Changes in extreme surges in the North Atlantic over the last century

Julie Cheynel[1], Lucia Pineau-Guillou[1], Pascal Lazure[1], Marta Marcos[2], Nicolas Raillard[1] and Florent Lyard[3]

[1] *Ifremer*

[2] *IMEDEA*

[3] *LEGOS*

Data Science pour les risques climatiques et côtiers

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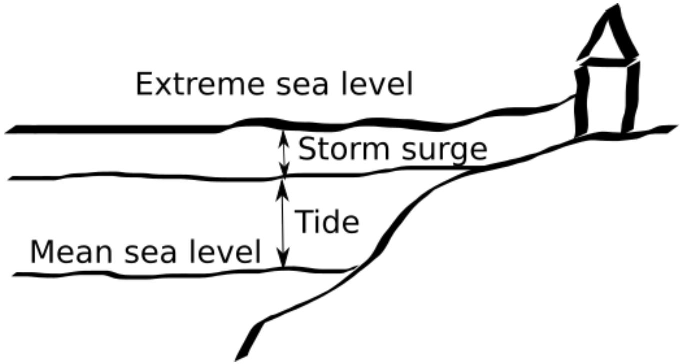
Context: the ClimEx project (2022-2025)

Changes in extreme sea levels in the North Atlantic

anr ClimEx

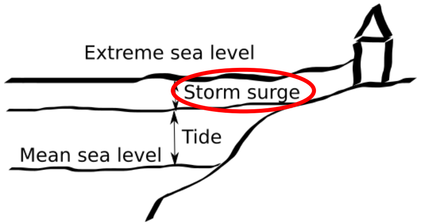
- How extreme sea levels are changing in a warming climate?
- What are the physical causes behind the observed changes?



Focus on tide and storm surge

Introduction

How extreme surges are changing along the North Atlantic coasts, since 1850?



Focus on storm surges from extra-tropical storms

State of the art:

- Consistently with storminess in the North Atlantic (e.g. *Feser et al., 2015*), storm surges display **strong interannual and multidecadal variability**, but **no clear long-term trend** at most sites over the last century (e.g. *Wahl and Chambers, 2015; Mawdsley and Haigh, 2016, Marcos and Woodworth, 2017*)

- Storm surge variability is partially explained by **large-scale atmospheric forcing**, i.e. NAO correlated (e.g. *Wahl and Chambers, 2016; Marcos and Woodworth, 2017)*

- Due to the large multidecadal variability, obtaining reliable long-term trends in storm surges requires long datasets. Long tide gauge records are sparse, satellite altimetry data records are short (<40 years)

  ➢ Alternative solution: development of **long hindcasts** from numerical models

Introduction

How extreme surges are changing along the North Atlantic coasts, since 1850?

1) Investigation of regional changes in winter storm surges, from tide gauge analysis
   - Data
   - Methods
   - Results

2) A secular sea level hindcast to investigate variability and trends of storm surges
   - Data: sea level hindcast
   - Validation
   - Improvement of wind-stress parametrization
   - Methods
   - Results

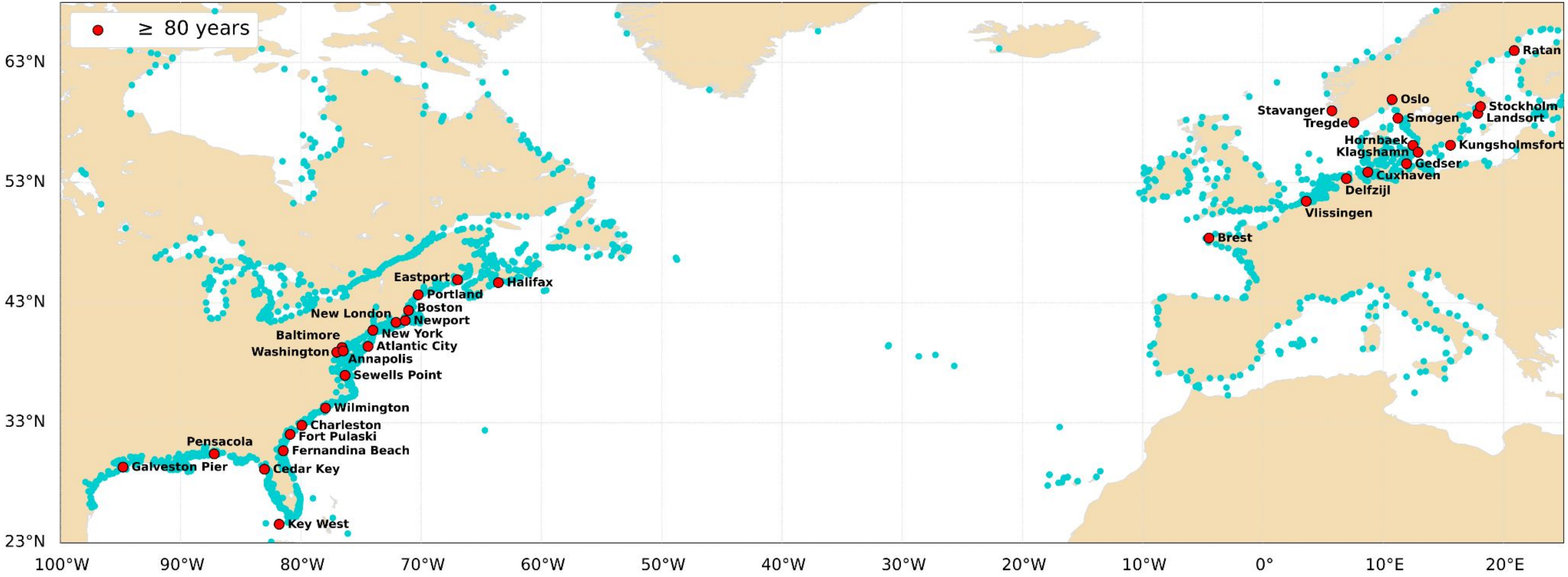
Summary

Perspectives

1) Investigation of regional changes in winter storm surges, from tide gauge analysis

