Global sea level rise and its local effects on the coastal environment

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Miami Beach in 2050 HTTP://SEALEVEL.CLIMATECENTRAL.ORG

[https://www.forbes.com/sites/jimdobson/2019/10/30/shocking-new-maps-show-how-sea-level-rise-will-destroy-coastal-cities-by-2050/?sh=4133b379456c]

[https://i.imgur.com/7L4LQ48.jpg]

Outline

Part 1: Sea level rise

- Past reconstructions
- Present observations
- Future projections + uncertainty

Part 2: Implications of sea level rise

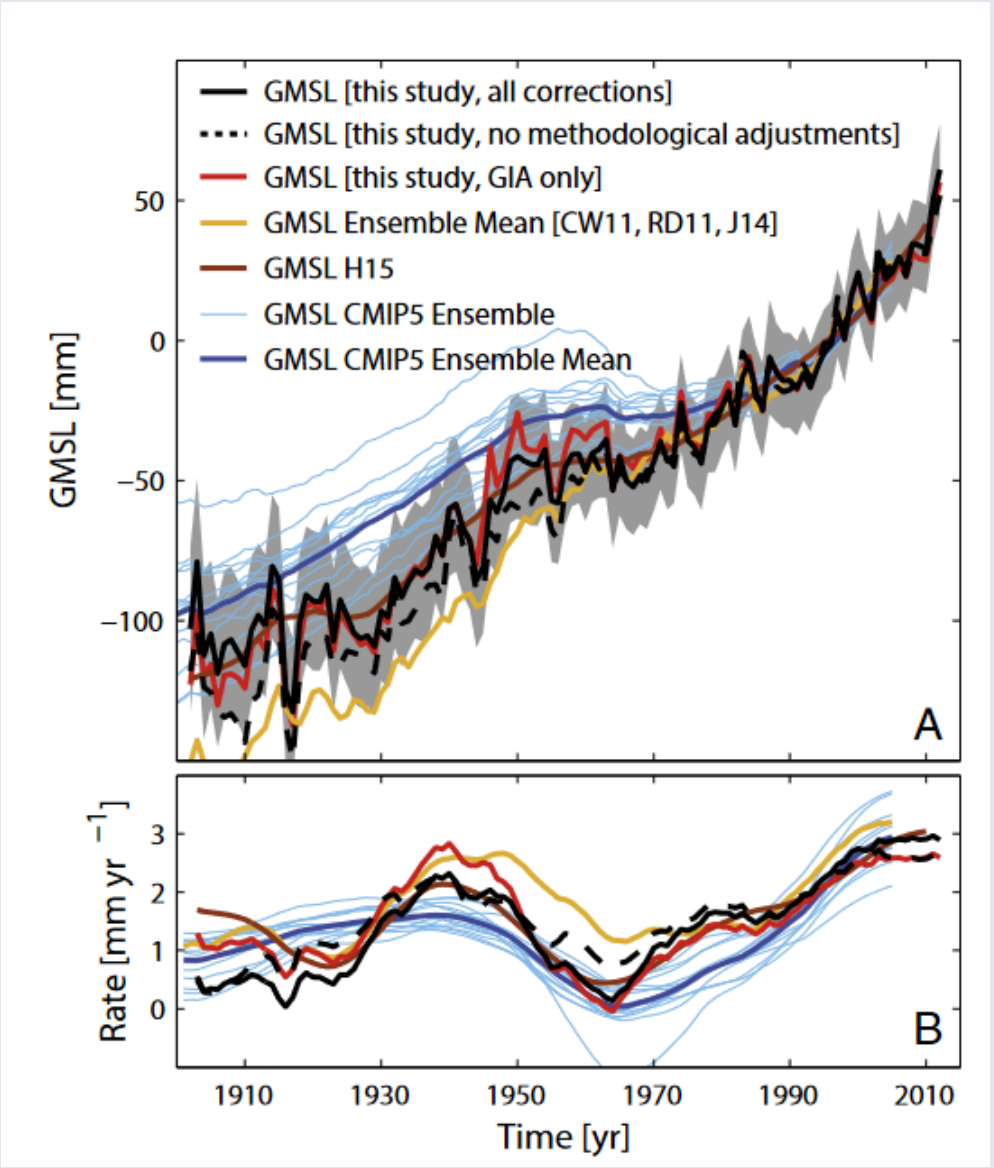
- Land loss + prevention
  - Beaches
  - Salt marshes and mangroves
  - Engineered coasts
- How will humans react?
  - „Sinking cities“ as an outlook into the future

Part 1: Sea level rise

Sea level rise – past reconstructions

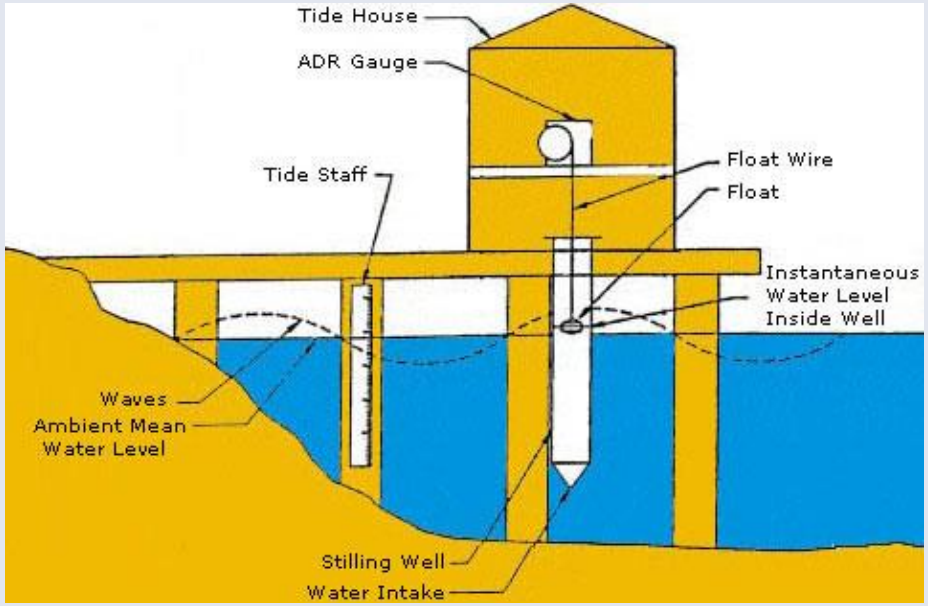
Reconstruction of global mean sea level (GMSL)

[Dangendorf, S., Marcos, M., Wöppelmann, G., Conrad, C.P., Frederikse, T., Riva, R., 2017. Reassessment of 20th century global mean sea level rise. PNAS 114, 5946–5951. https://doi.org/10.1073/pnas.1616007114]



Sea level rise – past reconstructions

Tide gauges – how they work



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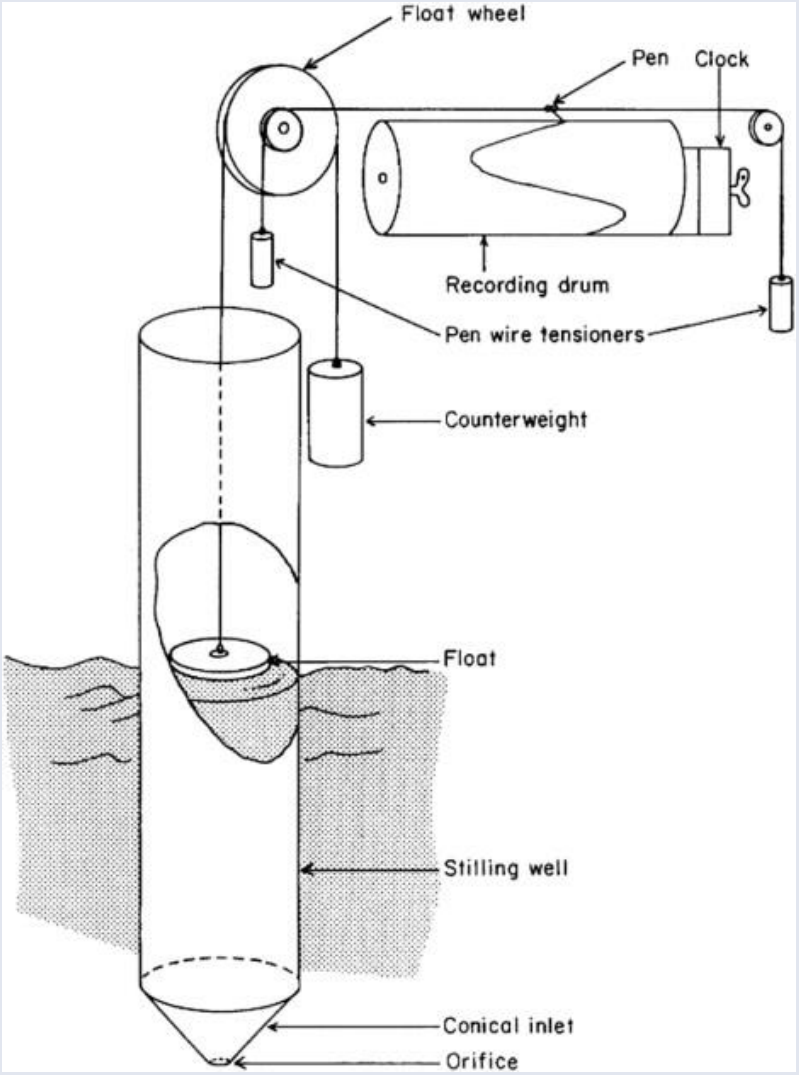

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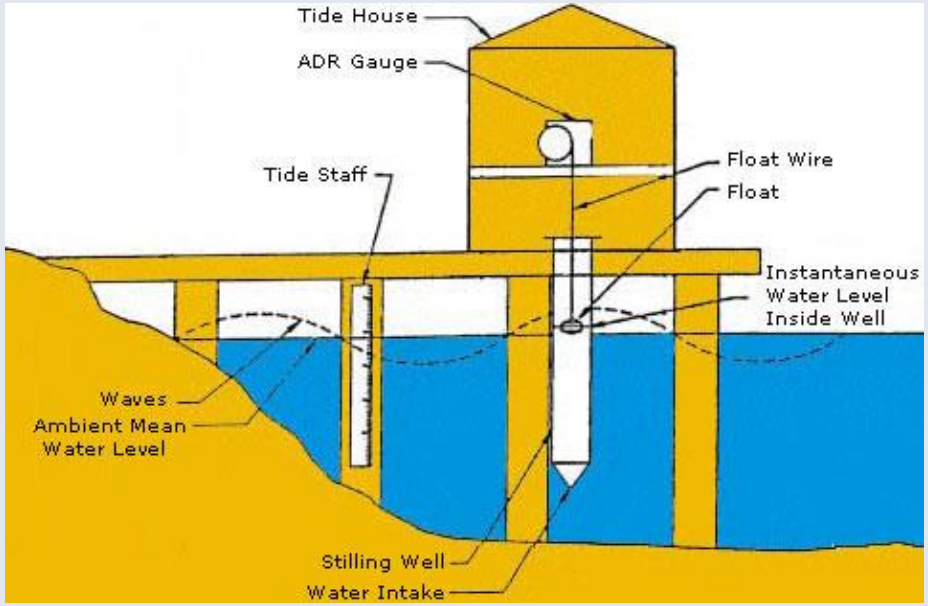

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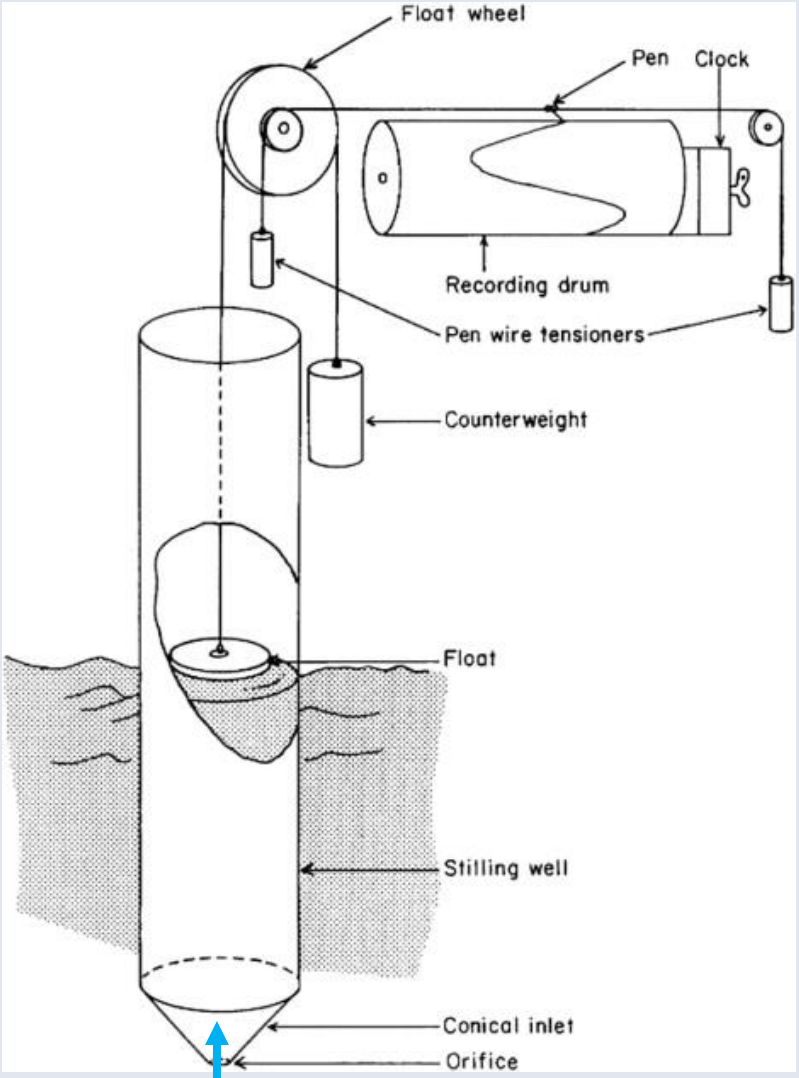

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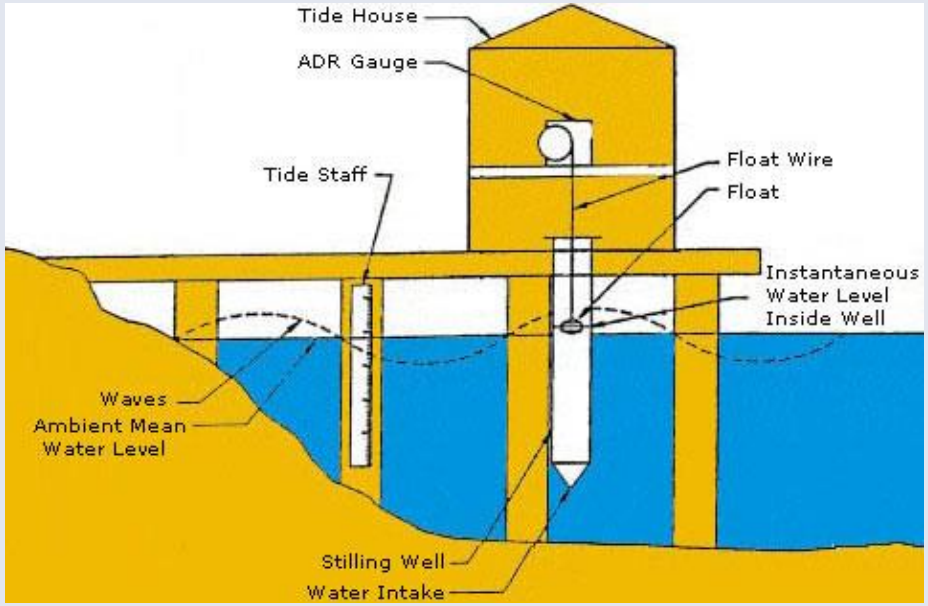

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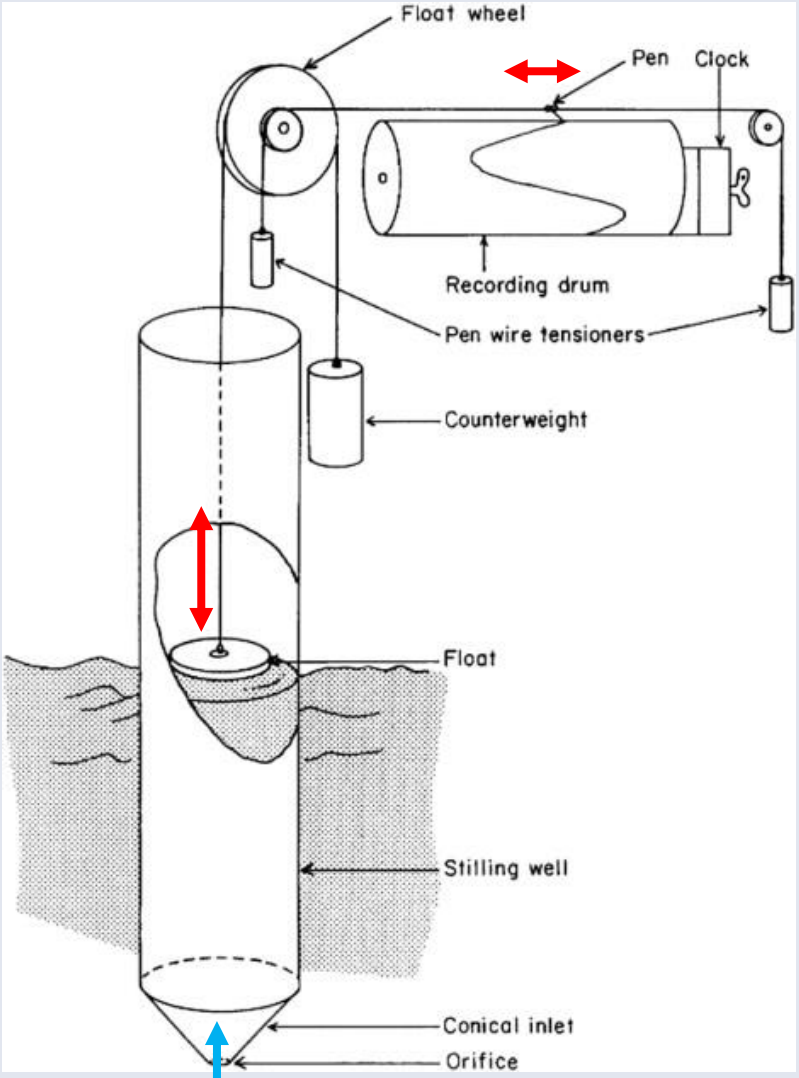

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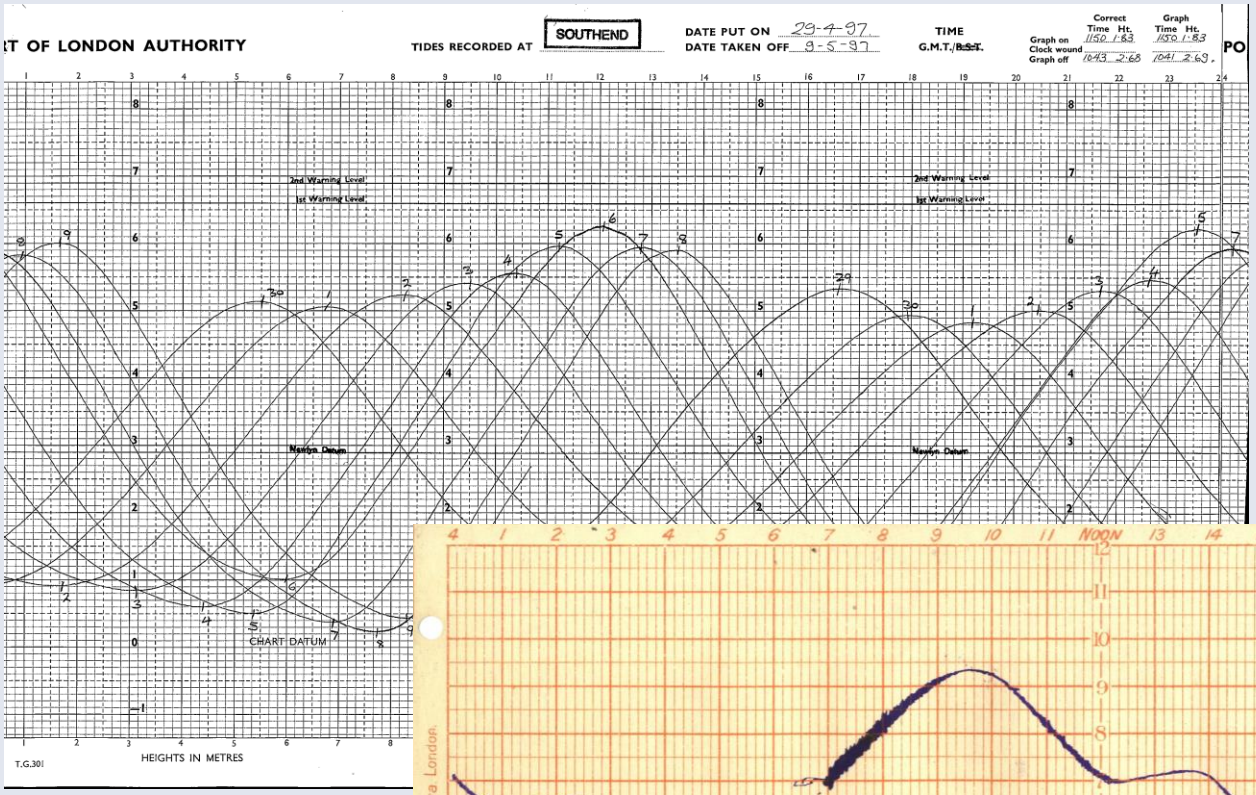
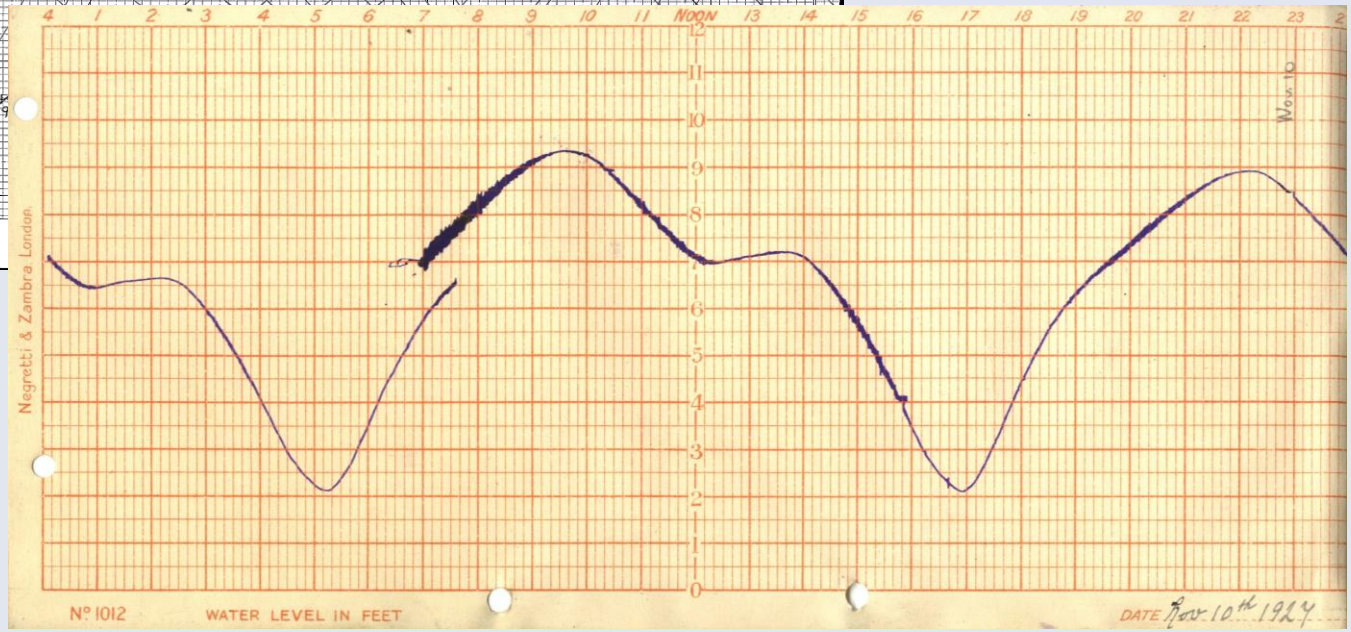


Examples of historic tide charts

Poole Harbour (UK)



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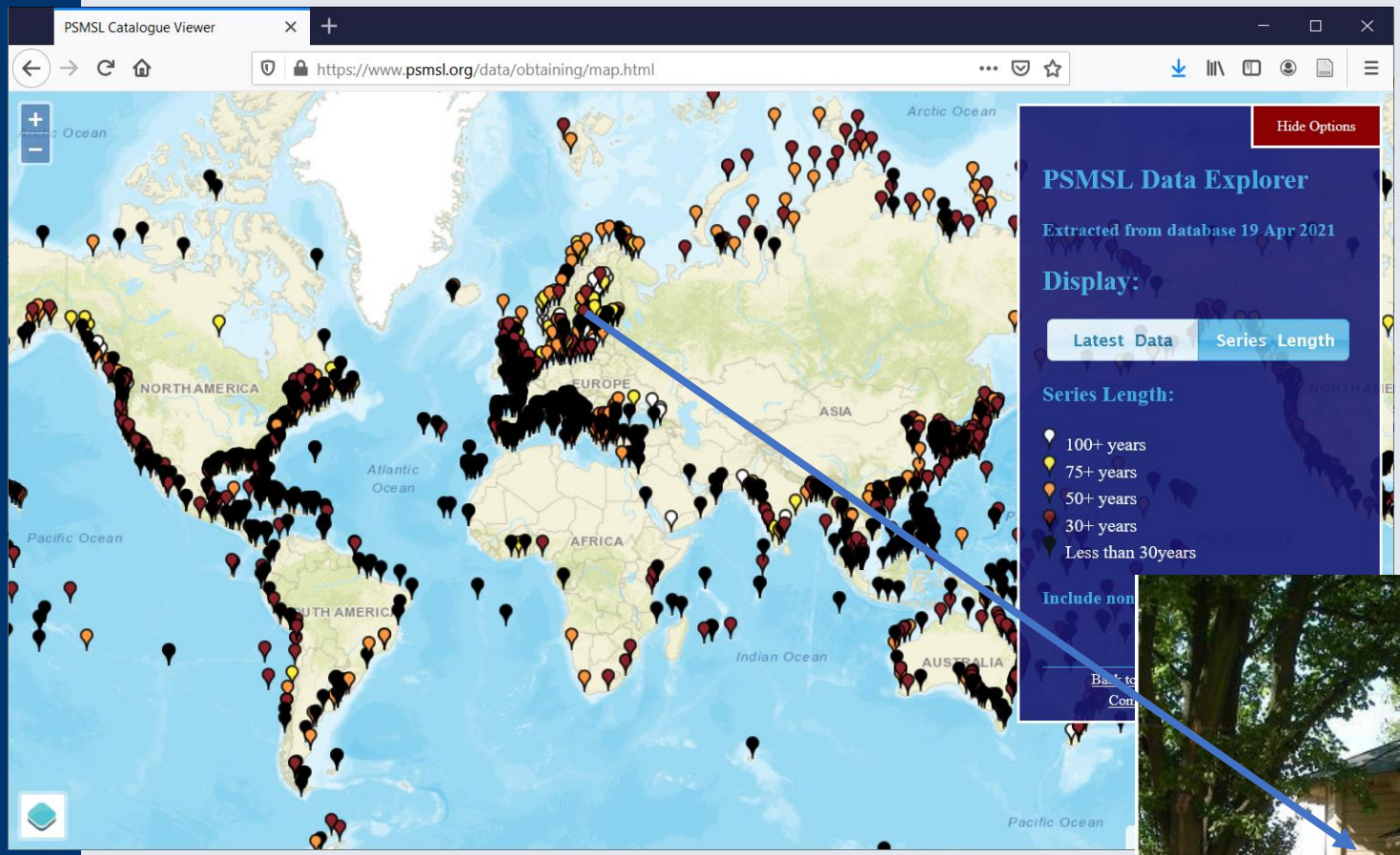

Stockholm tide gauge - data since 1744

[https://www.gloss-sealevel.org/sites/gloss/files/publications/documents/national-report-sweden-2017.pdf]

Sea level rise – past reconstructions

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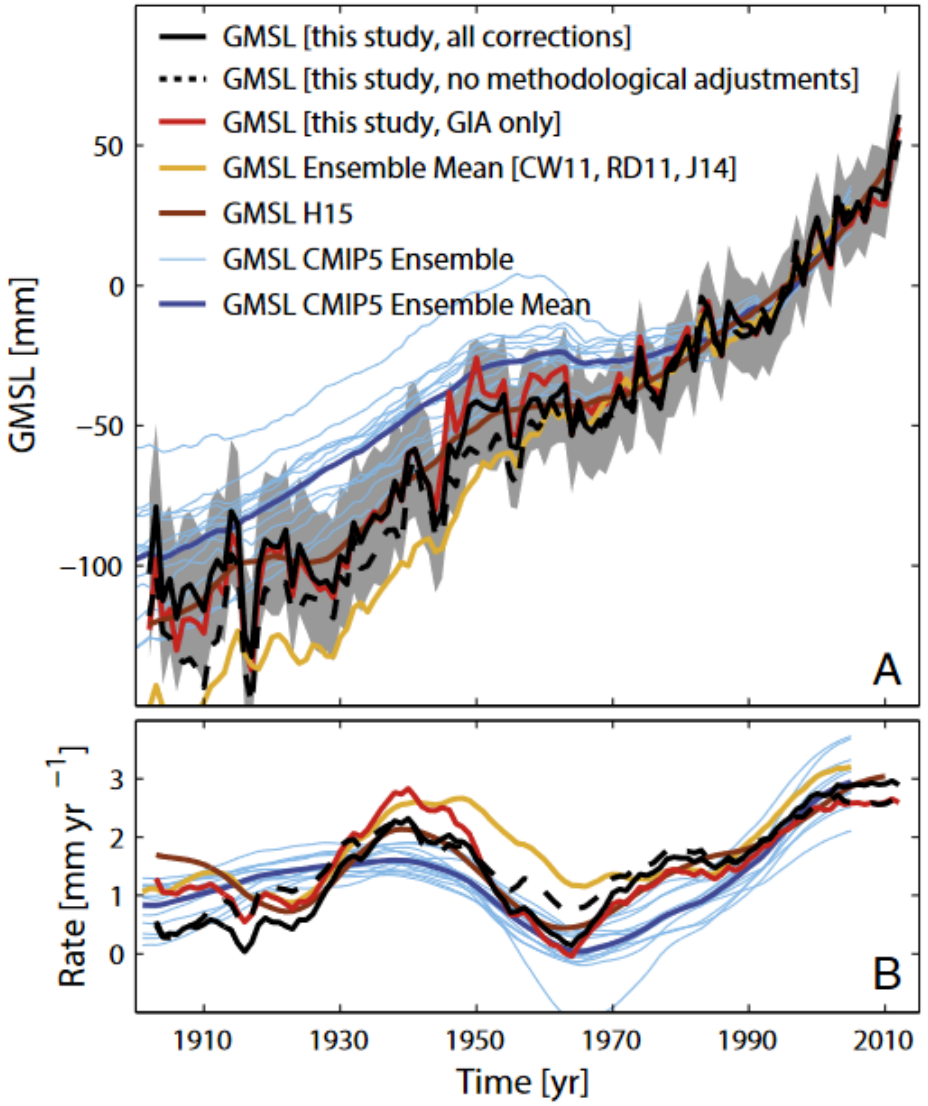
full reconstruction

without regional weighting



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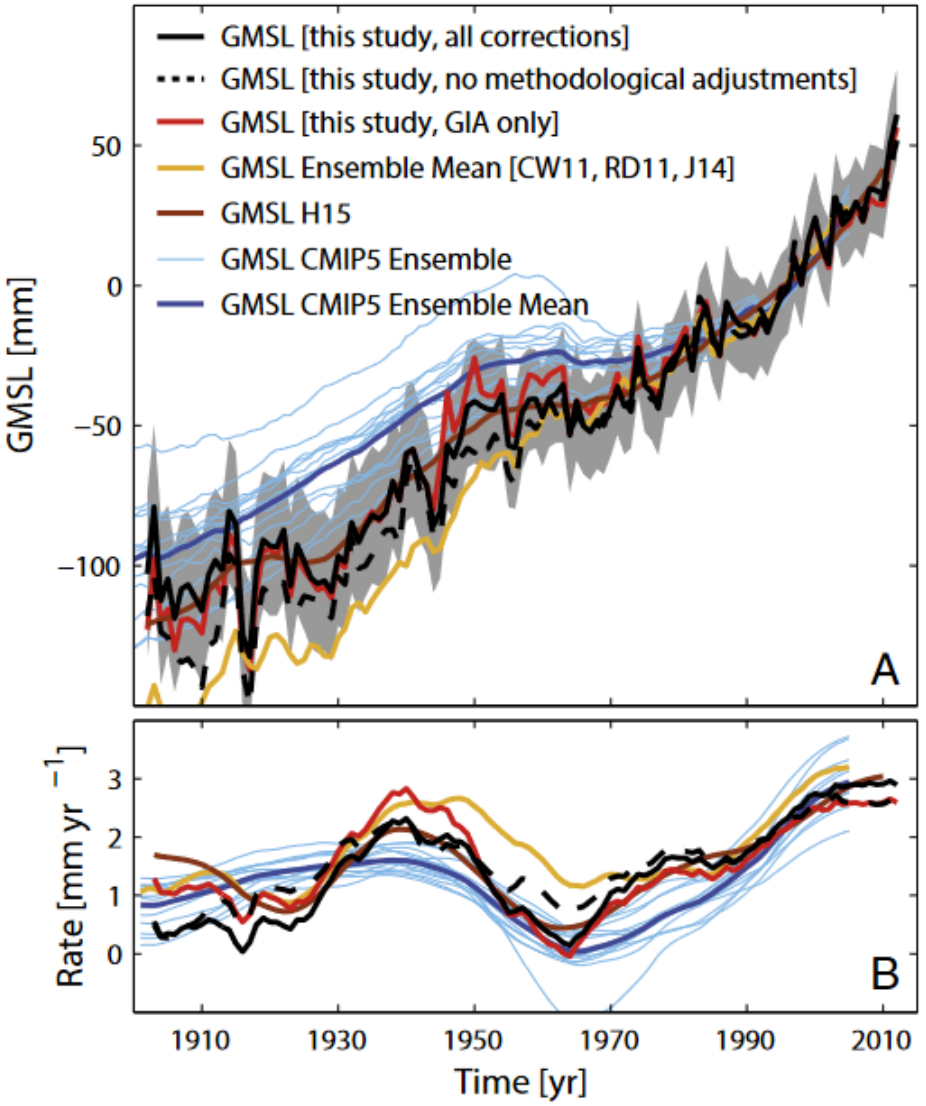
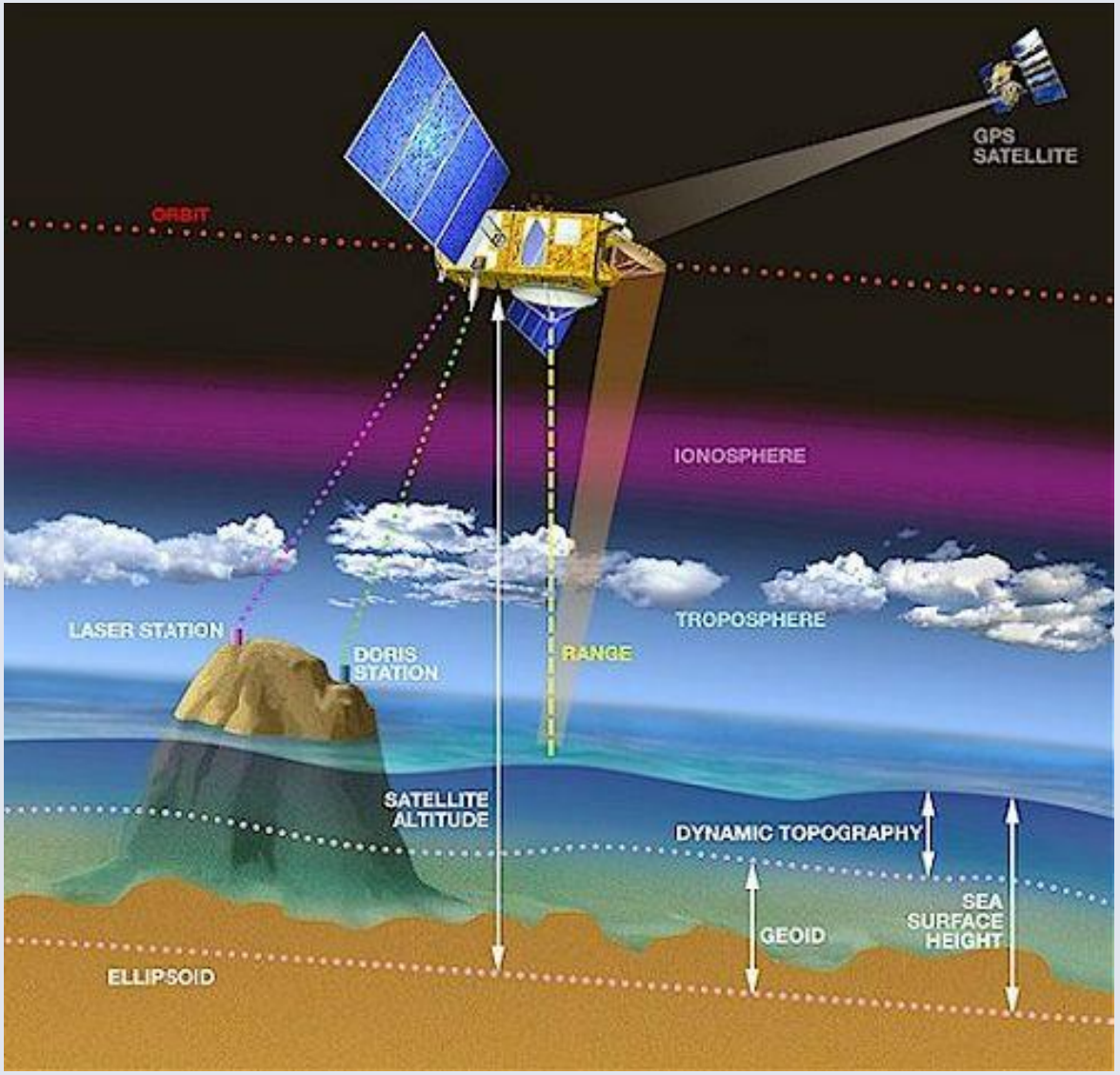
New York: Tidal range ~ 2.5 m
=› much larger than
past sea level rise!



