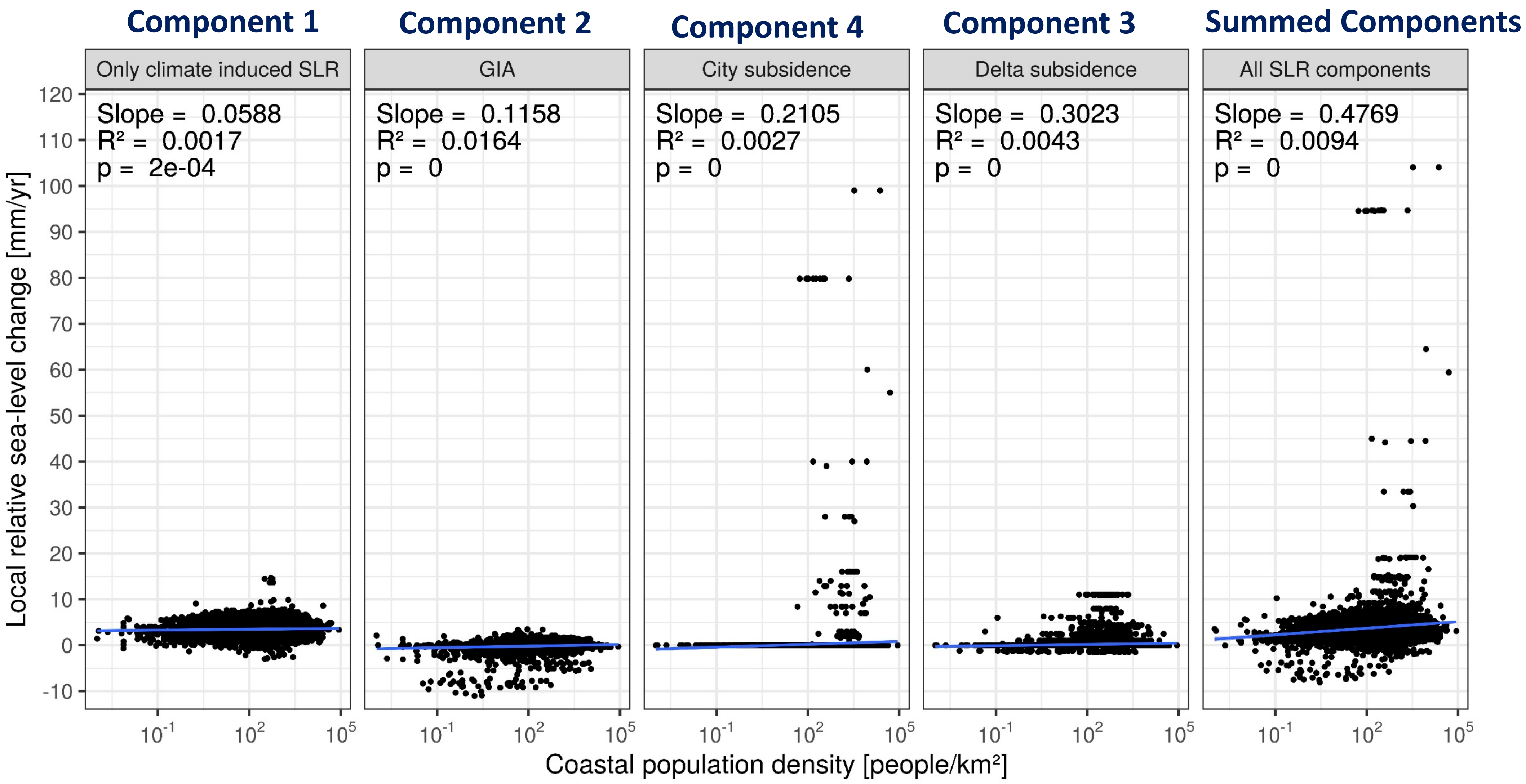
Indicating low elevation coastal zone population (LECZ) i.e. below 10-m elevation and the High Estimate of subsidence



Method

- Literature review drawing on best available data, including low and high estimates of mean additional subsidence in coastal cities
- The components are combined with the global DIVA model – the world's coast comprises ~12,000 linear segments: the total coastal length totals 691,017 km
- 6.5 percent and 0.8 percent of the world's coast comprises subsiding deltas, and subsiding cities, respectively
- Global low elevation coastal population (<10-m elevation) is 768 million (2015))
- South, South-east and East Asia collectively contain 71% of this coastal population (about 545 million people in 2015)
- Three quarters of the global coastal population are living in deltas and/or subsiding cities
- Relative sea-level rise is estimated by
  - coastal length (a typical geophysical measure – what does the average coast "see")
  - coastal population (a more novel exposure measure – what does the average coastal resident experience)