Data:

- Tide gauge sea level data from GESLA-3 (*Haigh et al., 2022*)
- Selection of **35 tide gauges**, with at least **80 years of winter data**



- Computation of surge (Sea level - Tide - Mean Sea Level)

1) Investigation of regional changes in winter storm surges, from tide gauge analysis

Methods:

- Statistical characterization of extreme surges, using the **GEV** (Generalized Extreme Value) distribution:

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

Cumulative distribution function of the GEV distribution (case ξ ≠ 0)

- For each year, μ and σ are obtained by fitting a GEV on **winter monthly maxima**, over a **21 year sliding window**

- ξ is fitted once on the whole dataset

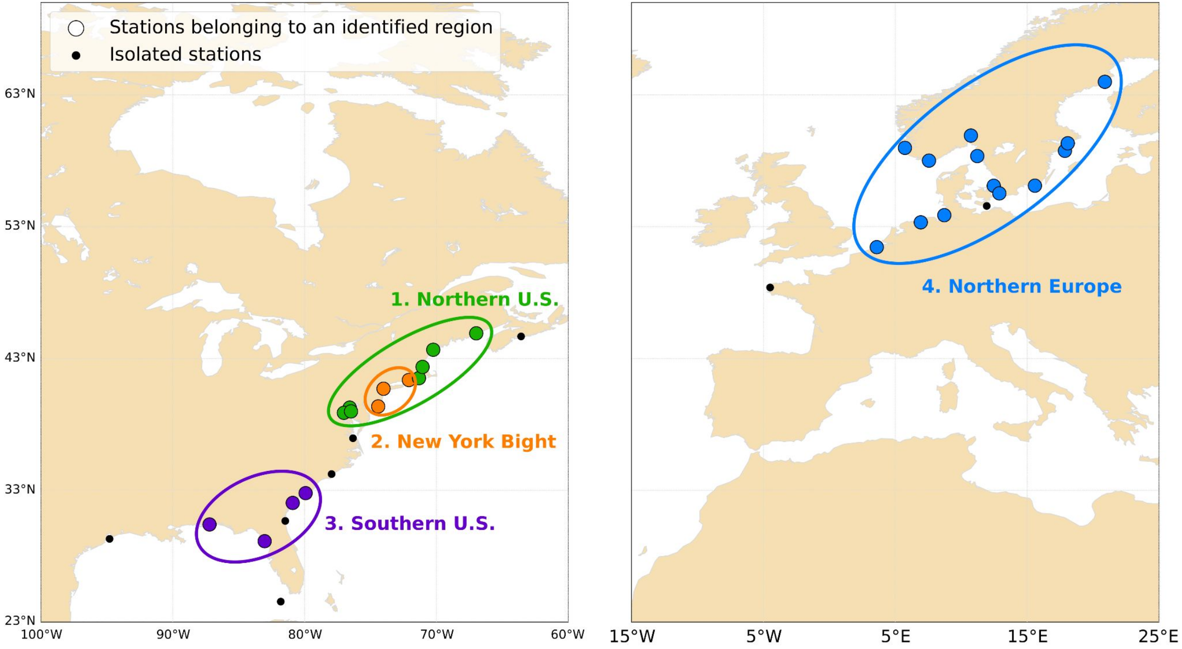
- Seasonality is included (Annual cycle in μ)

- For each year, the 10-yr return level is computed from the obtained distribution ($T_p = 1/(1-G(z_p))$)

- Return level time series are normalized and clustered (K-means algorithm)

1) Investigation of regional changes in winter storm surges, from tide gauge analysis

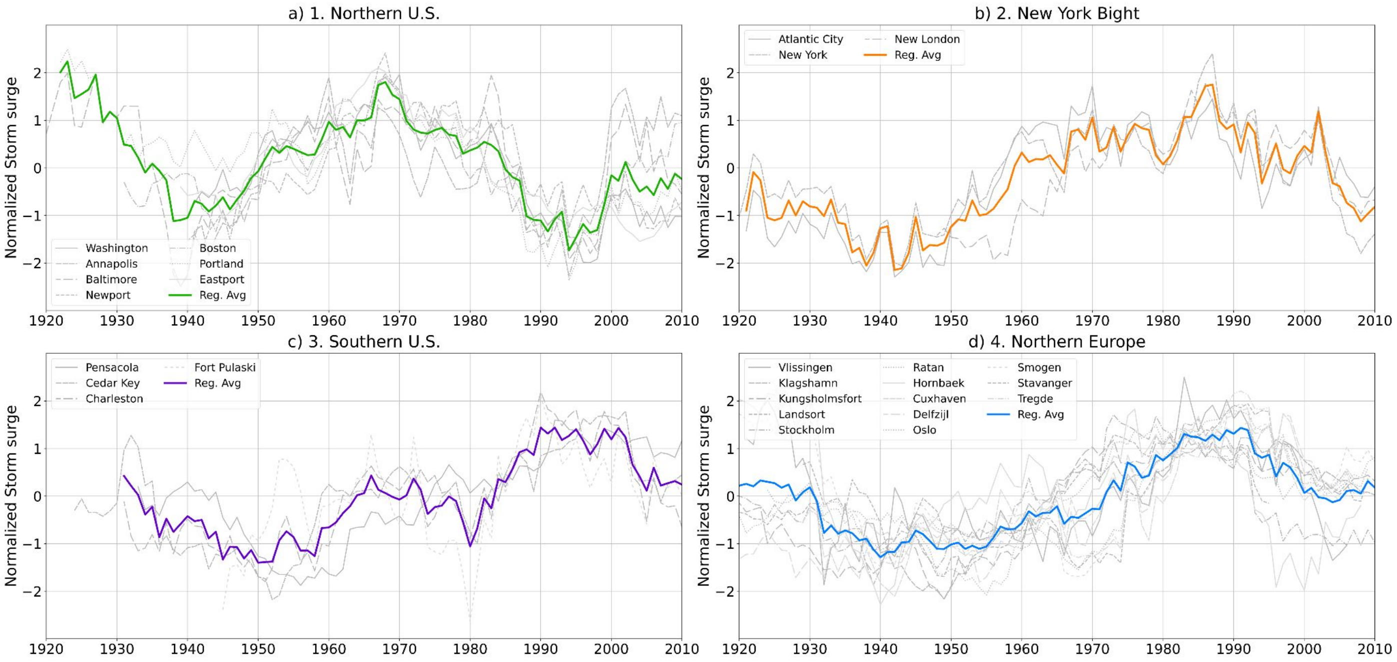
Results: The clustering algorithm identified 4 regions with coherent variations for storm surges



- Large coherent regions: large-scale processes drive the multidecadal changes in storm surges
- 23% of the stations are isolated: importance of local effects
- New York Bight region located inside Northern U.S. region: Local effects, like specific topography or river flow?