Sea level rise – present observations

Satellite altimetry – working principle

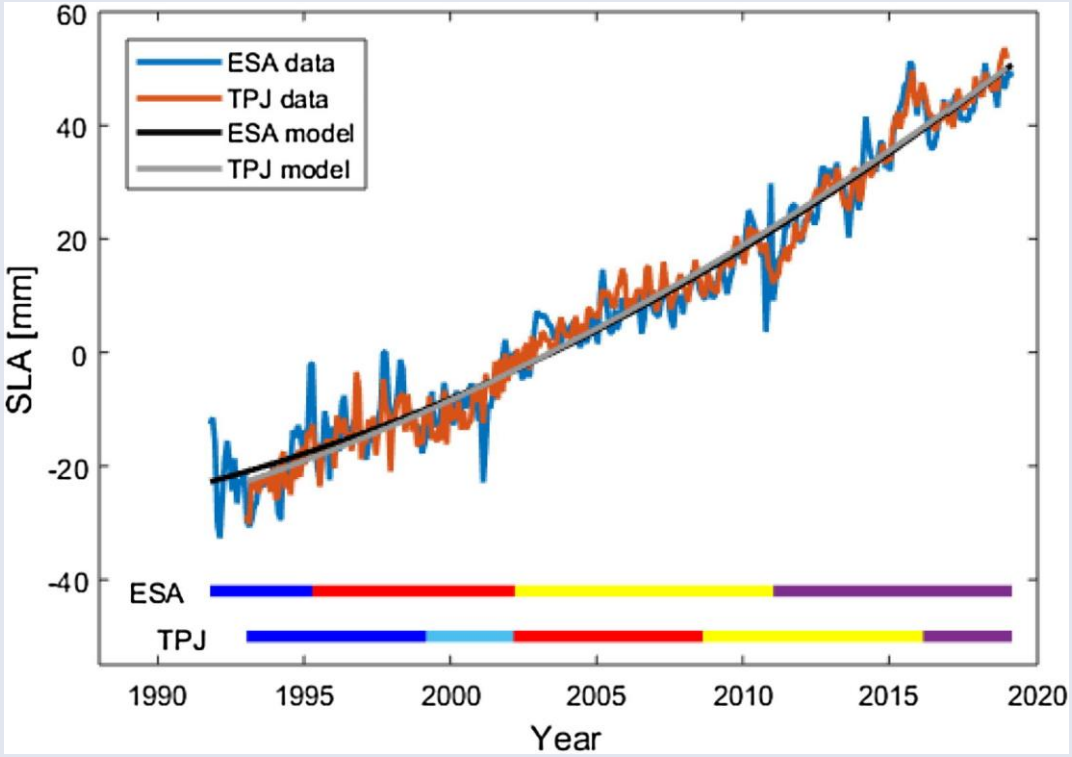
[http://www.altimetry.info/radar-altimetry-tutorial/how-altimetry-works/basic-principle/]



Sea level rise – present observations

Satellite altimetry – accelerated rise

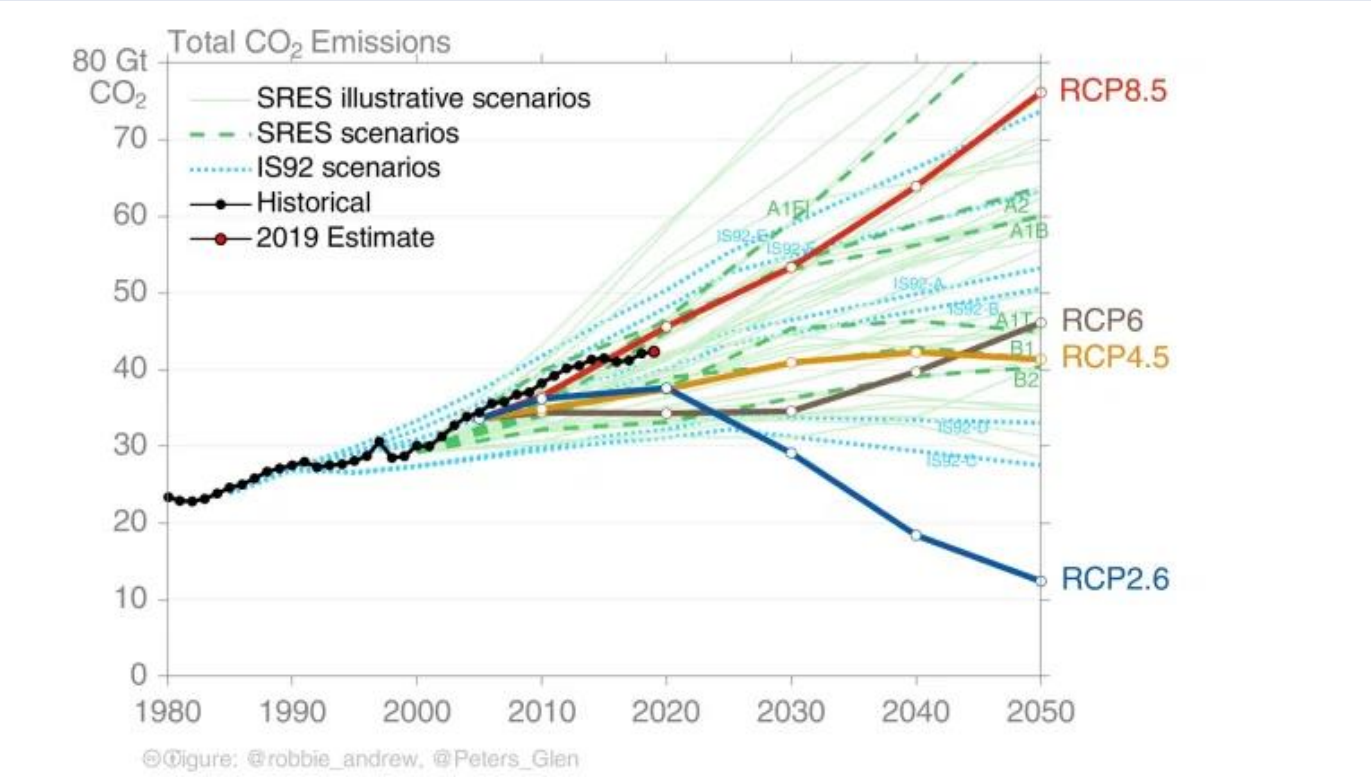
[Veng, T., Andersen, O.B., 2020. Consolidating sea level acceleration estimates from satellite altimetry. Advances in Space Research. https://doi.org/10.1016/j.asr.2020.01.016]



acceleration: ~0.08 mm/year²

=› ~70cm rise until 2100 if it continues

Sea level rise – future projections + uncertainty



[https://rogerpielkejr.files.wordpress.com/2020/02/petersco2-1.jpg?w=768&h=432]

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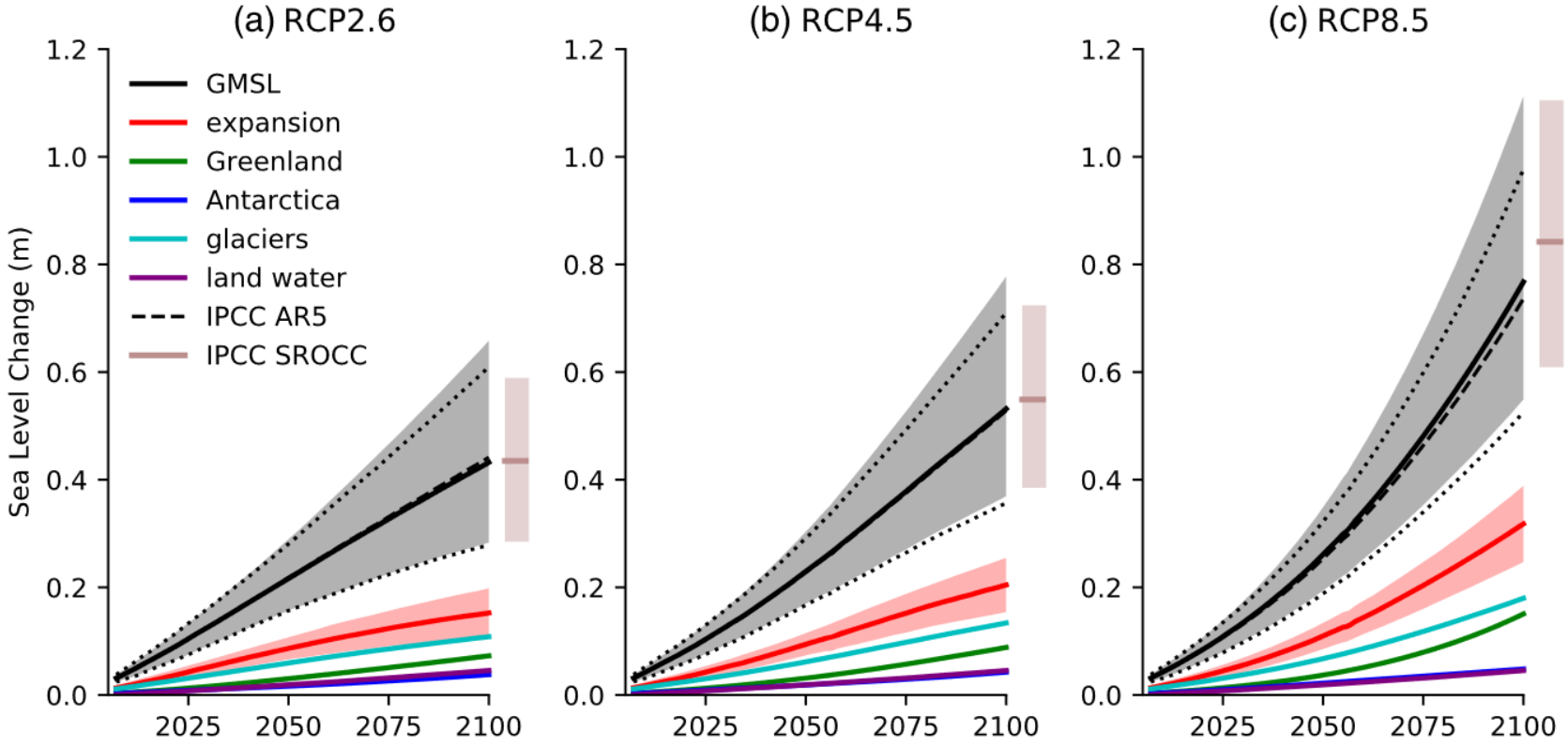
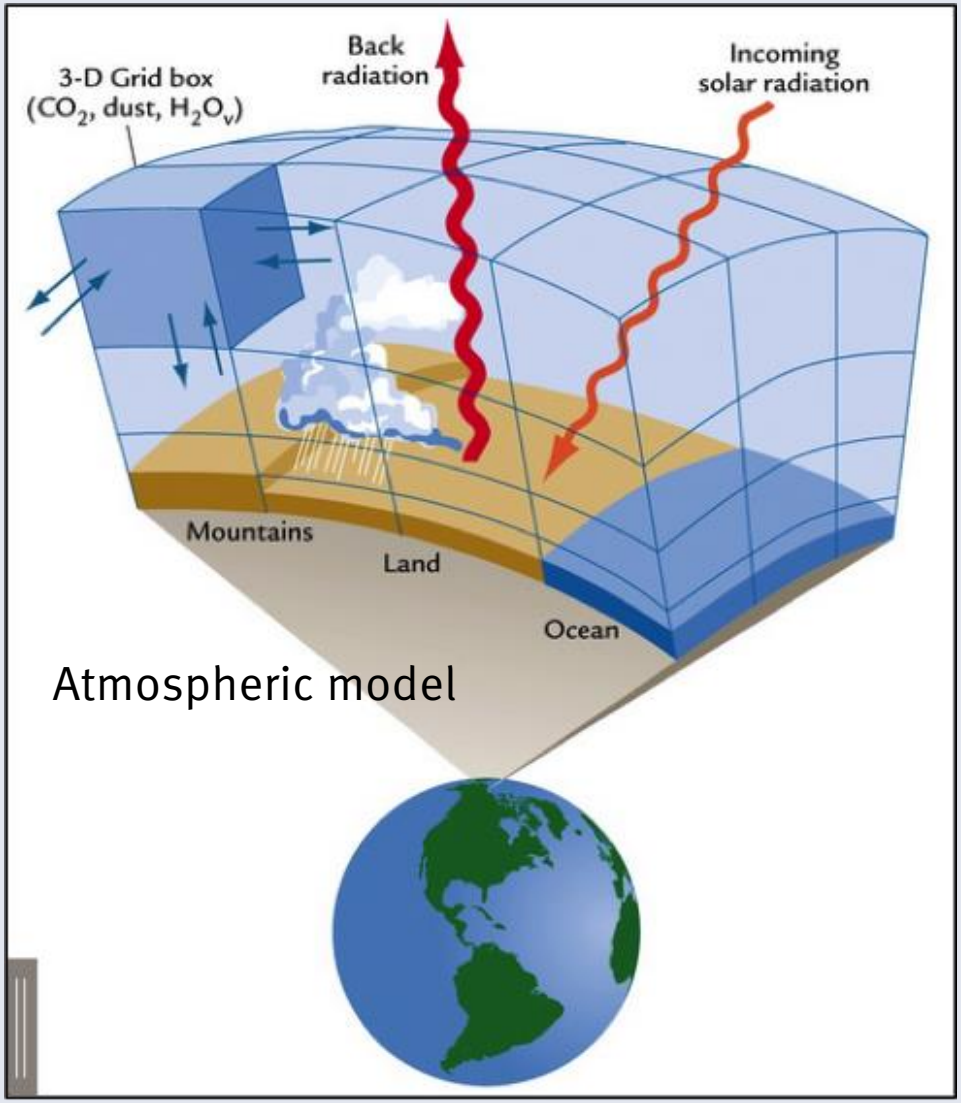


[Palmer, M.D., et al., 2020. Exploring the Drivers of Global and Local Sea-Level Change Over the 21st Century and Beyond. Earth's Future 8. https://doi.org/10.1029/2019EF001413]

Sea level rise – future projections + uncertainty

[https://patricktbrown.files.wordpress.com/2015/05/11.png]



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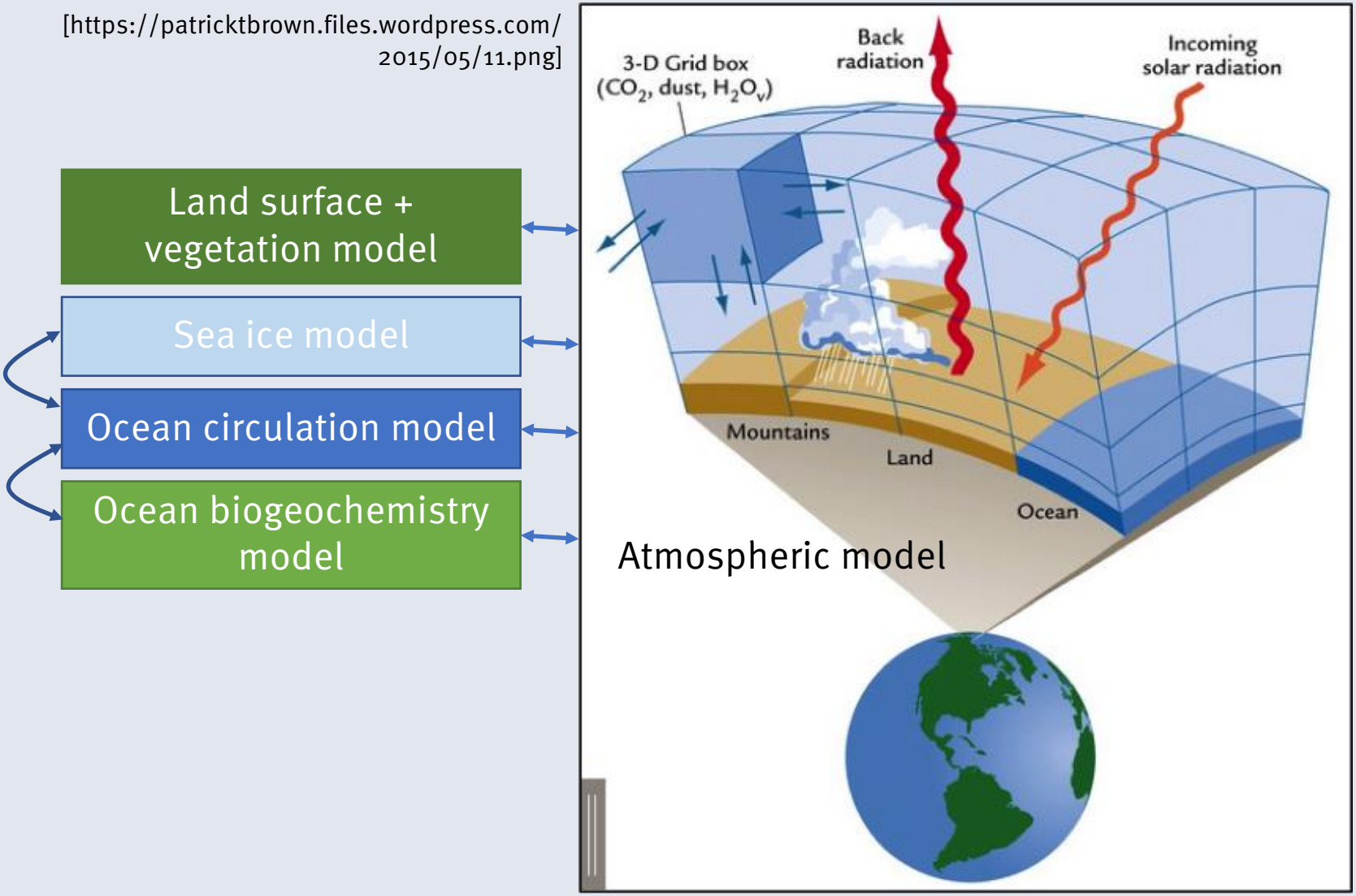

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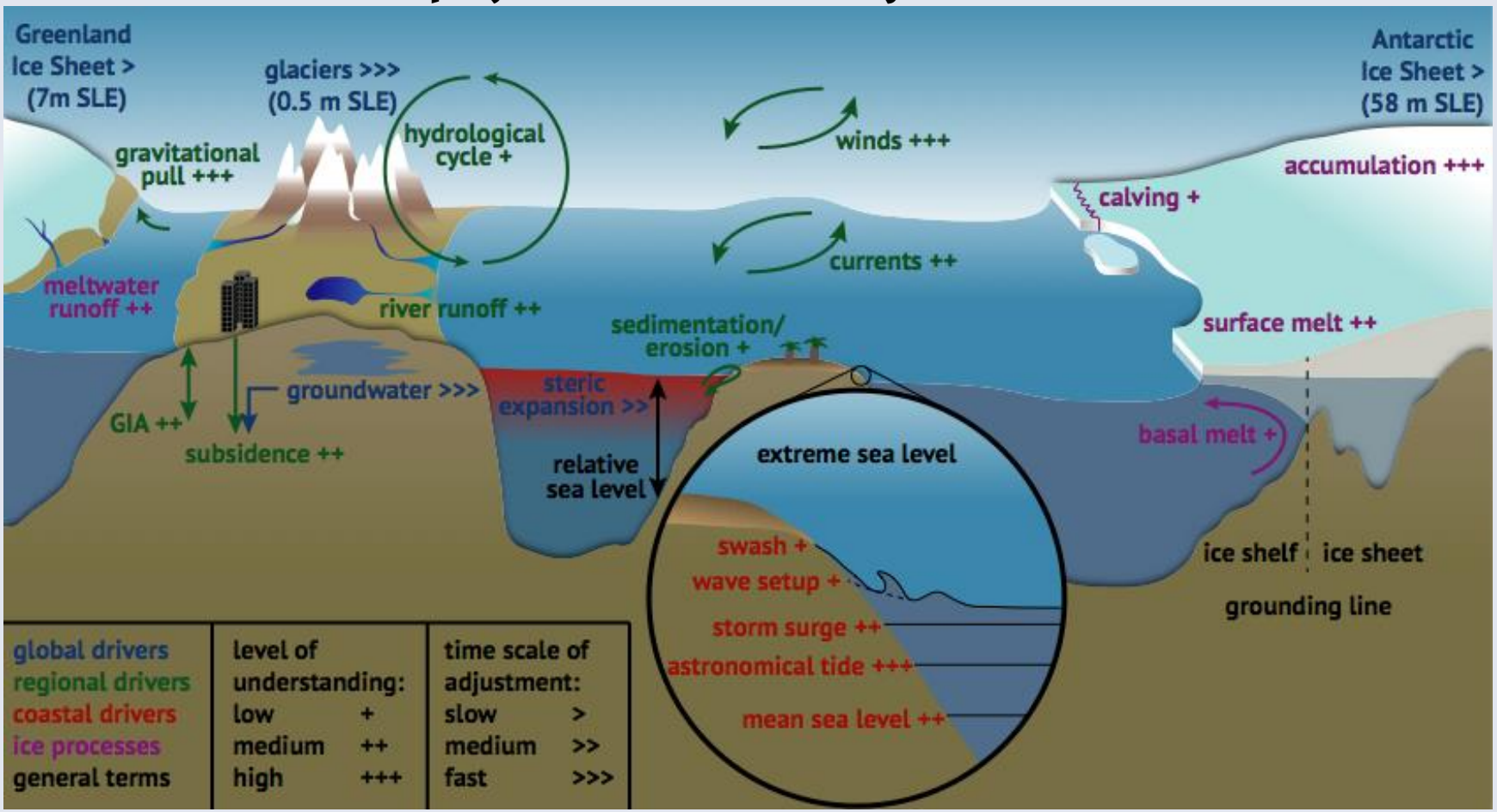

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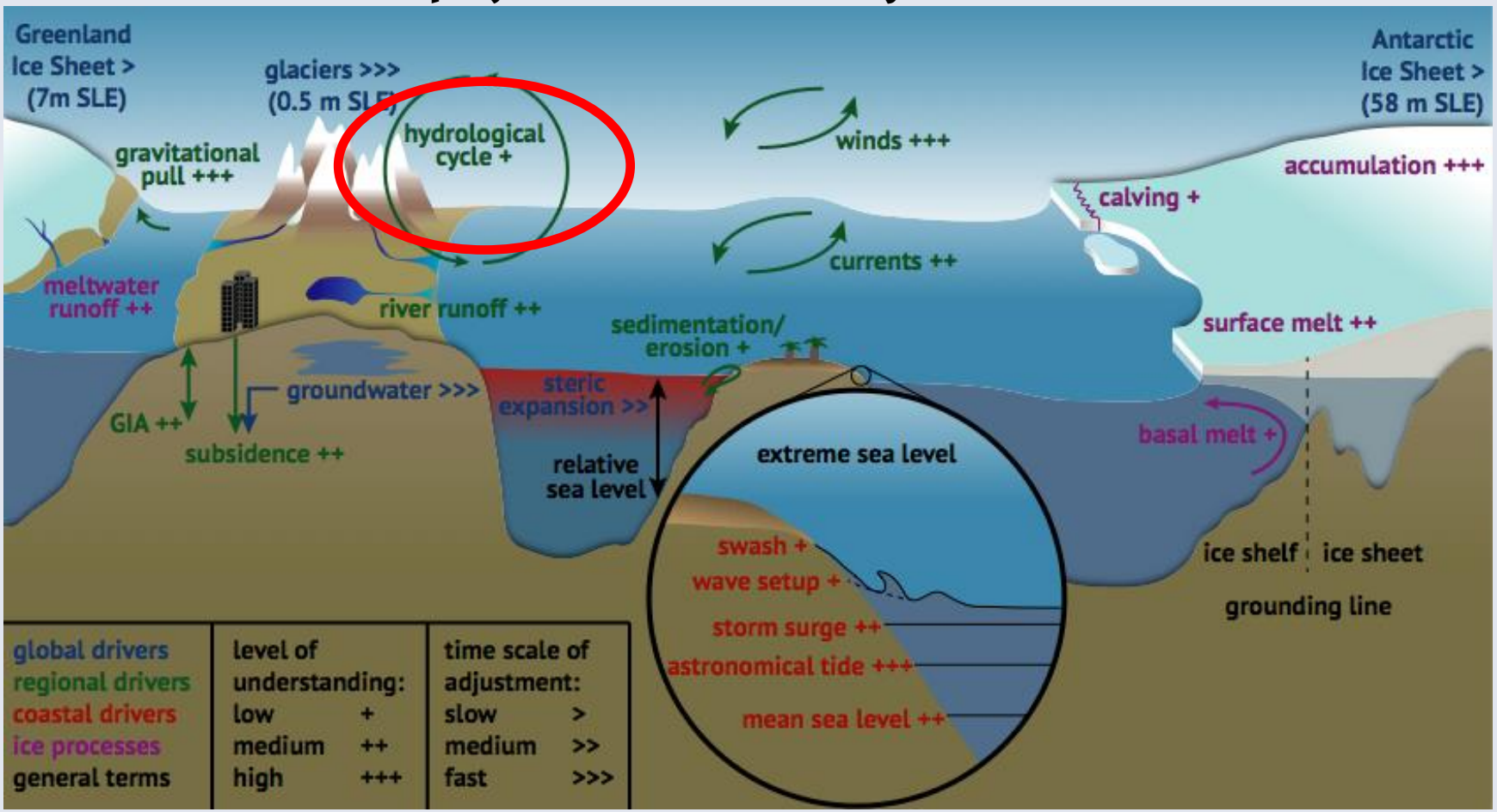

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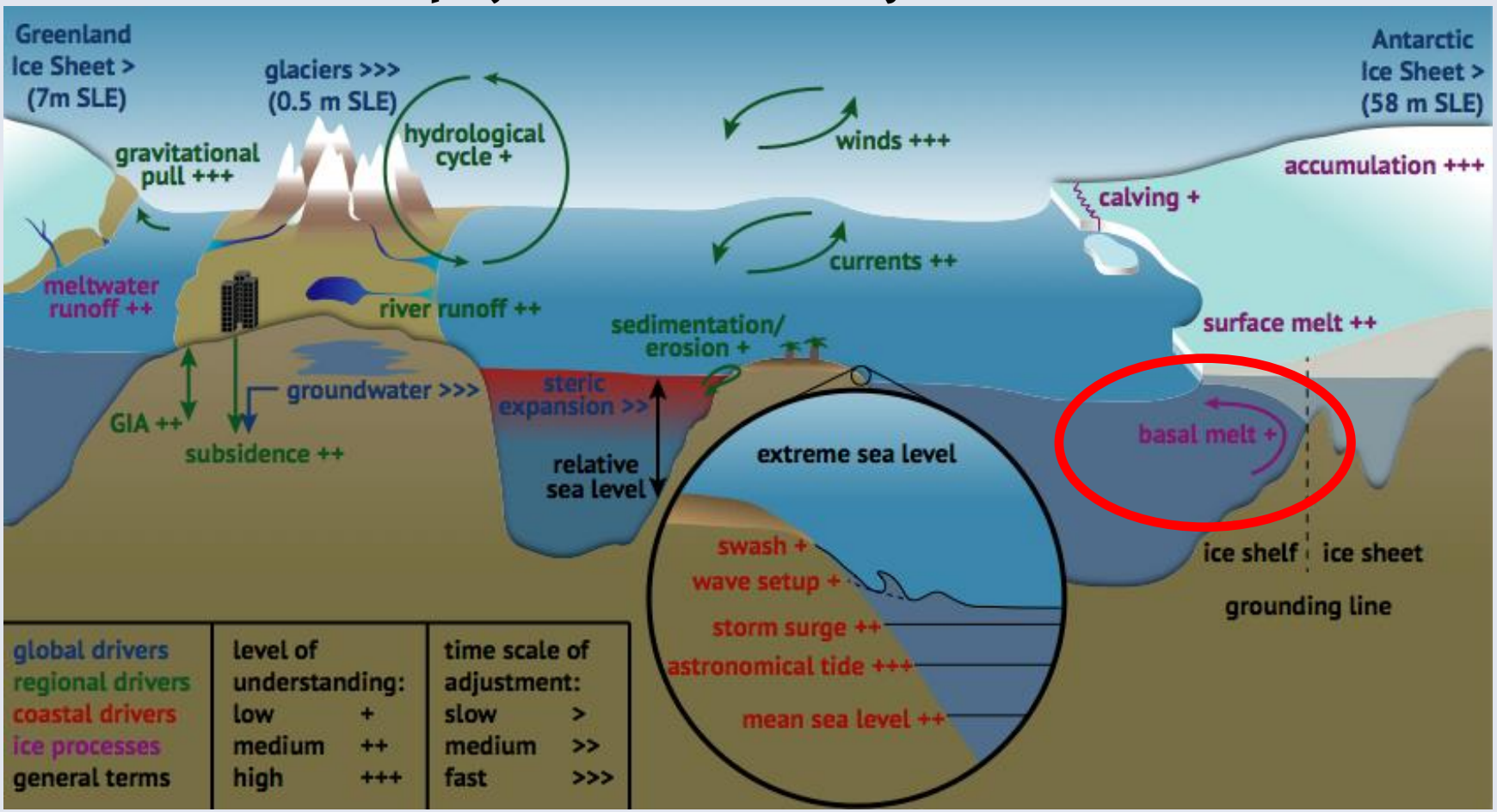

