

Tendances et variabilité multidécennale des composantes des niveaux marins extrêmes : niveau moyen, marée et surcotes

*Julie CHEYNEL (Shom), Lucia PINEAU-GUILLOU (Créocéan), Pascal
LAZURE (Ifremer / LOPS)*

Introduction

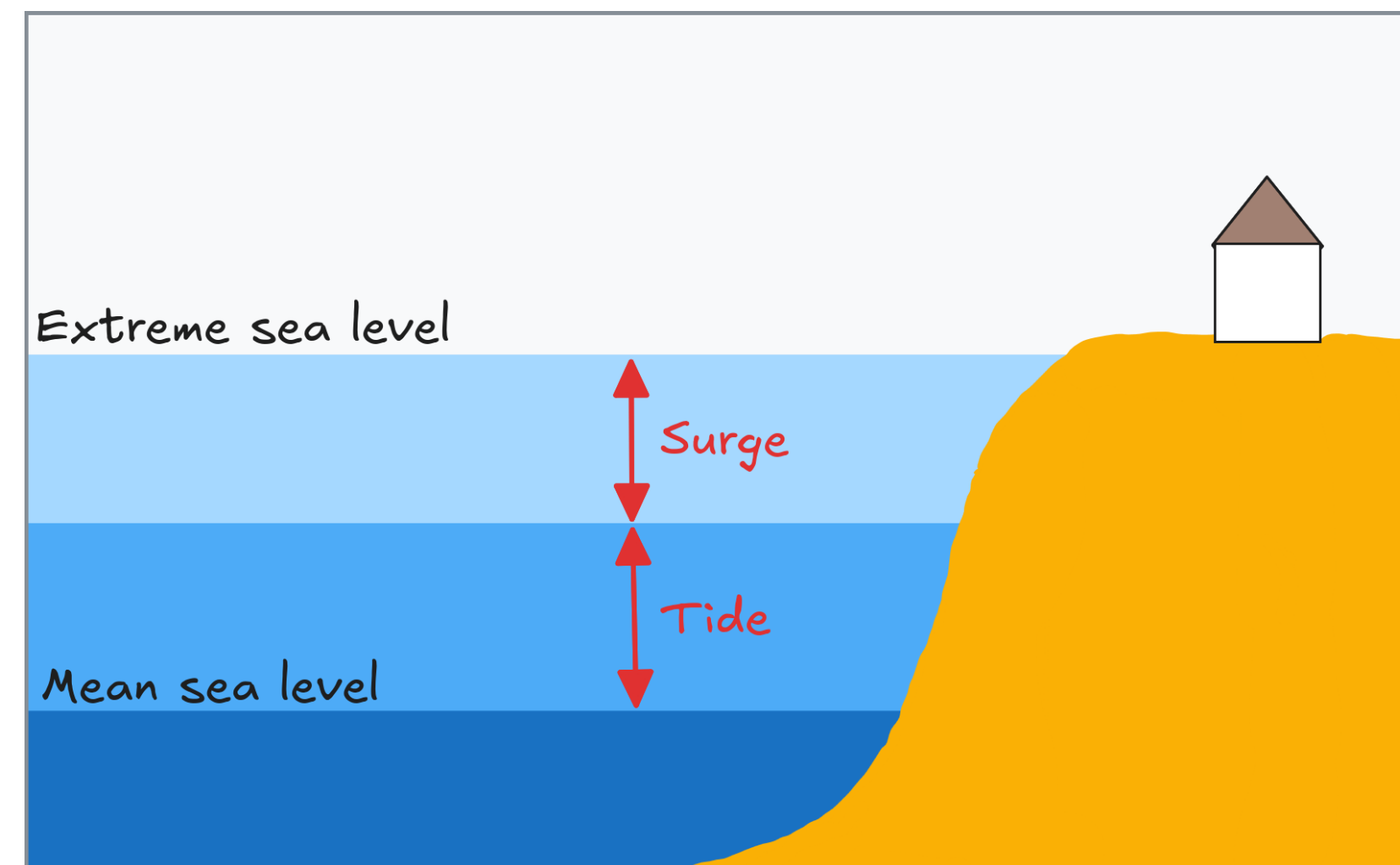
Hazards associated with coastal extreme sea levels are increasing:

- Rising intensity and frequency of extreme sea levels (*IPCC, 2021*)
- Growing population in coastal areas (~ 900 million people in 2020, *Reimann et al., 2023*)



Storm Xynthia,
Bay of Biscay, 2010

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**Extreme Sea Levels (ESLs) =
Mean Sea Level (MSL) + Tide + Surge**

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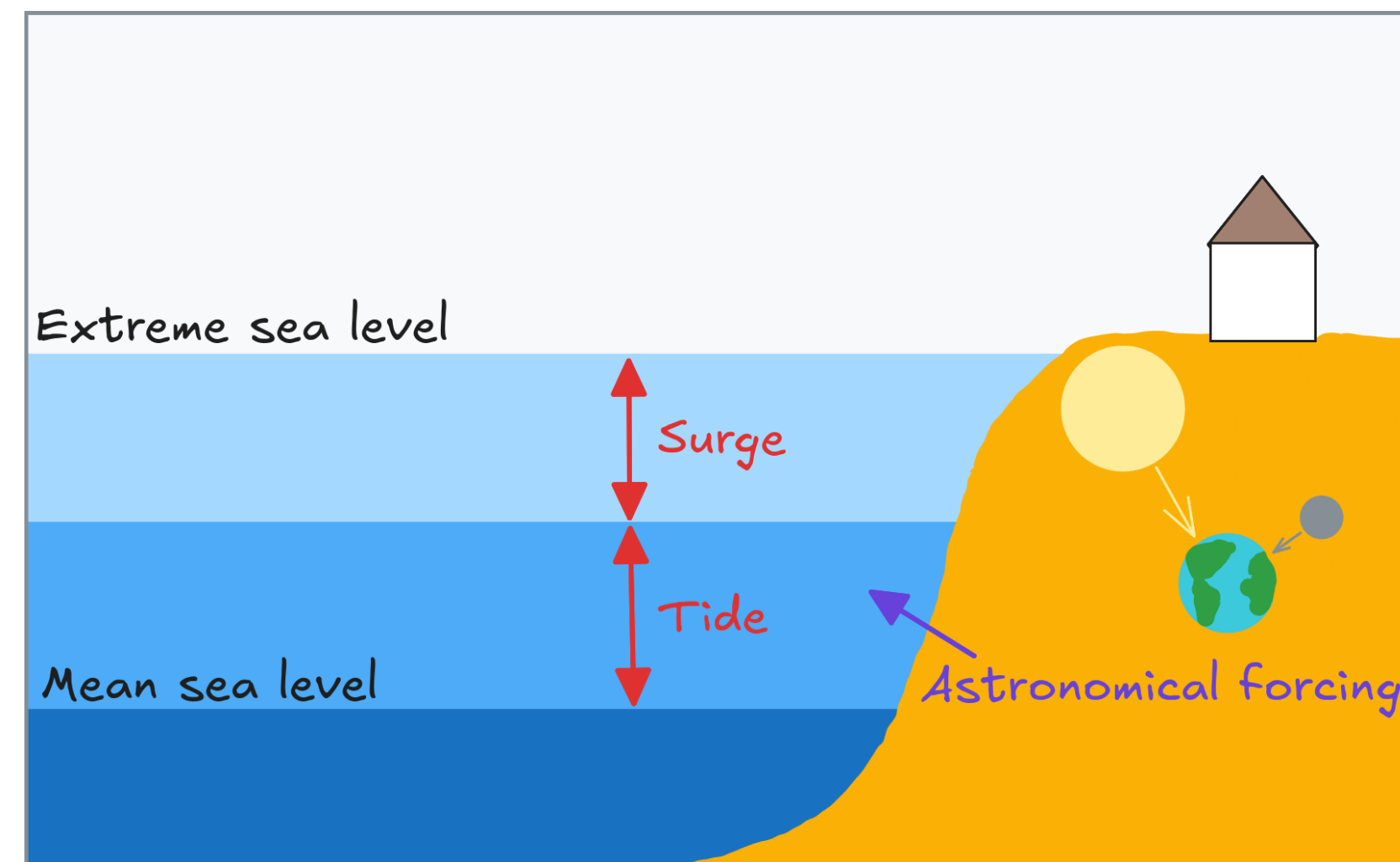
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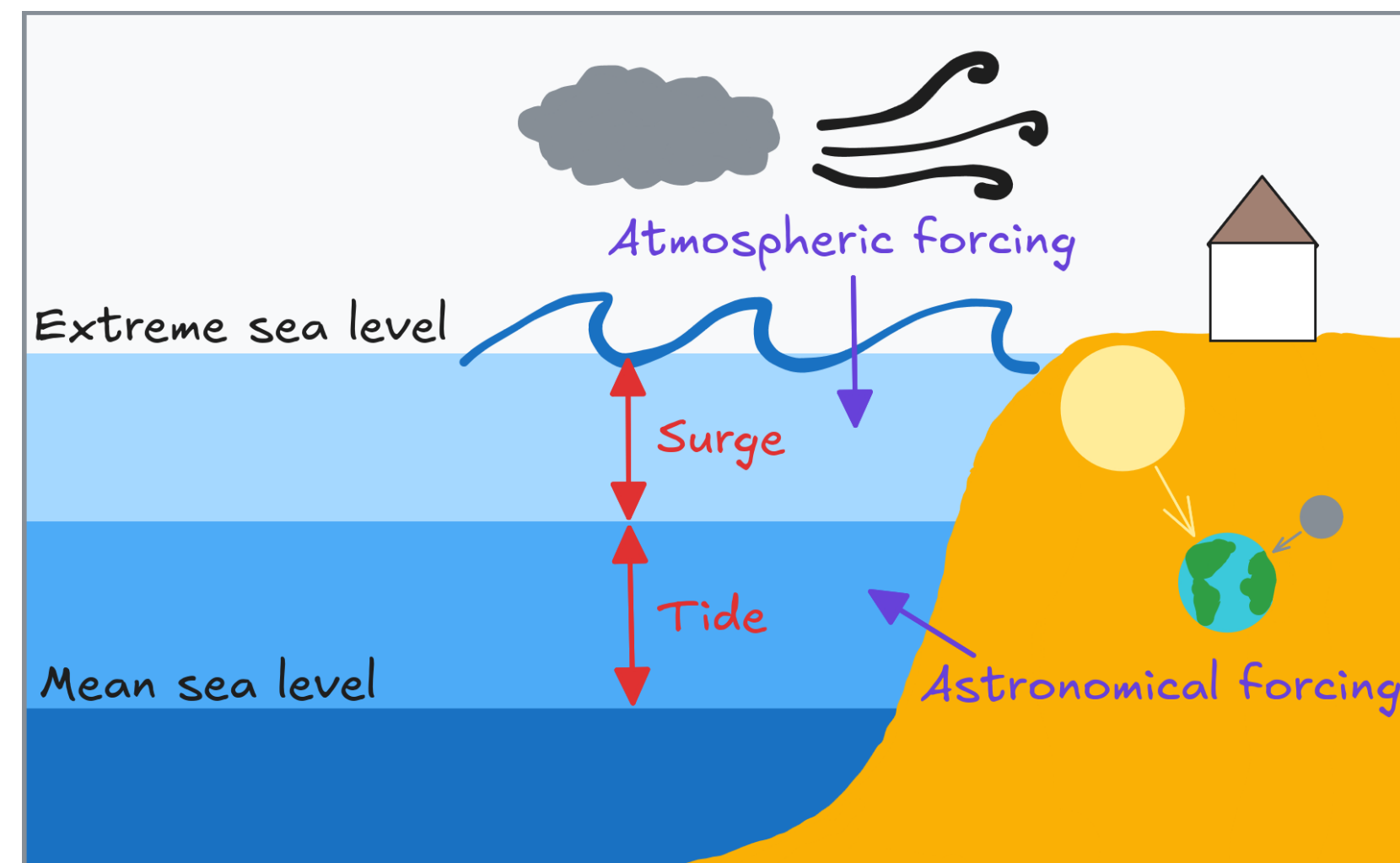
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**Extreme Sea Levels (ESLs) =
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State of the art

Mean sea level rise = main reason of the increase in ESLs (e.g. *Menéndez & Woodworth, 2010; Marcos & Woodworth, 2017*)

- Global MSL: + 20 cm over 1901–2018 (*Oppenheimer et al., 2019*)
- Acceleration: 3.7 mm/year over 2006–2018 vs 1.5 mm/year over 1902–2010 (*Oppenheimer et al., 2019*)
- Subsidence can amplify extreme sea levels

But any changes in tide or storm surges can also impact ESLs

- Significant trends in several regions (e.g. *Ray and Talke, 2019; Haigh et al., 2020; Menéndez and Woodworth, 2010; Marcos and Woodworth, 2017*), often smaller, but sometimes of the same order of magnitude than MSL trends (e.g. *Talke et al., 2014; Familkhalili and Talke, 2016; Calafat et al., 2022*)
- Large multidecadal variability, often associated with large-scale climate patterns (NAO, AMO, etc.) (e.g. *Wahl and Chambers, 2016; Pineau-Guillou et al., 2021; Cheynel et al., 2025*)

Objectives

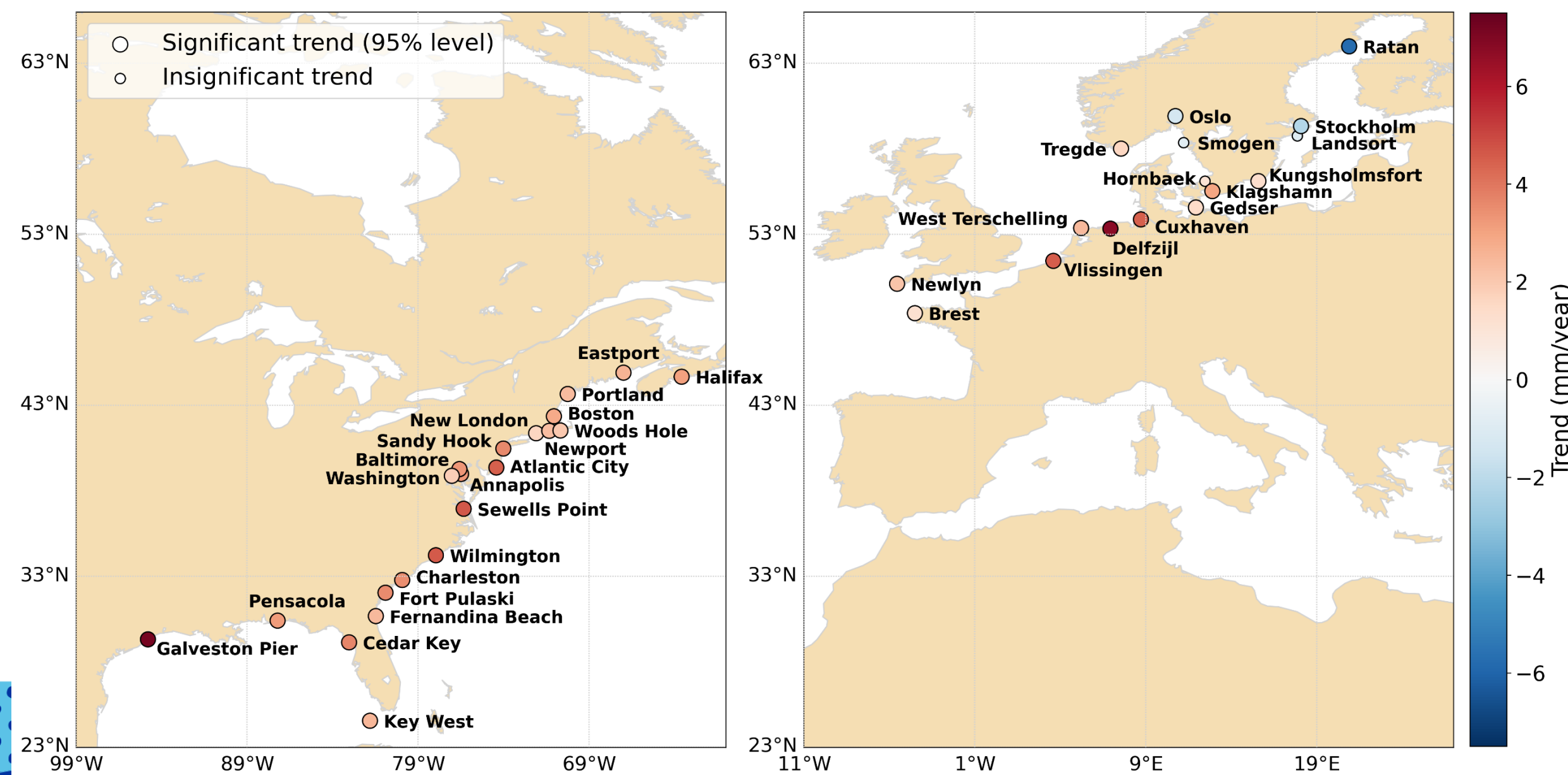
- 1) Compare the magnitude of long-term trends in MSL, tide and winter storm surges, in the North Atlantic**
- 2) Quantify the multidecadal variability in MSL, tide and winter storm surges, and compare to long-term trends**