1) Investigation of regional changes in winter storm surges, from tide gauge analysis

Results: In all regions, storm surges display large multidecadal variability



- The New York Bight (NYB) shows very different variations from the Northern U.S.
- Large spread in Europe: differences between North Sea / Baltic Sea, different physics
- Variations in the Northern Europe are close to the ones in the NYB (+ Southern U.S.)
- Significant correlations with large scale climate indices (NAO and AMO)

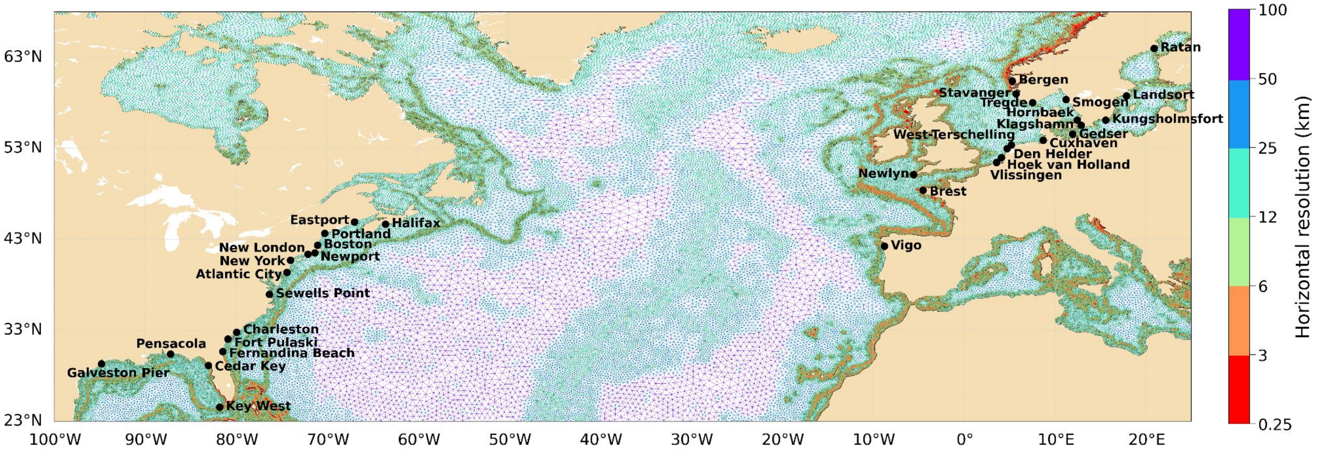
2) A secular sea level hindcast to investigate variability and trends of storm surges

Data: Development of a Sea Level hindcast with the Global Ocean Model TUGO

Hindcast over the 20th and 21st century (1900-2015), for the North Atlantic

Configuration and Parameters:

- TUGO 2D (barotropic model)
- FES2014 grid *(Lyard et al., 2021)*
- Tidal potential
- Atmospheric forcing: 20CRv3 *(Slivinski et al., 2019)*
- No waves
- Improvement of wind-stress parametrization, to better model extremes



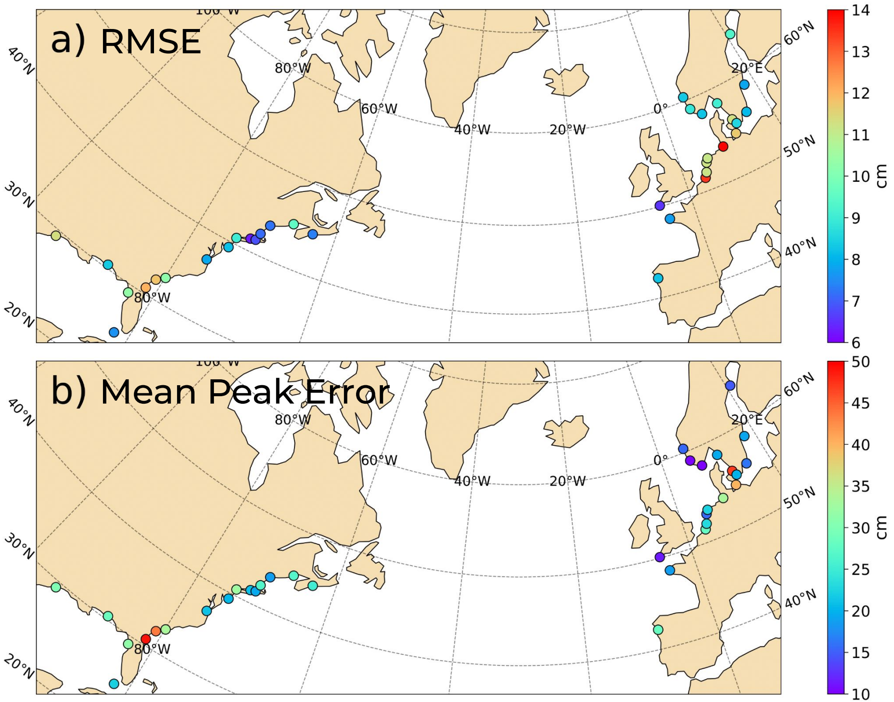
The ClimEx hindcast is now available for the scientific community:

- Output: hourly sea level and surge on a 0.1° grid, over 1900-2015
- DOI underway

2) A secular sea level hindcast to investigate variability and trends of storm surges