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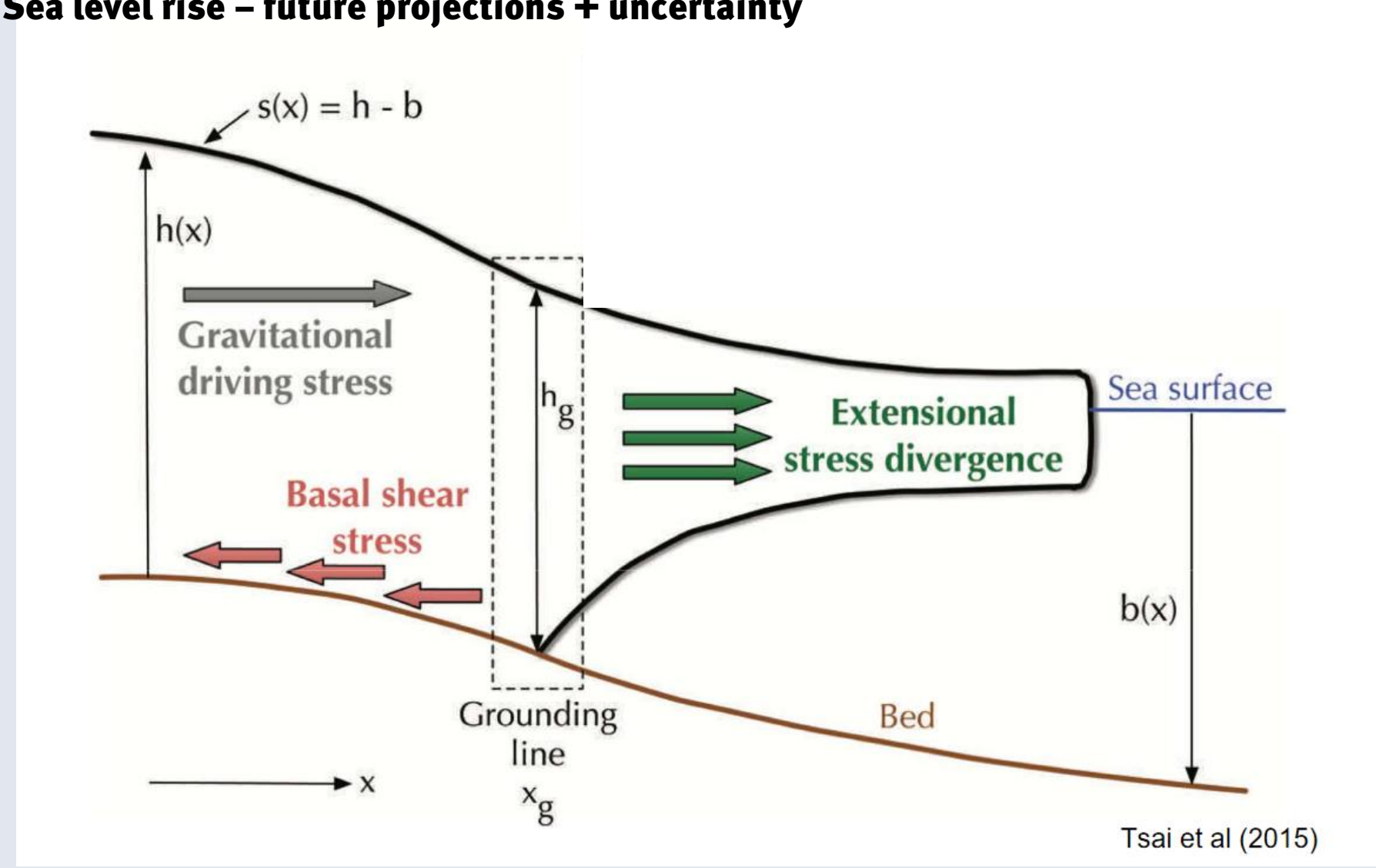

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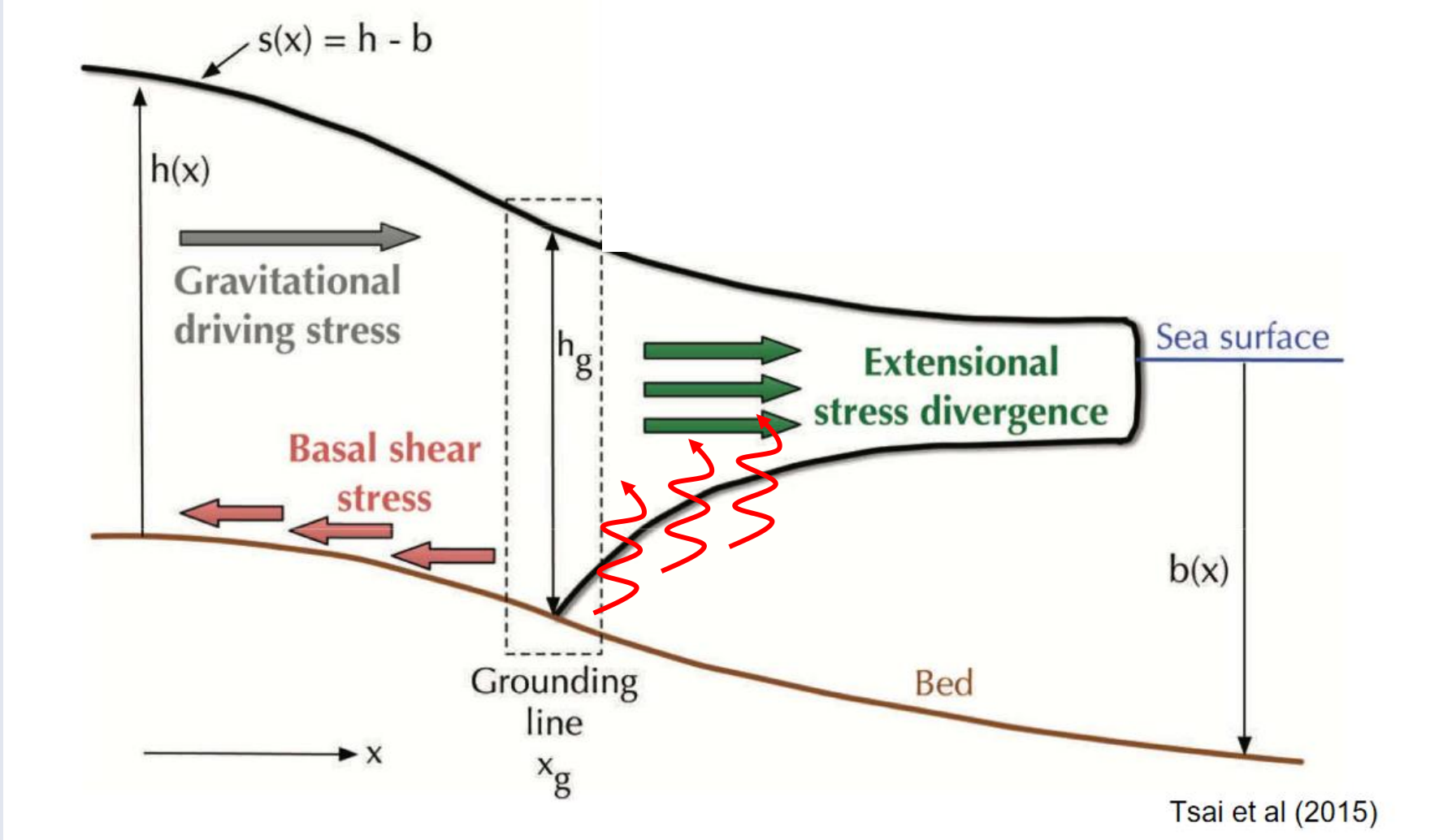

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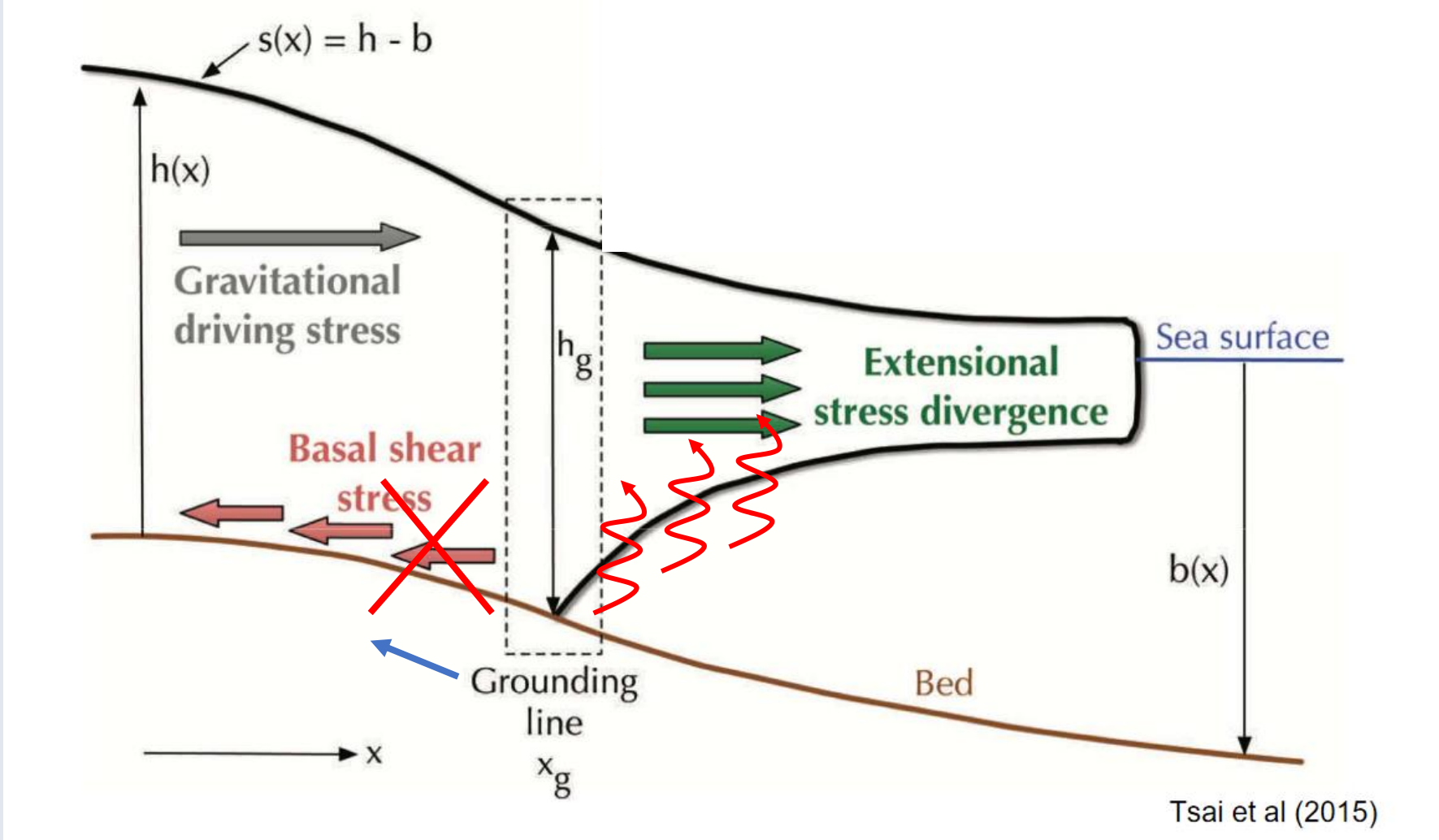

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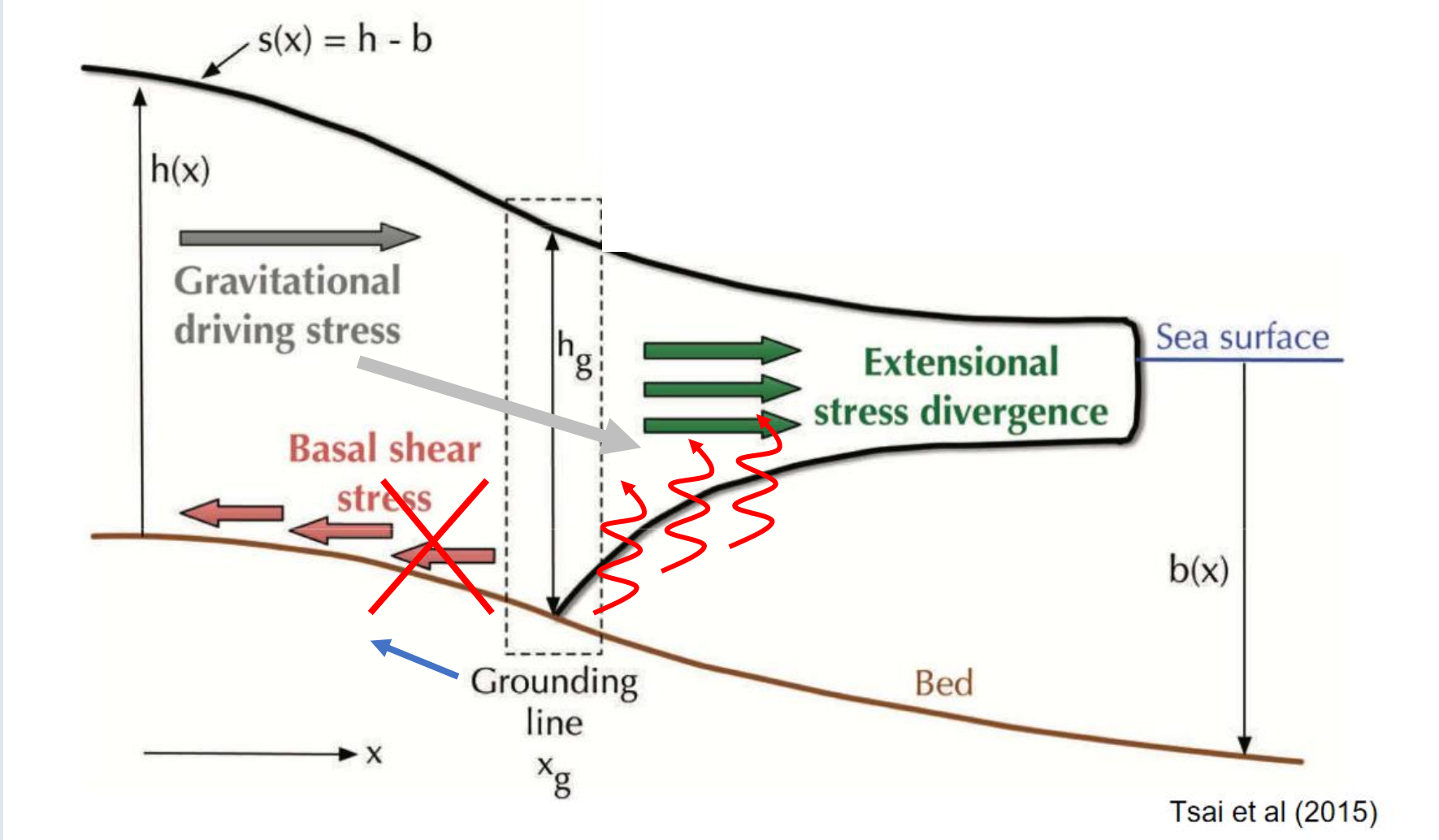

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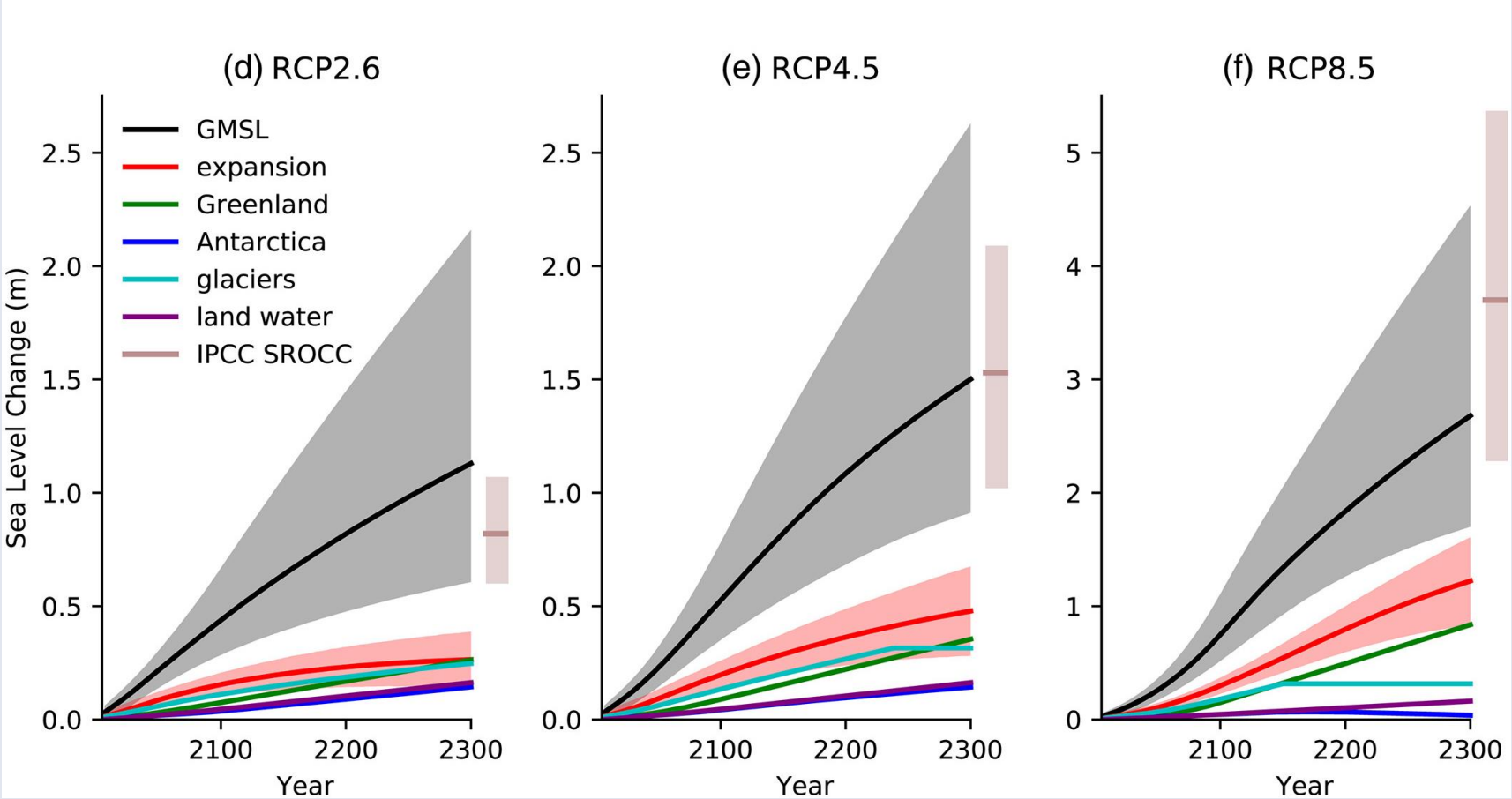

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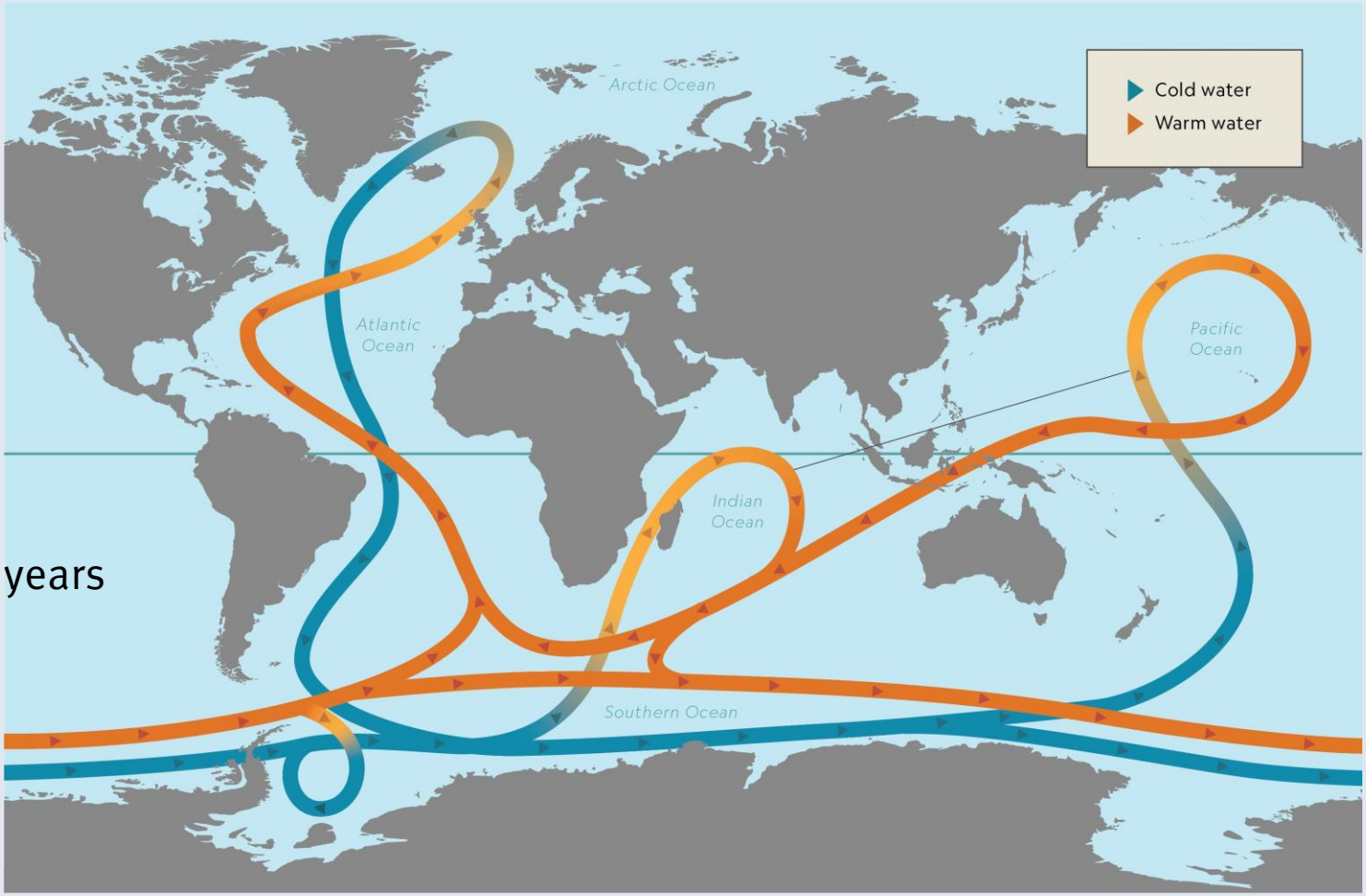
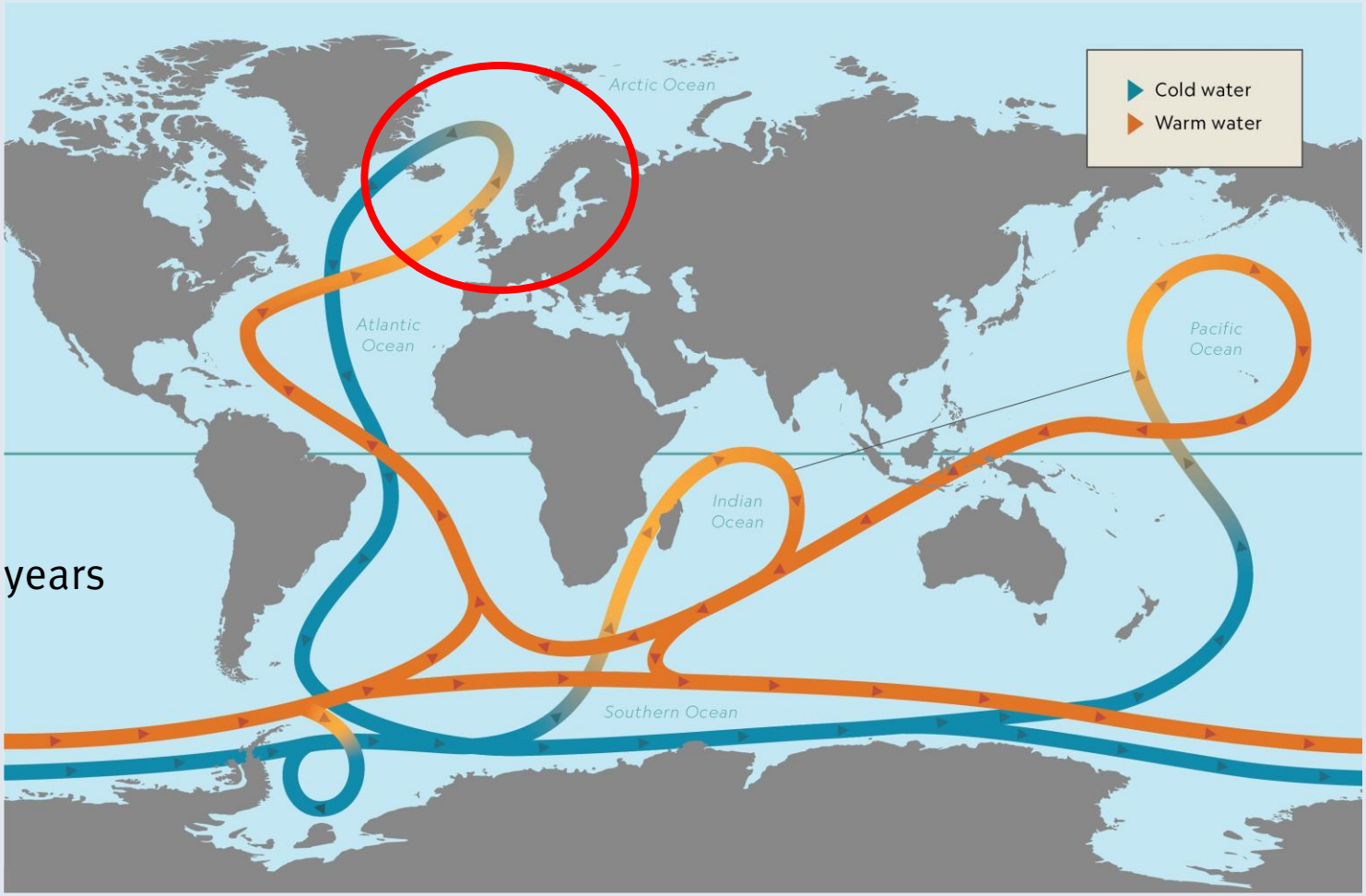


~1.000 years

[https://media.nationalgeographic.org/assets/photos/229/384/ac91cac1-7c59-4ae4-a2b0-0028aeea6d2c.jpg]

Sea level rise – future projections + uncertainty



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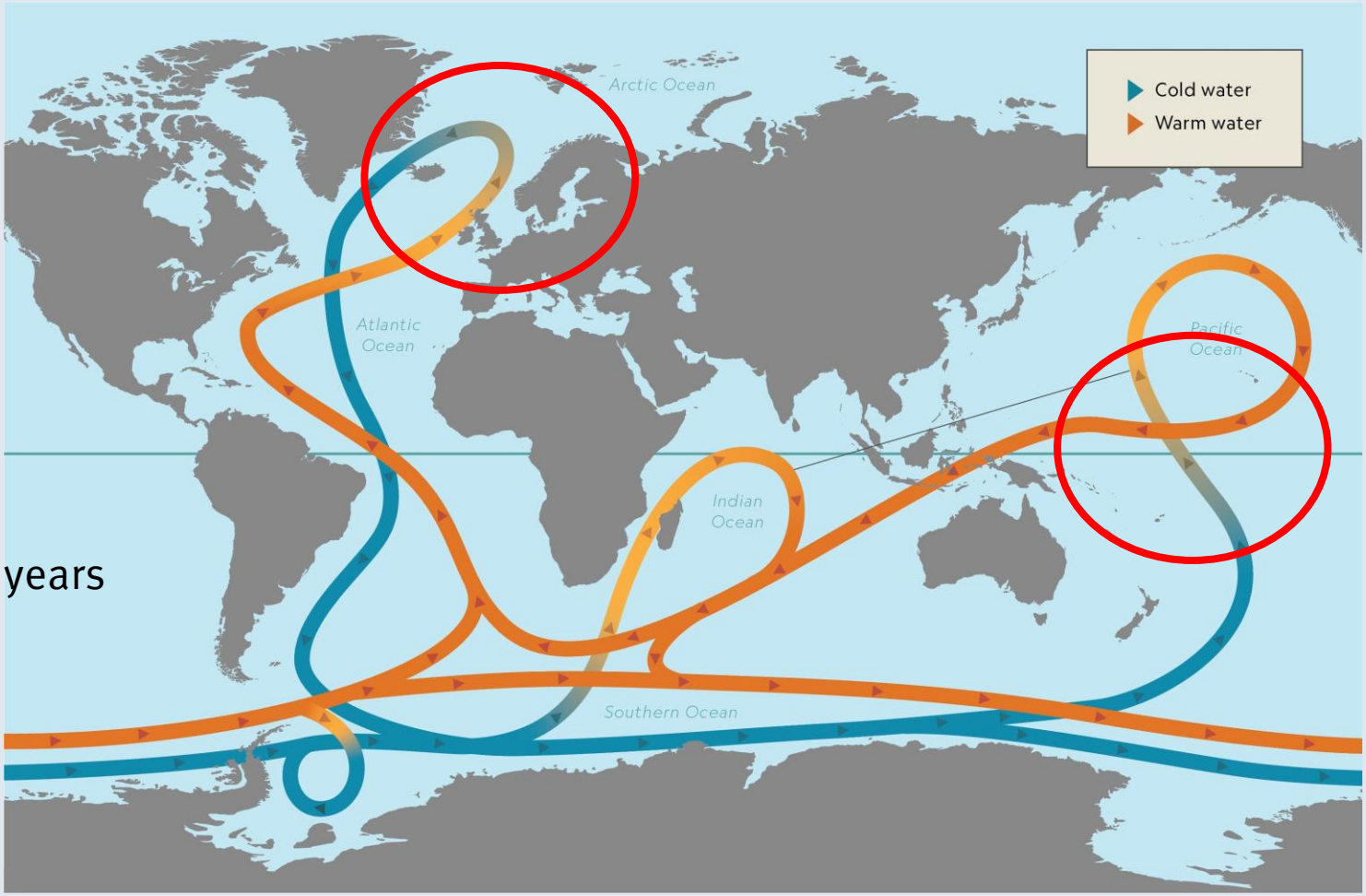