Sea-level components vs. population density



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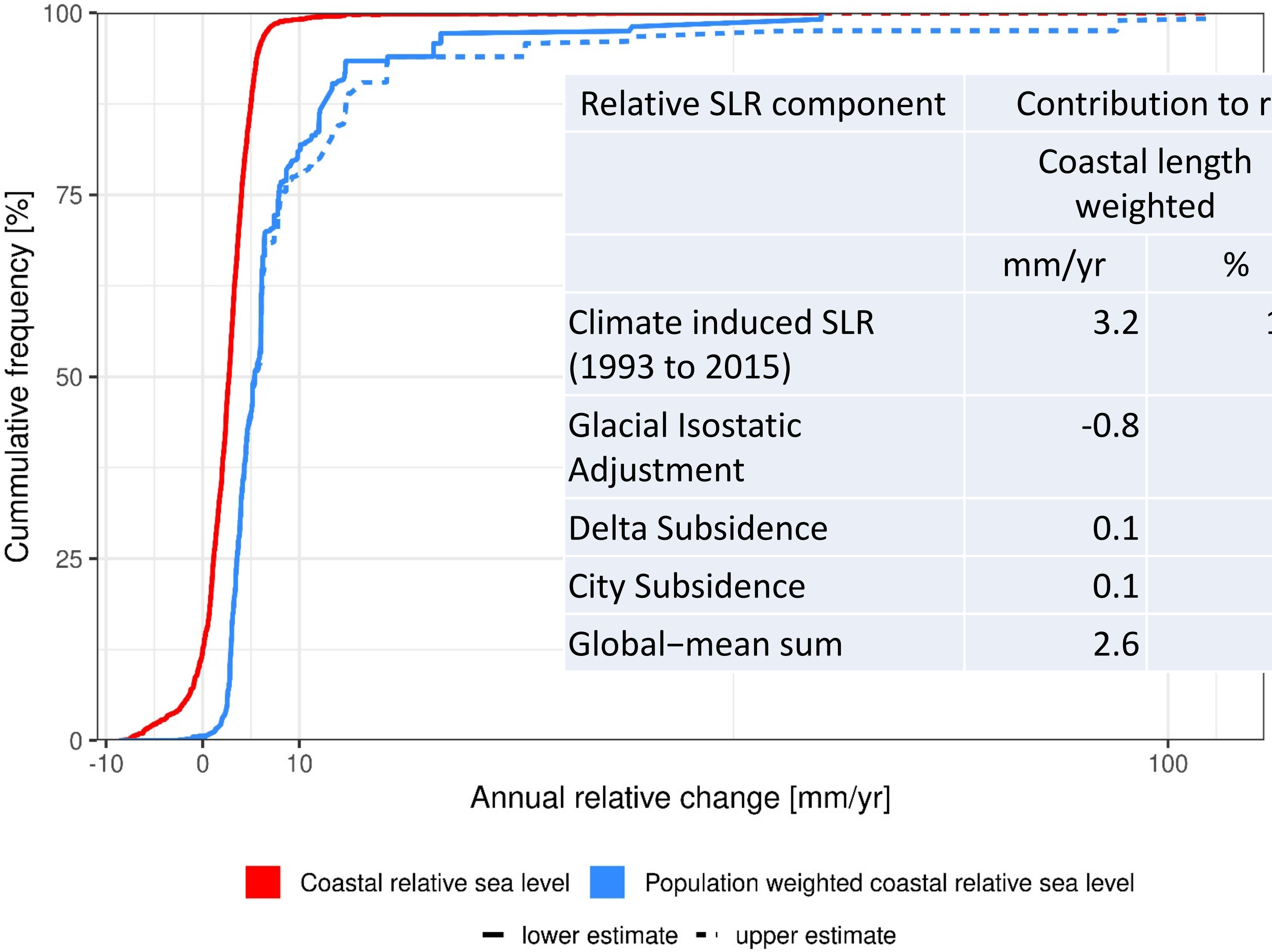
Cumulative distribution of contemporary global coastal length-weighted and population-weighted coastal relative sea-level rise



Relative SLR component	Contribution to relative sea−level change			
	Coastal length weighted		Coastal population weighted	
	mm/yr	%	mm/yr	%
Climate induced SLR (1993 to 2015)	3.2	122	3.8	39 to 49
Glacial Isostatic Adjustment	-0.8	-32	-0.3	-3
Delta Subsidence	0.1	4	1.6	16 to 21
City Subsidence	0.1	3	2.7 to 4.8	35 to 49
Global−mean sum	2.6		7.8 to 9.9	