Validation: Against 34 tide gauges from GESLA3 (>= 75 years of complete data + not too far inland):

- Root Mean Square Error (RMSE)
- Mean Peak Error (MPE) mean difference observed/modeled surges, for the highest surges (2 per year)



- Very good performance for average surges (RMSE = 9.3 cm)
- Good performance for extreme surges, despite underestimation (MPE = 24.7 cm)
- Overall similar performances to other state-of-the-art surge hindcasts (e.g. *Muis et al., 2016, Fernandez-Montblanc et al., 2020, Muis et al., 2020*)
- Better score (in %) for extremes along the European coasts, poorer score along the southern U.S. coasts (tropical cyclones)

2) A secular sea level hindcast to investigate variability and trends of storm surges

Improvement of wind-stress parametrization

- Wind stress classical formulation: $\tau = \rho_a u_*^2 = \rho_a C_d U_{10}^2$

- Default TUGO parametrization: *Hellerman and Rosenstein (1983)*:

$$10^3 C_d = 0.934 + 0.788 \times 10^{-1} U_{10} + 0.868 \times 10^{-1} \Delta T - 0.616 \times 10^{-3} U_{10}^2 - 0.12 \times 10^{-2} \Delta T^2 - 0.214 \times 10^{-2} U_{10}(\Delta T)$$

- But the wind drag is also dependant on the wave state, via the roughness length z_0 *(Charnock, 1955)*:

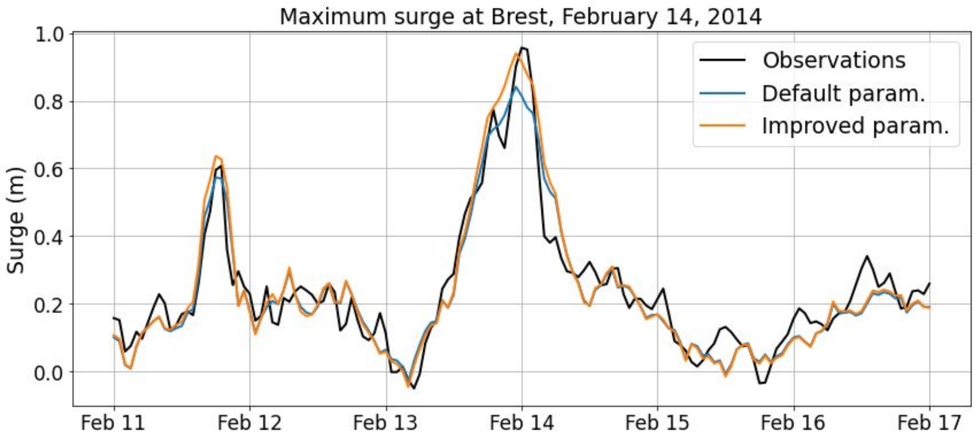
$$C_D = \frac{u_*^2}{u_{10}^2} = k^2 \left[ln \frac{z}{z_0} \right]^{-2}$$ with z_0 parametrized by: $$z_0 = \alpha_c \frac{u_*^2}{g}$$

α_c (Charnock parameter) can be set constant or given by wave models

- **Sensitivity analysis** for the 5-year period 2010-2014, at the 34 tide gauges, with different α_c

α_c = 0.014 (usual wind speed condition, *Muller et al., 2014*)
α_c = 0.022 (high wind speed condition, *Muller et al., 2014*)
α_c = 0.041 (*Muis et al., 2016*)

	RMSE	RMSE%	MPE	MPE%
Heller & Rosen	8.7 cm	10.6%	24.2 cm	28.6%
Chk, α_c = 0.014	9.3 cm	11.2%	30.9 cm	35.4%
Chk, α_c = 0.022	8.9 cm	10.8%	26.1 cm	30.7%
Chk, α_c = 0.041	8.6 cm	10.4%	17.7 cm	22.5%



- Almost no influence on moderate surges
- **Significant improvement for extreme surges:** α_c = 0.041: MPE reduced to 17.7 cm (22.5%), instead of 24.2 cm (28.6%) for the default parametrization
- Extreme surges are still underestimated, as often in storm surge modelling

Methods: Extreme Value Analysis

GEV (Generalized Extreme Value) distribution: $$G(z) = exp\left(-\left[1+\xi\left(\frac{z-\mu(t)}{\sigma(t)}\right)\right]^{\frac{-1}{\xi}}\right)$$

We used **non-stationary** location (μ) and shape (σ) parameters:

$$\mu(t) = \mu_0 + \boxed{\mu_a cos(\omega_a t + \phi_a) + \mu_{sa} cos(\omega_{sa} t + \phi_{sa})} + \boxed{\mu_t t} + \boxed{\mu_{NAO} NAO}$$

$$\sigma(t) = \sigma_0 + \boxed{\sigma_a cos(\omega_a t + \psi_a) + \sigma_{sa} cos(\omega_{sa} t + \psi_{sa})}$$

Trend

NAO dependence

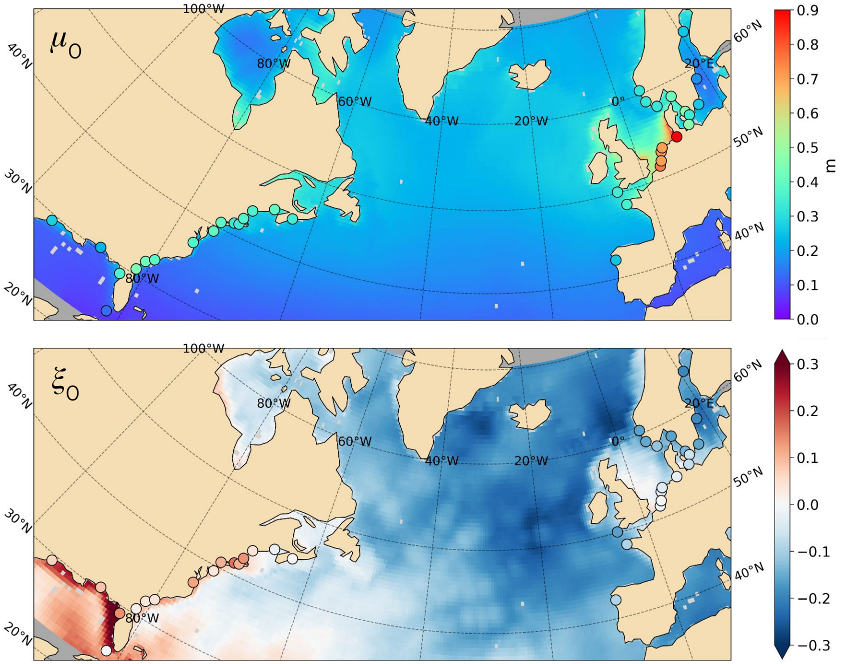
Seasonality (annual + semi-annual cycle)