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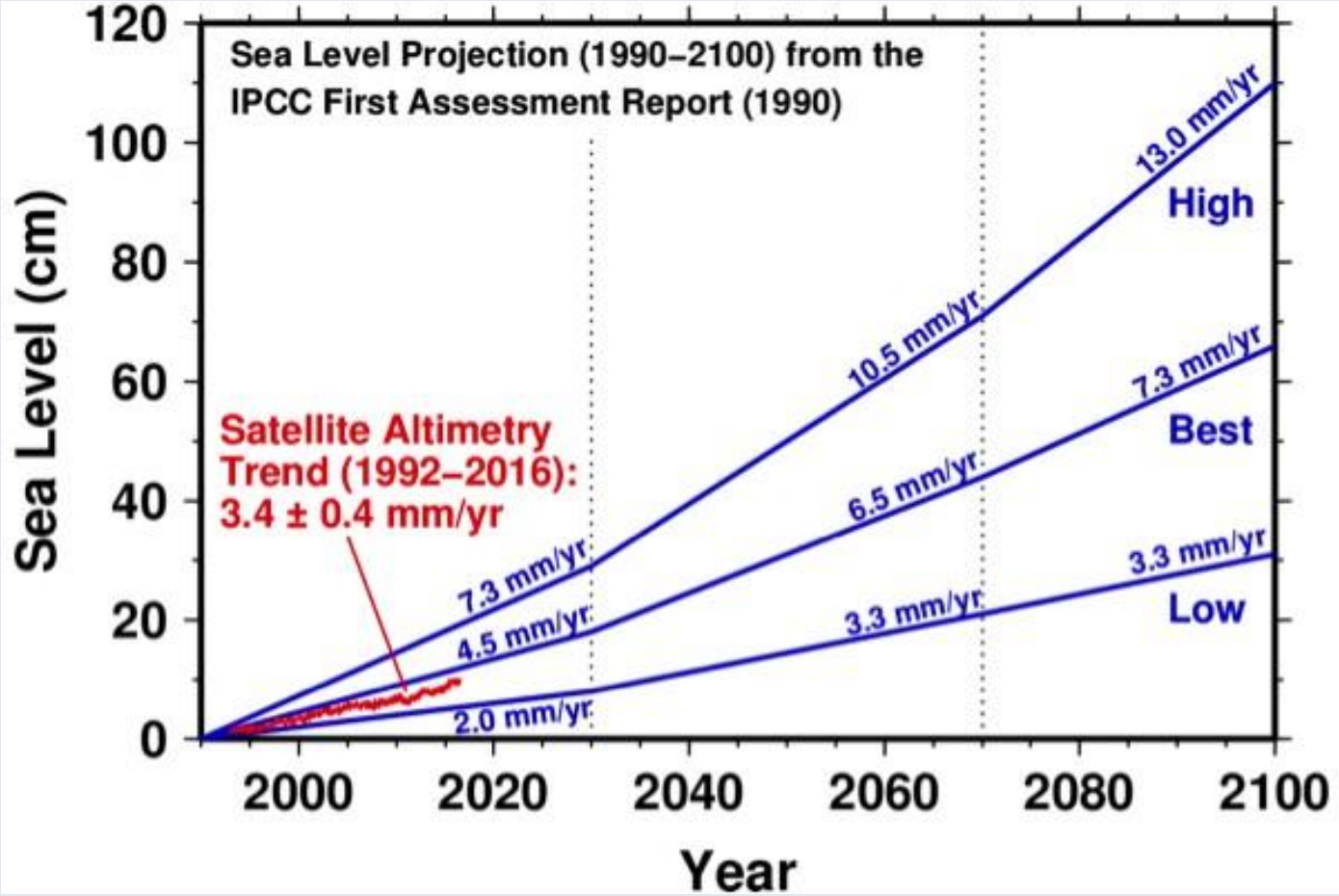
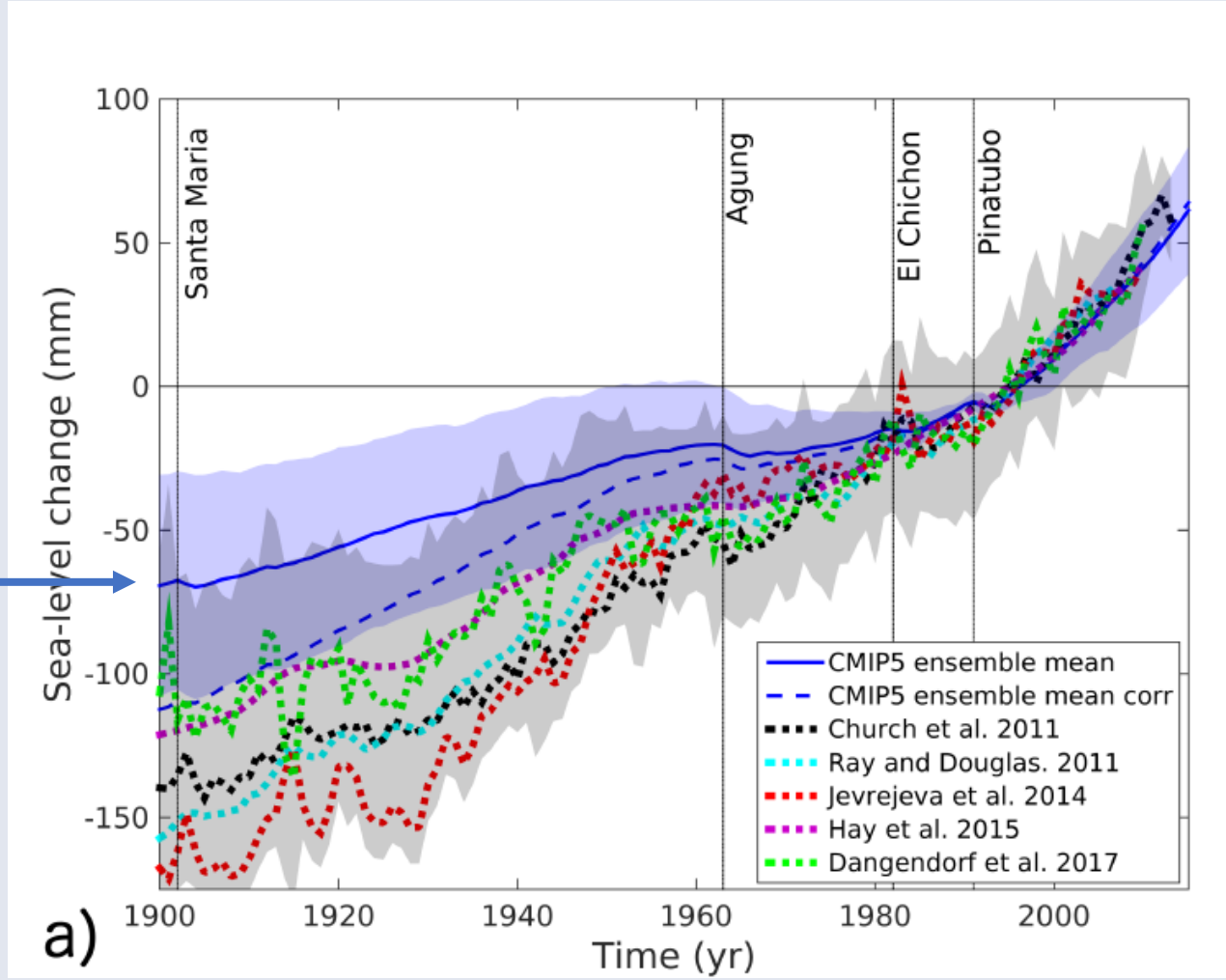


[https://blogs.egu.eu/divisions/gd/2017/09/13/modern-day-sea-level-rise/]

Sea level rise – future projections + uncertainty

IPCC models (AR5) tend to **underestimate** past sea level change

Especially warming of Greenland is underestimated



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Sea level rise – future projections + uncertainty

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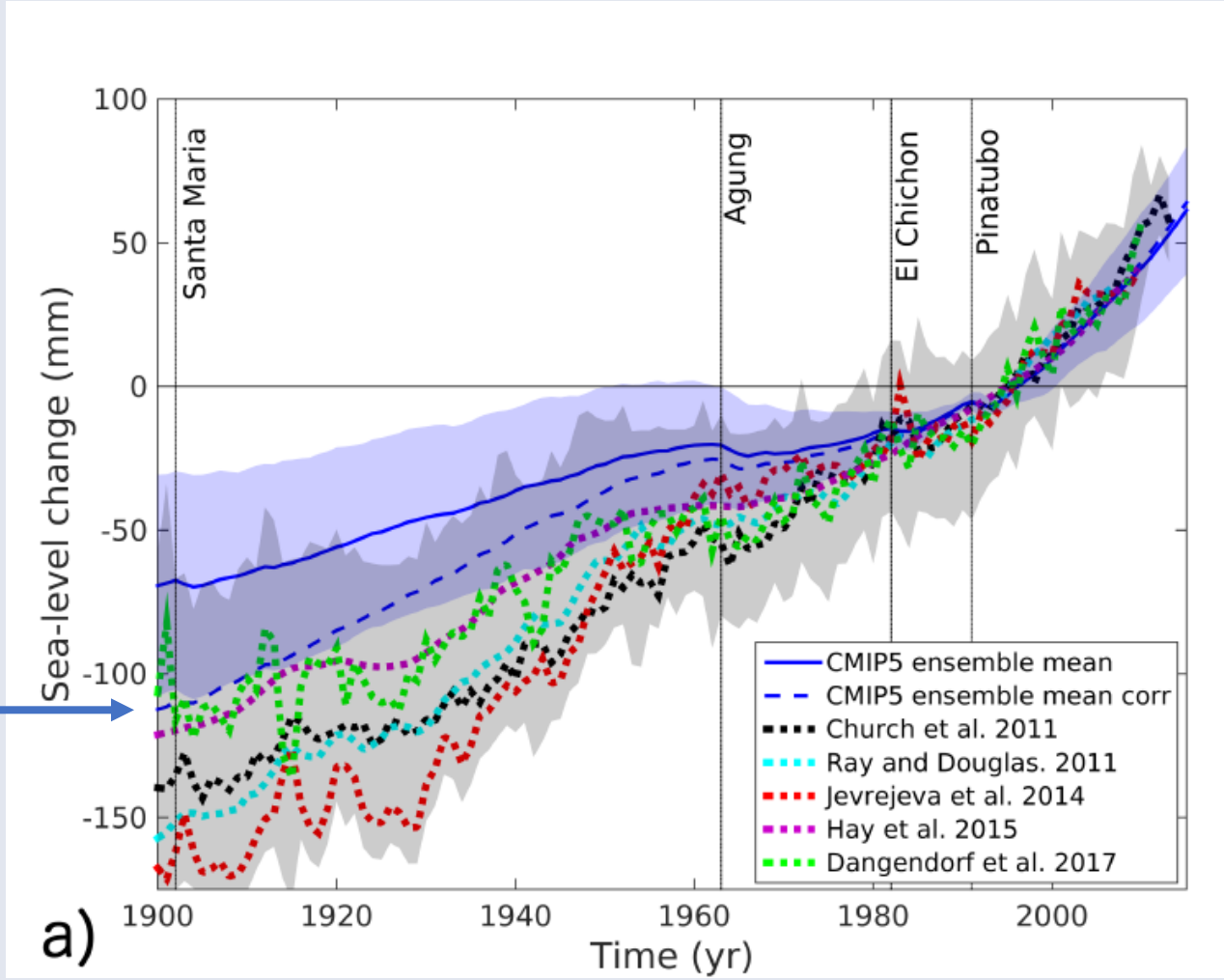
Using observed Greenland temperatures gives higher melt rate (blue dashed line)



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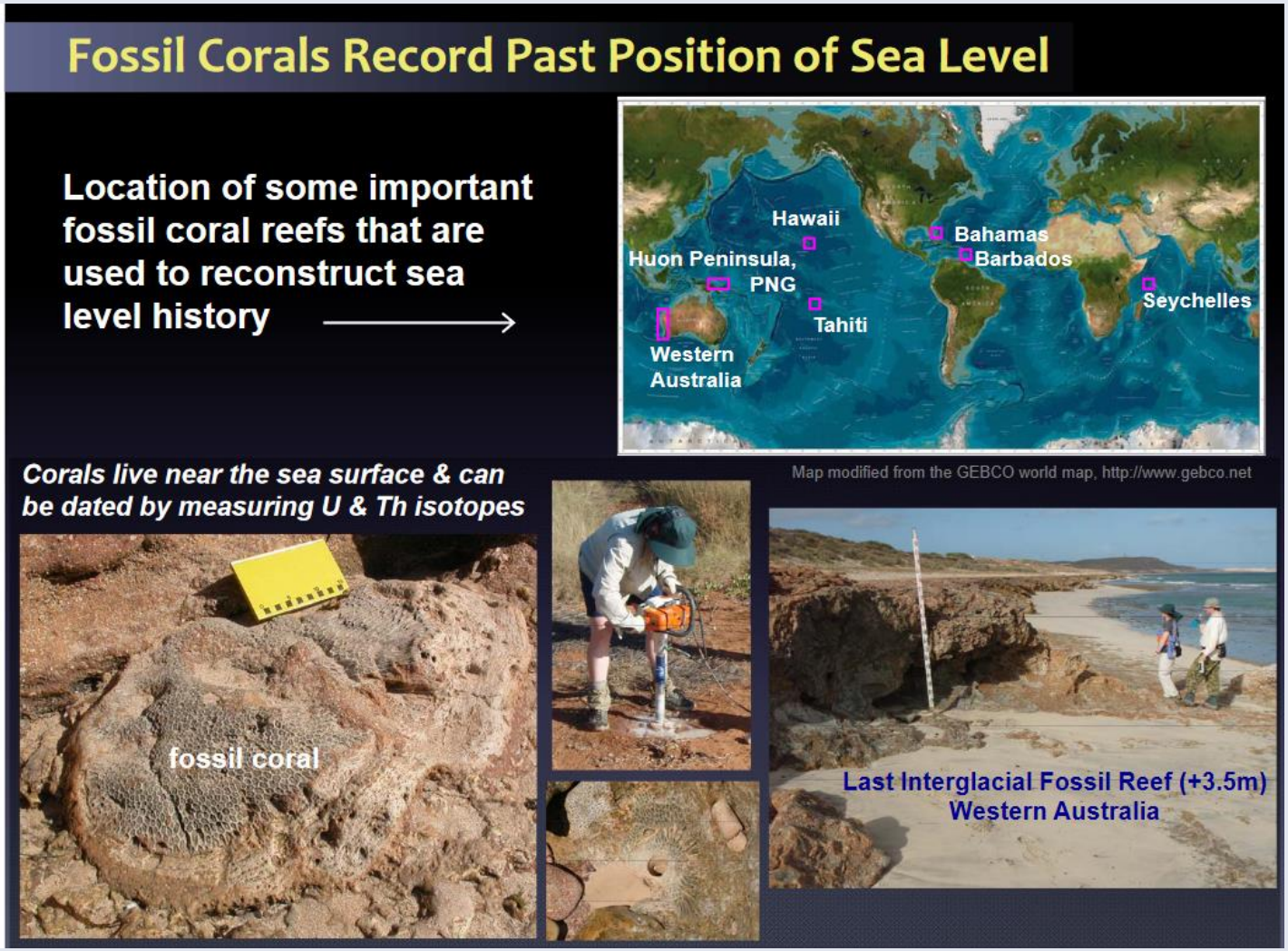


[Dutton, A. New perspectives on “old” data: What the earth’s past tells us about future sea-level rise. International WCRP/IOC conference on Regional Sea Level Changes and Coastal Impacts, 2017.]

Sea level rise – future projections + uncertainty

„Paleoclimate sensitivity“

⇒ +1 W/m² probably leads to a warming of ~0.6 - 1.3 K

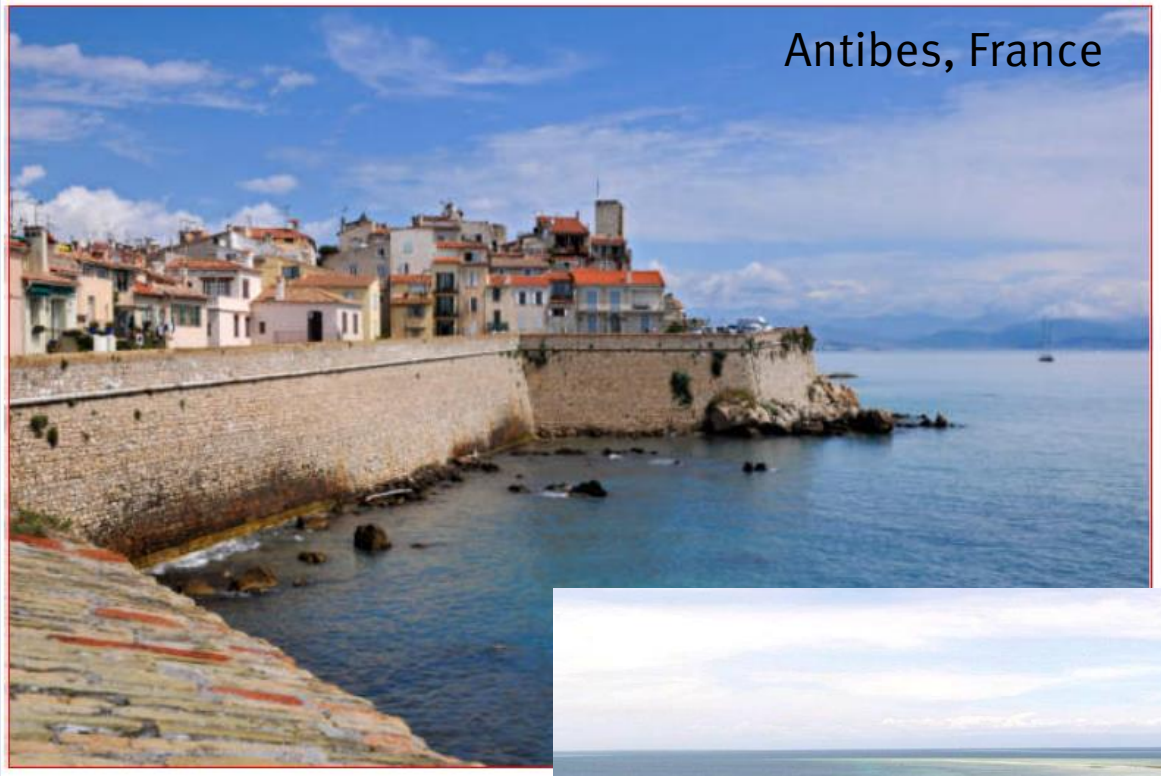
⇒ +100% CO2 (280 -› 560 ppm) gives a warming of ~ 2.2 - 4.8 K
⇒ Confirms IPCC models

(until now, we have ~ +46% CO2)

[Rohling, E.J.et al., 2012. Making sense of palaeoclimate sensitivity. Nature 491, 683–691. https://doi.org/10.1038/nature11574]

Part 2: Implications of sea level rise

Implications of level rise – land loss + prevention



[https://www.kunst-fuer-alle.de/english/art/artist/image/christian-musat/37804/1/669859/sea-and-town-of-antibes-in-france/index.htm]

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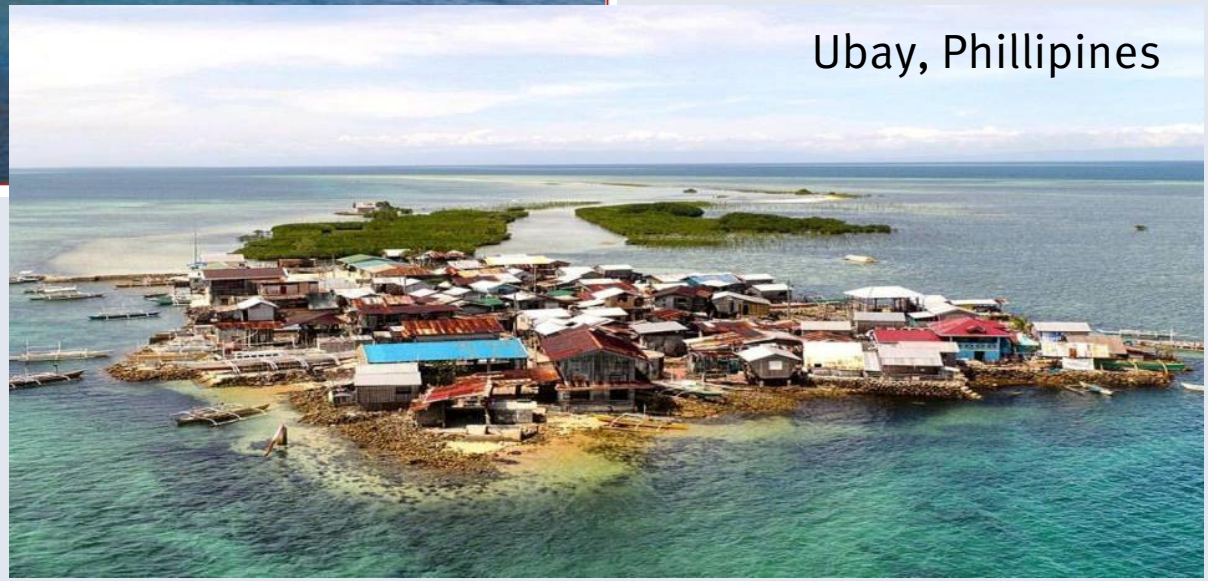
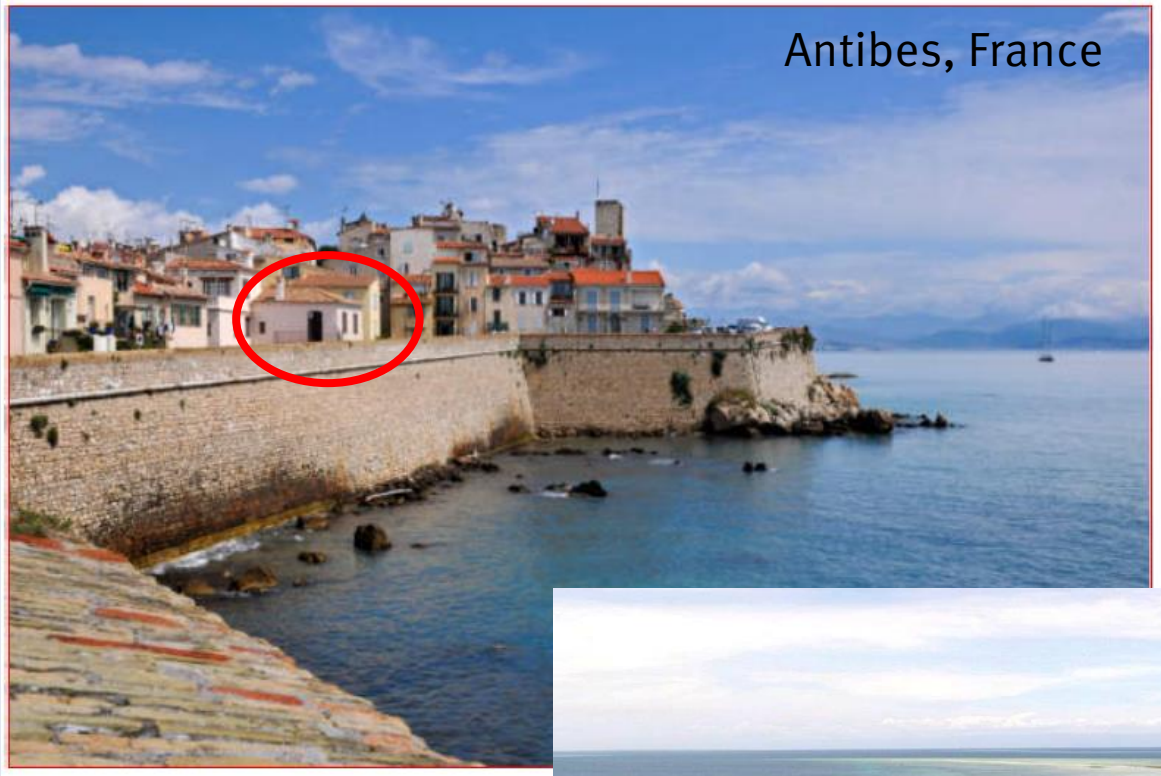


Implications of level rise – land loss + prevention



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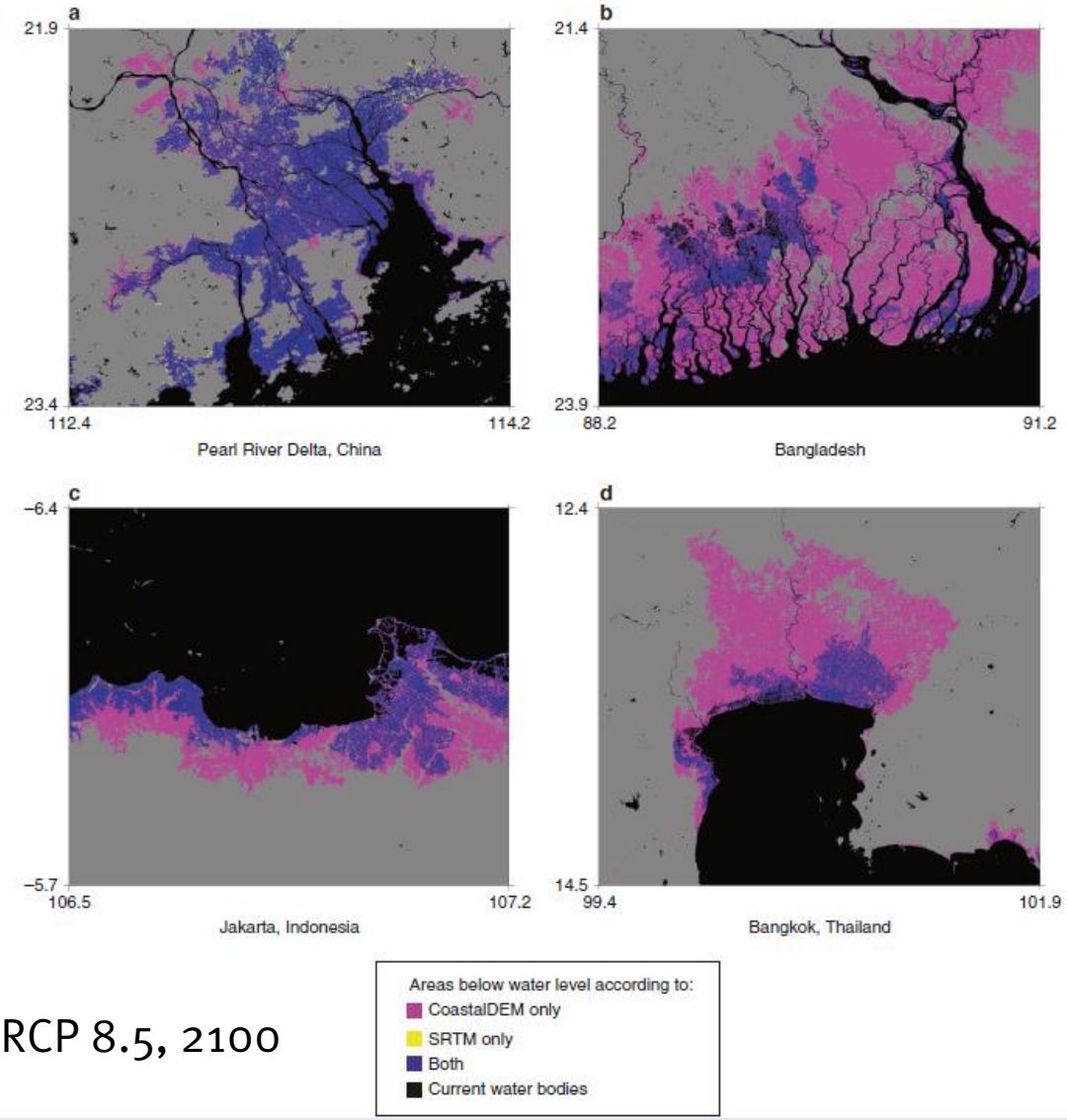
Implications of level rise – land loss + prevention

[Kulp, S.A., Strauss, B.H., 2019. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat Commun 10, 4844. https://doi.org/10.1038/s41467-019-12808-z]

60 - 340 million people may live below mean sea level in 2100 (worst case estimate)

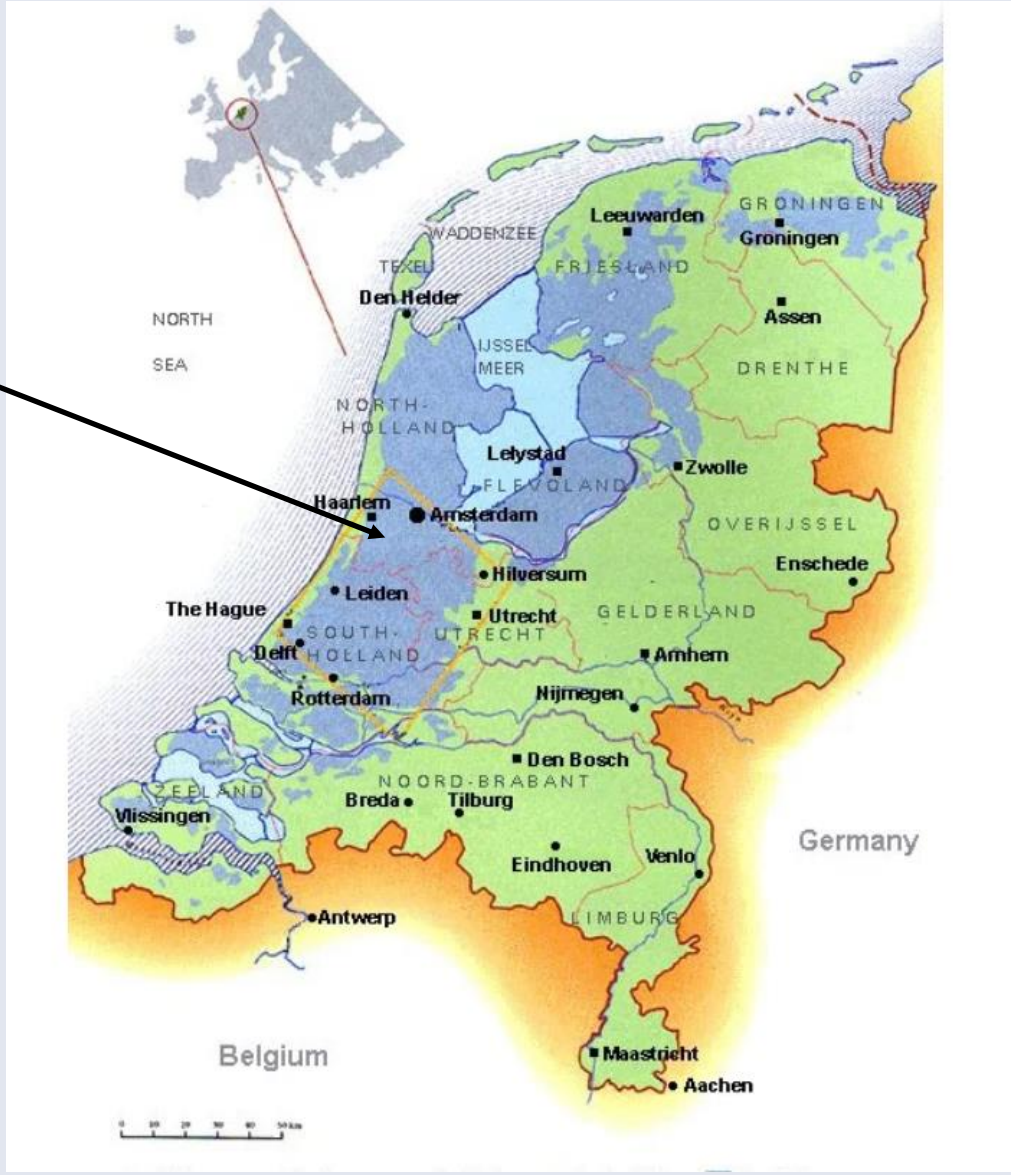


RCP 8.5, 2100

Implications of level rise – land loss + prevention

[https://www.reddit.com/r/MapPorn/comments/stmeg/parts_of_the_netherlands_below_sea_level_500_x_719/]

Netherlands: 3.9 million people living below mean sea level today



Implications of level rise – land loss + prevention – beaches

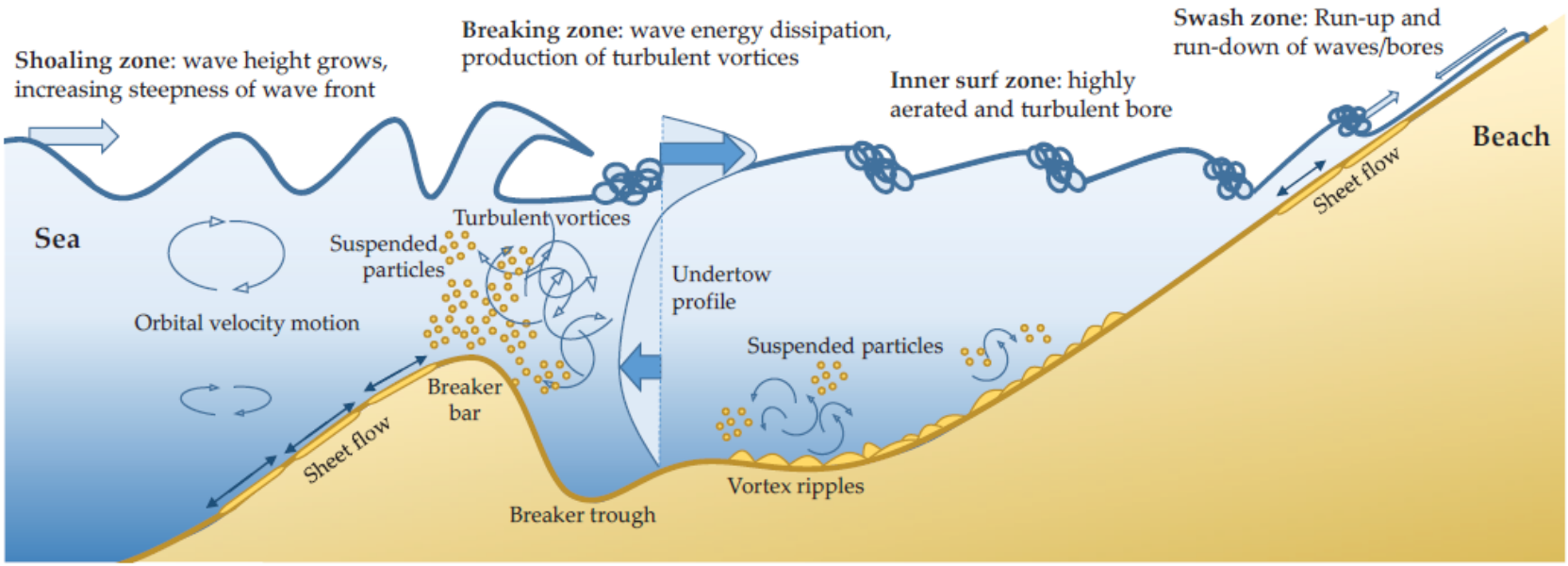


Figure 1.2. Conceptual drawing of cross-shore sediment processes in the near-shore region.