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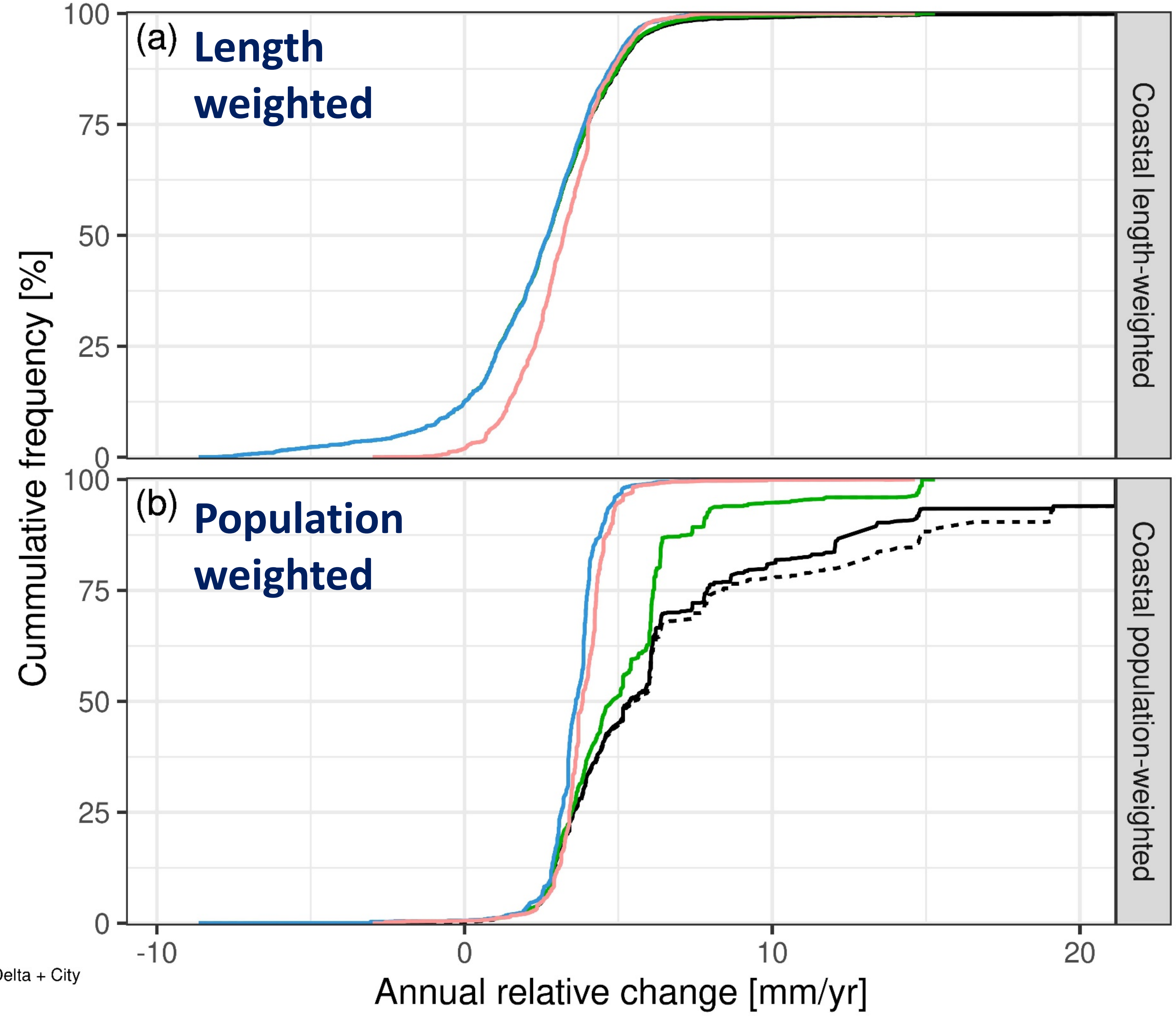