μ_0, μ_a, ϕ_a, μ_{sa}, ϕ_{sa}, μ_t, μ_{NAO}, σ_0, σ_a, ψ_a, σ_{sa} and ψ_{sa} are obtained by fitting a **GEV** on **monthly maxima** of the full 116 year period (maximum likelihood estimator)

2) A secular sea level hindcast to investigate variability and trends of storm surges

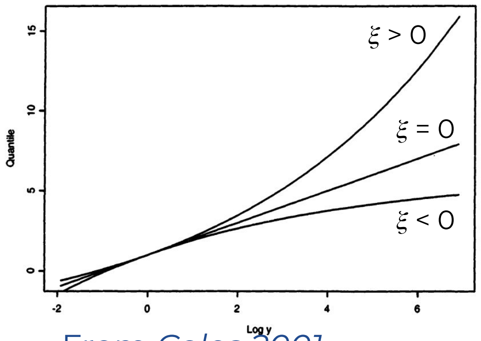
Results: Constant parameters

$$\mu(t) = \boxed{\mu_0} + \mu_a cos(\omega_a t + \phi_a) + \mu_{sa} cos(\omega_{sa} t + \phi_{sa}) + \mu_t t + \mu_{NAO} NAO$$
$$\xi = \boxed{\xi_0}$$



- Higher values in the North Sea: higher surges due to shallow waters
- Overall slight underestimation compared to observations, consistent with underestimation of extreme surges in the model

- North: ξ_0 < 0 (bounded upper limit for the distribution of extremes)
- Southern U.S. : ξ_0 > 0 (unbounded upper limit), occurrence of tropical cyclones

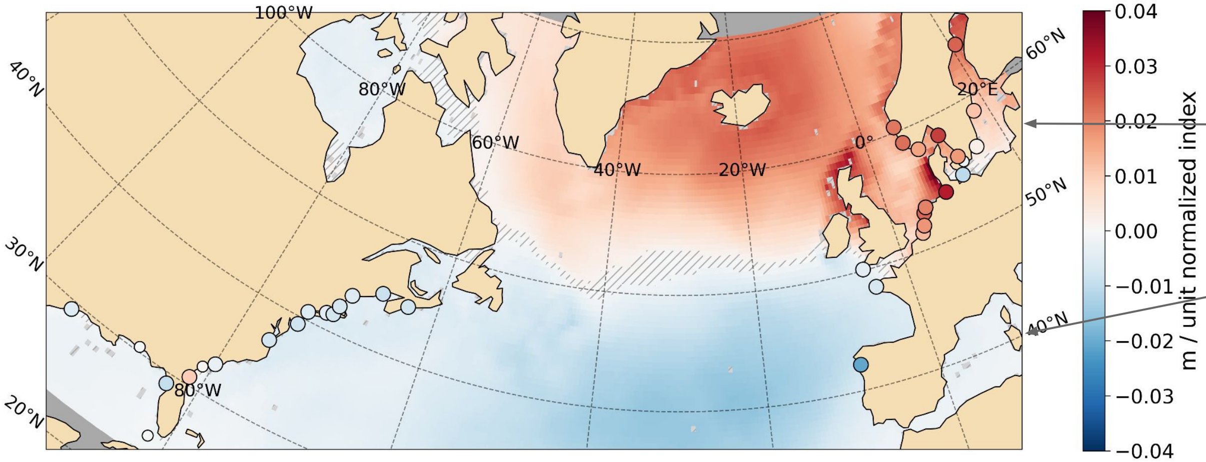


From *Coles 2001*

2) A secular sea level hindcast to investigate variability and trends of storm surges

Results: Dependence to NAO

$$\mu(t) = \mu_0 + \mu_a cos(\omega_a t + \phi_a) + \mu_{sa} cos(\omega_{sa} t + \phi_{sa}) + \mu_t t + \boxed{\mu_{NAO} NAO}$$



Positive dependance to NAO above 50°N

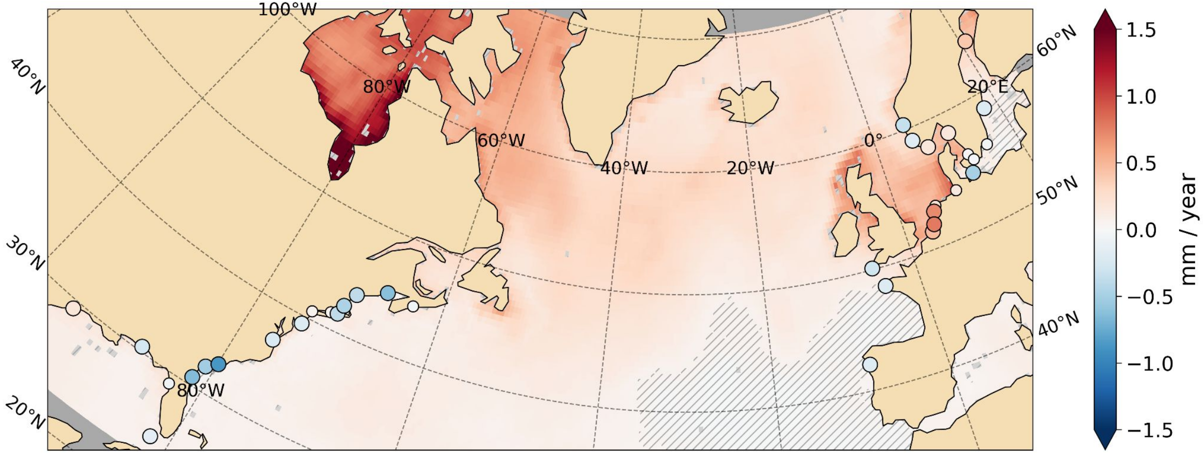
Negative below

- Due to the north eastward shift of the storm tracks during the NAO positive phase (e.g., *Pinto et al., 2009, Hurrell, 1995; Hurrell and Deser, 2010*)
- Extends from the coasts to the deep ocean
- Stronger in the North Sea: storm tracks + shallow water