[v.d.Zanden, J. Sand transport processes in the surf and swash zones. DOI:10.3990/1.9789036542456]

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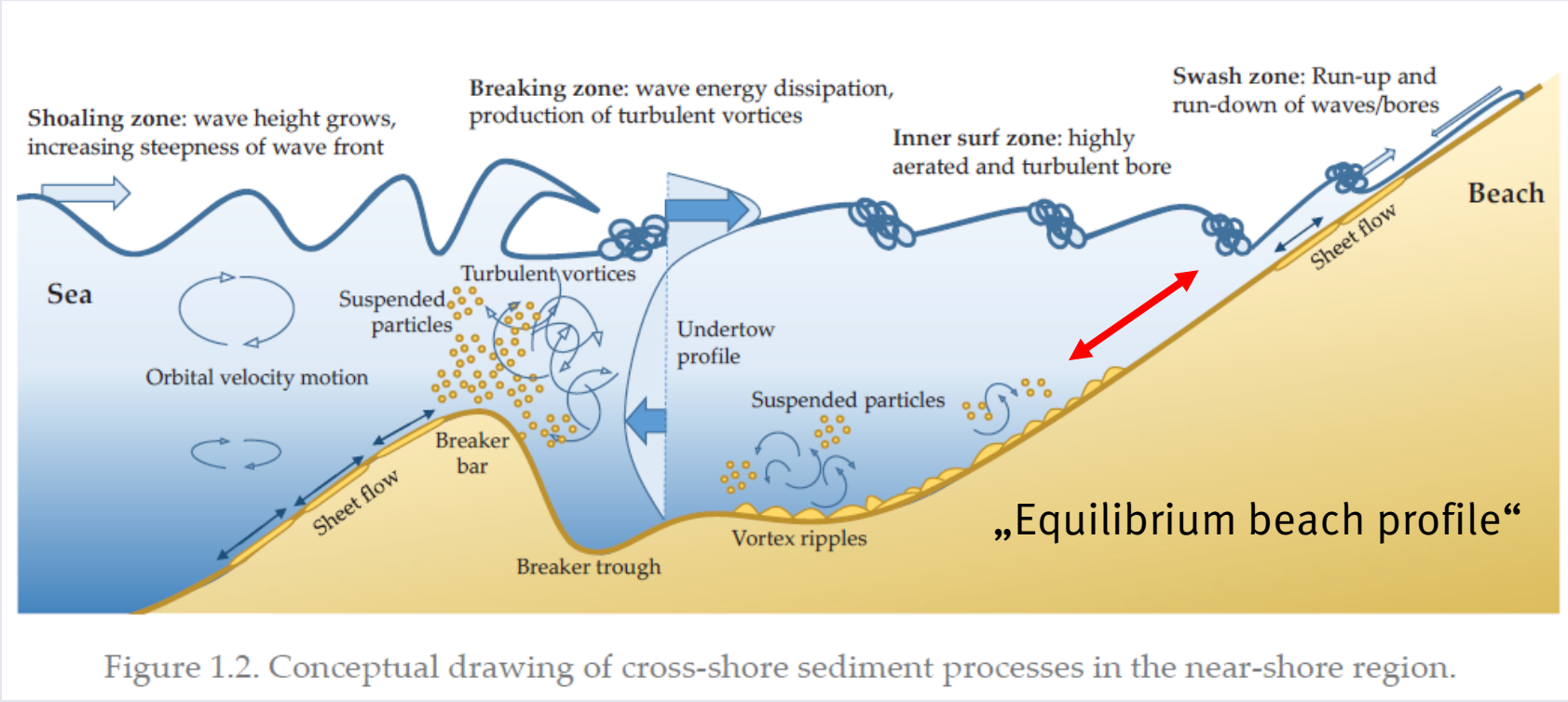

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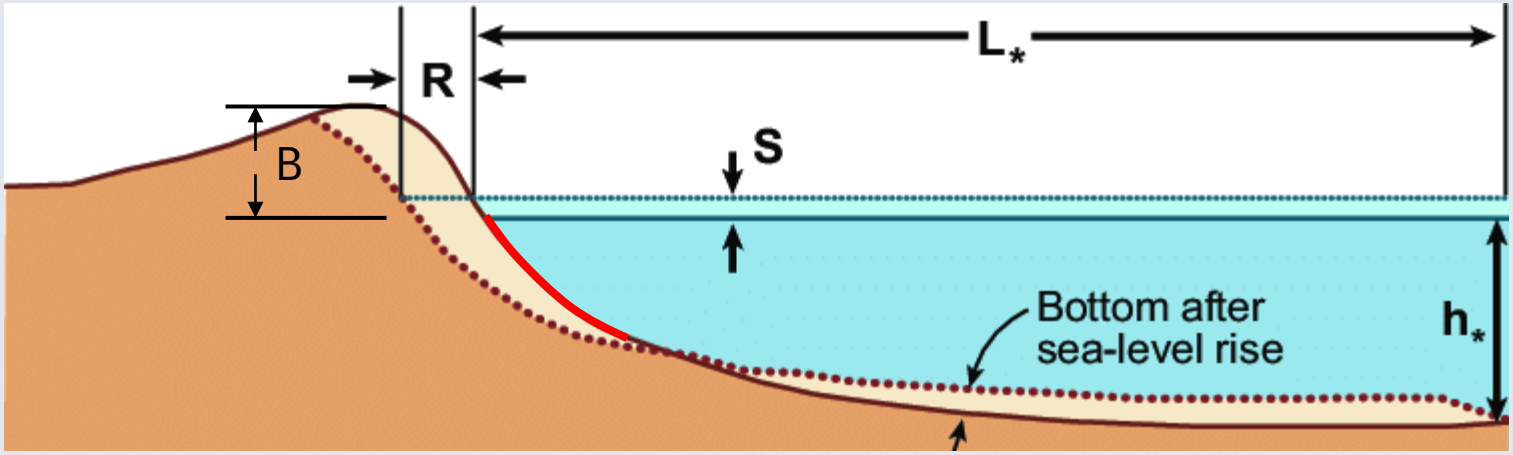
[v.d.Zanden, J. Sand transport processes in the surf and swash zones. DOI:10.3990/1.9789036542456]

Implications of level rise – land loss + prevention – beaches



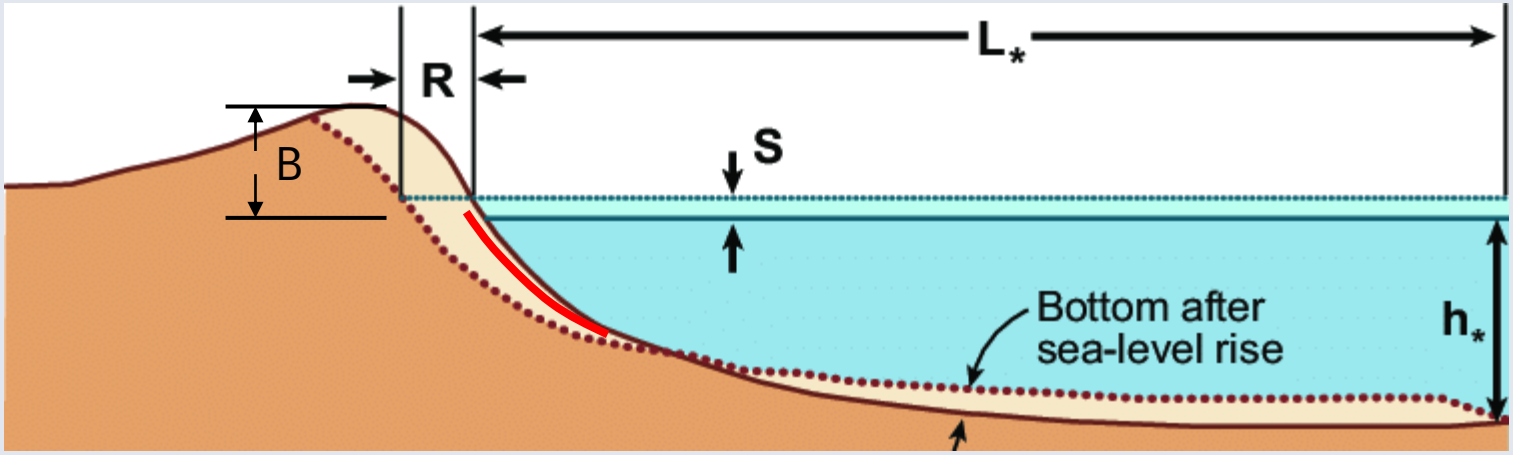
[https://www.researchgate.net/profile/Duncan-Fitzgerald/publication/272293985/figure/fig3/AS:578473321742337@1514930195957/The-Bruun-rule-of-shoreline-retreat-after-Cooper-Pilkey-2004.png]

Simple „Bruun Rule“ for estimating land loss:

$$R = \frac{S\,L}{h + B}$$

but: Heavily debated and critisized

Implications of level rise – land loss + prevention – beaches



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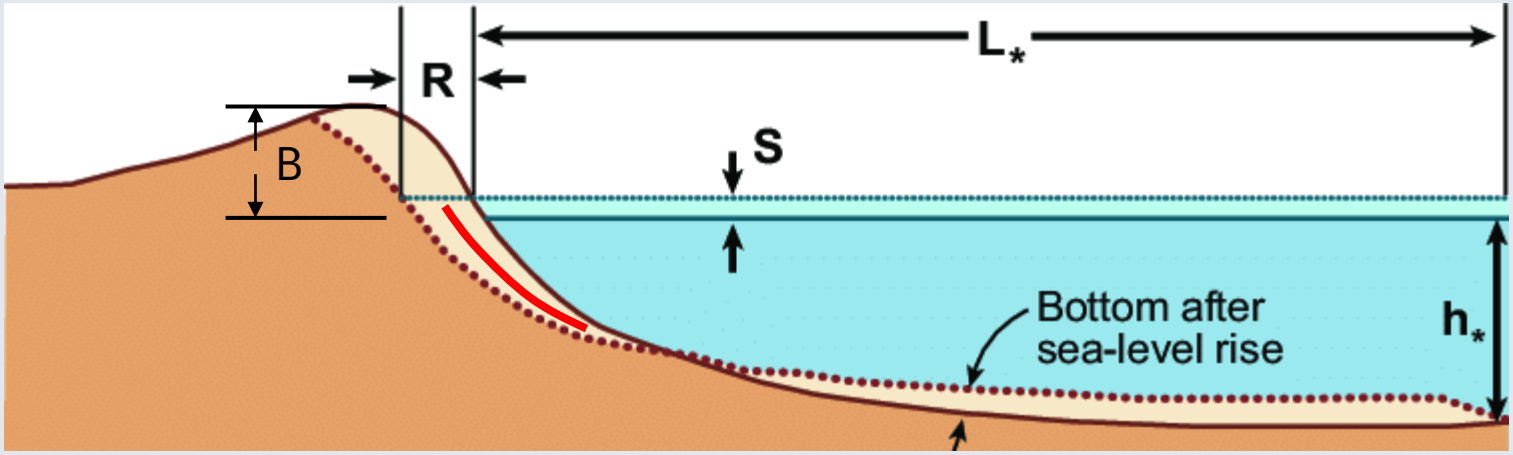

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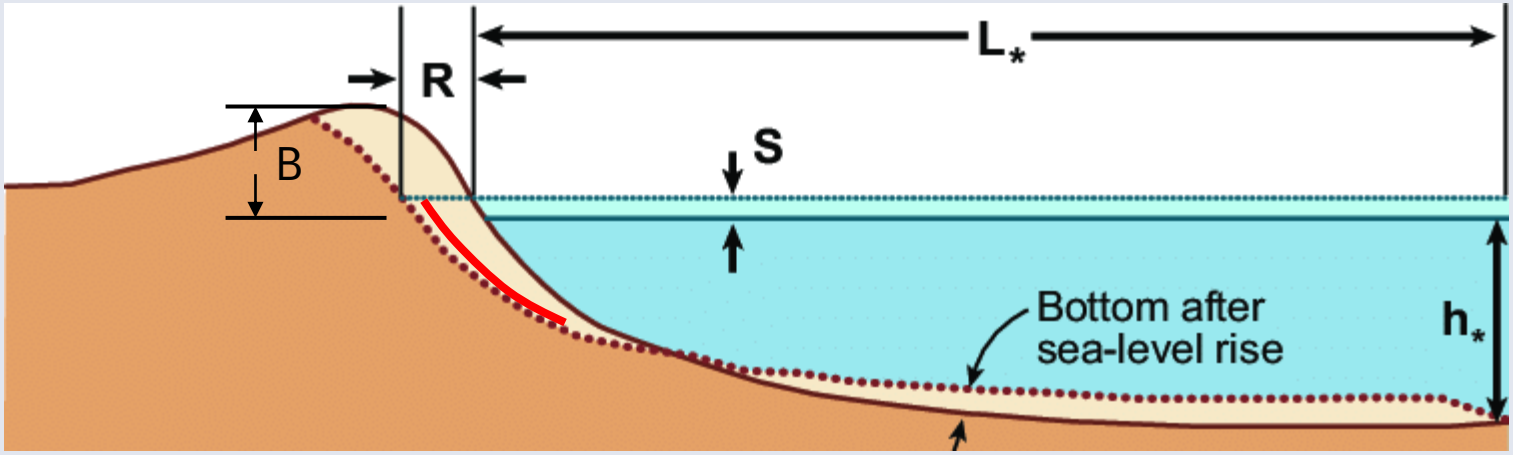

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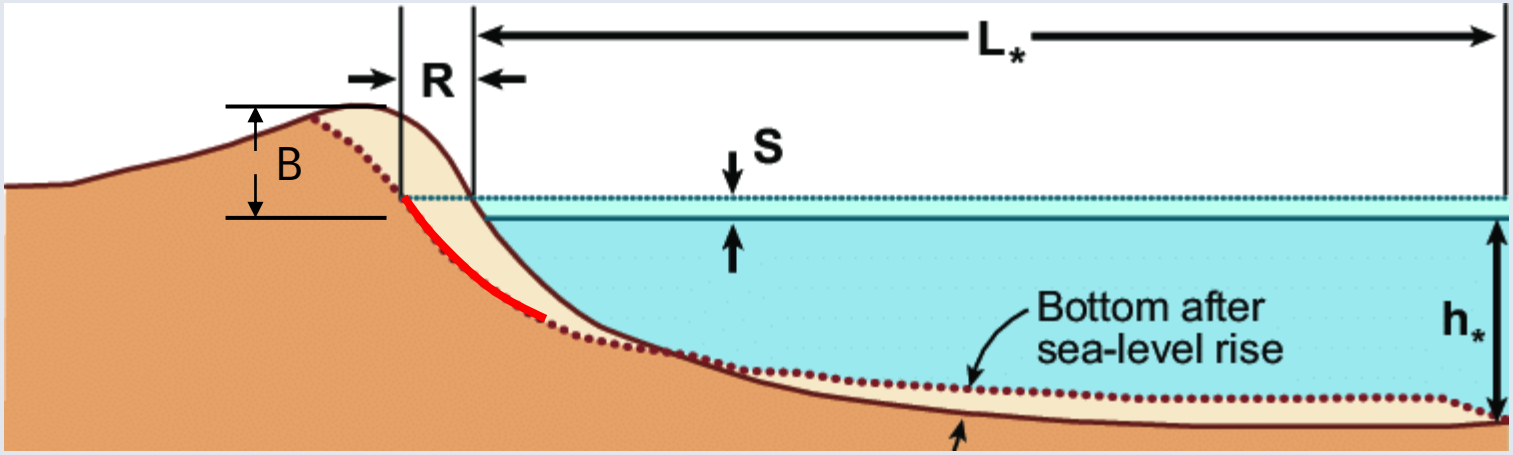

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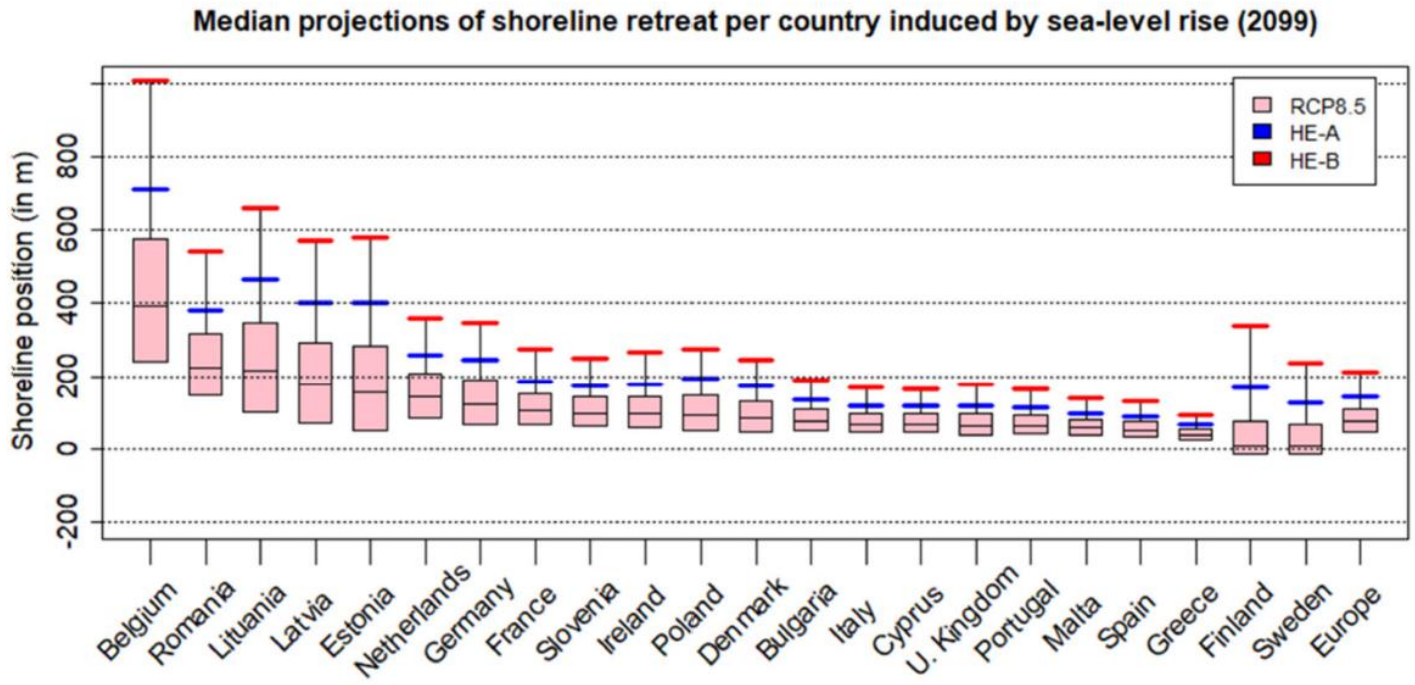
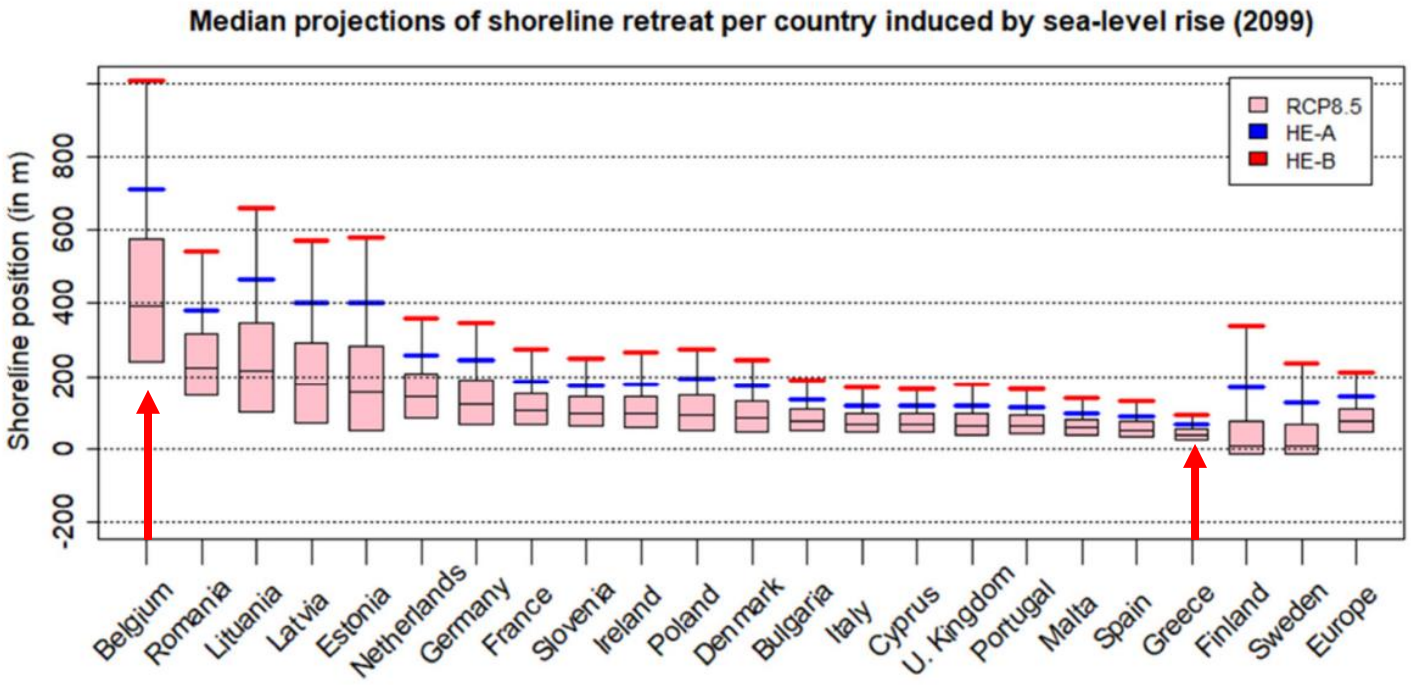


Figure 5. Projections of median shoreline retreat by 2099 of sandy coasts, per European country, calculated for (pink) the RCP8.5 likely range, (blue) high-end A, and (red) high-end B. Variable nearshore slope is considered here.

[Thiéblemont, R., Le Cozannet, G., Toimil, A., Meyssignac, B., Losada, I.J., 2019. Likely and high-end impacts of regional sea-level rise on the shoreline change of European sandy coasts under a high greenhouse gas emissions scenario. Water 11, 2607.]

Implications of level rise – land loss + prevention – beaches



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Implications of level rise – land loss + prevention – beaches

Beach nourishment as a measure of coastal protection

[https://upload.wikimedia.org/wikipedia/commons/thumb/f/fe/Beach_restoration_device.jpg/1280px-Beach_restoration_device.jpg]

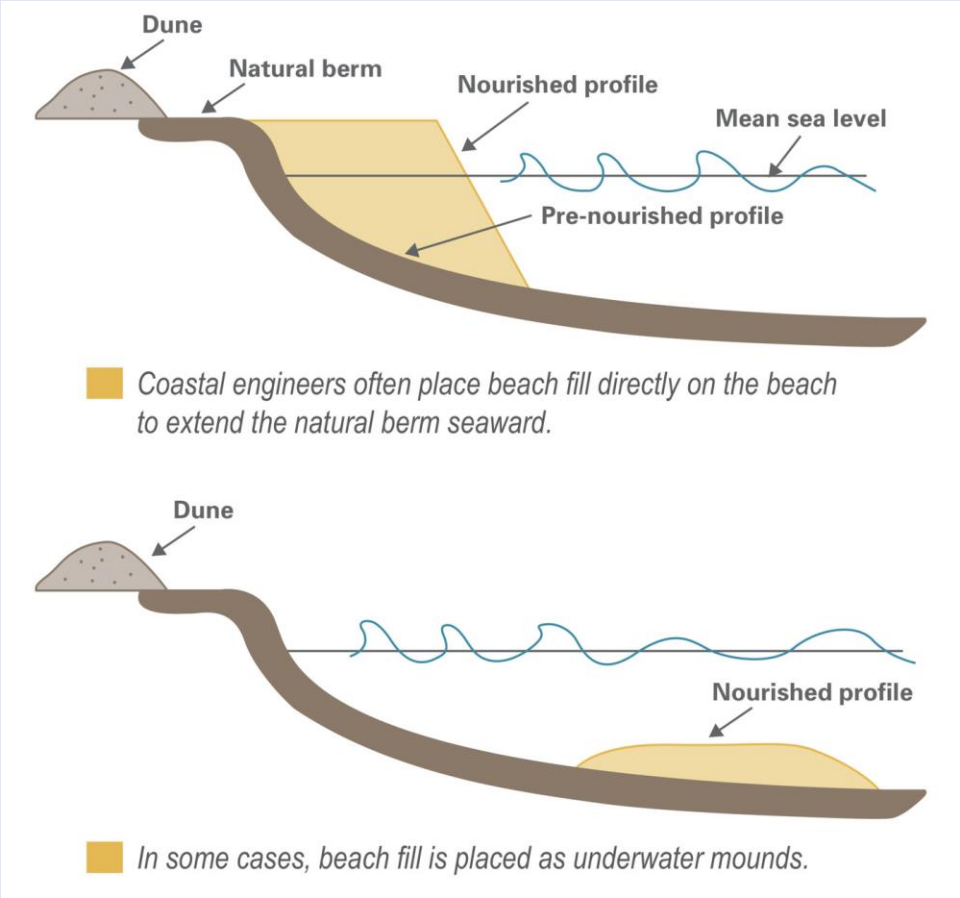
Implications of level rise – land loss + prevention – beaches

Beach nourishment	
Cost in Europe based on sailing distance of ca. 15 km	5–6 Euro/m^3
Cost for increasing sailing distance up to extra 25 km	0,2 Euro/m^3/km
For large projects in more remote locations where dredgers are not nearby	7–8 Euro/m^3
For small projects in more remote locations where dredgers are not nearby	30 Euro/m^3

[Rosendahl Appelquist, L., Halsnæs, K., 2015. The Coastal Hazard Wheel system for coastal multi-hazard assessment & management in a changing climate. Journal of Coastal Conservation 19. https://doi.org/10.1007/s11852-015-0379-7]

Implications of level rise – land loss + prevention – beaches

Beach nourishment as a measure of coastal protection



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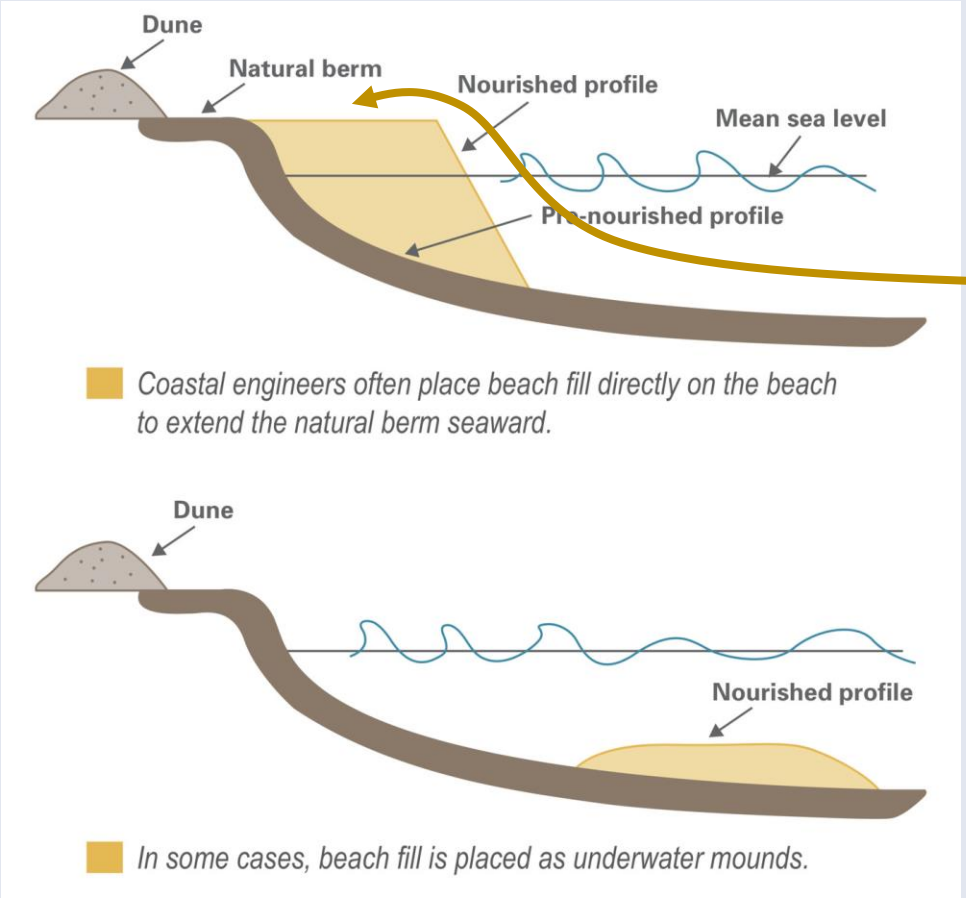
Implications of level rise – land loss + prevention – beaches

Beach nourishment as a measure of coastal protection



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Implications of level rise – land loss + prevention – beaches

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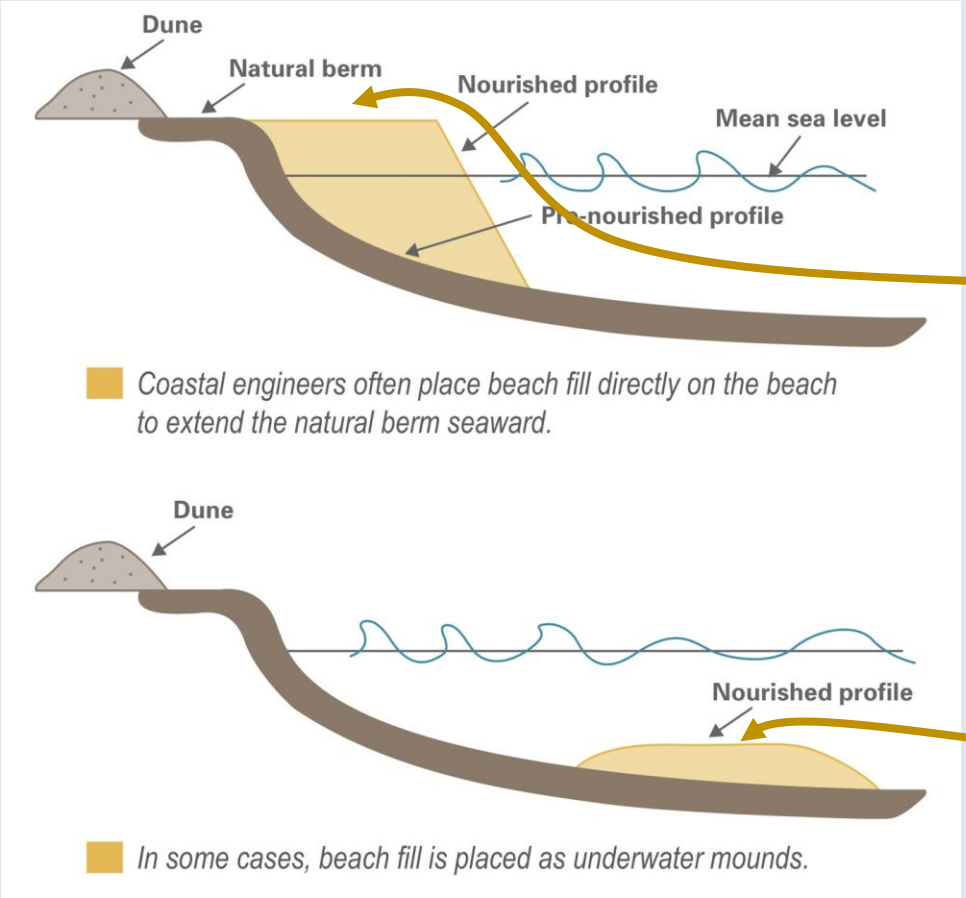

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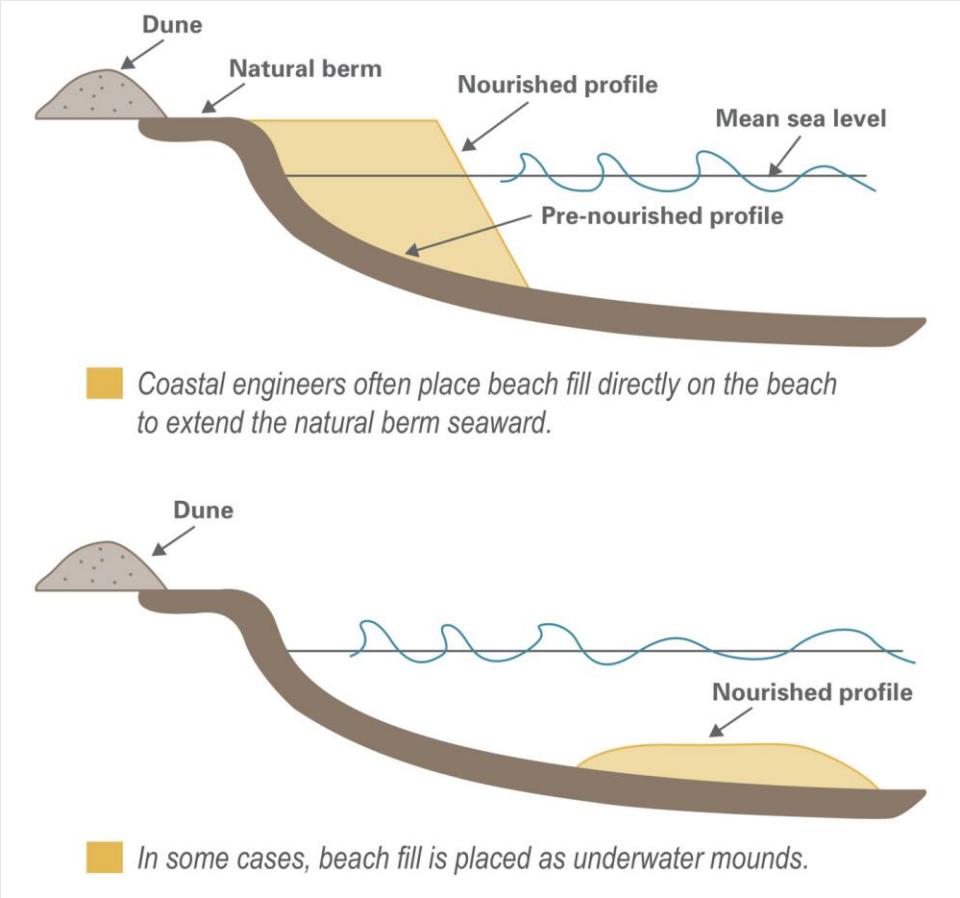
Implications of level rise – land loss + prevention – beaches

Beach nourishment as a measure of coastal protection

But:

Habitat destruction

Perturbing natural conditions, e.g. if the grain size differs



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Implications of level rise – land loss + prevention – beaches

A 20 km long pipe brings Mississippi sand into the delta.

Artificial sand banks transform into salt marshes that act as coastal defense.