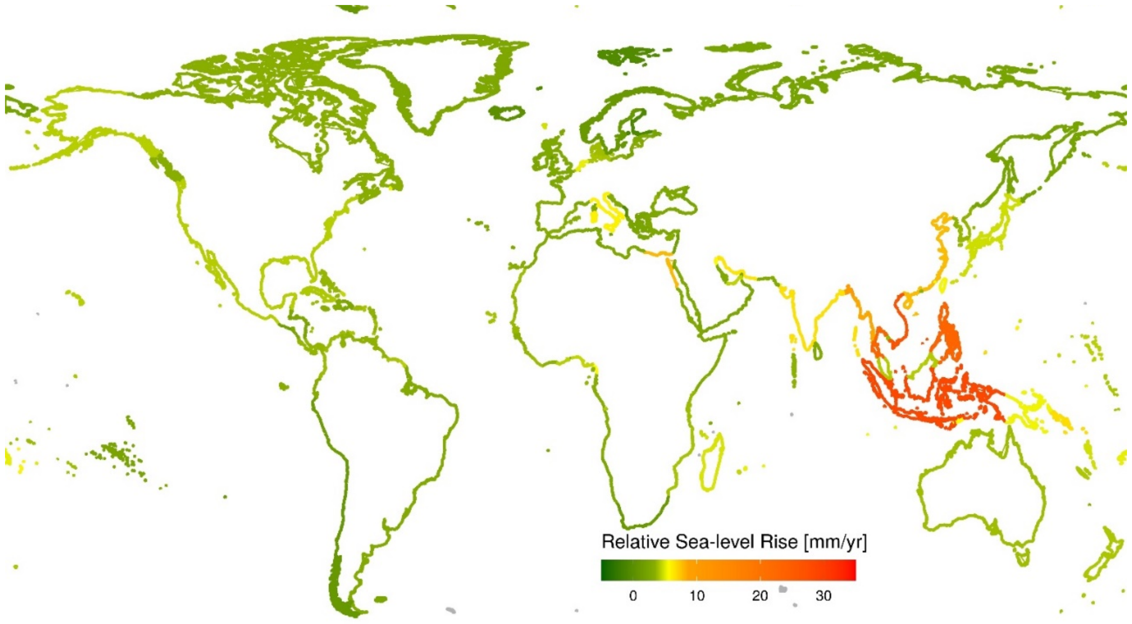
— lower estimate -- upper estimate

Climate Induced SLR
Climate Induced SLR + GIA
Climate Induced SLR + GIA + Delta
Climate Induced SLR + GIA + Delta + City

National Results for Relative Sea-Level Rise

Length Weighted

Population Weighted



Regional relative sea-level rise comparing length and population weightings – European Examples (see Table S4)

Region	Coastal Population (living in the Low Elevation Coastal Zone)		Relative Sea-Level Rise (mm/yr)	
	Count (millions)	Density (people/km^2)	Length-weighted	Population-weighted
Baltic Sea coast	4.6	136.0	0.3	2.5
North and West Europe	30.3	185.3	1.2	3.8-4.0
Northern Mediterranean	13.1	218.1	2.7	4.1

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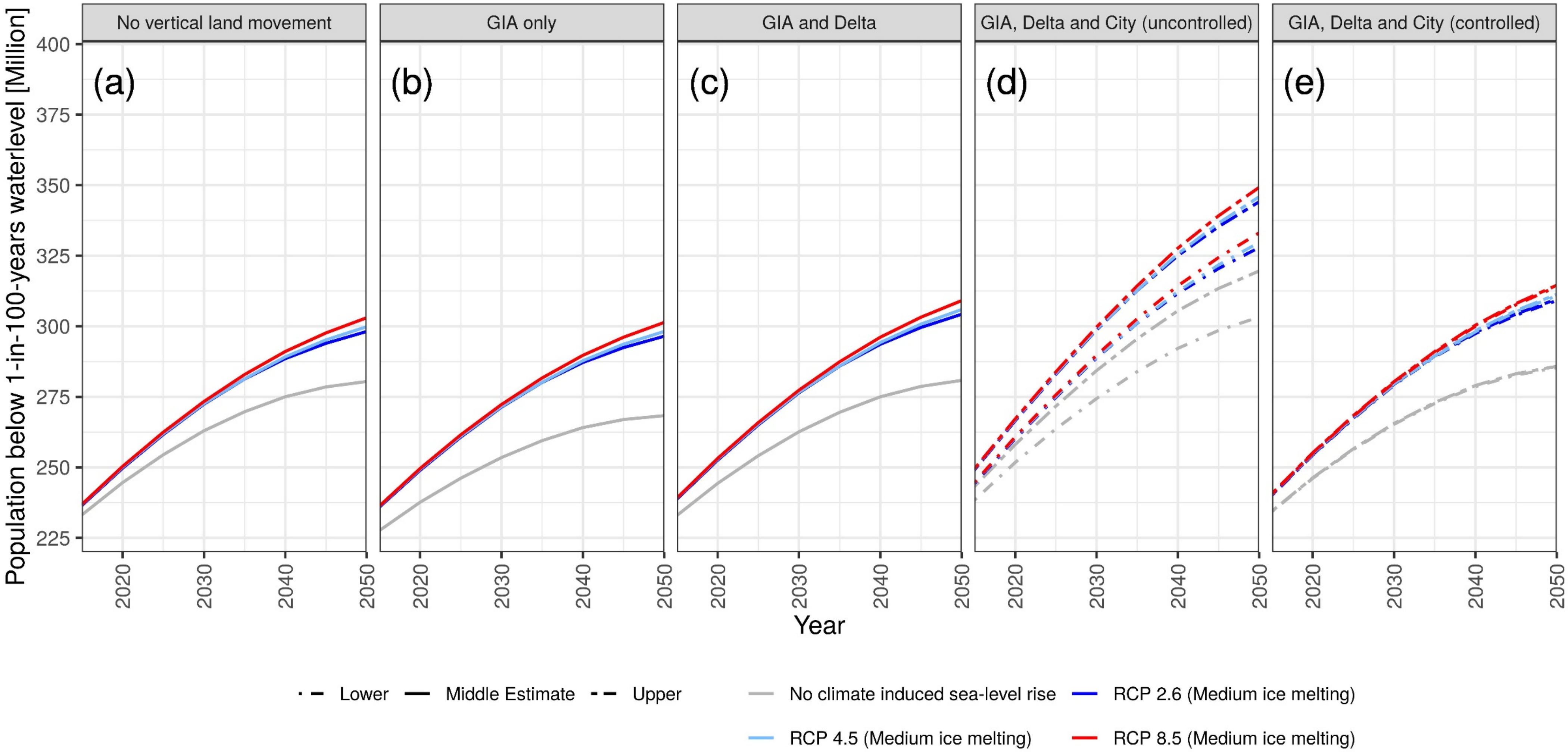
Population Exposure to 2050