Presentation outline:

- Sea level data
- Methods
- Long-term trends in MSL, M_2 tide and storm surges
- Long-term trends vs multidecadal variability
- Conclusion

Sea level data

- Hourly tide gauge data from **GESLA-4** (*Haigh et al., 2023, Woodworth et al., 2016, Caldwell et al., 2001*), published in 2025
- Selection of **37 tide gauges** with **≥ 80 years of winter data** over 1920-2024
- Focus on the winter season (October - March)

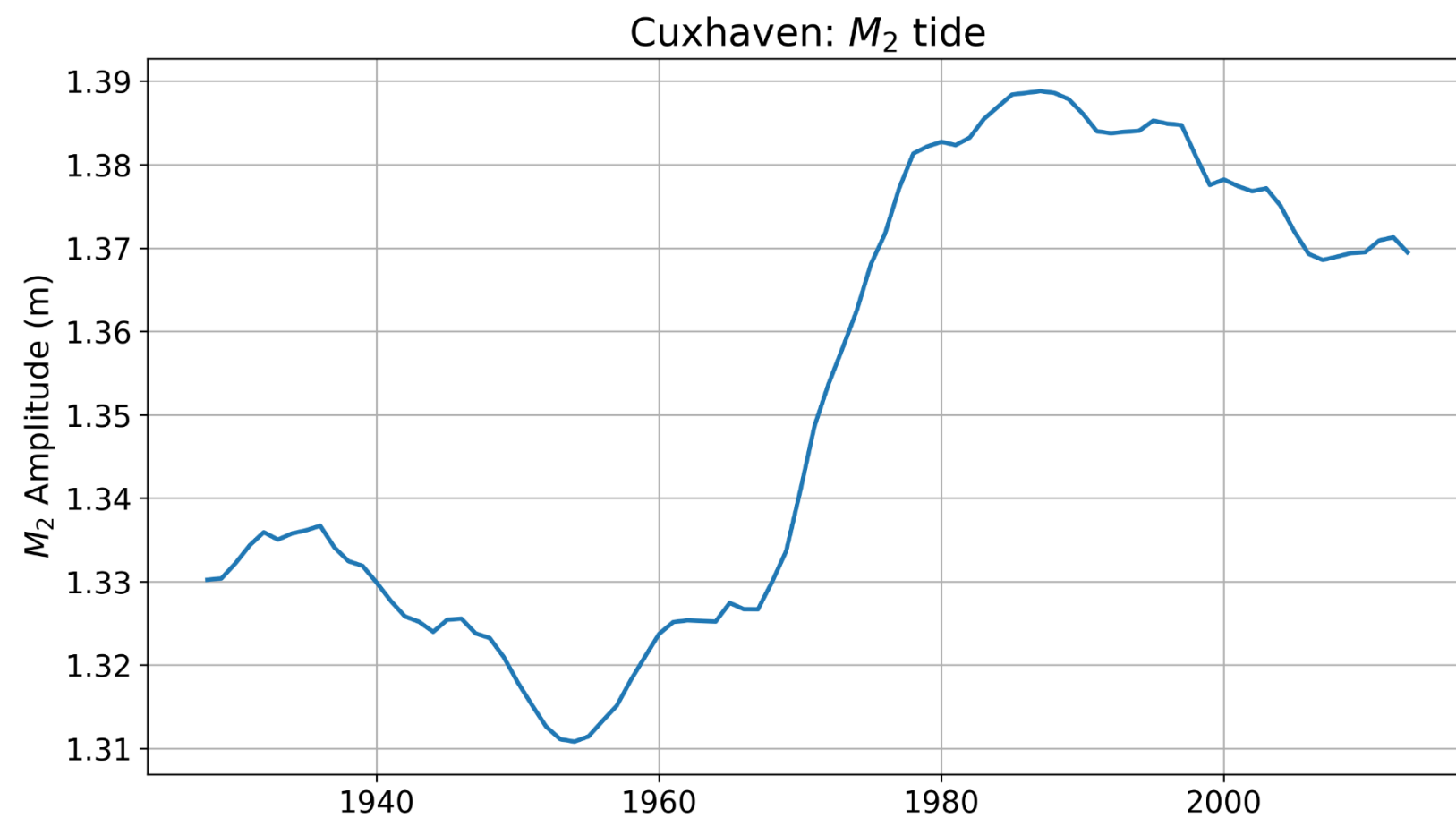


Extreme sea level trends over 1925-2014 (annual 99.9th percentile of hourly winter data)

Methods: Extraction of the sea level components

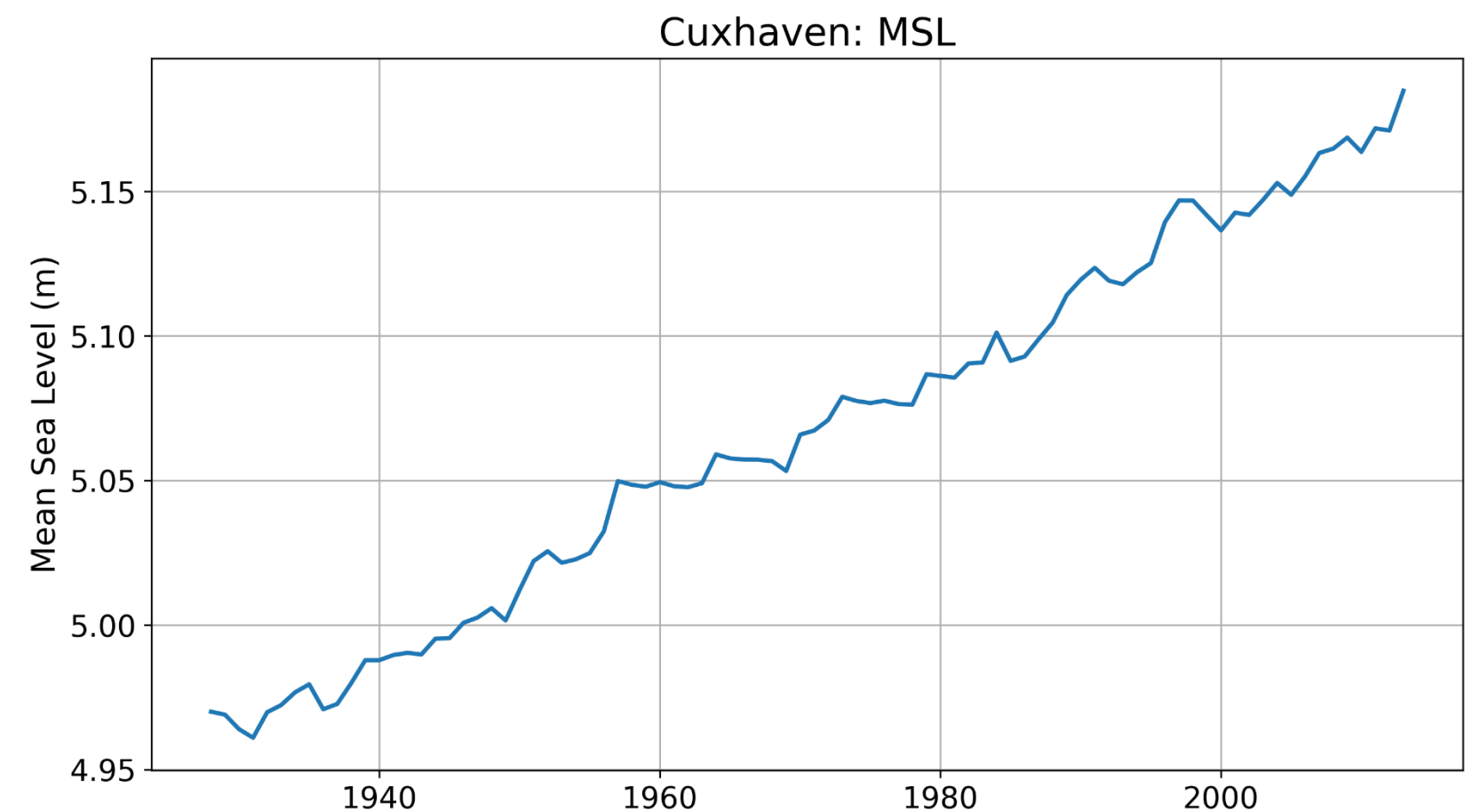
Tide:

- Harmonic analysis over a 21-yr sliding window, using U-TIDE (*Codiga, 2011*)
- Focus on M_2 amplitude



(Relative) MSL:

- Subtracting computed tide
- Yearly computation of winter median sea level
- Filtering over a 21-yr sliding window



Methods: Extraction of the sea level components

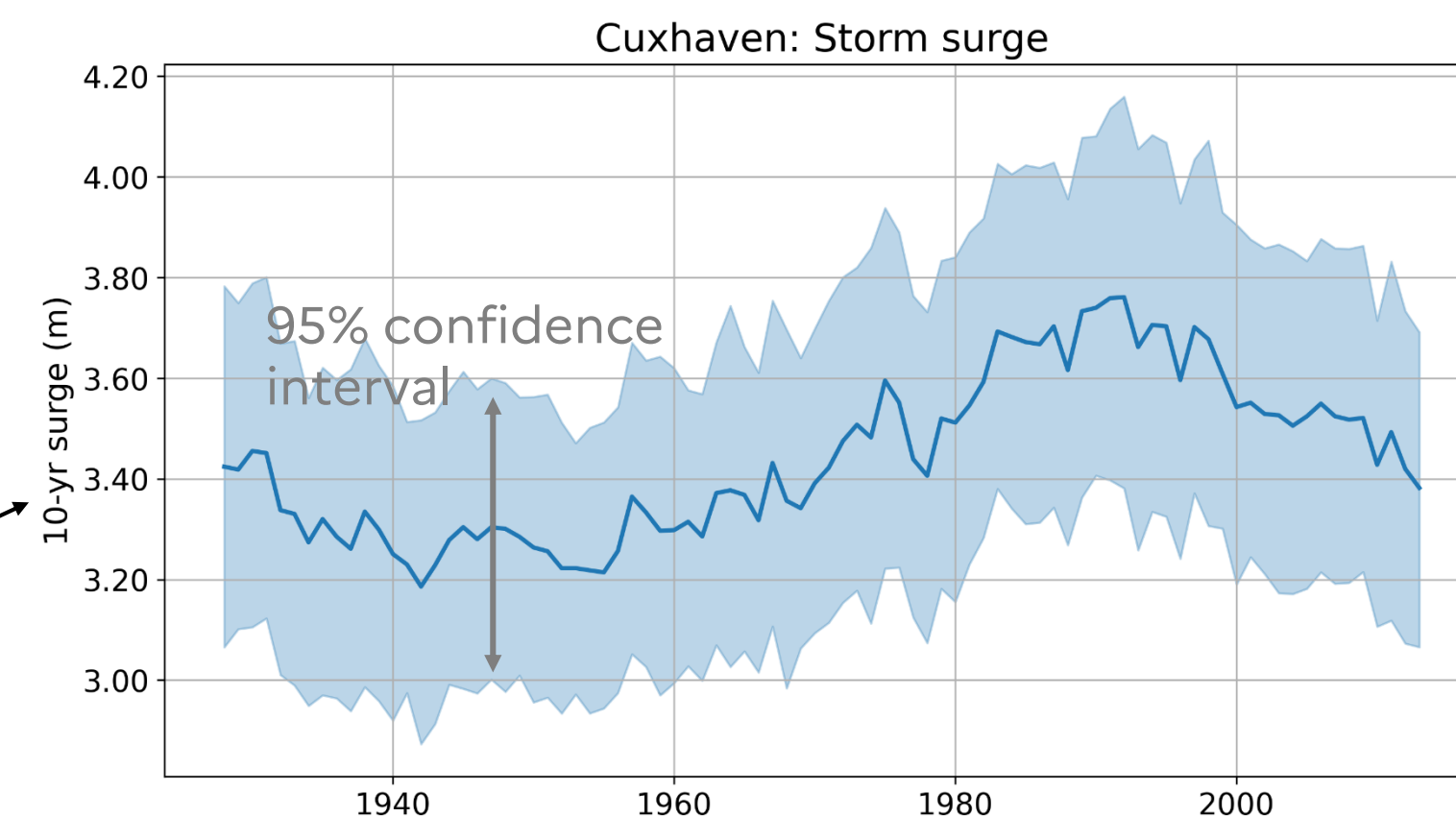
Storm surges:

- For each year, we removed the tide and MSL
- Statistical characterization with an **Extreme Value Analysis** (similarly as *Cheynel et al., 2025*):
 - Generalized Extreme Value Distribution (GEV):

$$G(z) = \exp \left(- \left[1 + \xi \left(\frac{z - \mu(t)}{\sigma} \right) \right]^{\frac{-1}{\xi}} \right)$$

Cumulative distribution function

- For each year, fit on winter monthly maxima, over a 21-yr sliding window
- Annual cycle in μ : $\mu(t) = \mu_0 + \mu_a \cos(\omega_a t + \phi_a)$
- Computation of the 10-yr return level with $T_p = 1/(1 - G(z_p))$



Methods: Trends and multidecadal variability

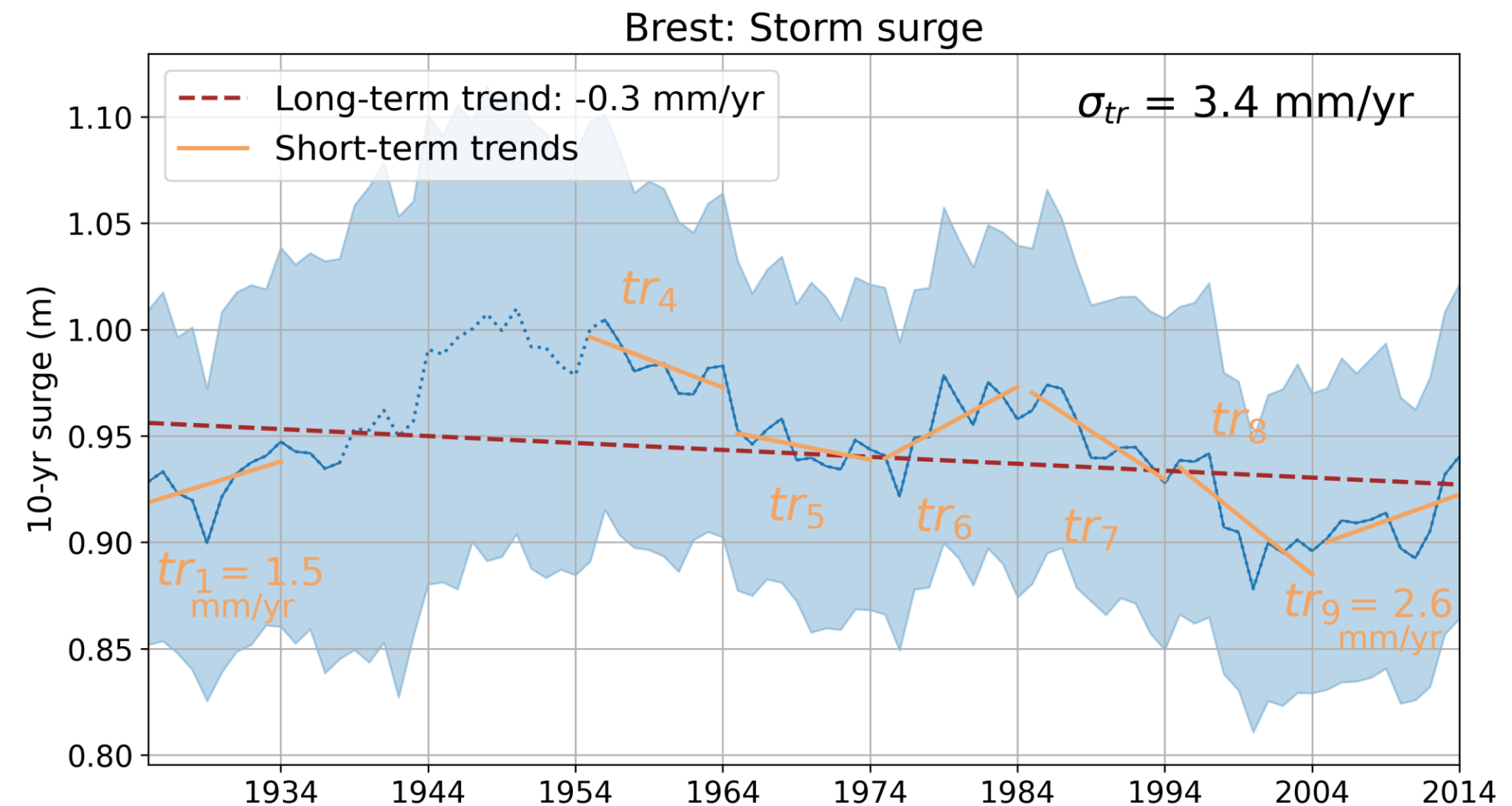
1) Long-term trends:

- Period 1925-2014
- Accounting for autocorrelation

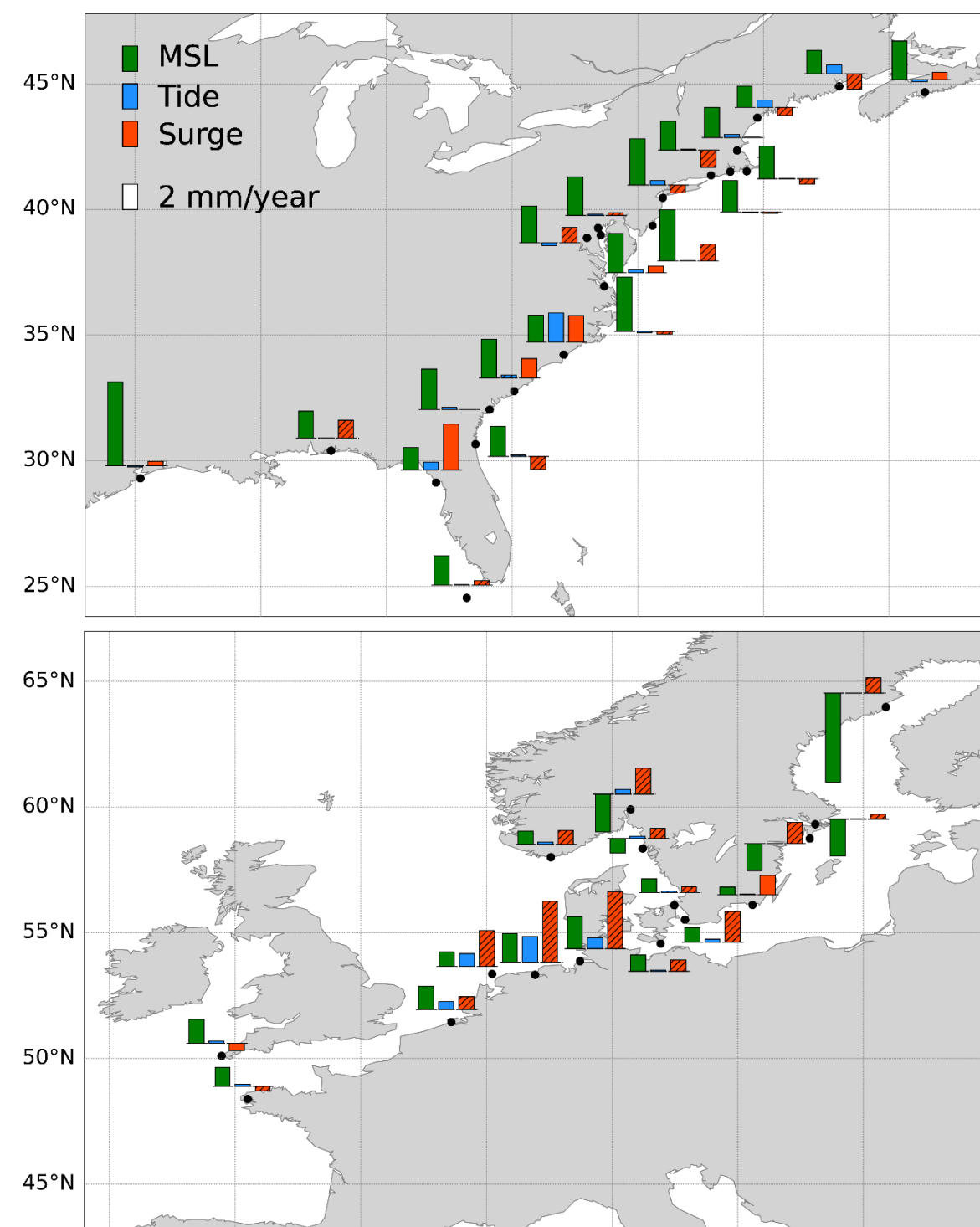
2) Multidecadal variability:

- We split the 1925-2014 data in an ensemble of 9 members (of 10 years)
- We computed trends for each member (tr_i)
- We computed σ_{tr} , the standard deviation

$$\sigma_{tr} = \sqrt{\frac{1}{9} \sum_{i=1}^9 (tr_i - \bar{tr})^2}$$

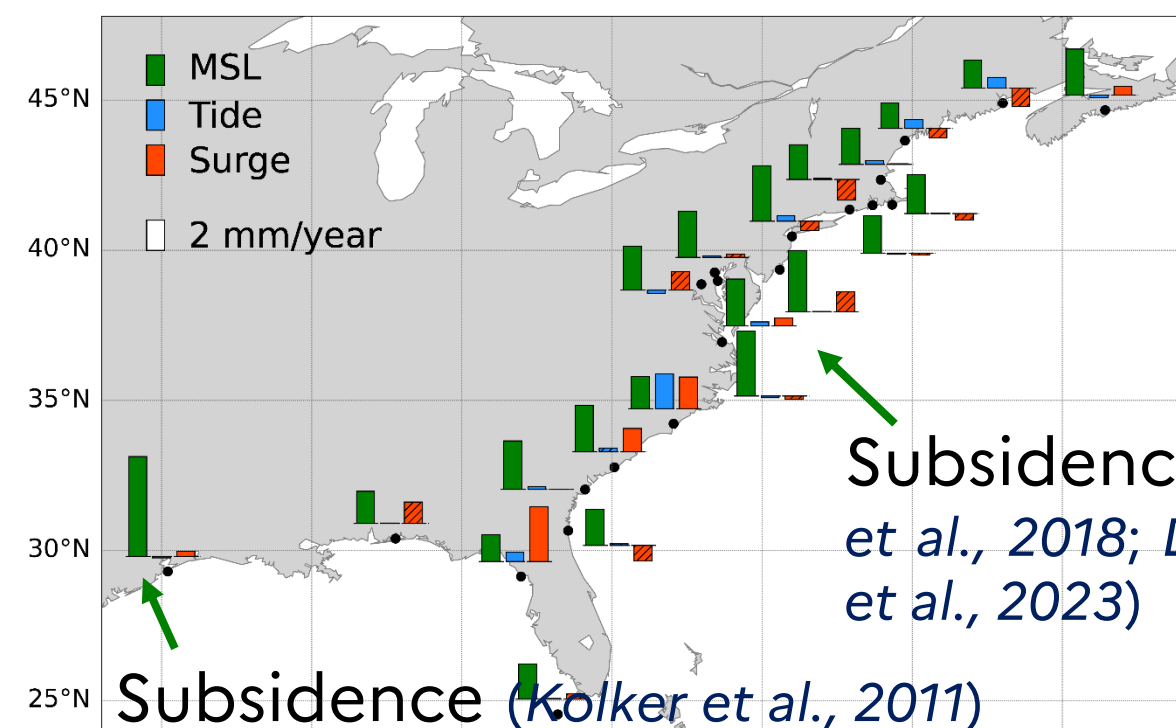


Long-term trends in MSL, M_2 tide and storm surges



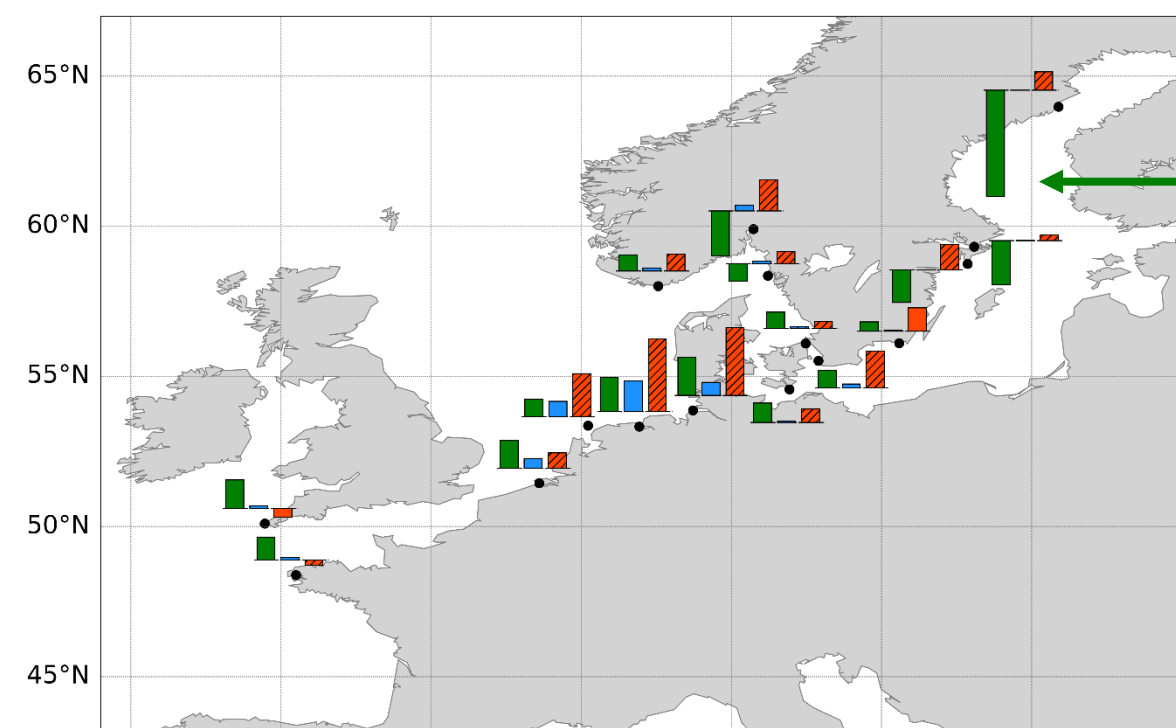
Linear trends over 1925-2014

Long-term trends in MSL, M_2 tide and storm surges



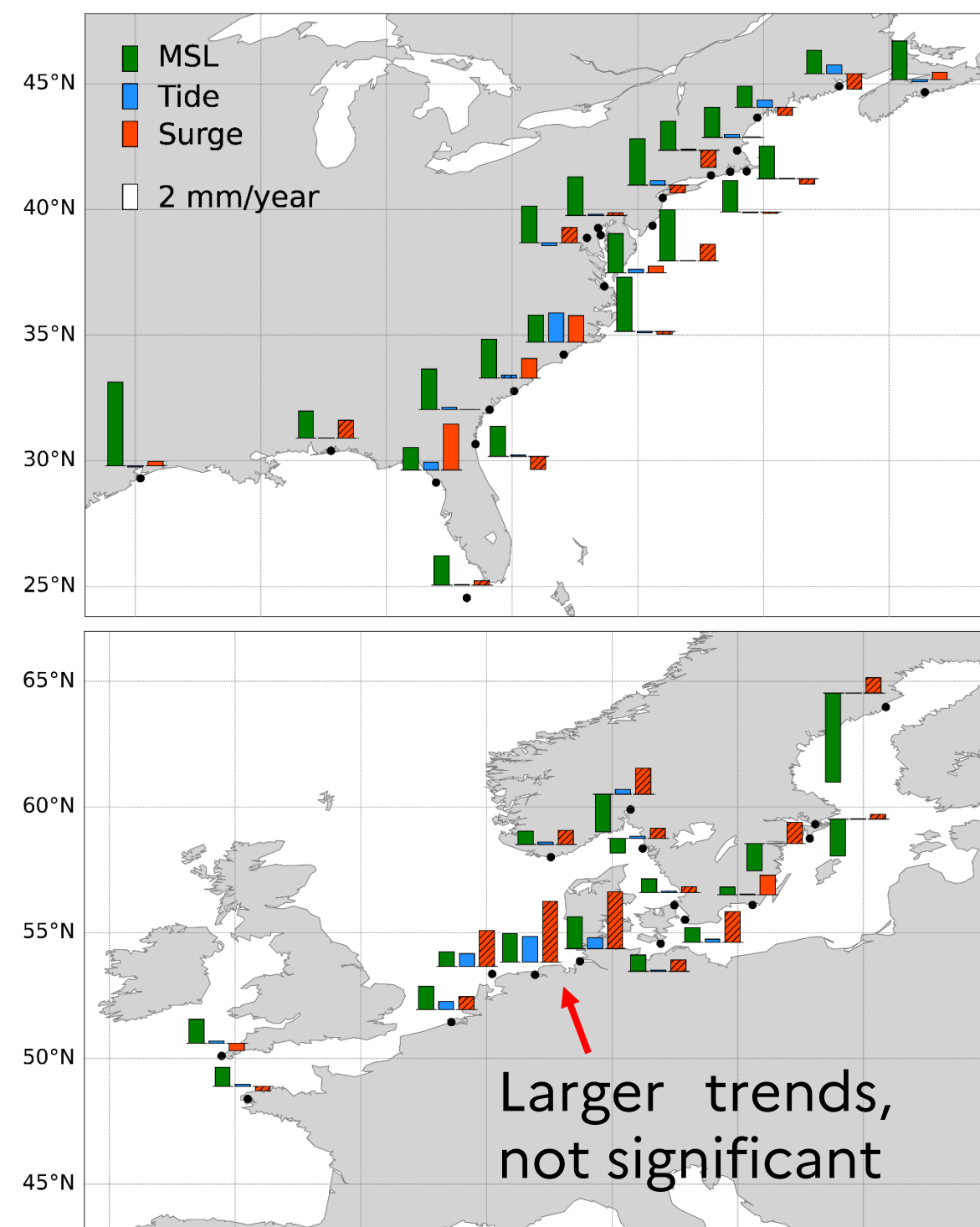
Linear trends over 1925-2014:

- At most stations (78%), trends in ESLs are dominated by trends in **MSL: mostly 1 to 4 mm/year**



Uplift (*Wöppelmann & Marcos, 2016; Whitehouse, 2018*)

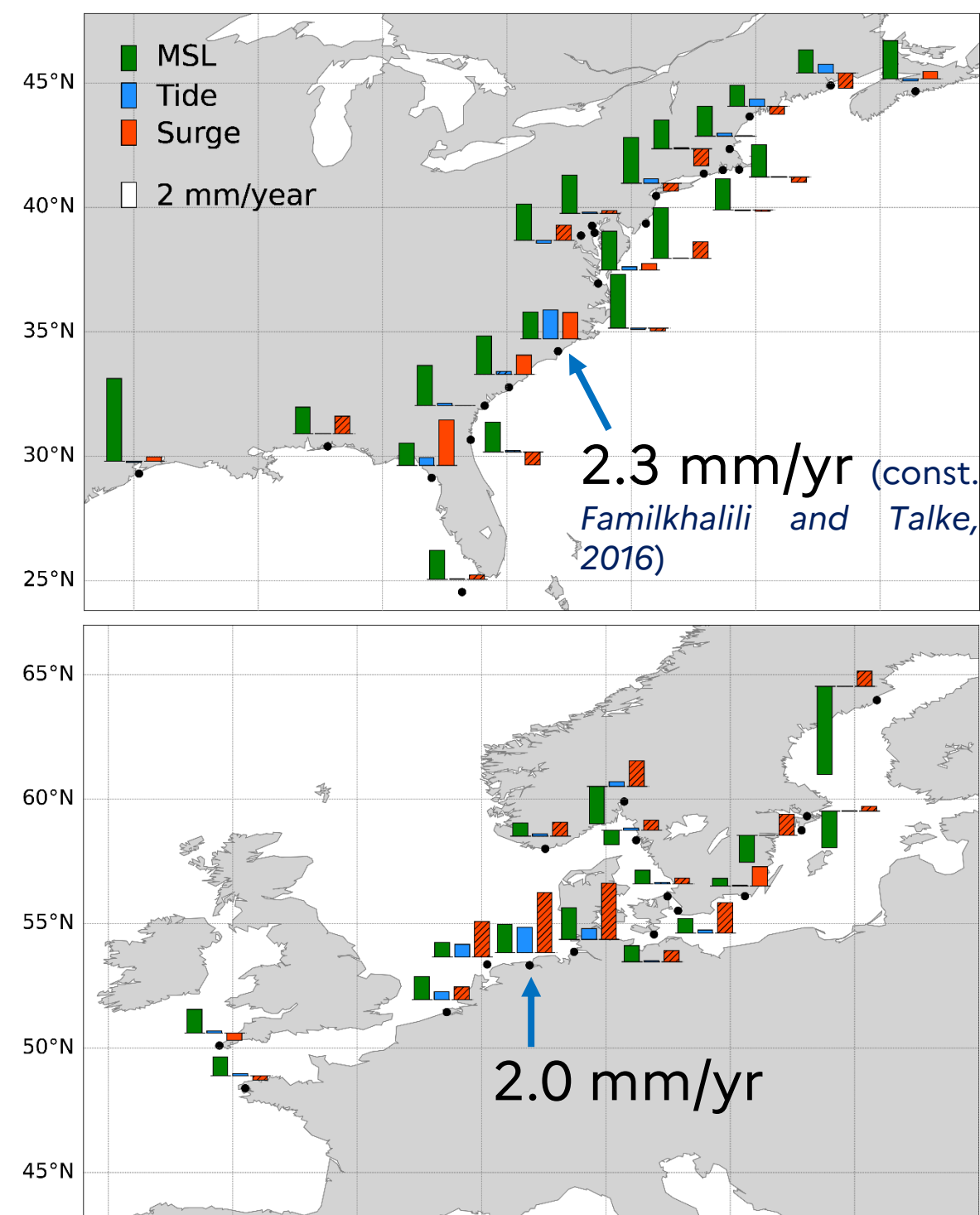
Long-term trends in MSL, M_2 tide and storm surges