[https://worldoceanreview.com/de/wor-5/kuesten-besser-schuetzen/meeresspiegelanstieg-begegnen/]

Implications of level rise – land loss + prevention – beaches

Sand mining for the building sector can cause coastal erosion

(Beach in Togo, also affected by the construction of a harbour)

[https://www.dw.com/en/togos-battle-with-coastal-erosion/a-38378211#]

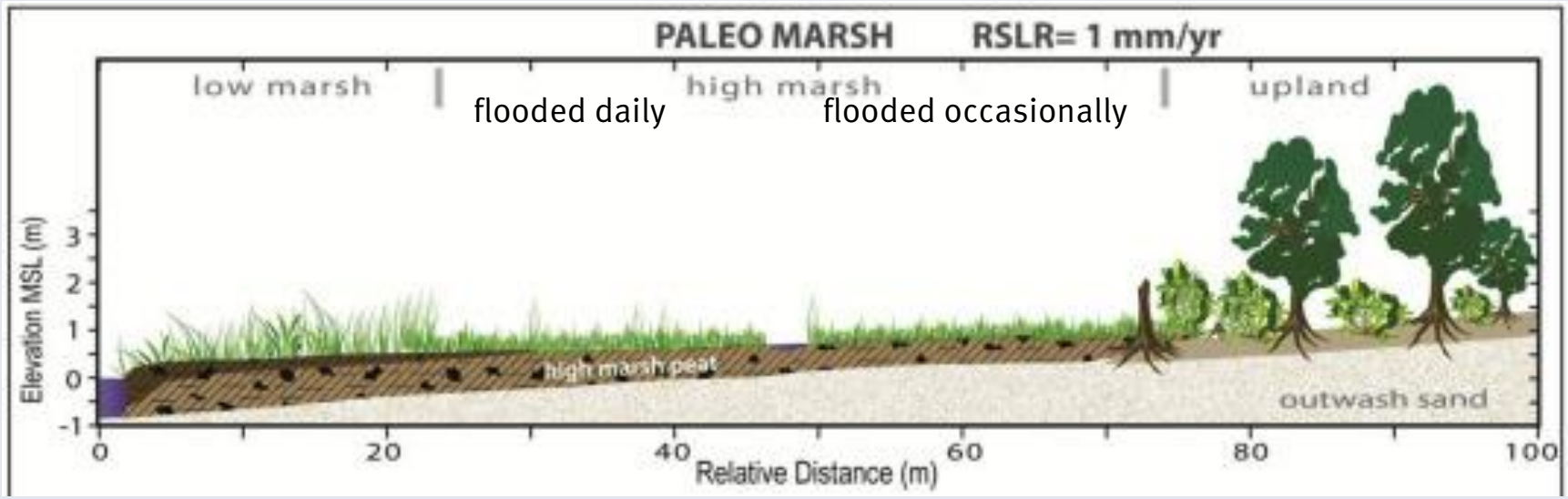
Implications of level rise – land loss + prevention – salt marshes and mangroves

[https://www.nature.scot/landscapes-and-habitats/habitat-types/coast-and-seas/coastal-habitats/saltmarsh]

Implications of level rise – land loss + prevention – salt marshes and mangroves

[https://i.pinimg.com/originals/cd/41/37/cd413732169bf68a50d755062fe3f91a.jpg]

Implications of level rise – land loss + prevention – salt marshes and mangroves



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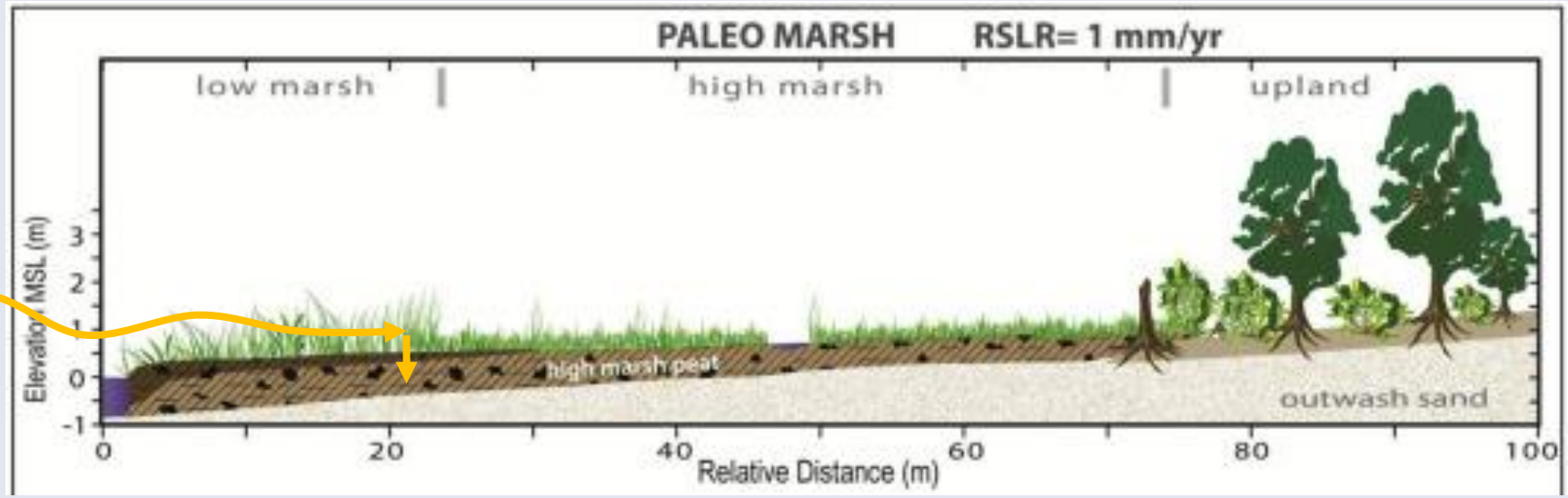
Implications of level rise – land loss + prevention – salt marshes and mangroves



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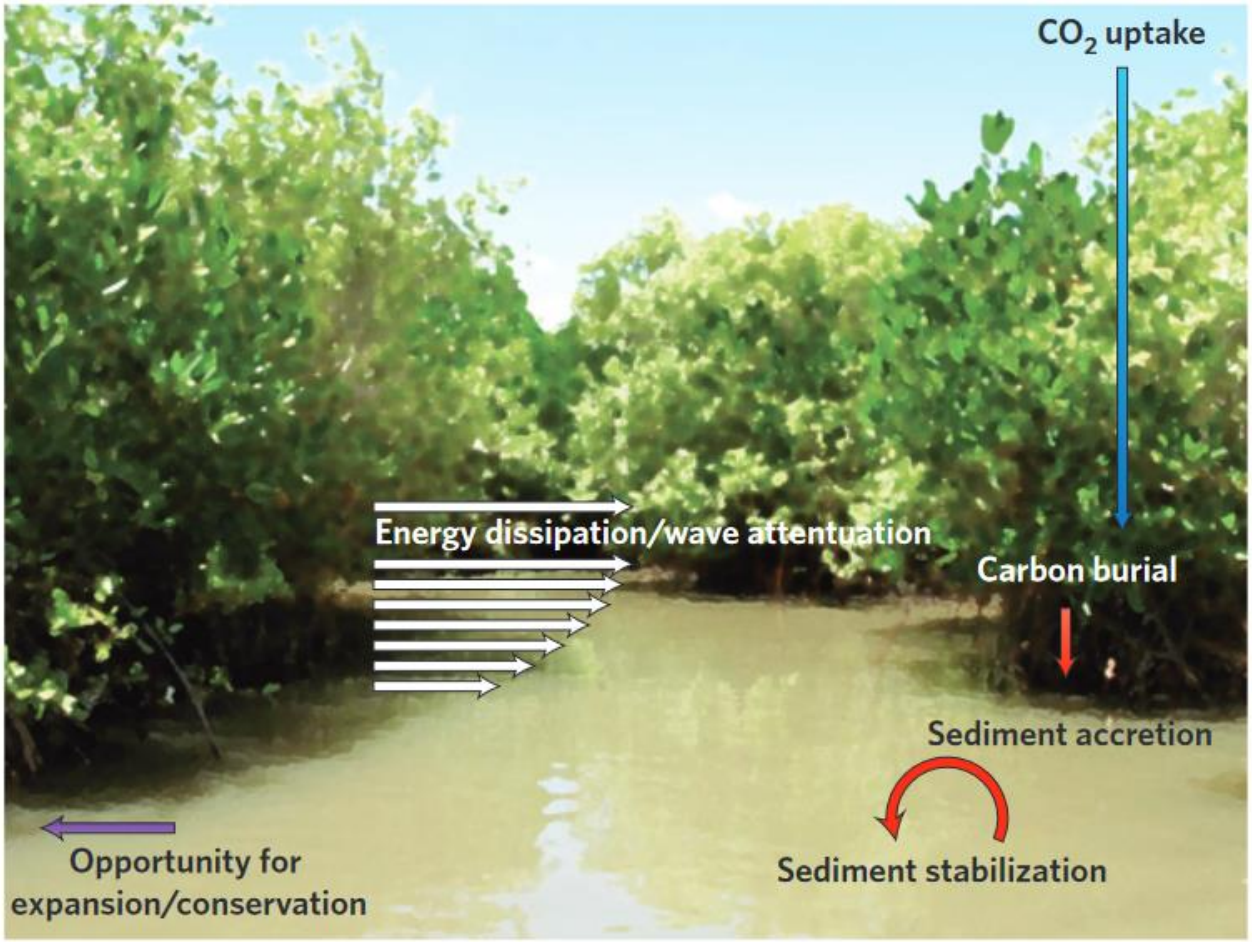
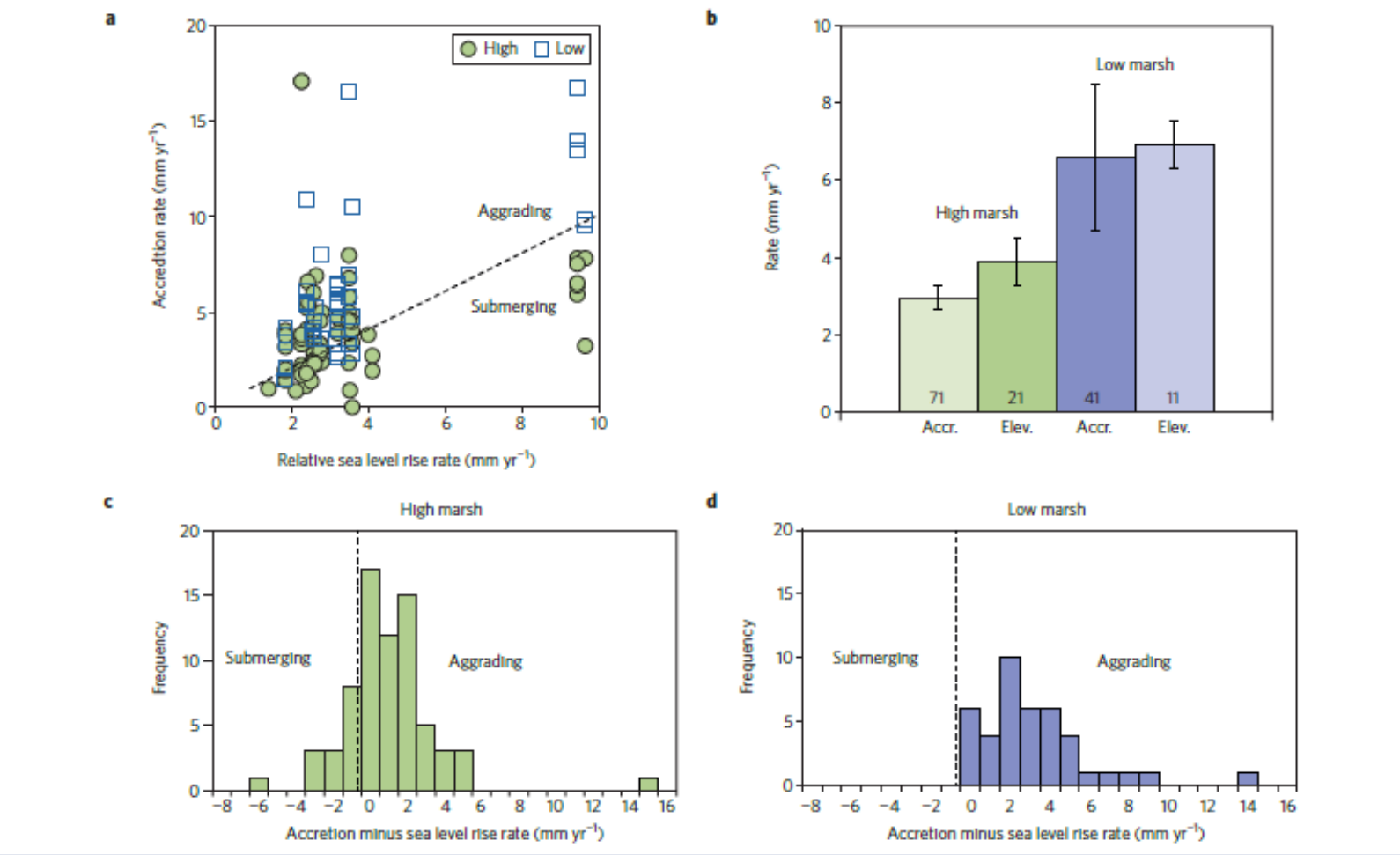
Implications of level rise – land loss + prevention – salt marshes and mangroves



[Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nature Clim Change 3, 961–968. https://doi.org/10.1038/nclimate1970}

Implications of level rise – land loss + prevention – salt marshes and mangroves



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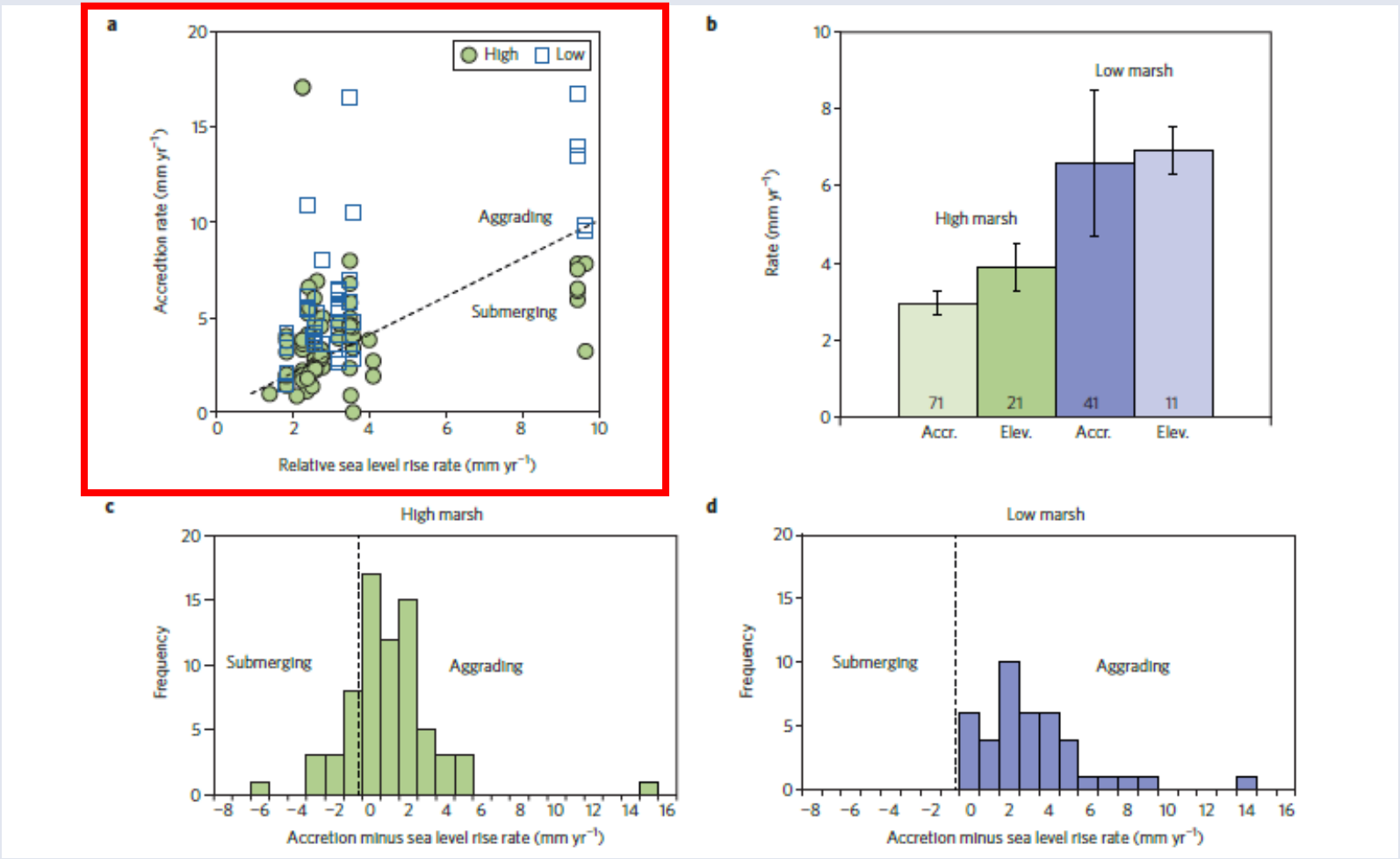

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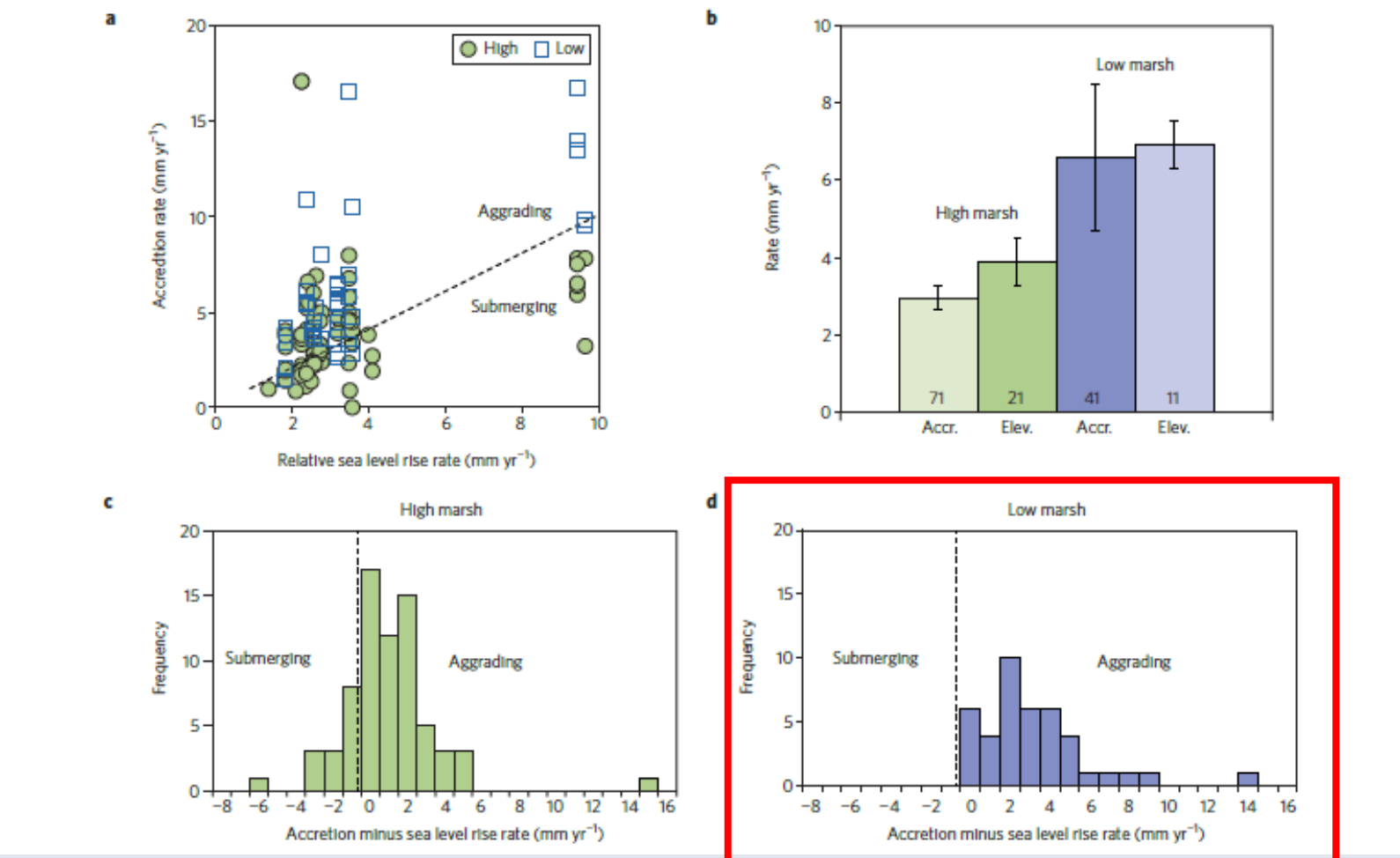

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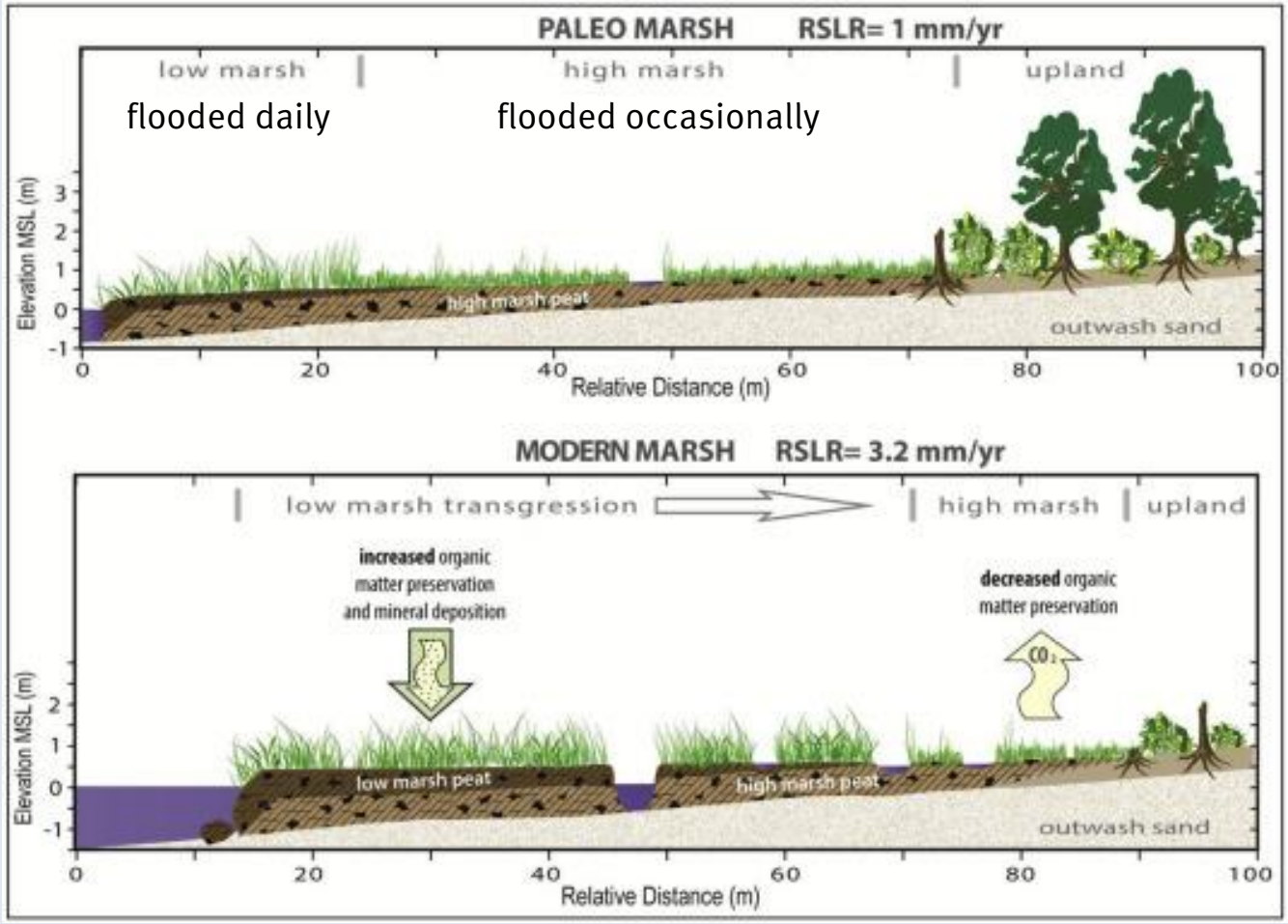
Implications of level rise – land loss + prevention – salt marshes

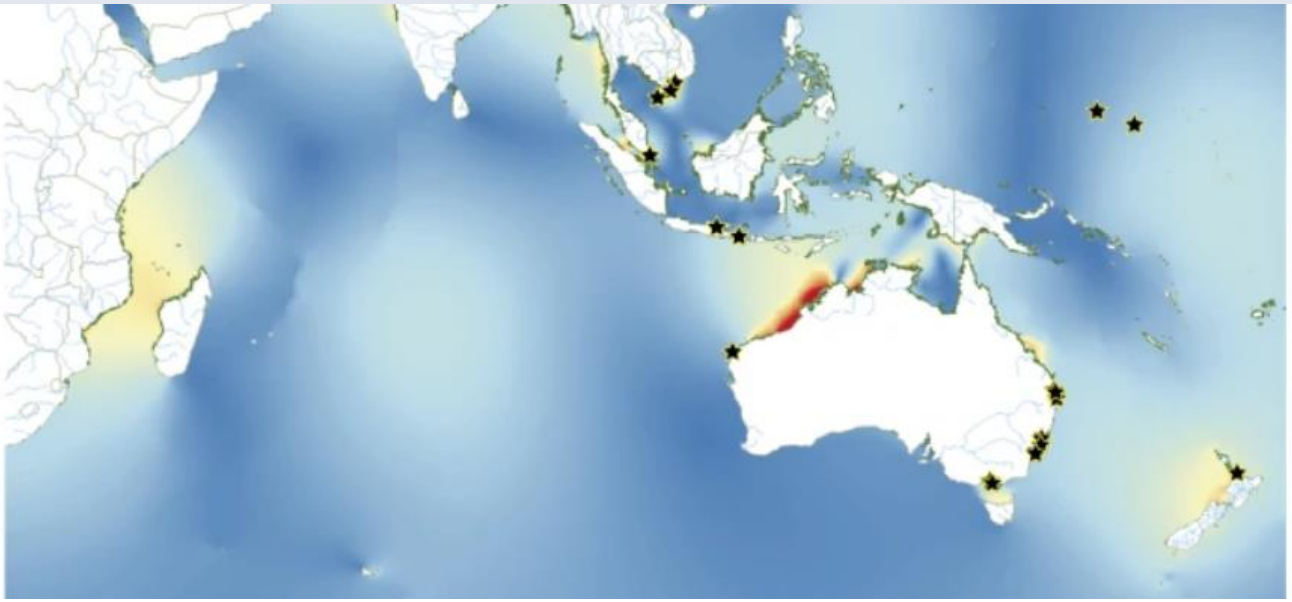


[https://ars.els-cdn.com/content/image/1-s2.0-S0272771418306851-gr6.jpg]

Implications of level rise – land loss + prevention – salt marshes and mangroves

Mangroves can also grow vertically if sea level rises

[Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R., Rogers, K., Saunders, M.L., Sidik, F., Swales, A., Saintilan, N., Thuyen, L.X., Triet, T., 2015. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature 526, 559–563. https://doi.org/10.1038/nature15538]



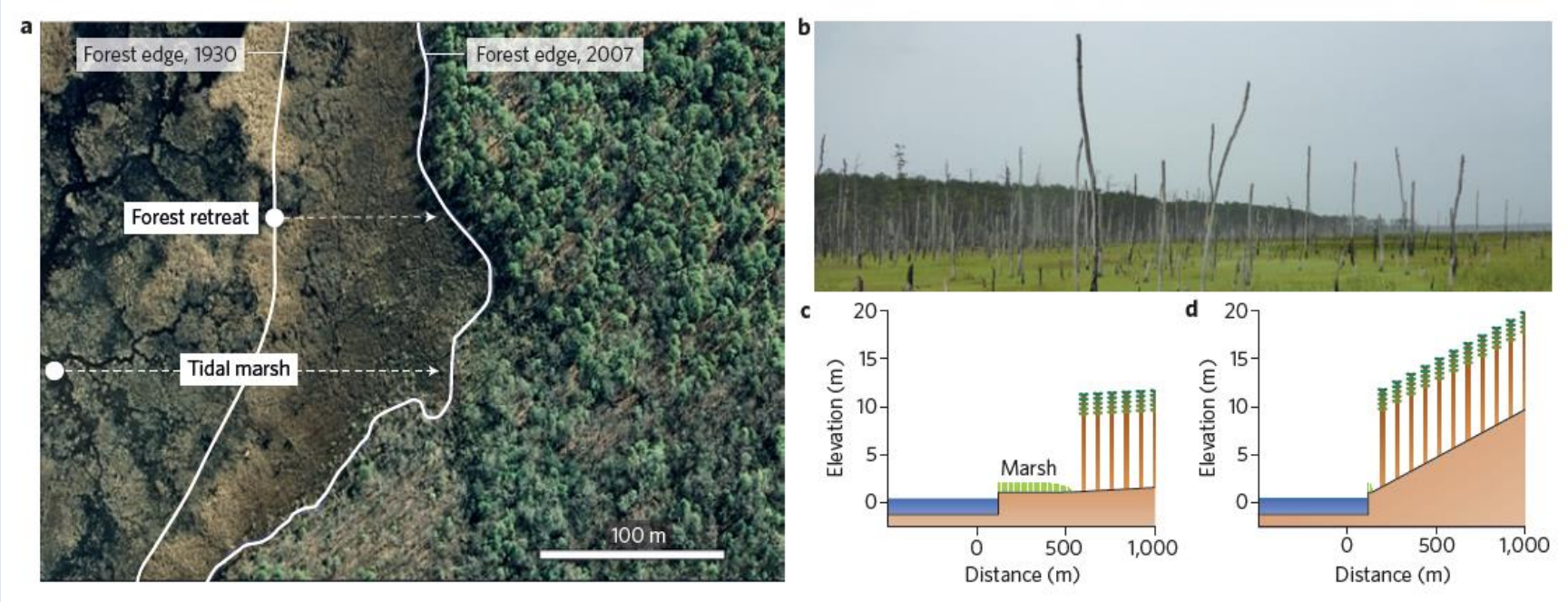
69% of investigated mangroves could not keep pace today

⇒ Depends on

- Tidal range
- Sediment supply
- …

Implications of level rise – land loss + prevention – salt marshes and mangroves

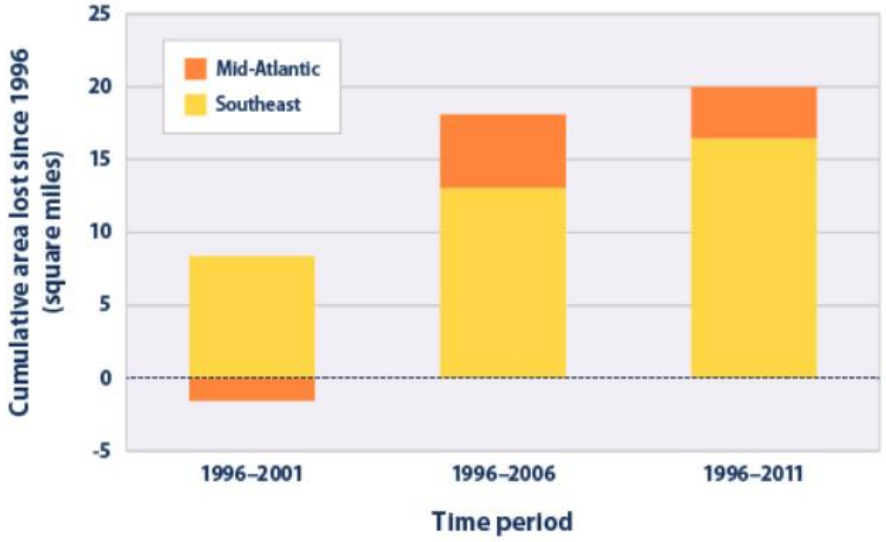
Delaware bay estuary, New Jersey, USA:
Landward migration of salt marshes



[Kirwan, M.L., Temmerman, S., Skeehan, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. Nature Climate Change 6, 253–260.]

Implications of level rise – land loss + prevention – salt marshes and mangroves

Figure 1. Land Loss Along the Atlantic Coast, 1996–2011



Share this indicator:

Web update: May 2014

This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid–Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new land.