2) A secular sea level hindcast to investigate variability and trends of storm surges

Results: Long-term trends, **1900-2015**

$$\mu(t) = \mu_0 + \mu_a cos(\omega_a t + \phi_a) + \mu_{sa} cos(\omega_{sa} t + \phi_{sa}) + \boxed{\mu_t t} + \mu_{NAO} NAO$$



- Modeled surges show mostly positive or non-significant trends
    - Consistent with other studies using 20CR (e.g., *Donat et al., 2011, Wang et al., 2012, Tadesse et al., 2022*)
    - But not always consistent with observations

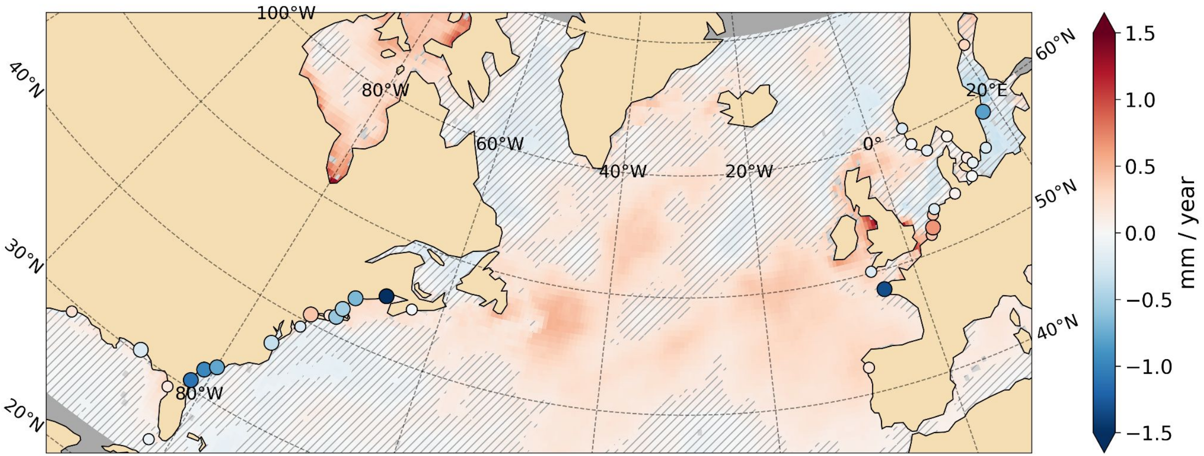
- Inhomogeneities in the 20CR dataset prior to 1940-1950 (e.g., *Wang et al., 2013; Krueger et al., 2013; Emanuel, 2024*)

➢ Spurious trends in 20CR atmospheric forcing due to a lack of assimilated data in the early 20th century?

2) A secular sea level hindcast to investigate variability and trends of storm surges

Results: Long-term trends, **1960-2015**

$$\mu(t) = \mu_0 + \mu_a cos(\omega_a t + \phi_a) + \mu_{sa} cos(\omega_{sa} t + \phi_{sa}) + \boxed{\mu_t t} + \mu_{NAO} NAO$$



- Modeled surges show mostly small or non significant trends (≤ ± 1 mm/year almost everywhere)
- High positive trends along the coasts of Great Britain (up to 1.4 mm/year), consistent with *Calafat et al. (2022)*
- Still some inconsistencies with observations (Brest, Gulf of Maine, Southern U.S)

➢ Caution when computing long-term trends with 20CR for the beginning of the 20th century

Summary

- We identified 4 regions of coherent multidecadal variability for winter storm surges, from tide gauge analysis

Cheynel J., Pineau-Guillou L., Lazure P. , Marcos M. and Raillard N. (2025). **Regional changes in extreme storm surges revealed by tide gauge analysis**. Ocean Dynamics, 75, 29. https://doi.org/10.1007/s10236-025-01675-6

- We developed a sea level hindcast covering 1900-2015, with the 2D global ocean model TUGO, forced with 20CRv3
- Overall very good performance for average surges (Mean RMSE = 9.3 cm), and good performance for extreme surges, despite an underestimation of extremes (Mean MPE = 24.7 cm)
- We applied a non-stationary Generalized Extreme Value analysis on modeled and observed surges
- The variability of extreme surges (dependance to NAO + seasonality *not shown*), is overall well reproduced
- Long-term trends are overall small (≤ ± 1 mm/year), but 20CR must be used with caution when computing trends over long periods
- Limitation of the model: waves are not considered

Submitted: Cheynel J. , Pineau-Guillou L. , Lazure P. , Marcos M. , Lyard F. and Raillard N. **A secular sea level hindcast (1900-2015) to investigate extreme surges variability and trends in the North Atlantic.**

Perspectives

Investigation of the physical causes, from the sea level hindcast analysis

- Apply the same analysis as on tide gauges in part 1), on the model grid points: time-varying 10-yr return levels, and K-means clustering

- The model will help disentangle changes due to atmospheric changes, and other changes, for instance due to river discharge or other local effects

- Understand the physical causes:
    - Investigation of local effects, e.g., fluvial discharge in the New York Bight?
    - Investigation of changes in atmospheric forcing, e.g. increase of wind intensity in the North Sea until 1990?