Linear trends over 1925-2014:

- At most stations (78%), trends in ESLs are dominated by trends in **MSL**: mostly 1 to 4 mm/year
- Trends in **storm surges** are overall smaller: mostly $< \pm 1.5$ mm/year

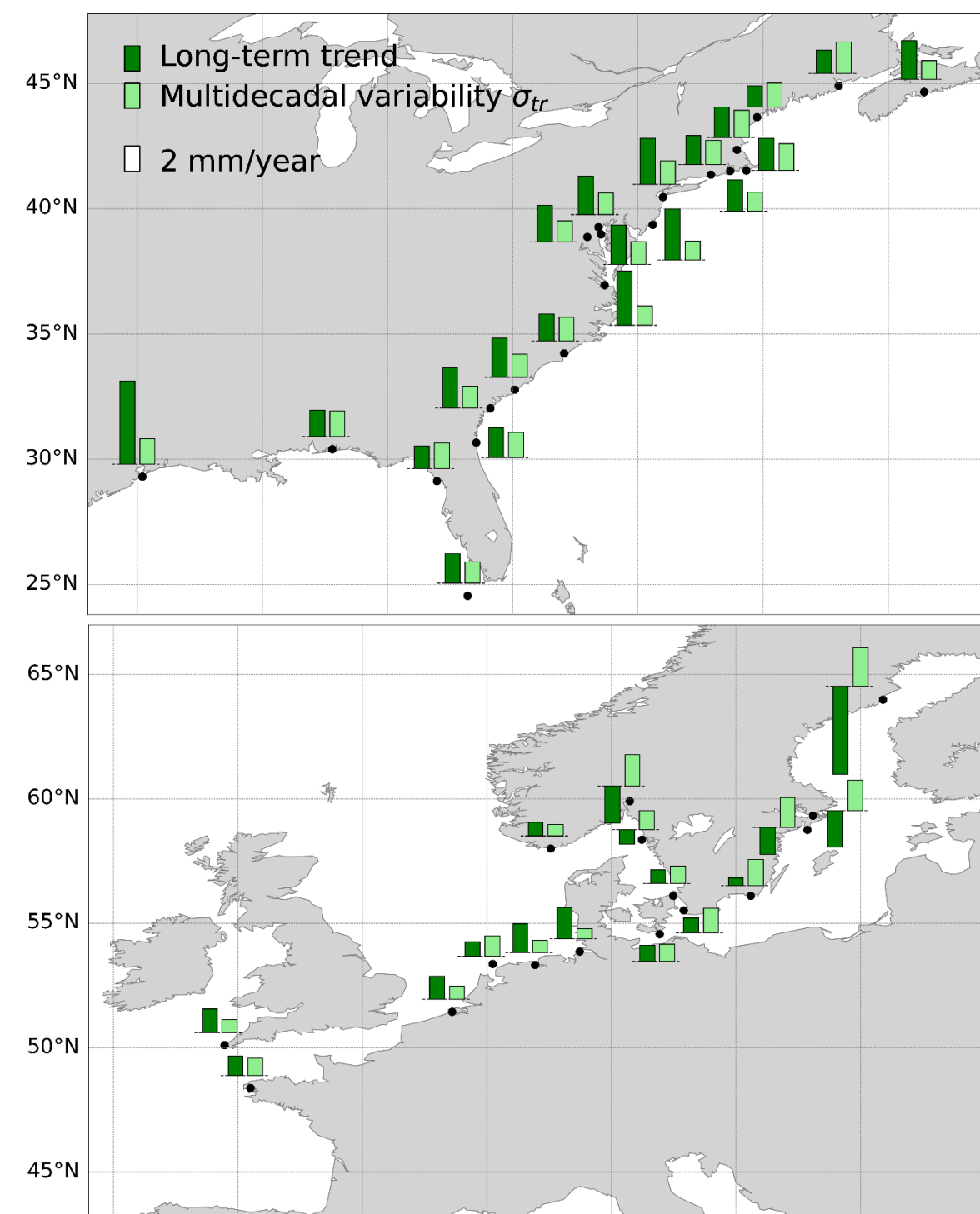
Long-term trends in MSL, M_2 tide and storm surges



Linear trends over 1925-2014:

- At most stations (78%), trends in ESLs are dominated by trends in **MSL**: mostly 1 to 4 mm/year
- Trends in **storm surges** are overall smaller: mostly $< \pm 1.5$ mm/year
- Trends in **tide** are even smaller overall: mostly $< \pm 0.5$ mm/year

Long-term trends vs multidecadal variability



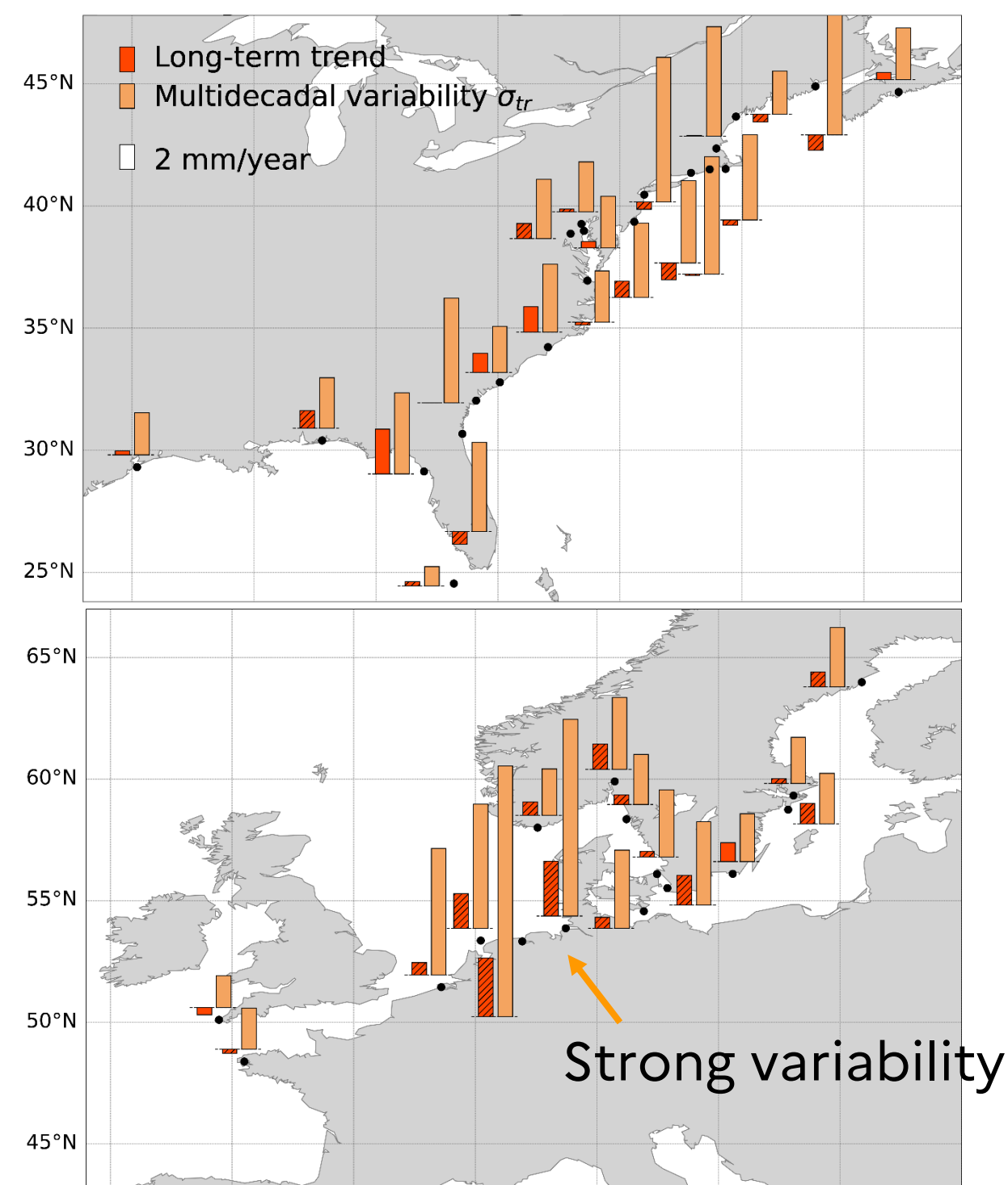
Mean Sea Level:

Multidecadal variability σ_{tr} < Long-term trends (73% of tide gauges)
typically ≤ 2 mm/year typically 2-3 mm/year

Variability can be due to:

- Vertical land motion not related to GIA (e.g. *Kolker et al., 2011*)
- Changes in ocean circulation or variability in large scale atmospheric patterns (*Woodworth et al., 2019*)
- Non-linear rate of sea level rise (*Oppenheimer et al., 2019*)

Long-term trends vs multidecadal variability



Storm surges:

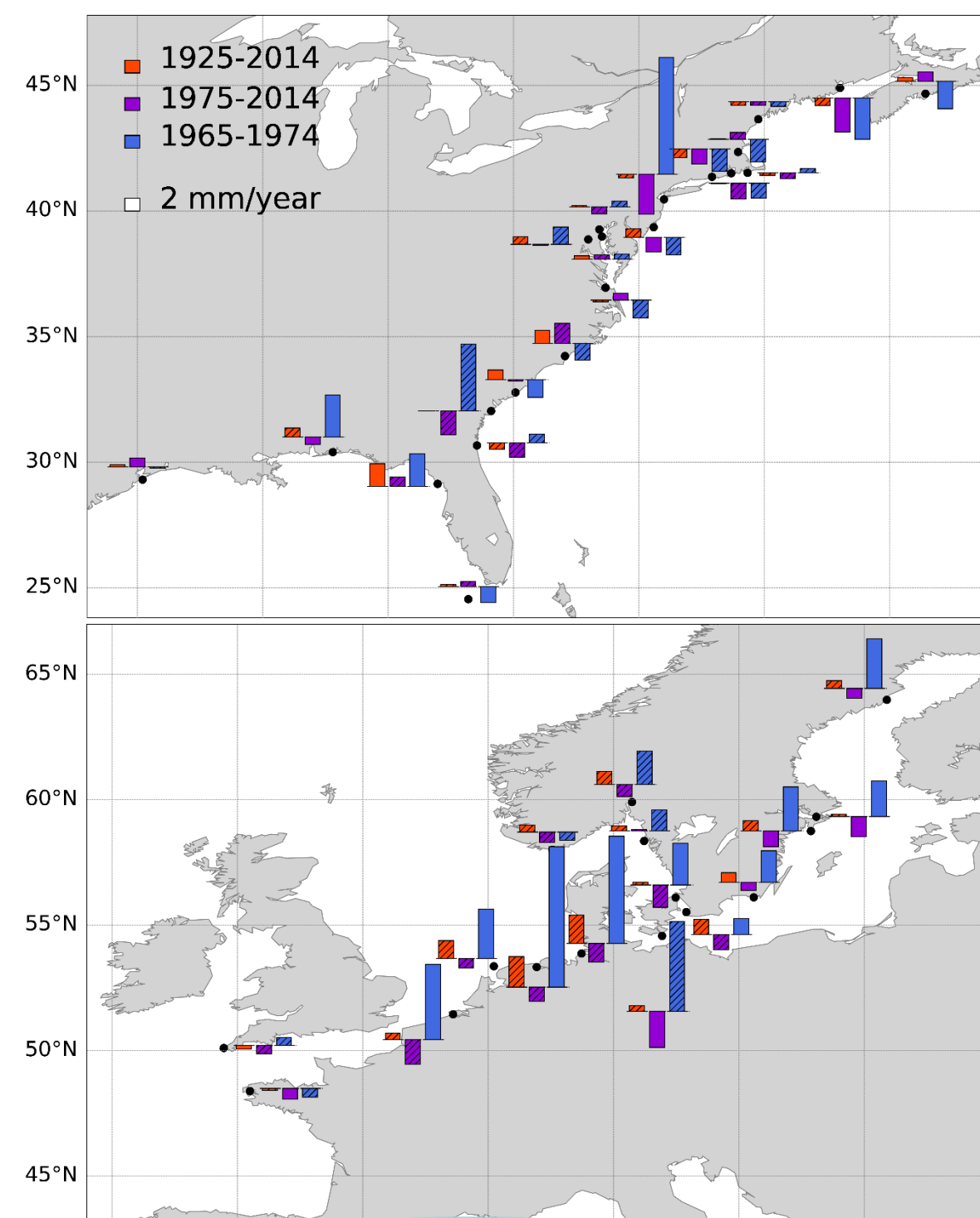
Multidecadal variability σ_{tr} $\gg$ Long-term trends (all tide gauges)
typically ≥ 2 mm/year typically ± 1 mm/year

Variability mainly due to:

Large-scale climate patterns (NAO, AMO, etc.) (e.g. Dangendorf et al., 2014; Talke et al., 2014; Wahl & Chambers, 2016; Marcos & Woodworth, 2017)

➤ Variability reflects partly climate internal variability

Long-term trends vs multidecadal variability



Storm surges: trends on 3 different periods

Multidecadal variability can strongly influence the trends on storm surges, depending on the computation period

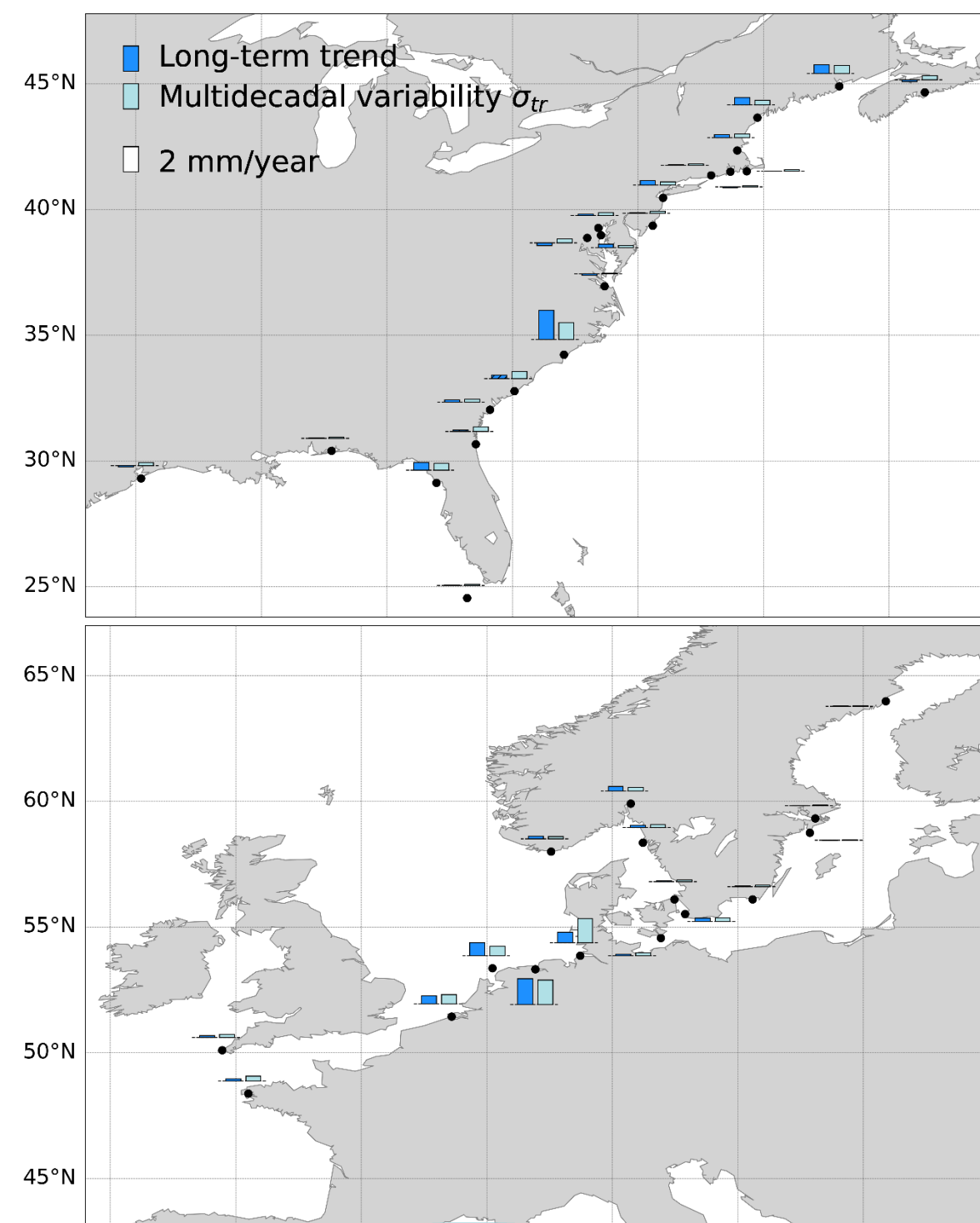
Brest:

- 1925-2014: -0.3 ± 0.2 mm/year
- 1975-2014: -1.7 ± 0.5 mm/year
- 1965-1974: -1.4 ± 1.6 mm/year

Cuxhaven:

- 1925-2014: 4.5 ± 1.0 mm/year
- 1975-2014: -3.0 ± 2.8 mm/year
- 1965-1974: 17.1 ± 8.9 mm/year

Long-term trends vs multidecadal variability



Tide:

Both **long-term trends** and **multidecadal variability** are relatively small overall

typically < 0.5 mm/year

Conclusion

Using 37 tide gauges, we computed the long-term trends (1925-2014) and quantified the multidecadal variability in winter (relative) mean sea level, M_2 tide, and 10-yr surge

1) Long-term trends: **MSL** (1 to 4 mm/yr) > **Storm surges** ($\leq \pm 1.5$ mm/yr) > **Tide** ($\leq \pm 0.5$ mm/yr)

2) Multidecadal variability is strong for storm surges (typically ≥ 4 mm/yr). Trends computed on short records are likely the signature of multidecadal variability, rather than long-term trends

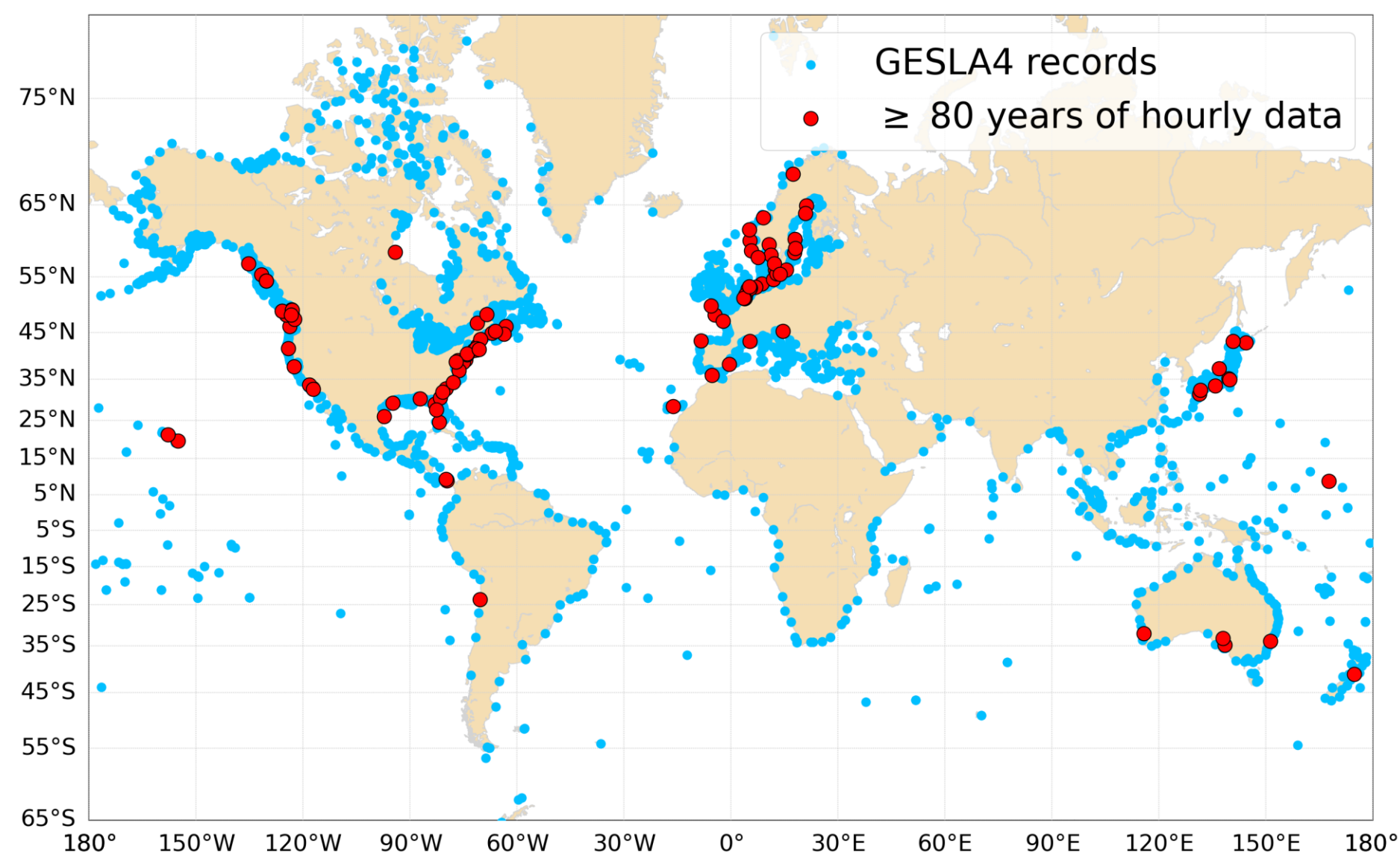
➤ Multidecadal variability in extreme sea levels must be taken into account (in addition to long-term trends) to estimate future coastal risks

In review: Cheynel J., Pineau-Guillou L., Lazure P.

«Trends vs multidecadal variability in extreme sea level components: mean sea level, tide and storm surges »

Closing remark

Long tide gauge records are needed to investigate long-term trends and multidecadal variability in extreme sea levels



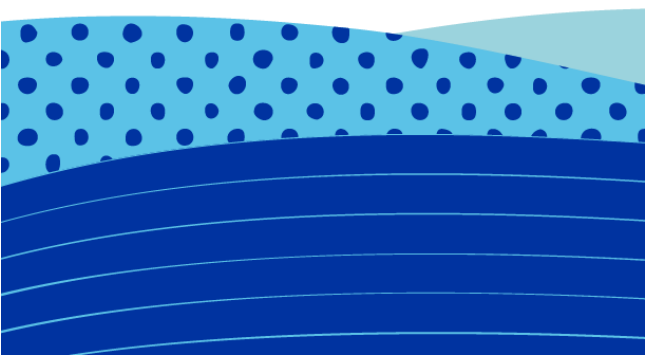
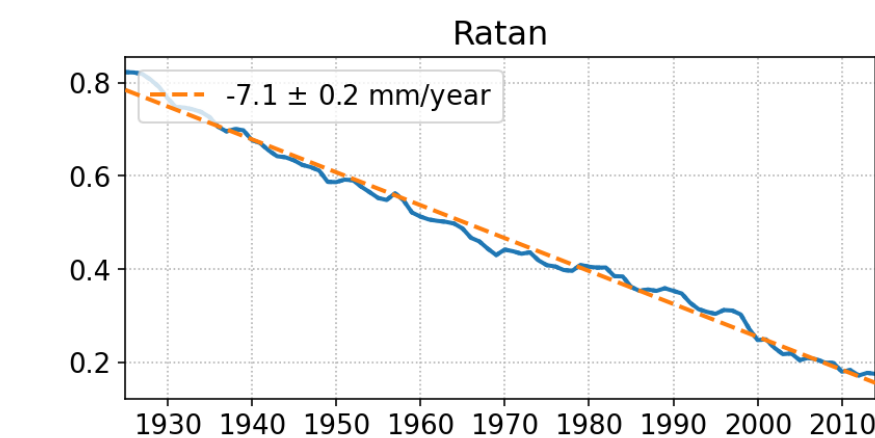
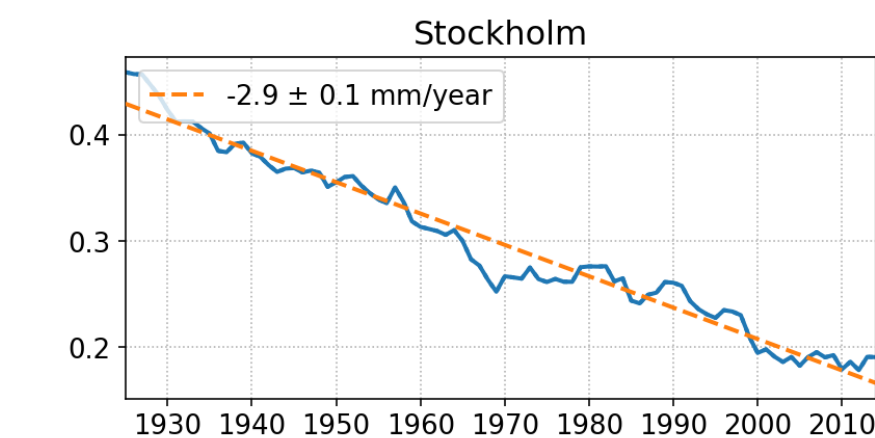
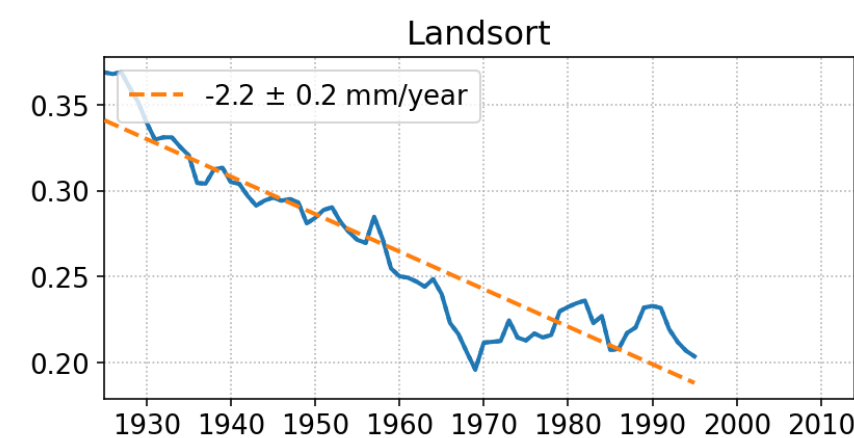
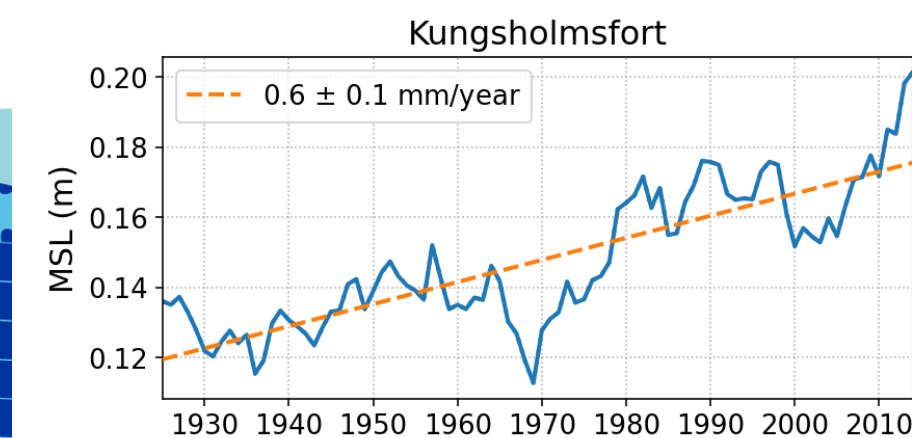
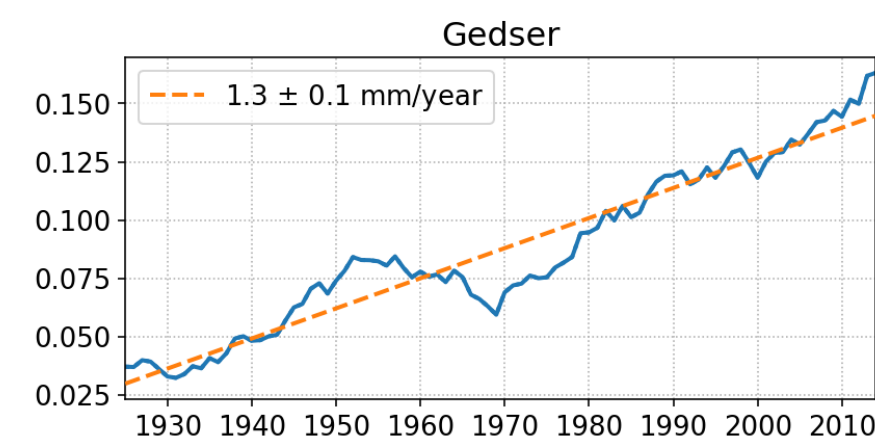
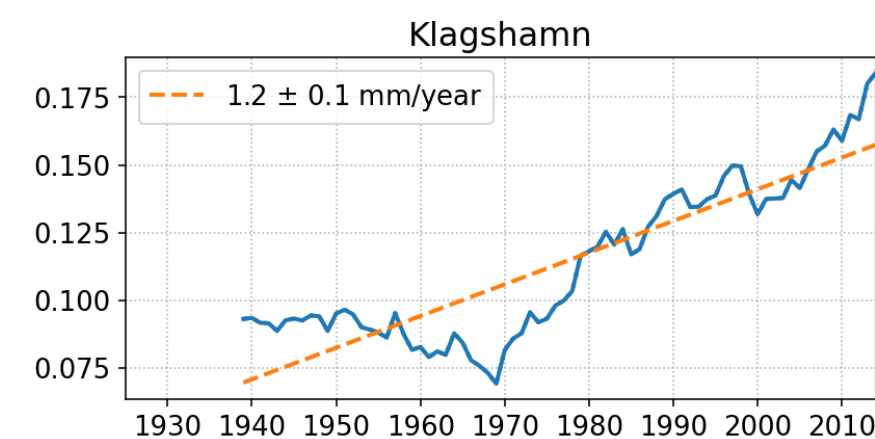
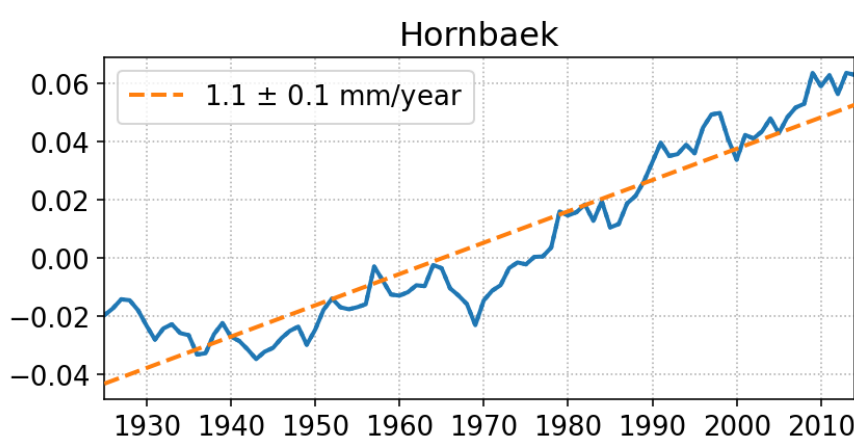
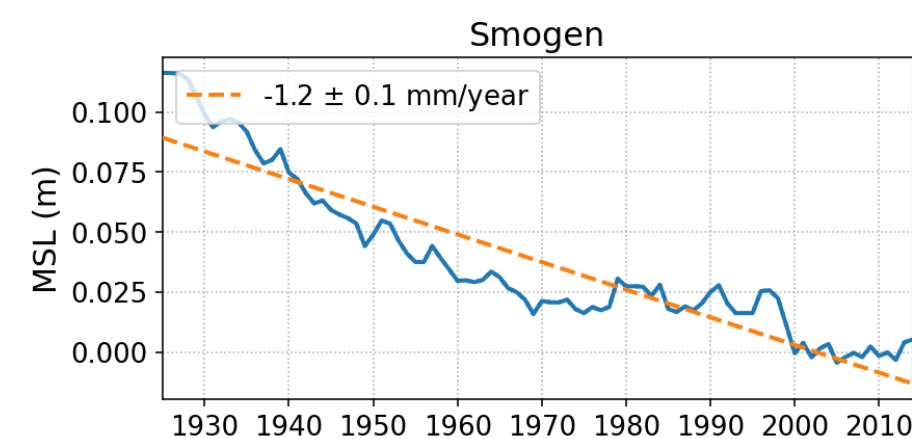
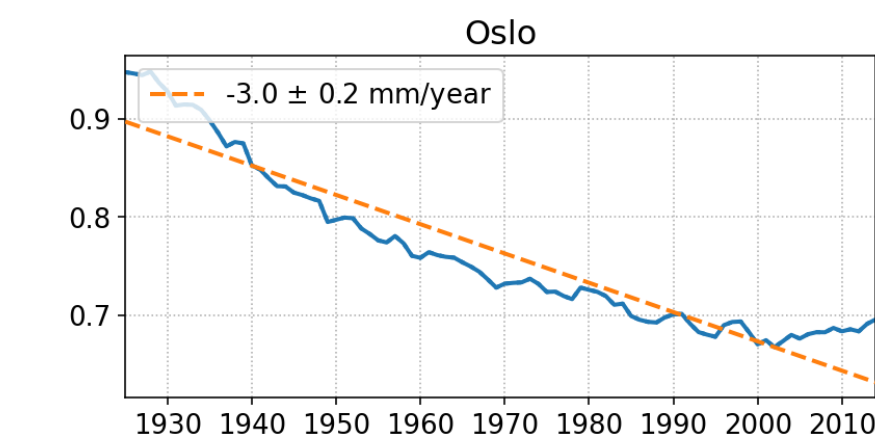
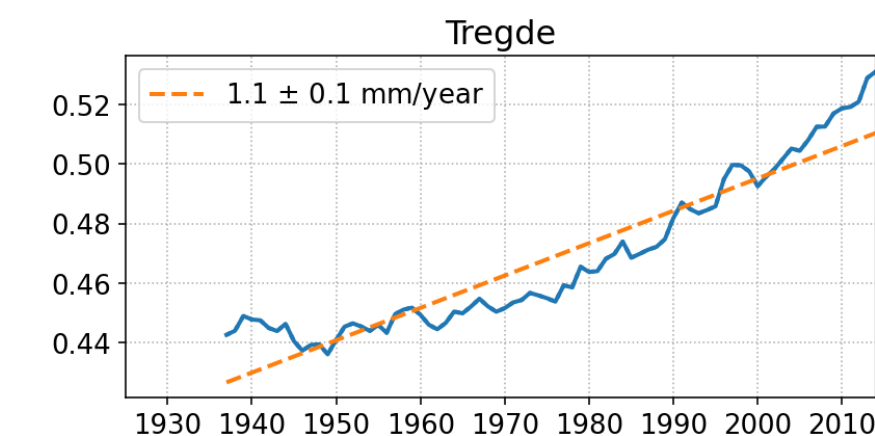
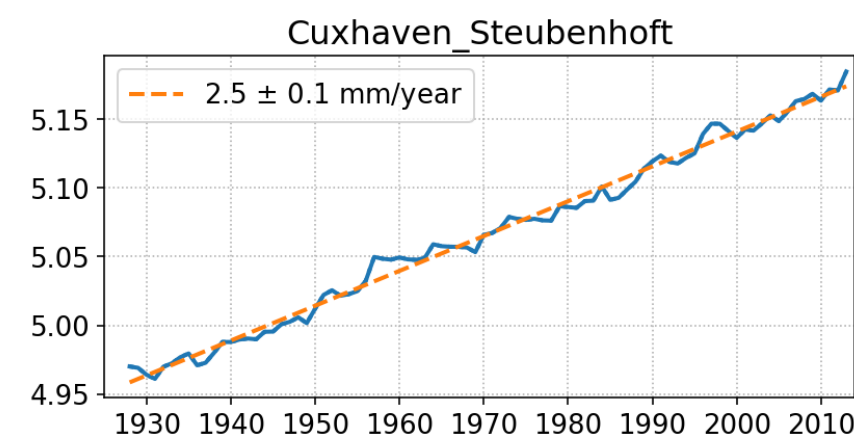
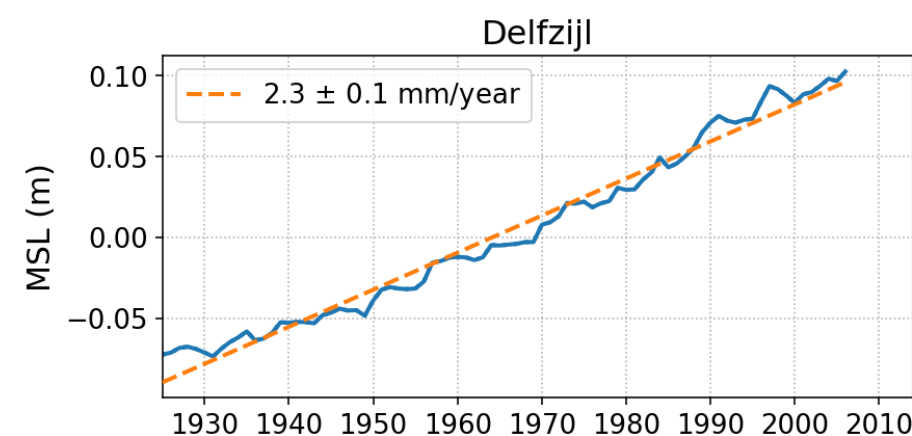
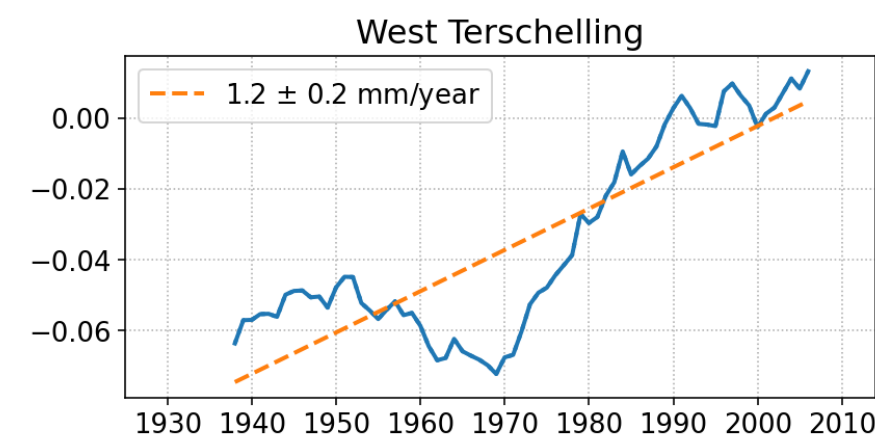
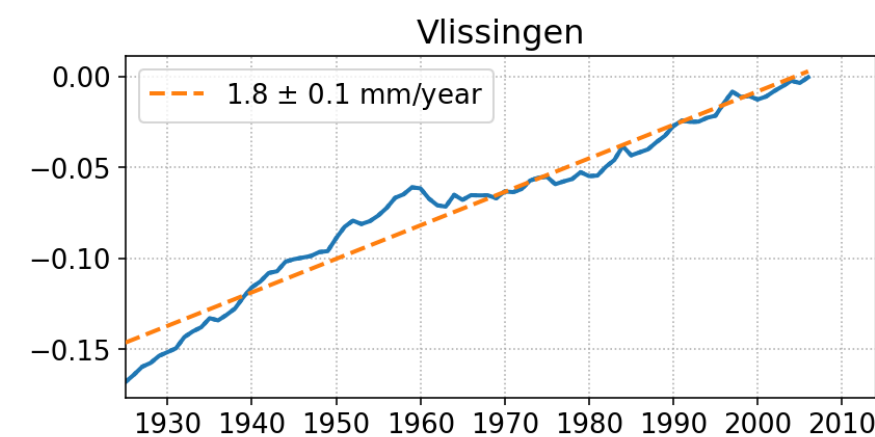
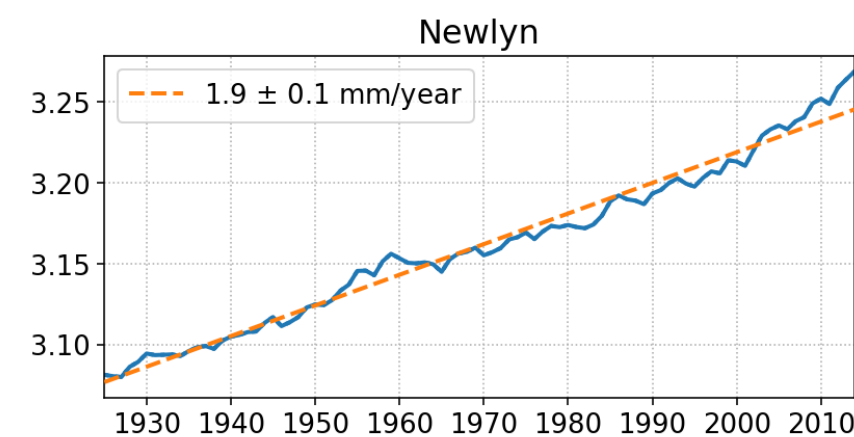
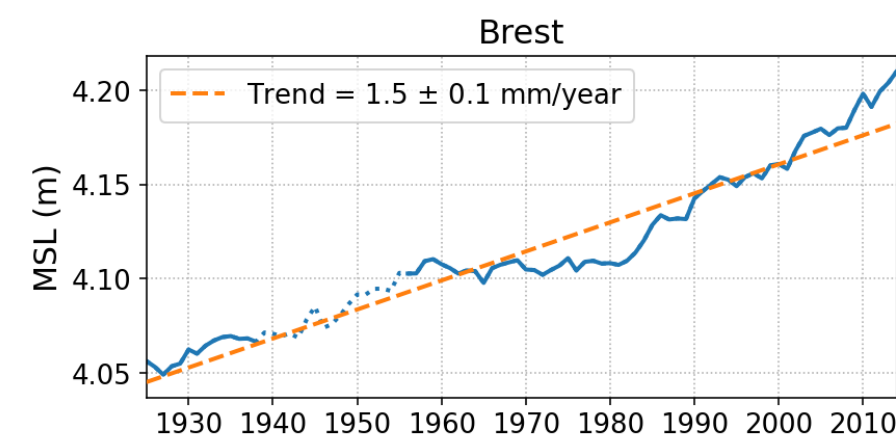
- But tide gauges having more than 80 « complete » years of hourly data are rare
- Spatial coverage is uneven, higher density in the Northern hemisphere
- Sea-level data archaeology efforts are essential for improving temporal and spatial data coverage