Data source: NOAA, 2013 [2]

Key Points

- Roughly 20 square miles of dry land and wetland were converted to open water along the Atlantic coast between 1996 and 2011. (For reference, Manhattan is 33 square miles.) More of this loss occurred in the Southeast than in the Mid–Atlantic (see Figure 1).
- The data suggest that at least half of the

Background

Notes

Data Sources

Technical Documentation

[https://coast.noaa.gov/digitalcoast/stories/atlantic-epa.html]

Implications of level rise – land loss + prevention – salt marshes and mangroves

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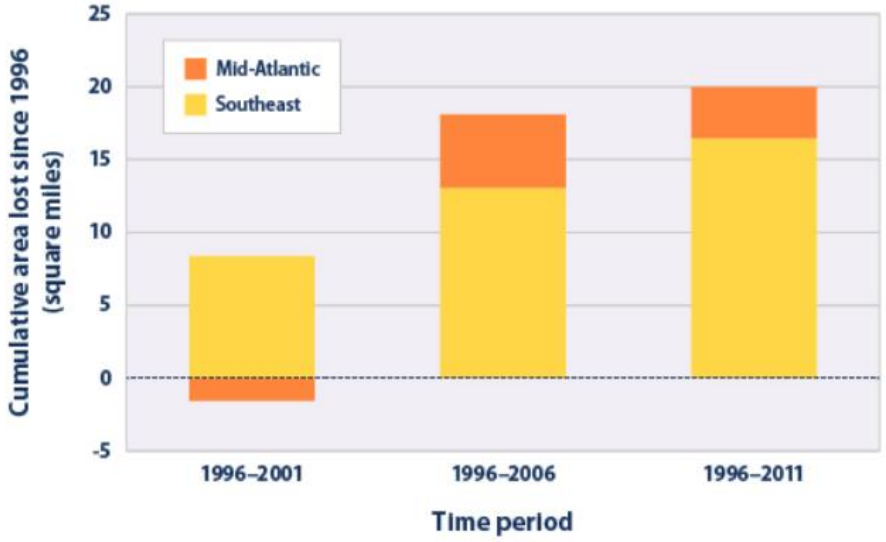

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~15 m on average

2165 miles

[https://coast.noaa.gov/digitalcoast/stories/atlantic-epa.html]

Implications of level rise – land loss + prevention – salt marshes and mangroves

Water pollution can damage salt marshes

(here: Eutrophication by nitrate and phosphate caused algal mats)

[Wasson, K., Jeppesen, R., Endris, C., Perry, D.C., Woolfolk, A., Beheshti, K., Rodriguez, M., Eby, R., Watson, E.B., Rahman, F., Haskins, J., Hughes, B.B., 2017. Eutrophication decreases salt marsh resilience through proliferation of algal mats. Biological Conservation 212, 1–11. https://doi.org/10.1016/j.biocon.2017.05.019]

Implications of level rise – land loss + prevention – salt marshes and mangroves

Shrimp farming

[https://qph.fs.quoracdn.net/main-qimg-b68d60b839e1b540e9e6bb843c31f4a9]

Oil extraction

1-3% of mangroves are lost every year due to anthropogenic destruction

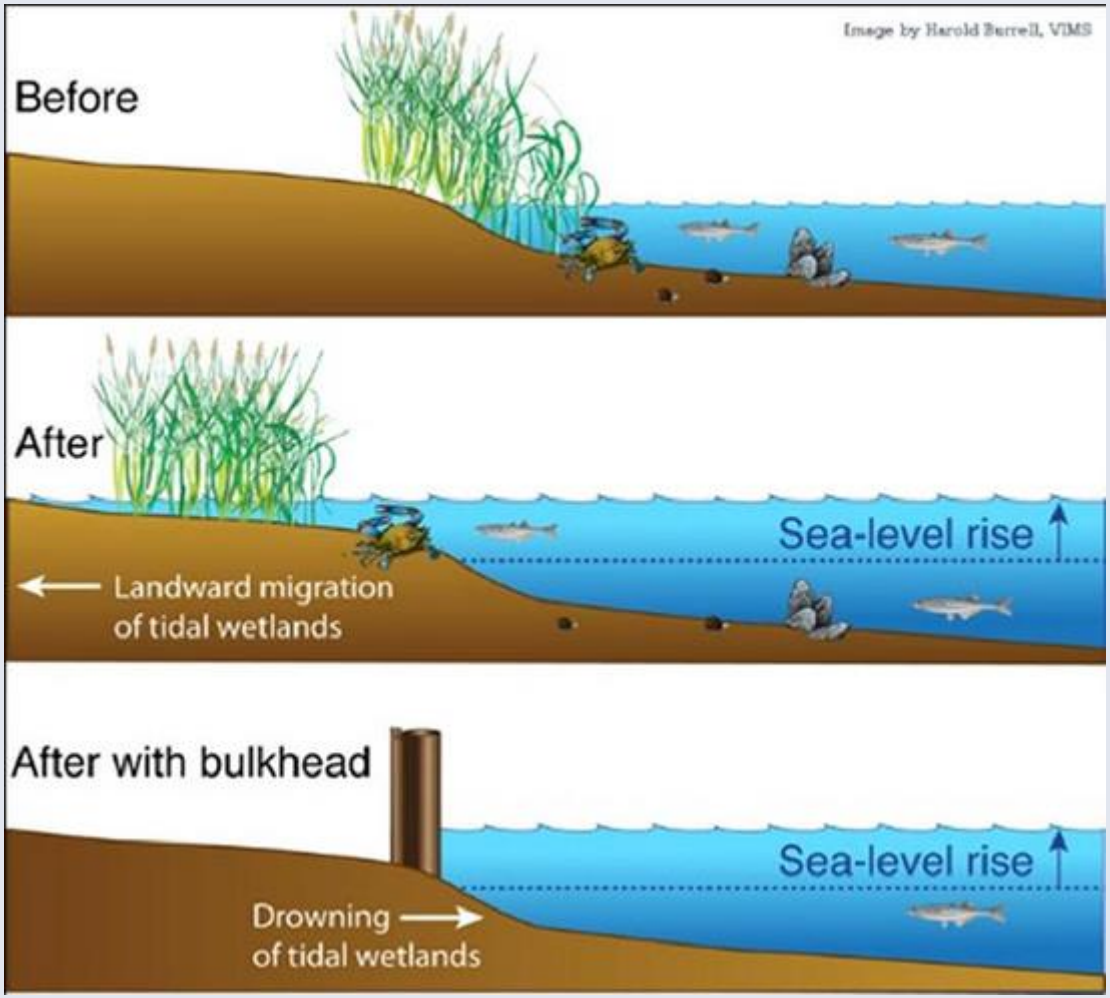
[Duarte et al. 2013}

[https://content.globalforestwatch.org/wp-content/uploads/2019/05/Rob-Oo-1920x1080.jpg]

Implications of level rise – land loss + prevention – salt marshes and mangroves

The principle of „coastal squeeze“:

Hard protection methods lead to habitat loss



[https://media.fisheries.noaa.gov/dam-migration-miss/md_InuILPzBsk67.jpg?1560546154]

Implications of level rise – land loss + prevention – engineered coasts

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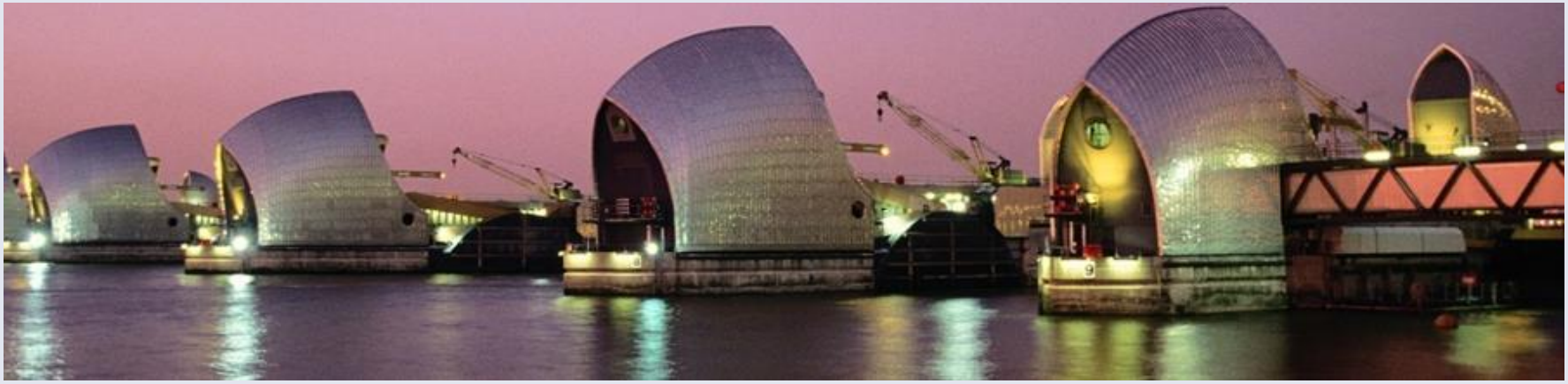
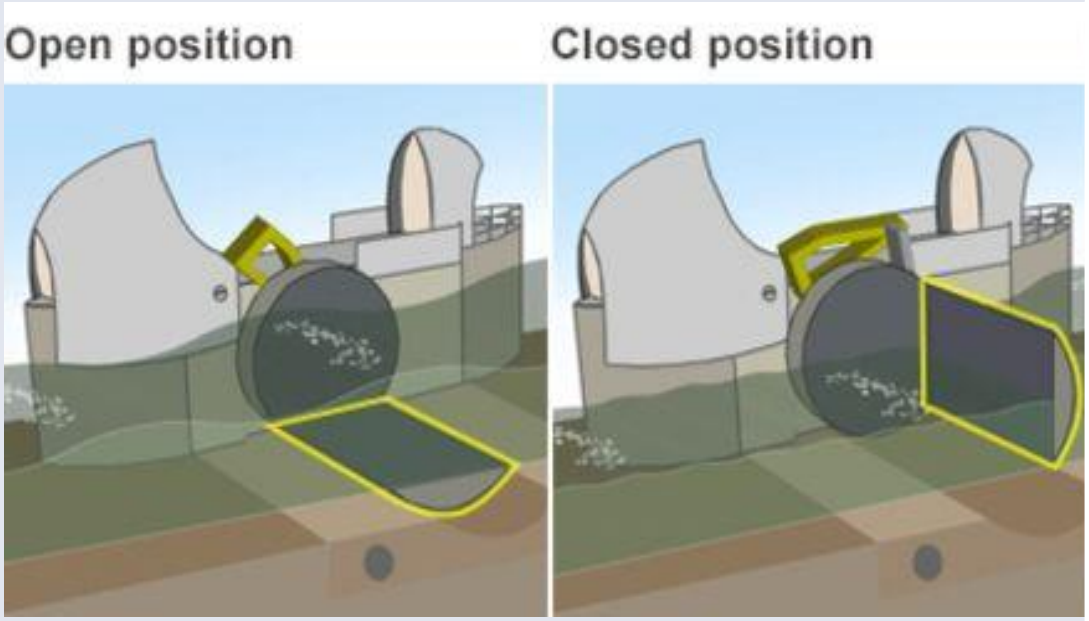
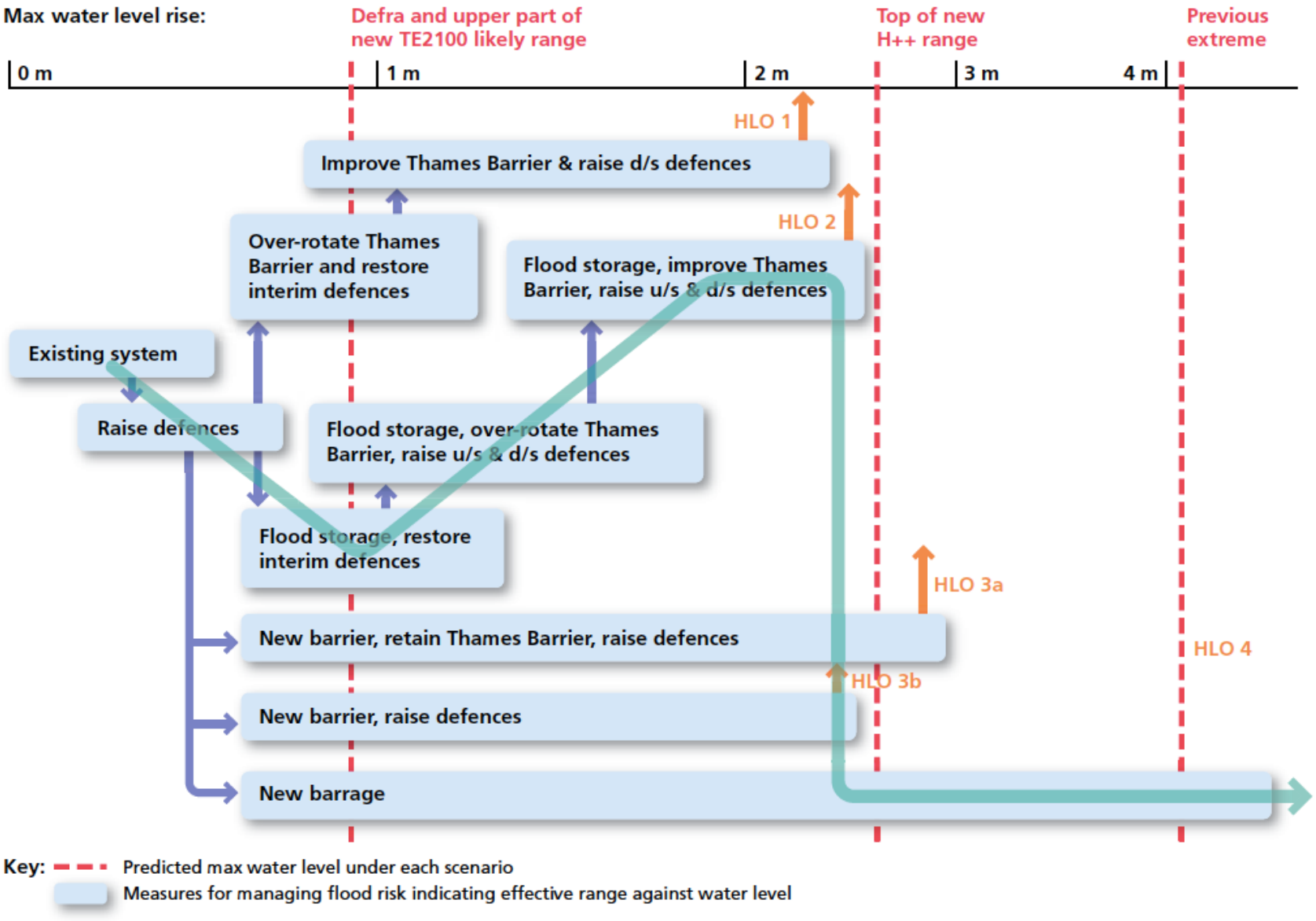




Implications of level rise – land loss + prevention – engineered coasts



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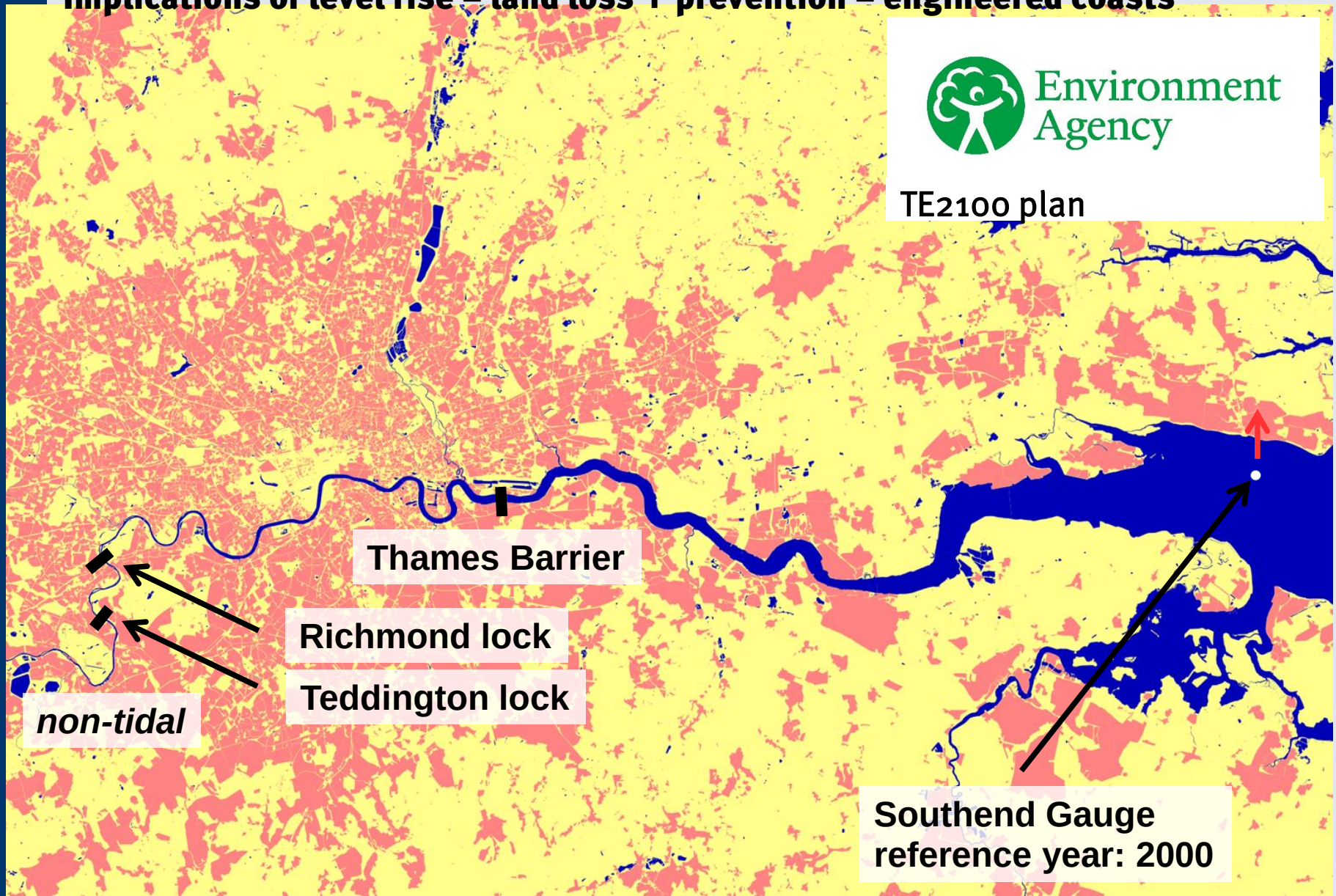
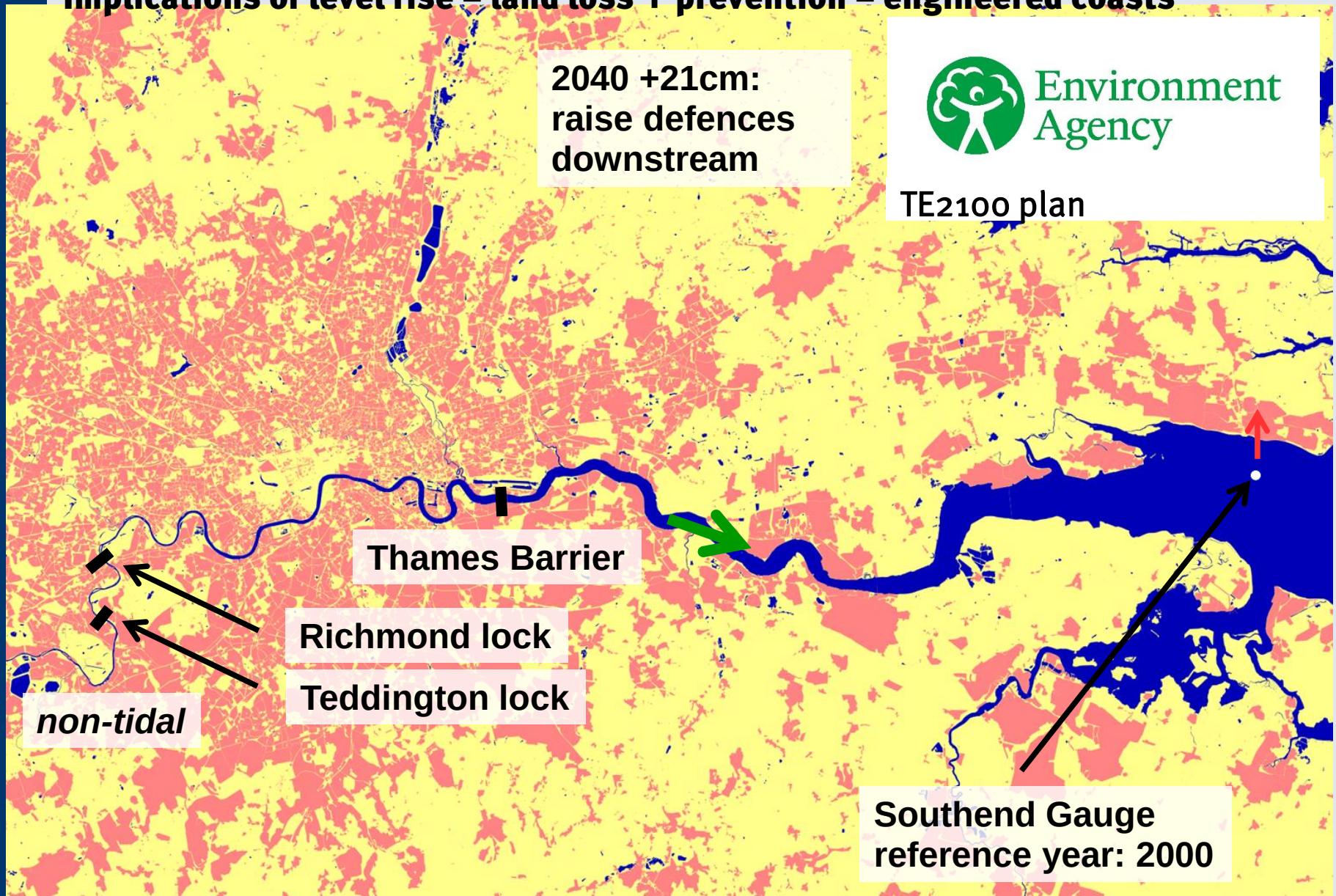


Implications of level rise – land loss + prevention – engineered coasts



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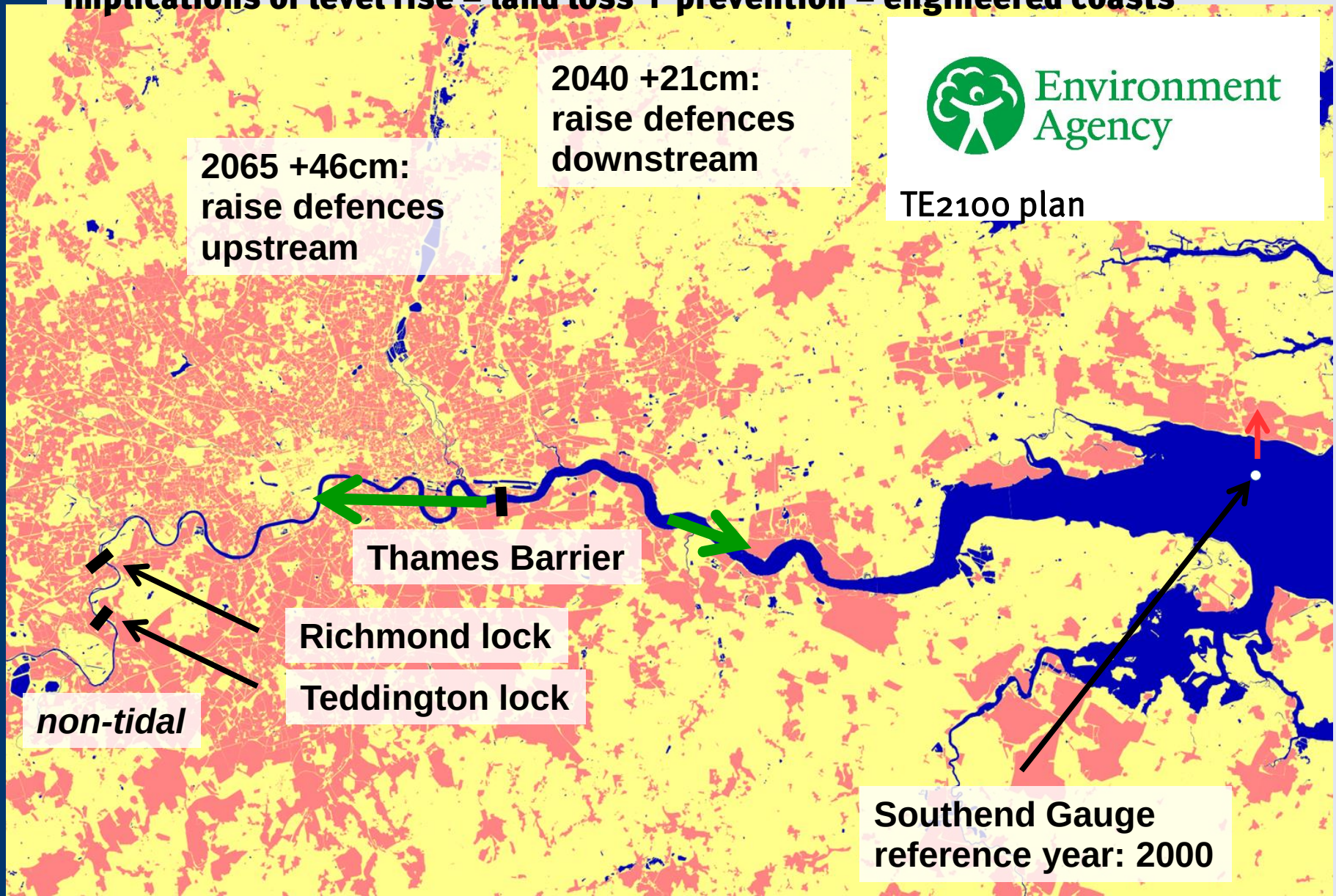
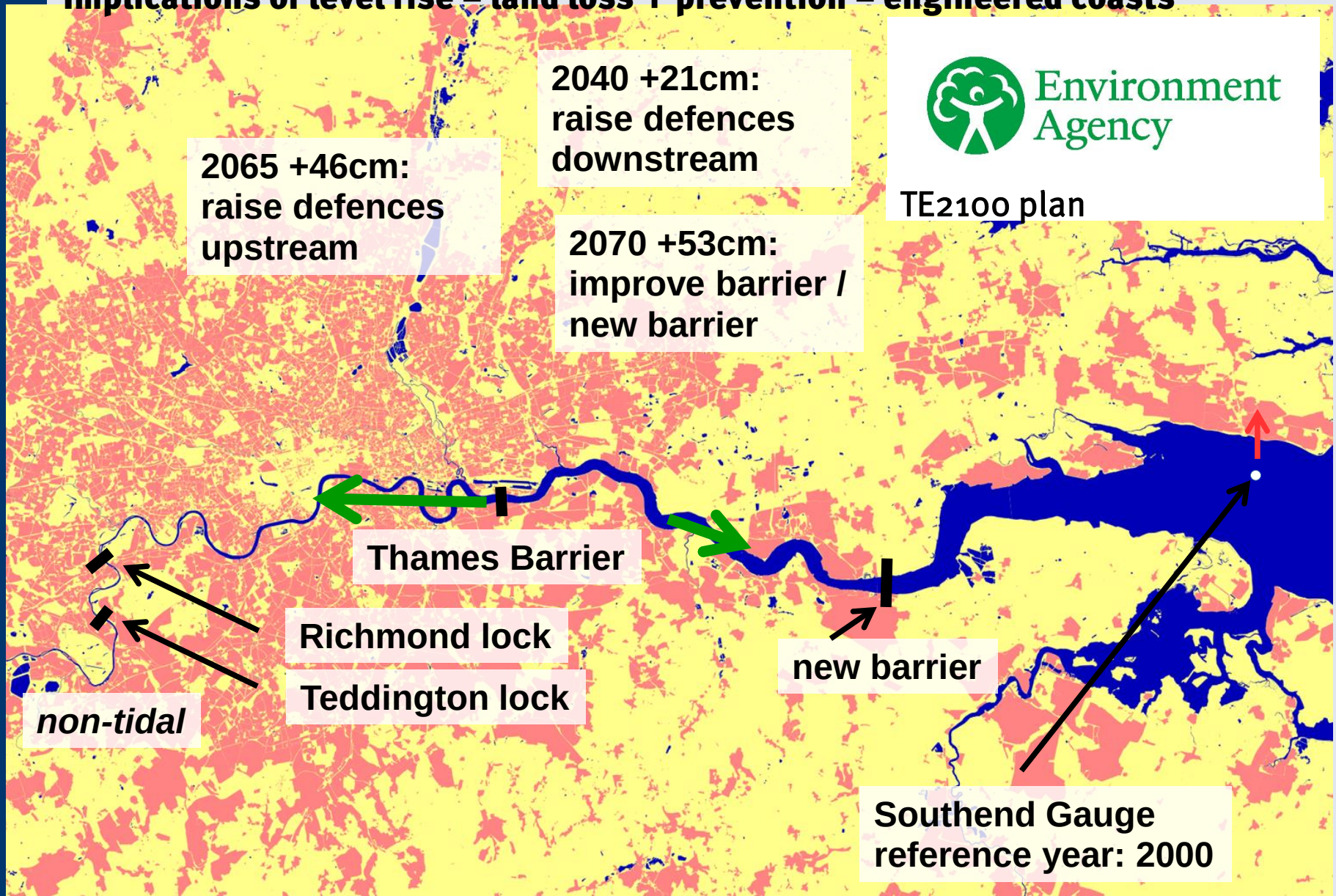


Implications of level rise – land loss + prevention – engineered coasts



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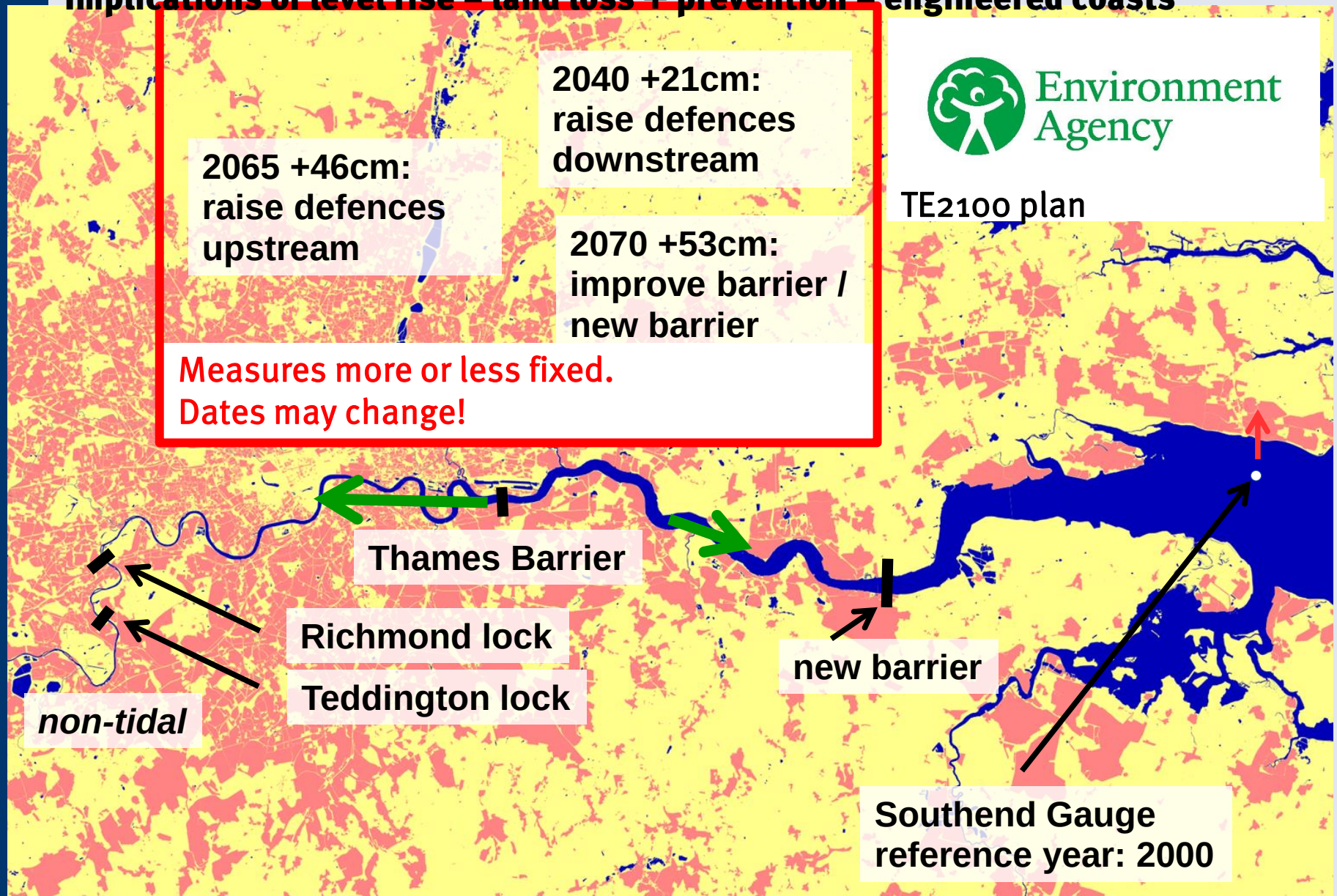
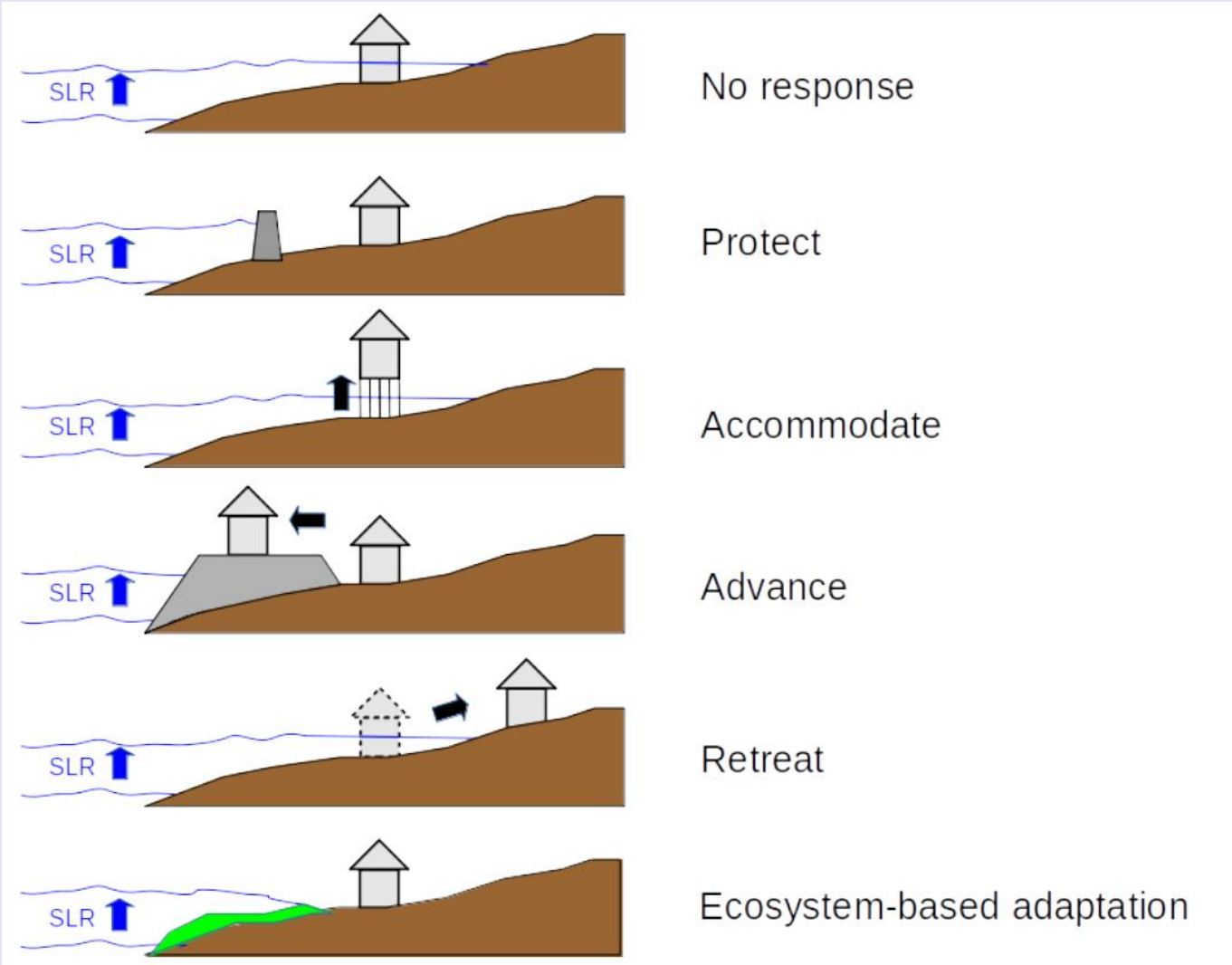


Implications of level rise – societal response



[https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_Chapter4.pdf]

Implications of level rise – „Sinking cities“ as a look into the future

[Esteban, M. Adapting to Sea Level Rise: Real Lessons from Land Subsidence in Japan, Indonesia and the Philippines. International WCRP/IOC conference on Regional Sea Level Changes and Coastal Impacts, 2017.]