Appendix 0: Details on the GEV analysis

Extreme surges were estimated yearly, using Extreme Value Theory:

(Classically used, e.g. *Wahl and Chambers, 2015*; *Marcos and Woodworth, 2017*; *Reinert et al., 2021*)

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

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

Cumulative distribution function of the GEV distribution $(\xi \neq 0)$

- μ and σ and are obtained by fitting a GEV on winter monthly maxima, over a 21 year sliding window. ξ is kept constant (fitted once on the whole dataset)

- Seasonality in μ and σ (BIC and AIC to assess the best fit):

$$\left.\begin{aligned}\mu(t) &= \mu_0 + \mu_s cos(\omega_s t + \phi_s)\\ \sigma(t) &= \sigma_0\end{aligned}\right\}$$

Annual cycle in μ, no cycle in σ

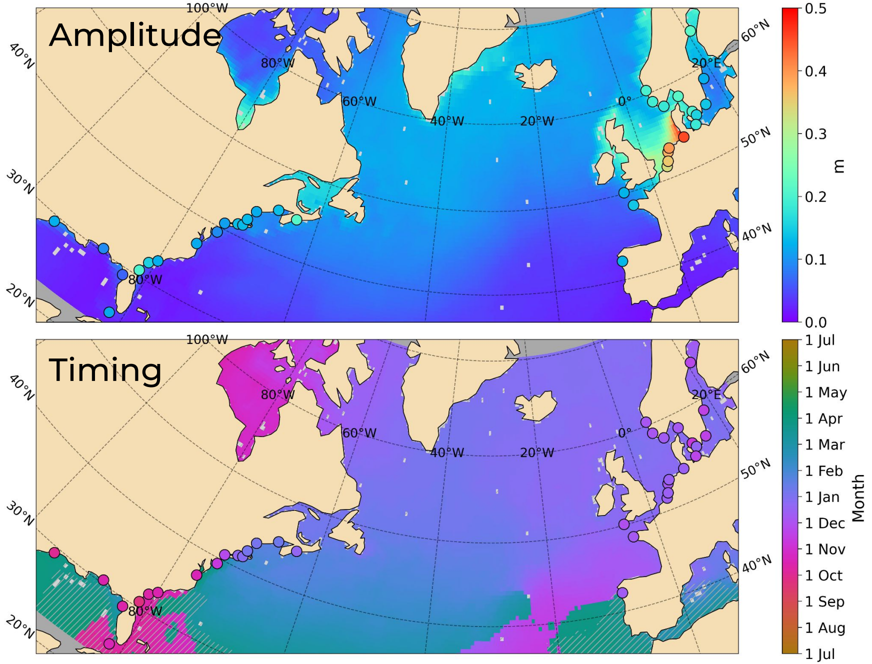
- Cumulative distribution function of the GEV for annual maxima:

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

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

Appendix 1: Seasonal cycle in μ

$$\mu(t) = \mu_0 + \boxed{\mu_a cos(\omega_a t + \phi_a) + \mu_{sa} cos(\omega_{sa} t + \phi_{sa})} + \mu_t t + \mu_{NAO} NAO$$

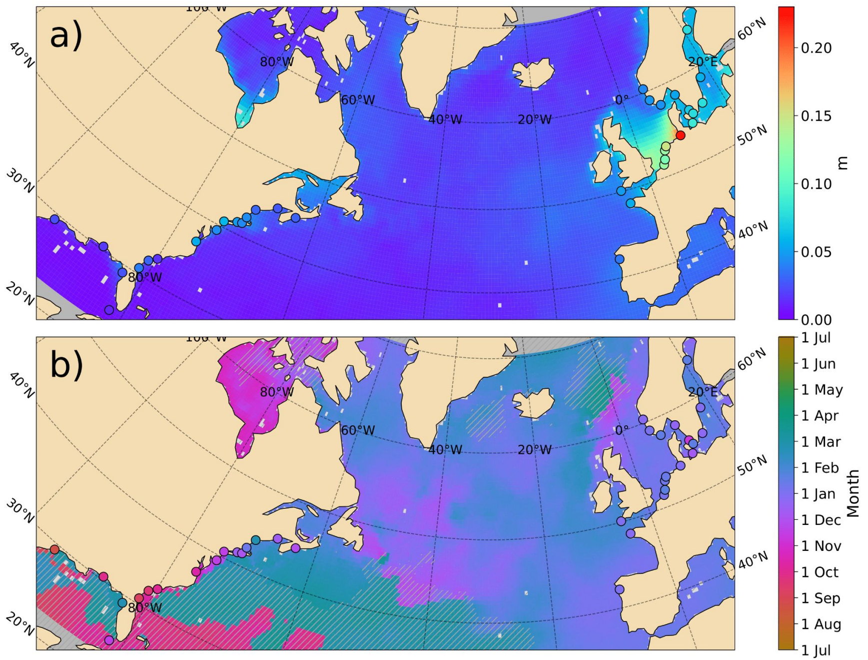


- Amplitude usually around 10-20 cm, higher in the North Sea (30-40 cm, ~ 50% of μ_0)
- Underestimation in southern U.S., likely due to the underestimation of tropical cyclones

- North: storm surge season in winter (December), dominance of extratropical storms
- Southern U.S. : storm surge season in autumn (September - October), dominance of tropical cyclones