Merci de votre attention

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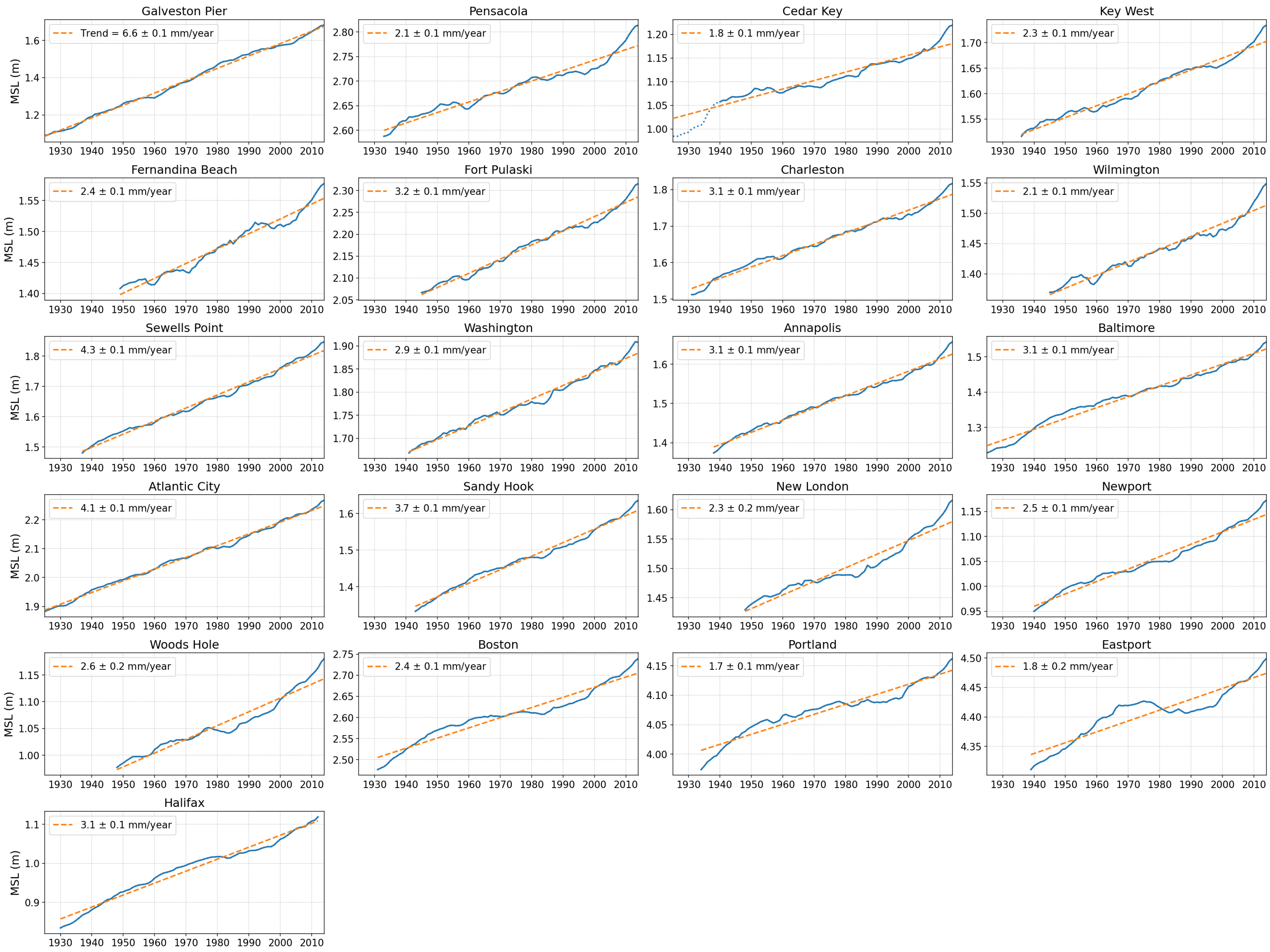
Appendix

MSL:



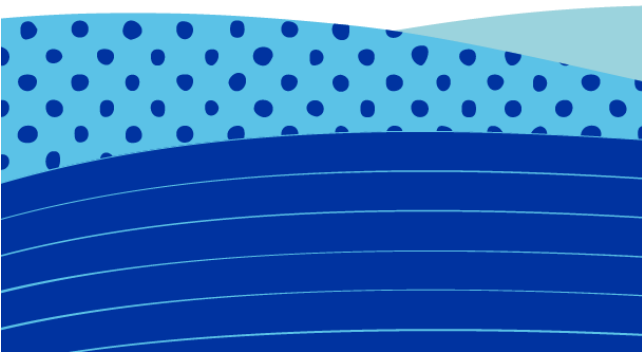
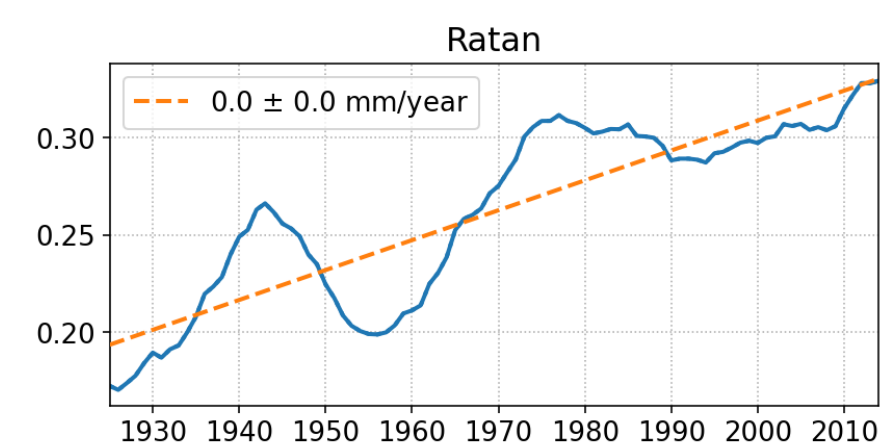
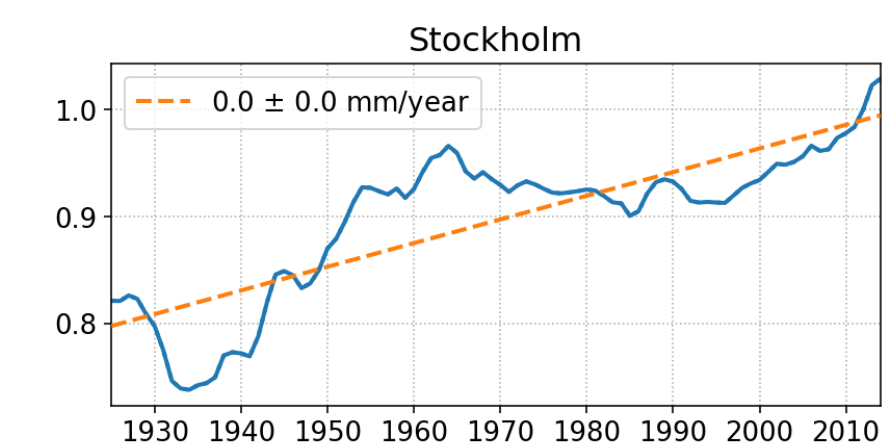
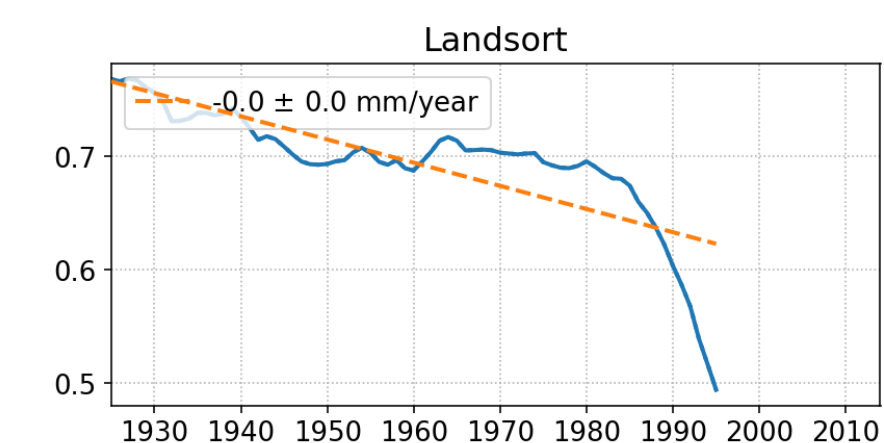
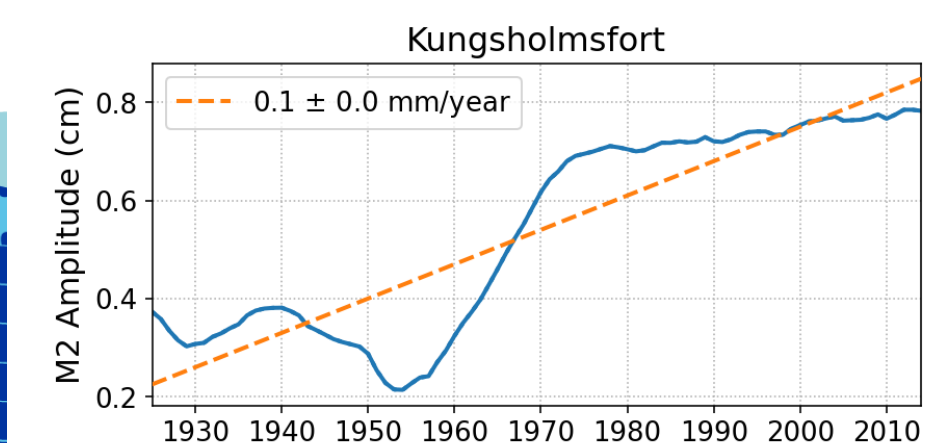
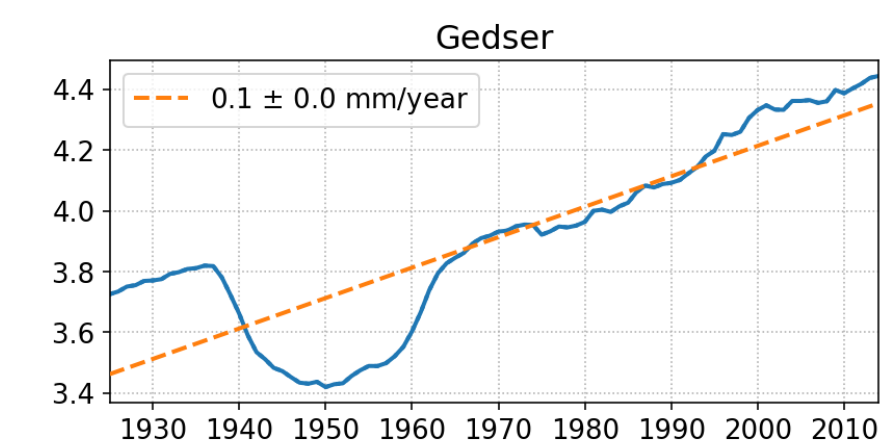
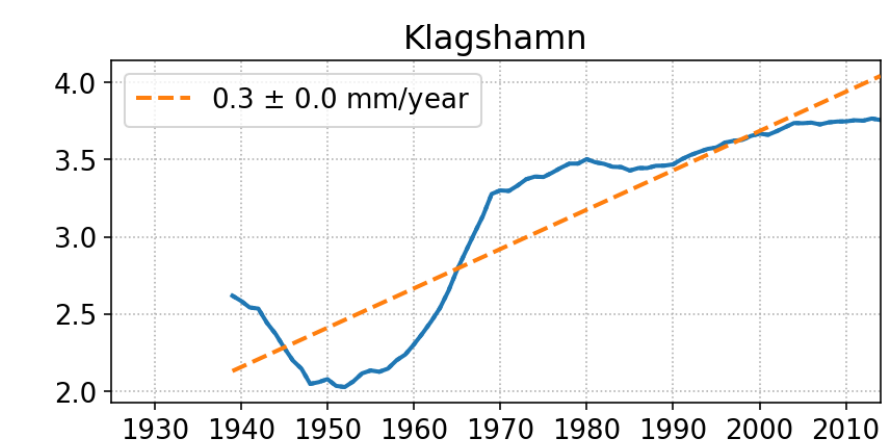
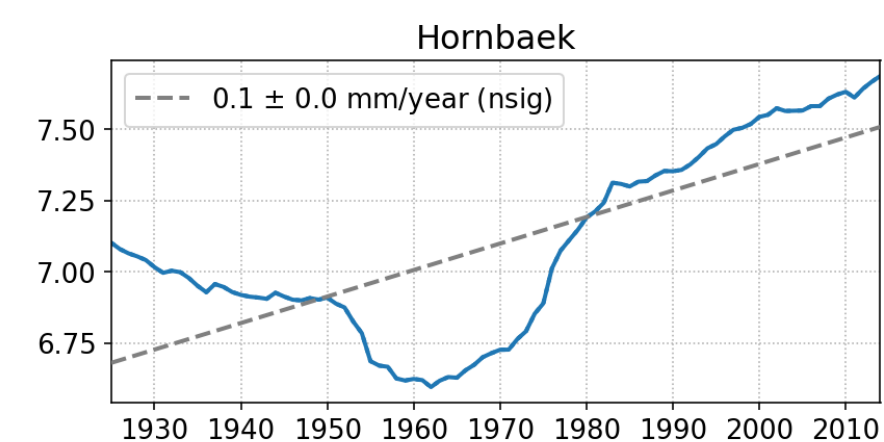
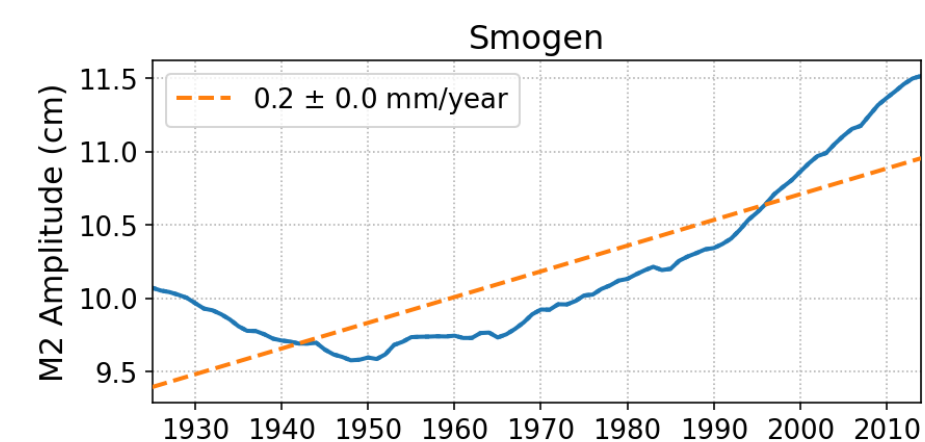
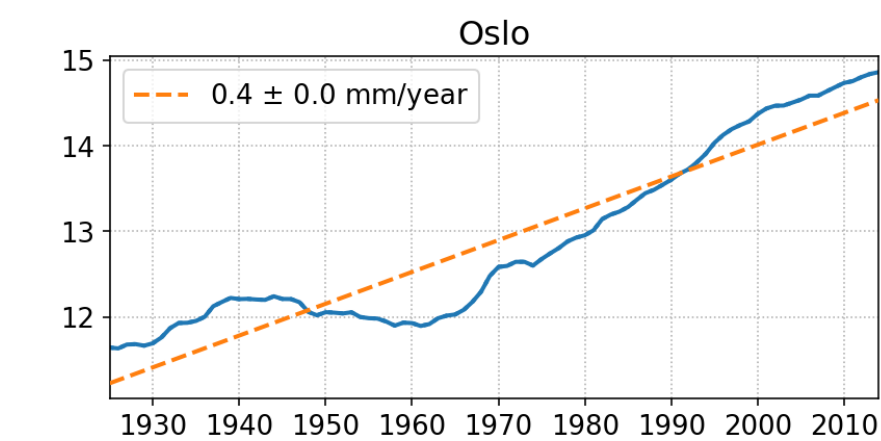
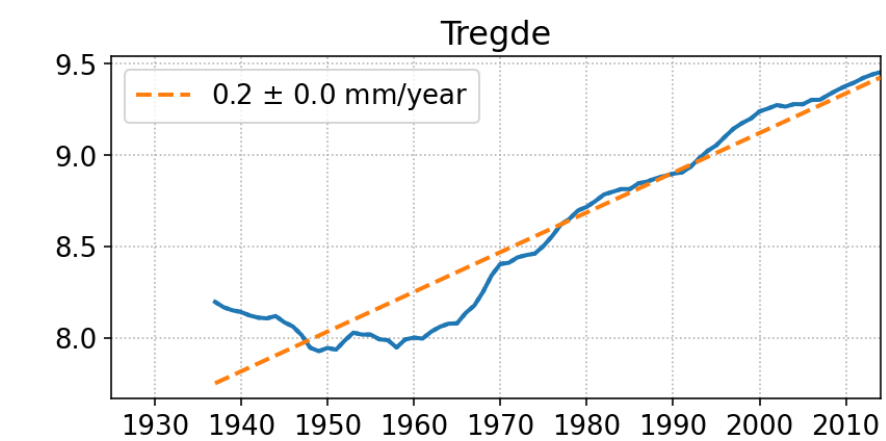
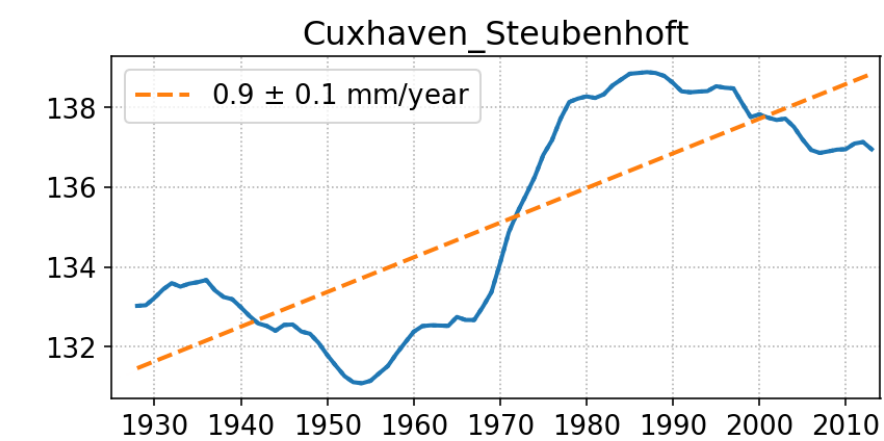
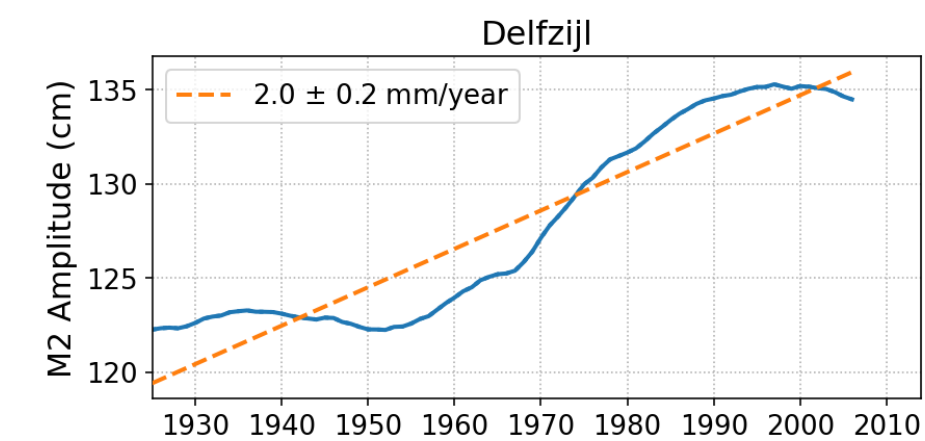
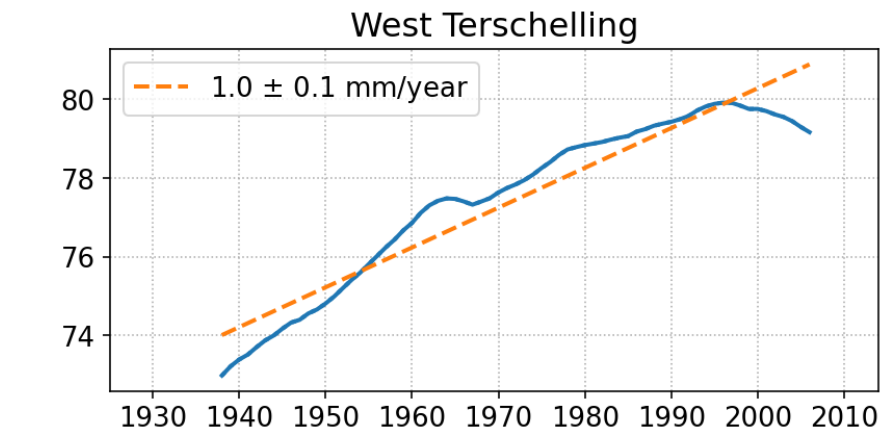
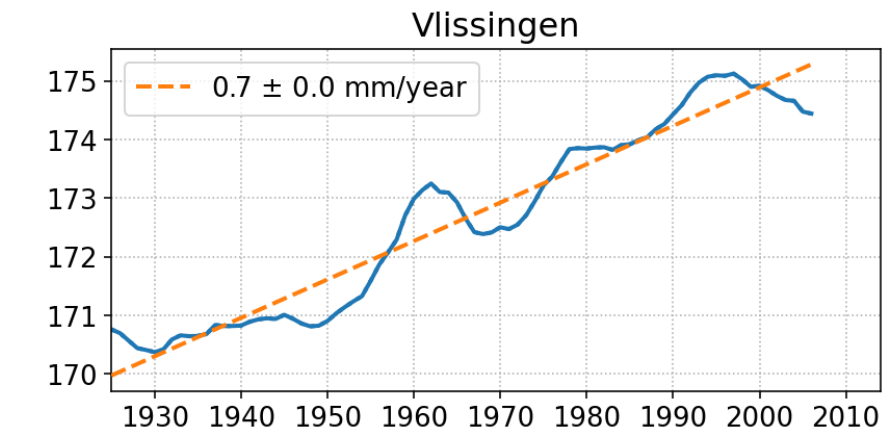
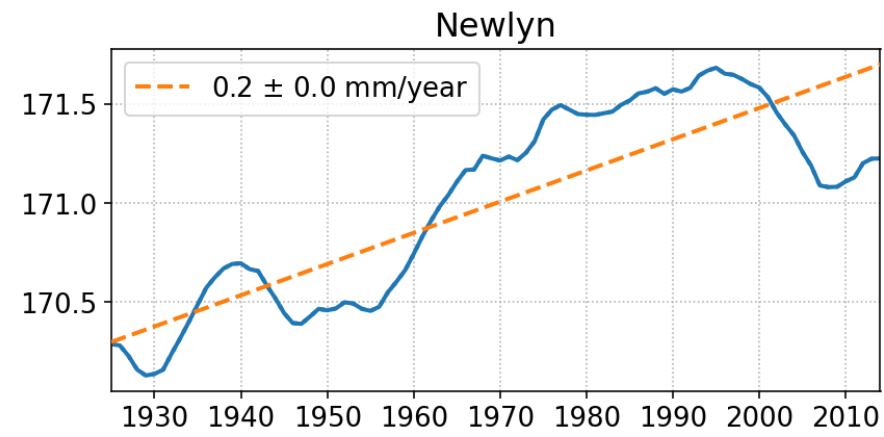
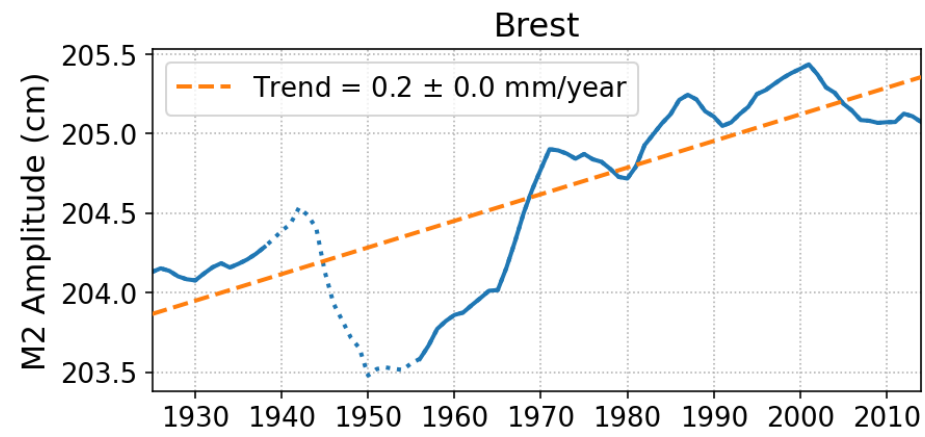
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MSL:



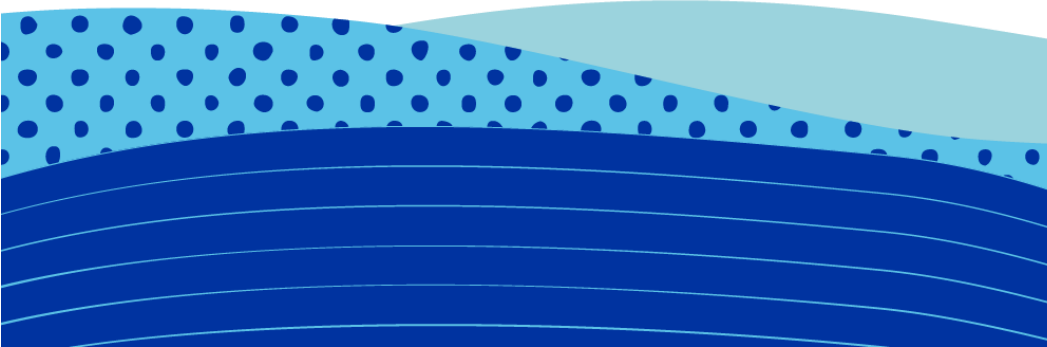
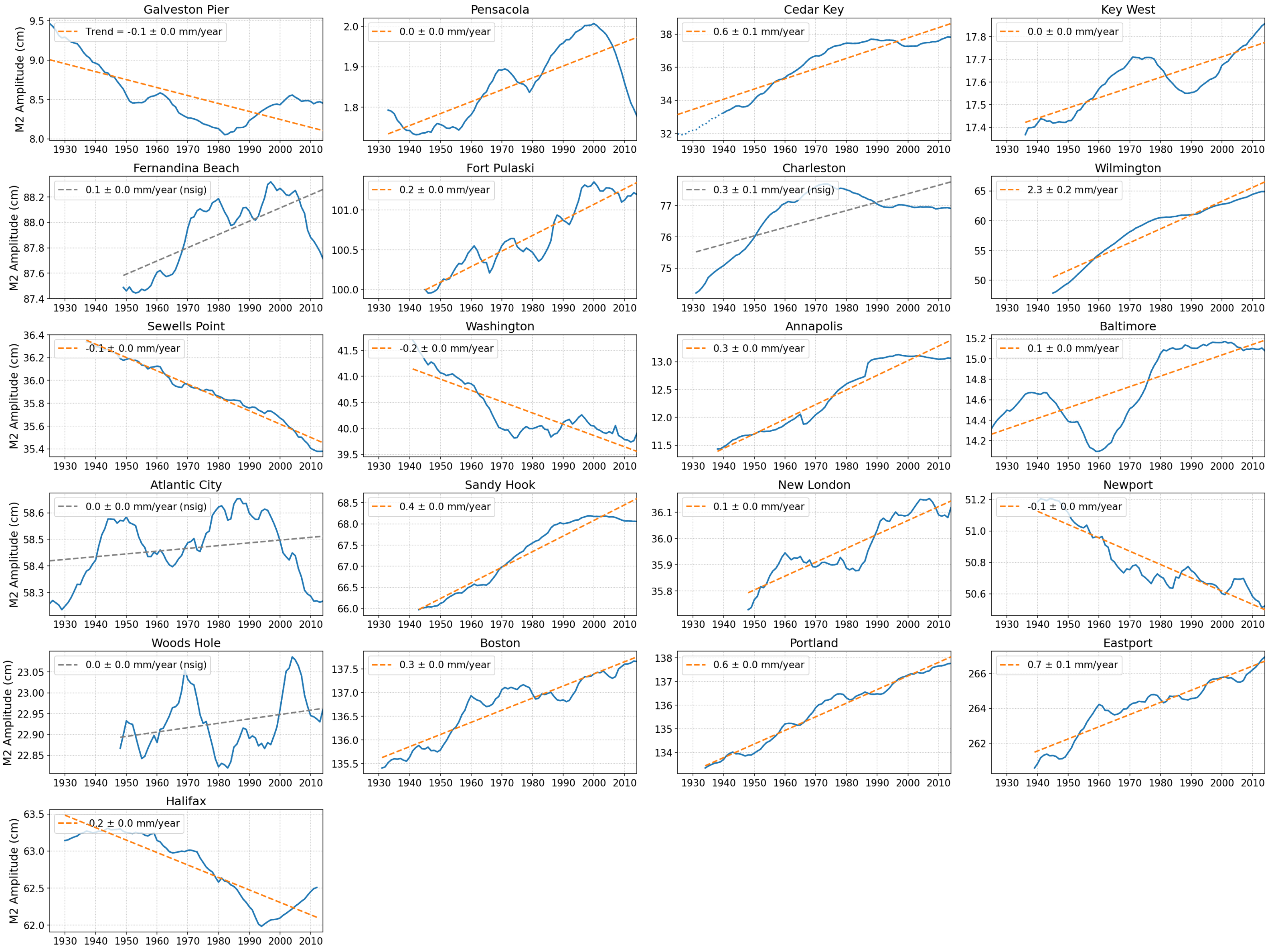
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M₂ tide:



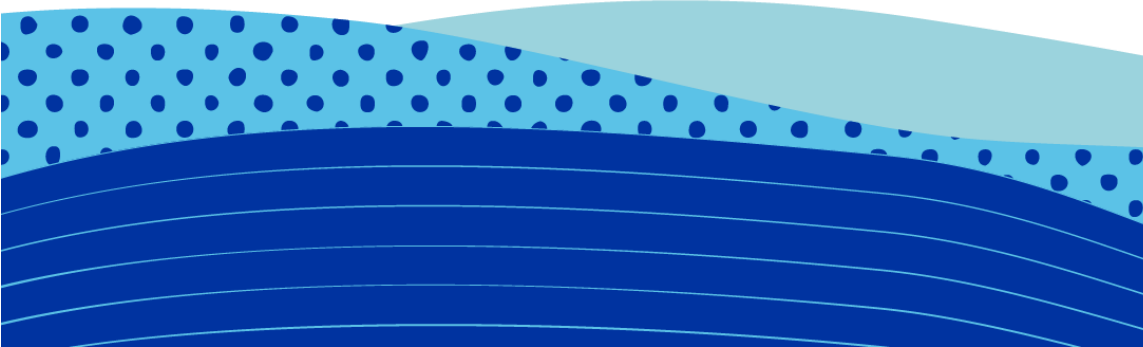
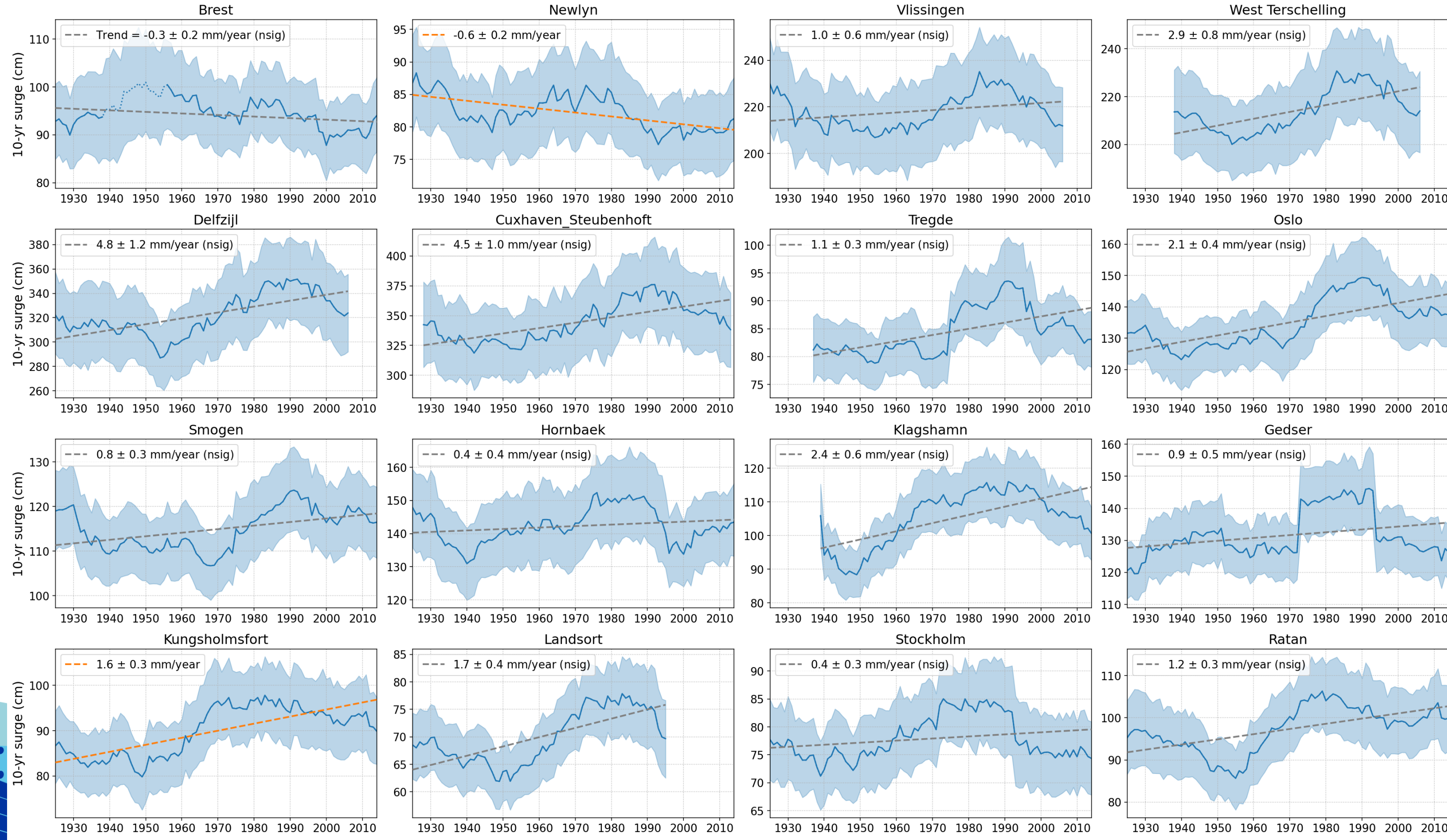
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M₂ tide:



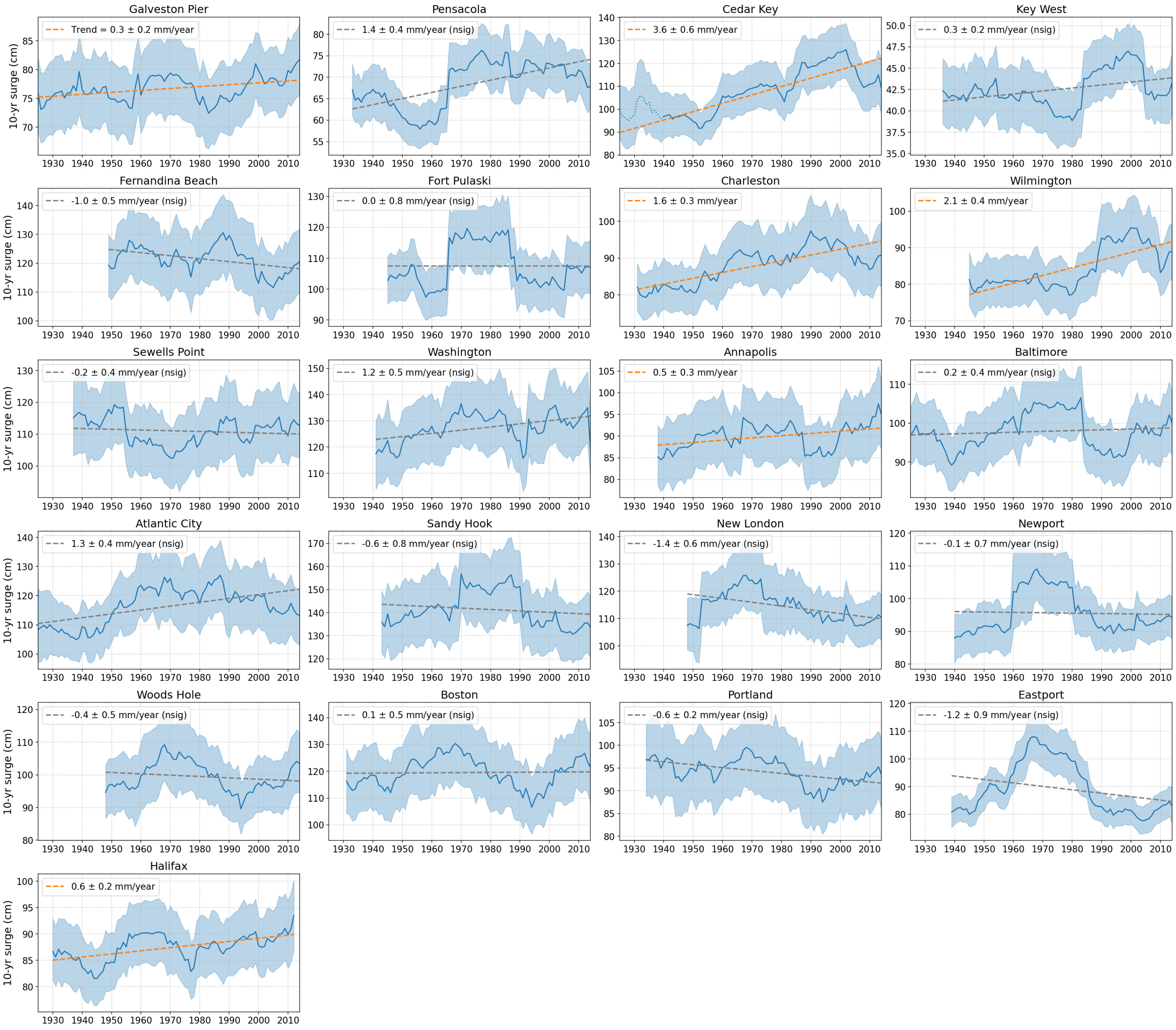
Appendix

10-yr surge:



Appendix

10-yr surge:



Appendix

Details on the GEV analysis

Extreme surges were estimated yearly, using Extreme Value Theory:

Extreme values follow some specific distributions, e.g. GEV (Generalized Extreme Value):

$$G(z) = \exp \left(- \left[1 + \xi \left(\frac{z - \mu(t)}{\sigma} \right) \right]^{\frac{-1}{\xi}} \right) \quad \text{Cumulative distribution function of the GEV distribution}$$

- μ and σ are obtained by fitting a **GEV on winter monthly maxima**, over a 21 year sliding window. ξ is kept constant
- Seasonality in μ and σ (BIC and AIC to assess the best fit):

$$\left. \begin{aligned} \mu(t) &= \mu_0 + \mu_s \cos(\omega_s t + \phi_s) \\ \sigma(t) &= \sigma_0 \end{aligned} \right\} \text{Annual cycle in } \mu, \text{ no cycle in } \sigma$$

- Cumulative distribution function of the GEV for **annual maxima**:

$$\begin{aligned} G_{\text{year}}(z) &= P(M_{\text{year}} \leq z) \\ &= P(M_{\text{oct}} \leq z) * P(M_{\text{nov}} \leq z) * P(M_{\text{dec}} \leq z) * P(M_{\text{jan}} \leq z) * P(M_{\text{feb}} \leq z) * P(M_{\text{mar}} \leq z) \\ &= G_{\text{oct}}(z) * G_{\text{nov}}(z) * G_{\text{dec}}(z) * G_{\text{jan}}(z) * G_{\text{feb}}(z) * G_{\text{mar}}(z) \end{aligned}$$

- Return level associated to the return period period T_p with: $T_p = 1 / (1 - G_{\text{year}}(z_p))$