Implications of level rise – „Sinking cities“ as a look into the future

Ubay, Phillipines
Earthquake in 2013
Land dropped by 1 m

- Before earthquake: Flooded during strong typhoons
- After earthquake: Completely flooded during spring tides (e.g. 1 hour daily floods for 1 week around new and full moon)

[Esteban, M. Adapting to Sea Level Rise: Real Lessons from Land Subsidence in Japan, Indonesia and the Philippines. International WCRP/IOC conference on Regional Sea Level Changes and Coastal Impacts, 2017.]

Implications of level rise – „Sinking cities“ as a look into the future

Ubay, Phillipines
Earthquake in 2013
Land dropped by 1 m

- Before earthquake: Flooded during strong typhoons
- After earthquake: Completely flooded during spring tides (e.g. 1 hour daily floods for 1 week around new and full moon)

[https://www.theguardian.com/world/2019/feb/01/enduring-the-tide-the-flooded-philippine-islands-that-locals-wont-leave]

Implications of level rise – „Sinking cities“ as a look into the future

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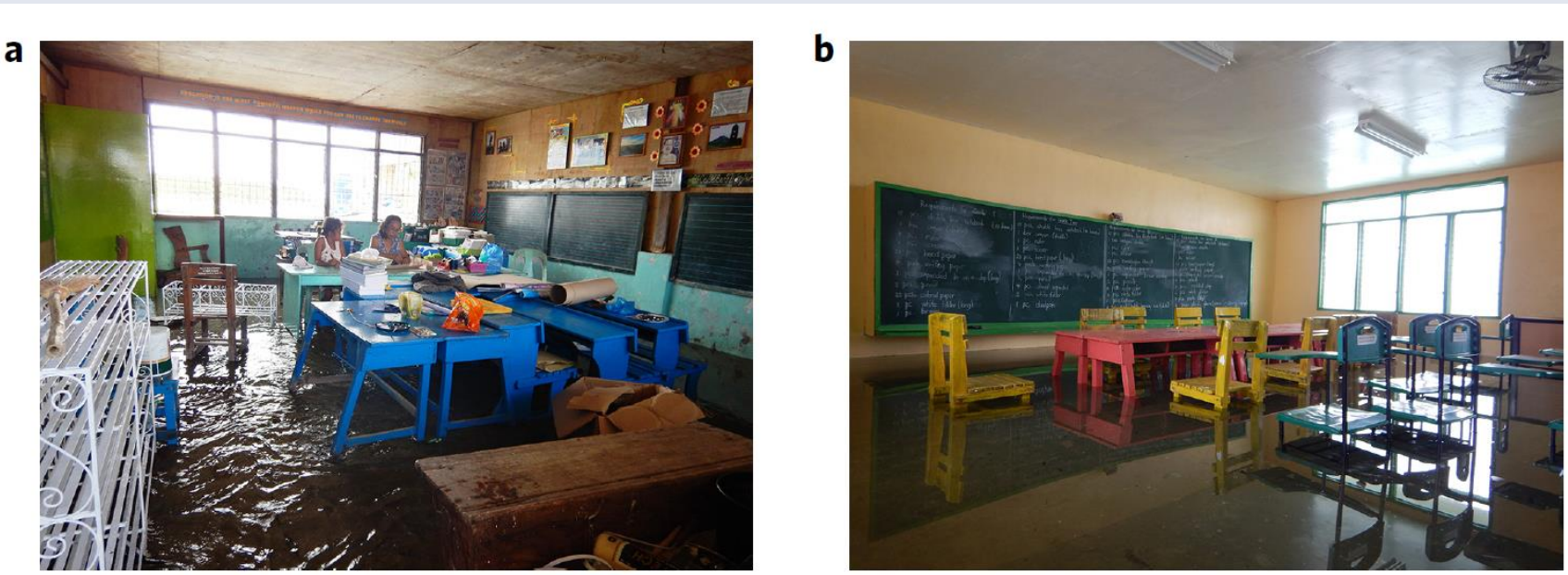
Implications of level rise – „Sinking cities“ as a look into the future

Schools in Pangapasan and Ubay during a high-tide flooding event in 2016



[Laurice Jamero, Ma., Onuki, M., Esteban, M., Billones-Sensano, X.K., Tan, N., Nellas, A., Takagi, H., Thao, N.D., Valenzuela, V.P., 2017. Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. Nature Clim Change 7, 581–586. https://doi.org/10.1038/nclimate3344]

Implications of level rise – „Sinking cities“ as a look into the future

Adaptation strategies on the nearby island of Batasan

[Esteban, M. Adapting to Sea Level Rise: Real Lessons from Land Subsidence in Japan, Indonesia and the Philippines. International WCRP/IOC conference on Regional Sea Level Changes and Coastal Impacts, 2017.]

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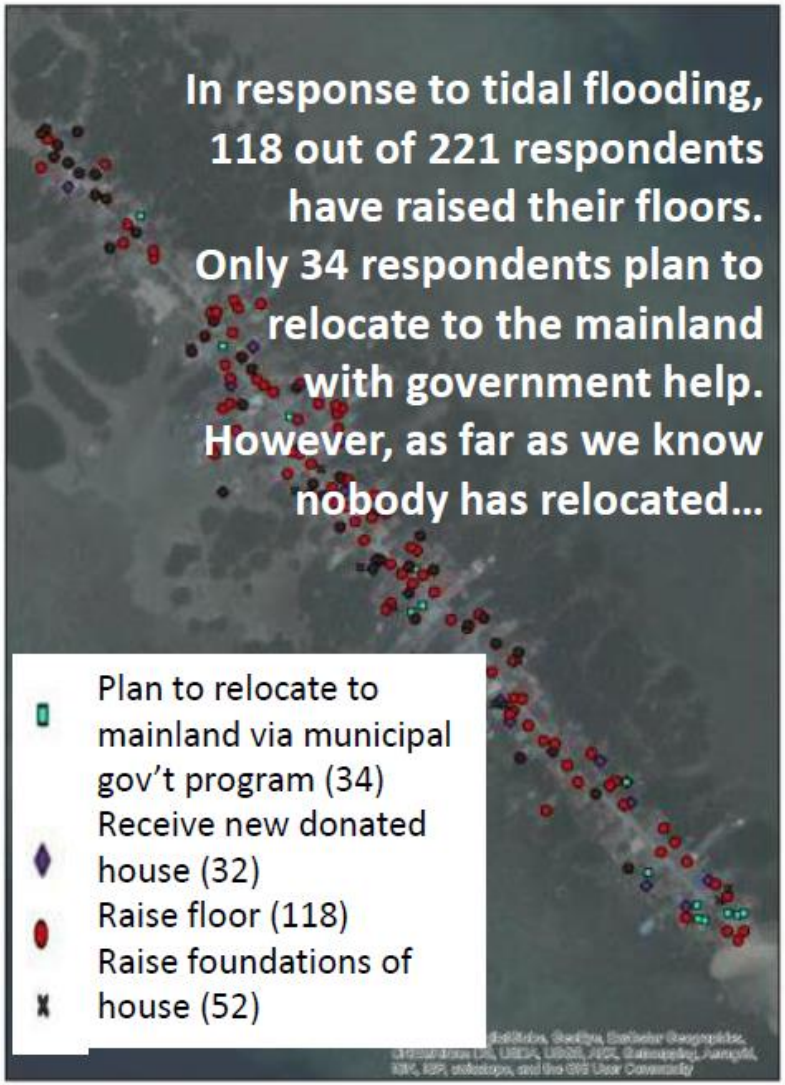
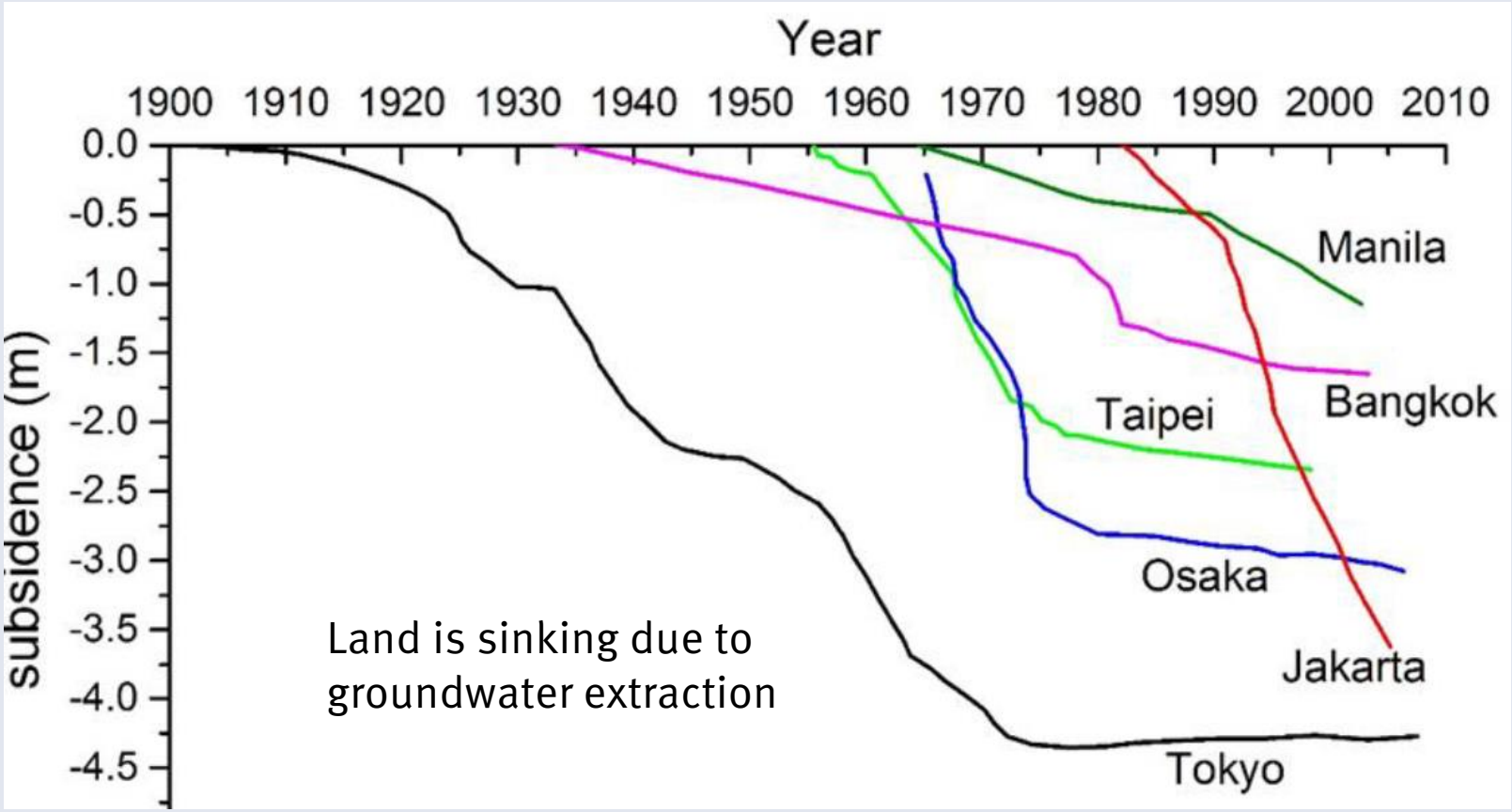


Implications of level rise – „Sinking cities“ as a look into the future



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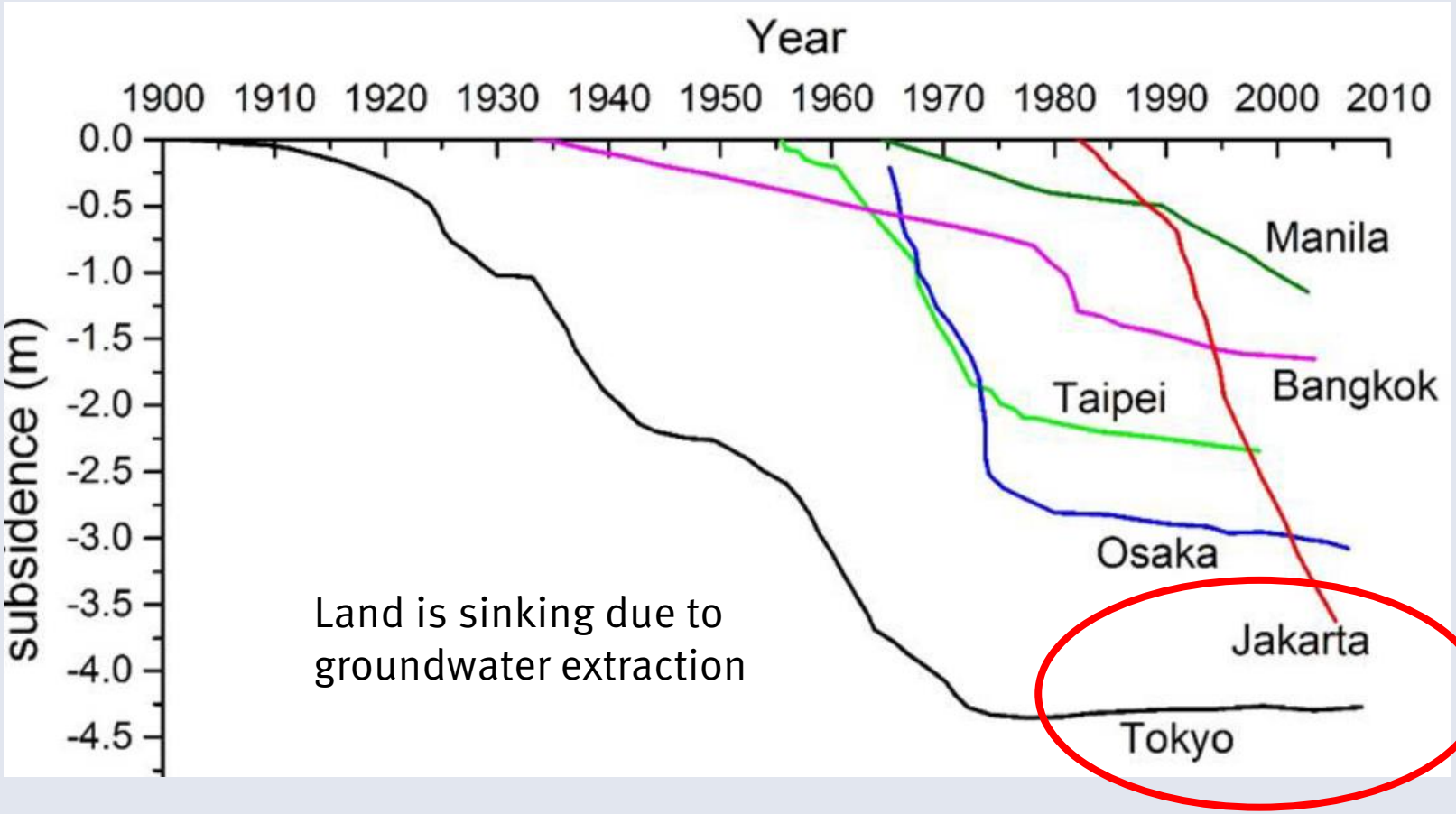

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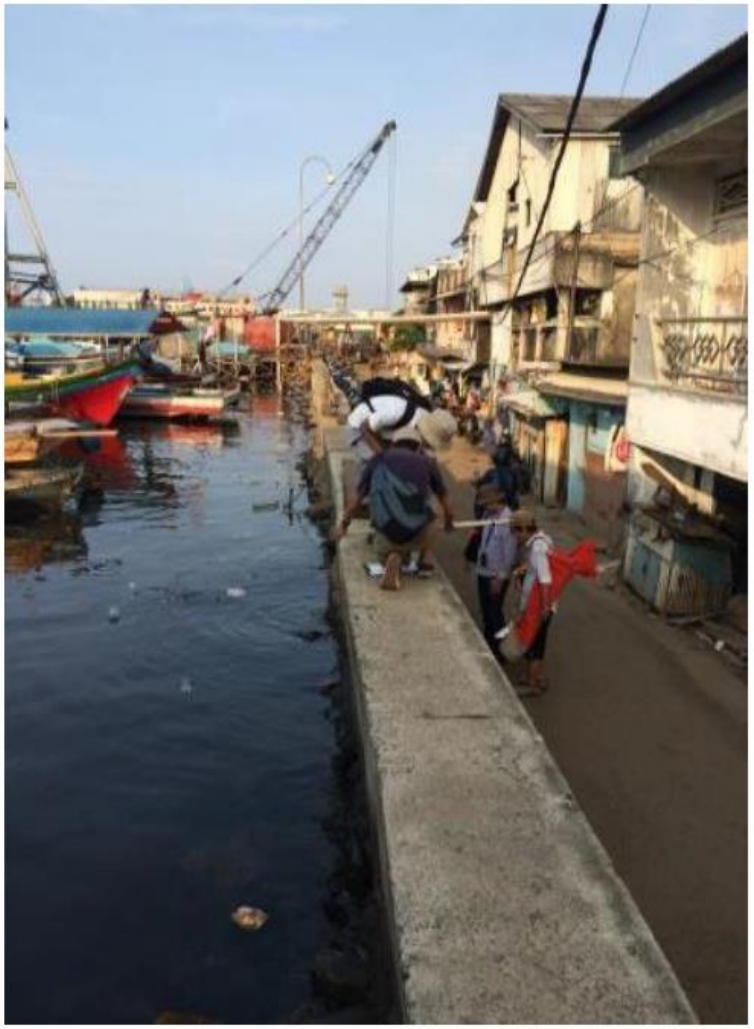

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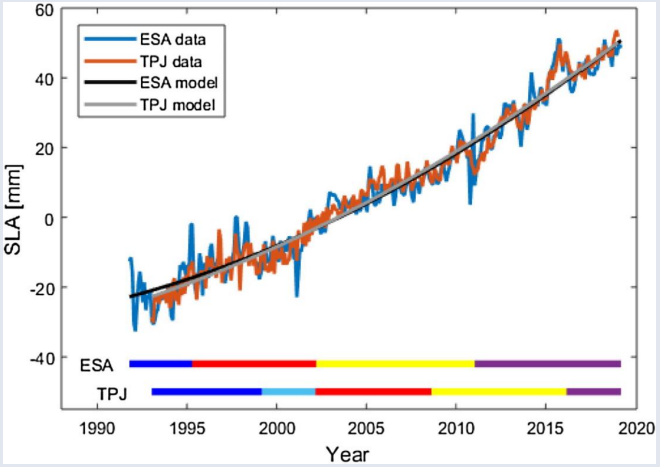
Implications of level rise – „Sinking cities“ as a look into the future

Tokyo

[Esteban, M. Adapting to Sea Level Rise: Real Lessons from Land Subsidence in Japan, Indonesia and the Philippines. International WCRP/IOC conference on Regional Sea Level Changes and Coastal Impacts, 2017.]

Summary 1 / 3

Sea level has risen by ~16 cm since 1900 and is rising faster today (almost 4 mm/year)



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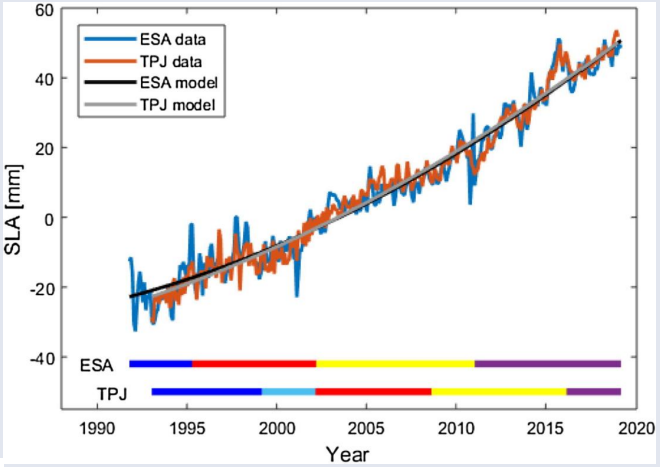

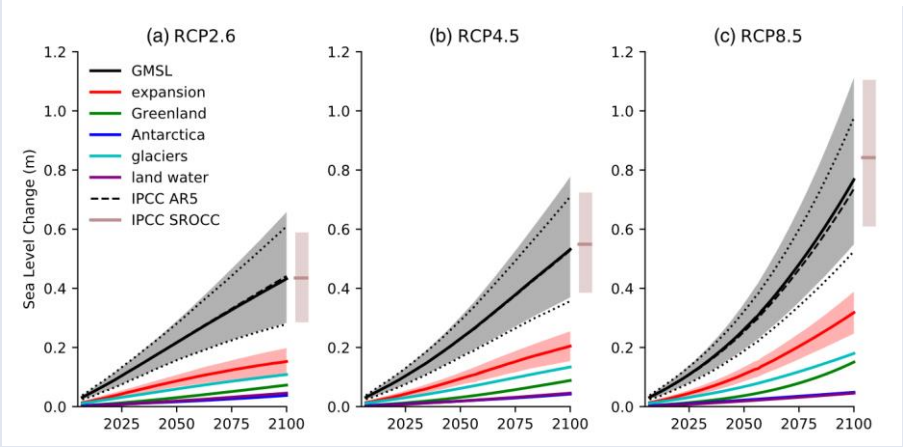

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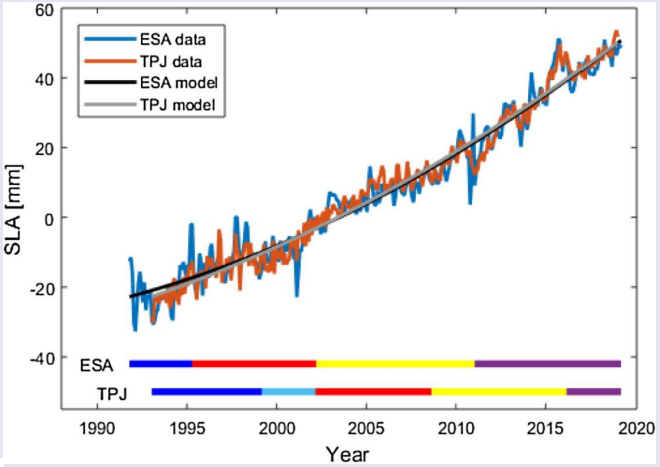

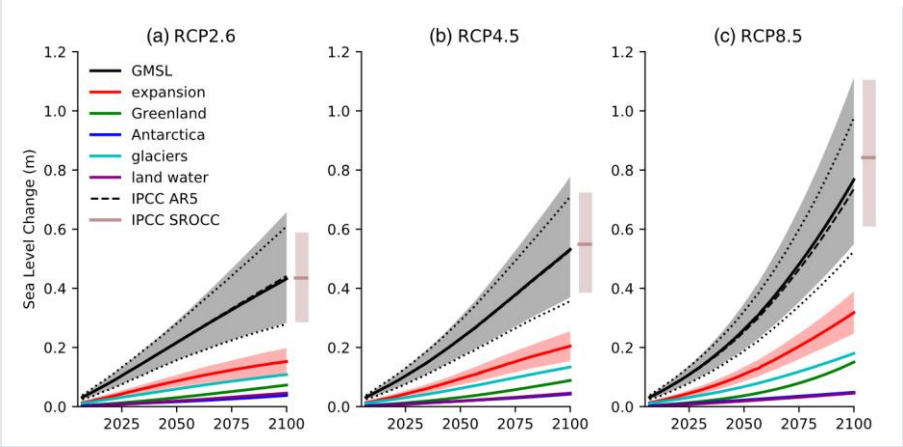

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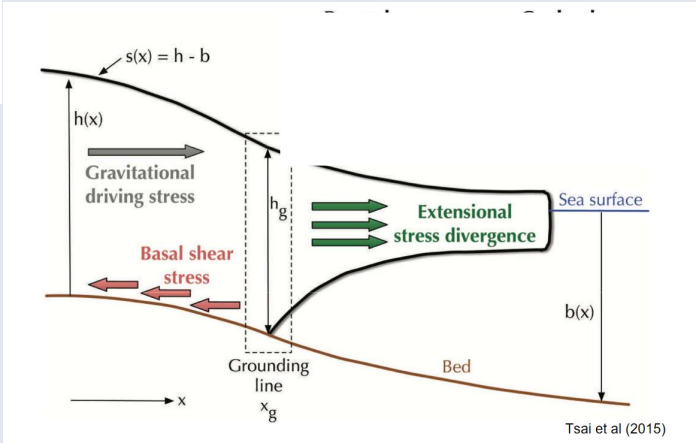
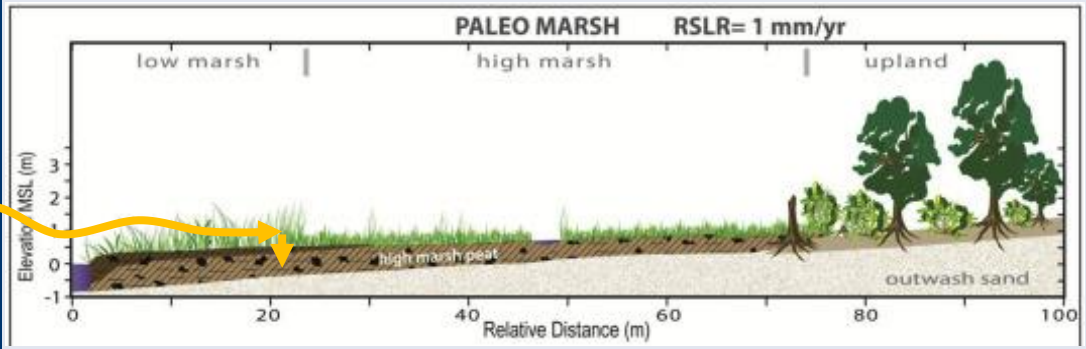
Large uncertainties arise from the unknown melting rate of the Antarctic ice

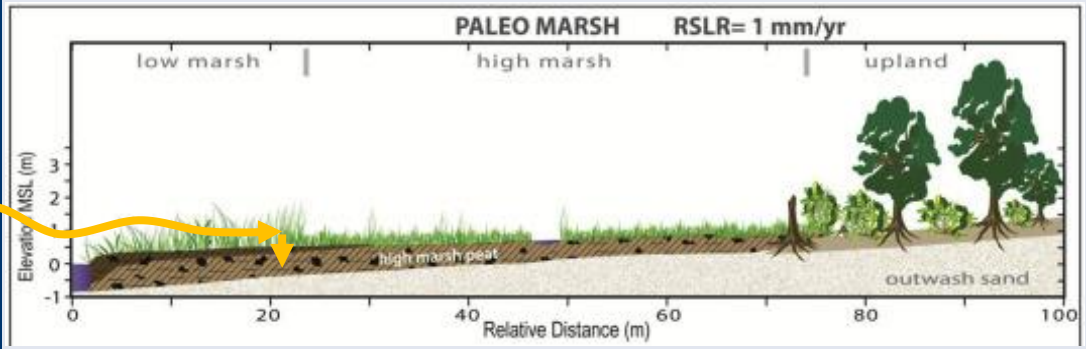


Summary 2 / 3



If sea level rise is slow enough, a lot of natural coasts (beaches, salt marshes, mangroves) can grow with the rising sea level

Summary 2 / 3



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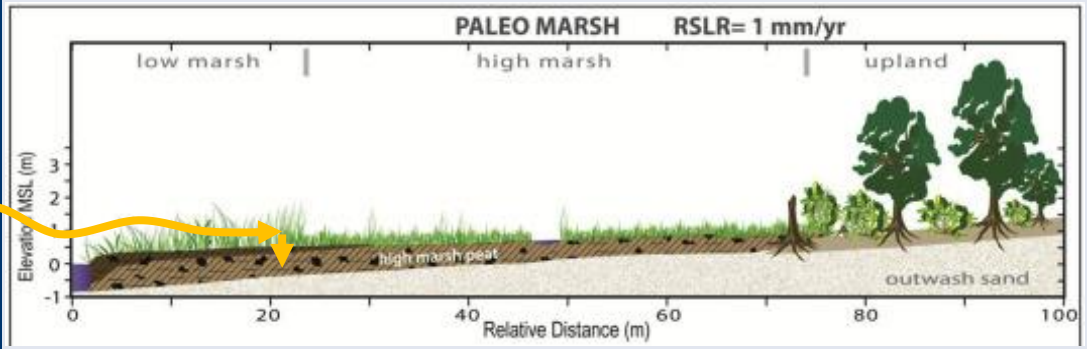
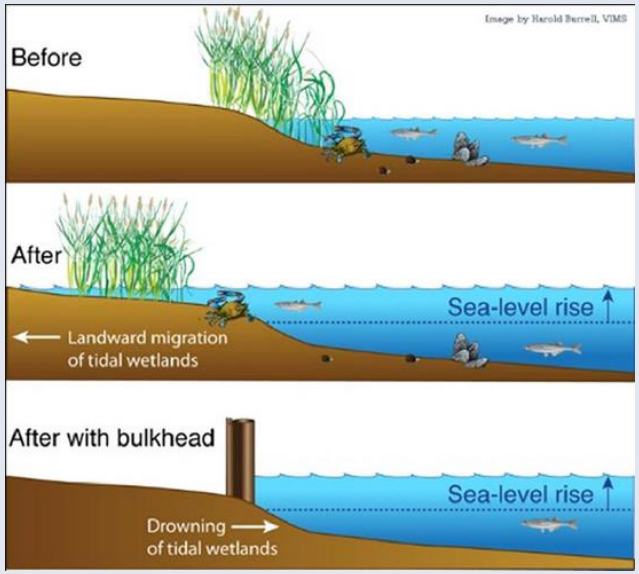


If sea level rise is slow enough, a lot of natural coasts (beaches, salt marshes, mangroves) can grow with the rising sea level

Additional human-induced pressures may, however, lead to the destruction of these environments

Very different effects between rich countries (can afford protection) and poor countries (cannot).

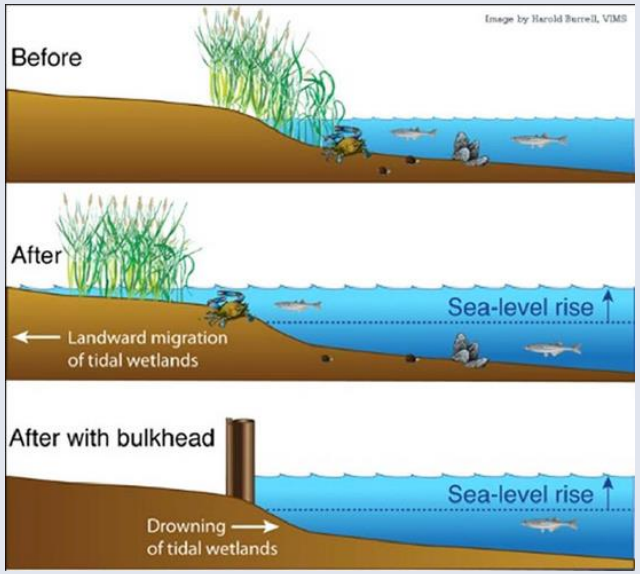
Summary 3 / 3



Landward migration of coastal ecosystems can be hindered by hard protection measures

=› „coastal squeezing“

Summary 3 / 3



Landward migration of coastal ecosystems can be hindered by hard protection measures

=› „coastal squeezing“

Examples of sinking land provide a „look into the future“:

Coastal residents will not easily relocate but rather accept a higher risk

Thank you!