assumes RCP scenarios and other components continue to 2050 with SSP2 population – in (e) controlled subsidence scenario for cities of 5 mm/yr

Comp. 1 | **Comp. 1 & 2** | **Comp. 1, 2 & 3** | **All Components** | **Subsidence control (in cities)**



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Concluding Remarks

- Global-average coastal relative sea-level rise (SLR) was 2.5 mm/yr over the last two decades.
- However, coastal inhabitants experienced a much larger average relative SLR (estimated at 7.8 to 9.9 mm/yr) as they are concentrated in areas that sink, experiencing much higher risks and response needs.
- Human-induced subsidence needs more regional/global consideration – there is an intersection of climate and Sendai agendas – responding to human-induced subsidence and climate change are complementary.
- A prerequisite of this is a better understanding of relative SLR
  - What is relative sea-level rise today? (observations)
  - What might relative sea-level rise be in the future? (a modelling framework)
  - What can we do about it? – mitigation (subsidence control) and adaptation

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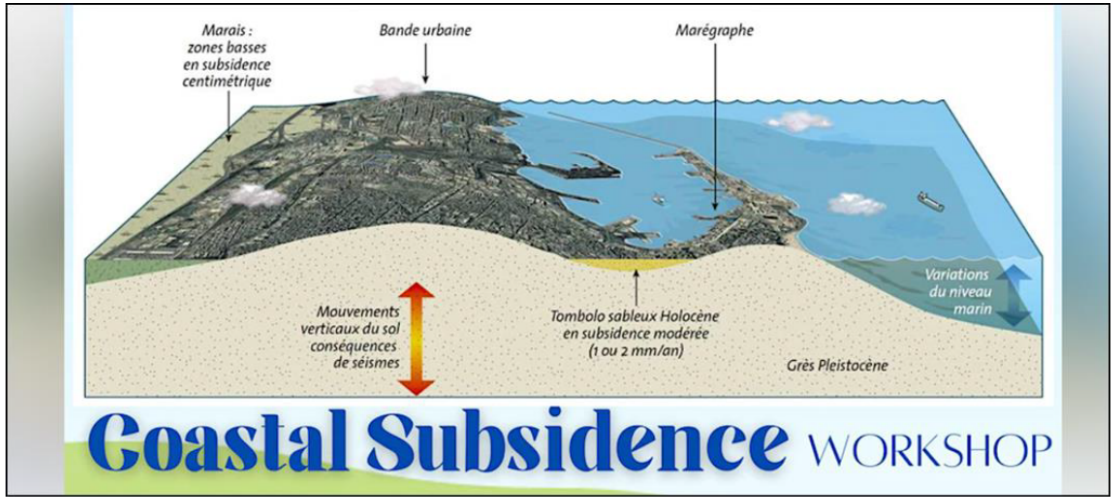

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