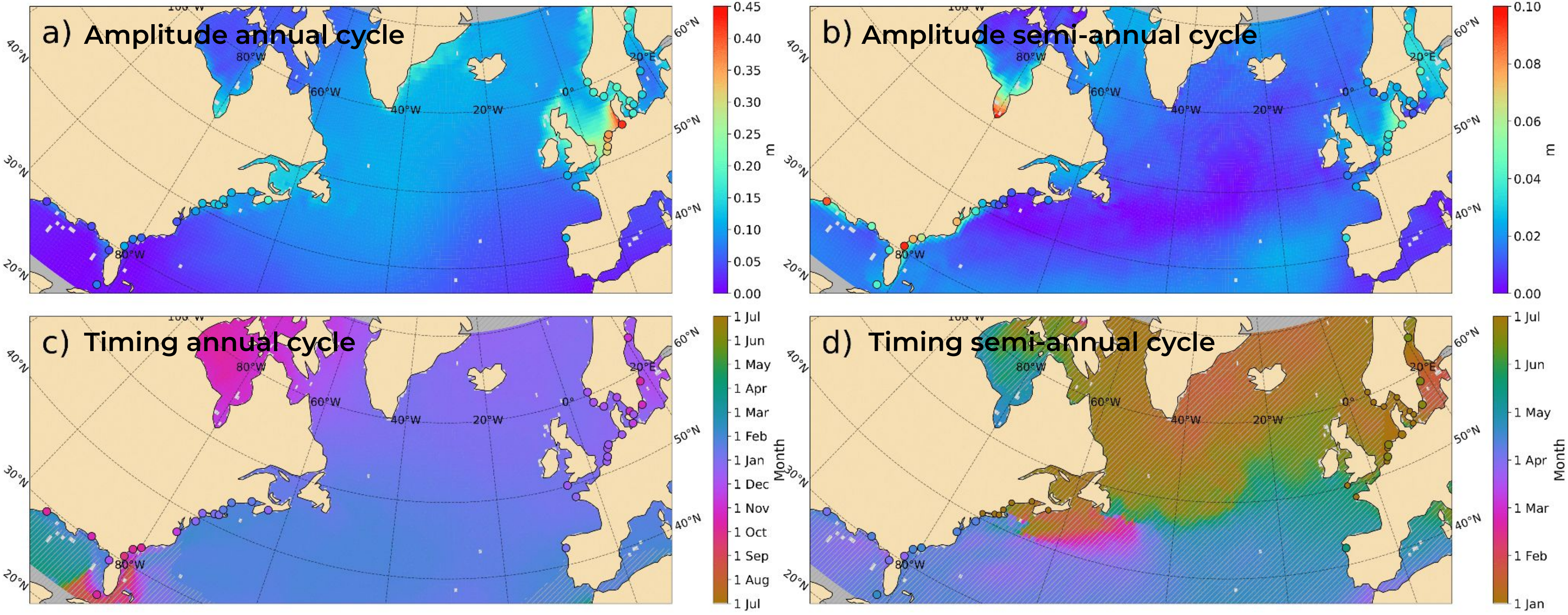
Appendix 2: Seasonal cycle in σ

$$\sigma(t) = \sigma_0 + \boxed{\sigma_a cos(\omega_a t + \psi_a) + \sigma_{sa} cos(\omega_{sa} t + \psi_{sa})}$$

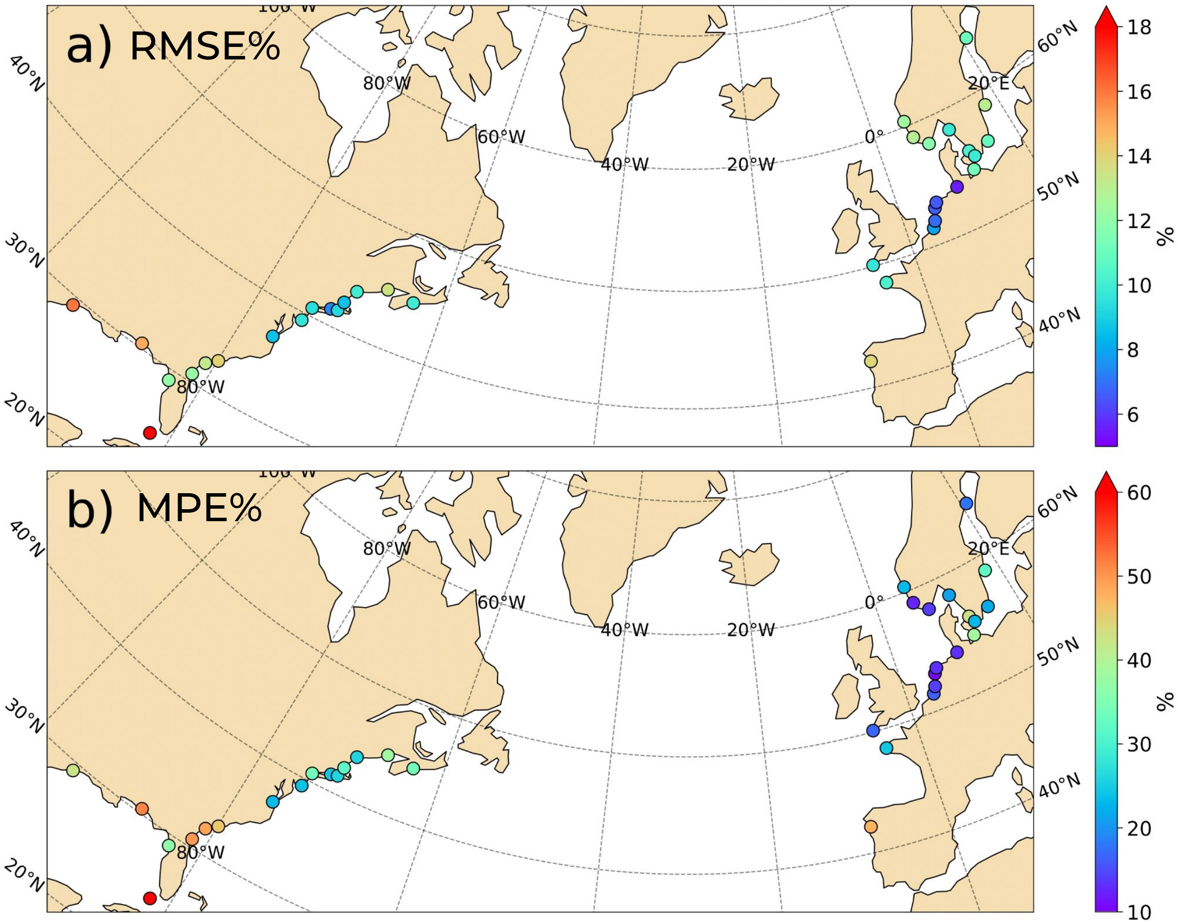


- ➢ Overall similar pattern as for μ

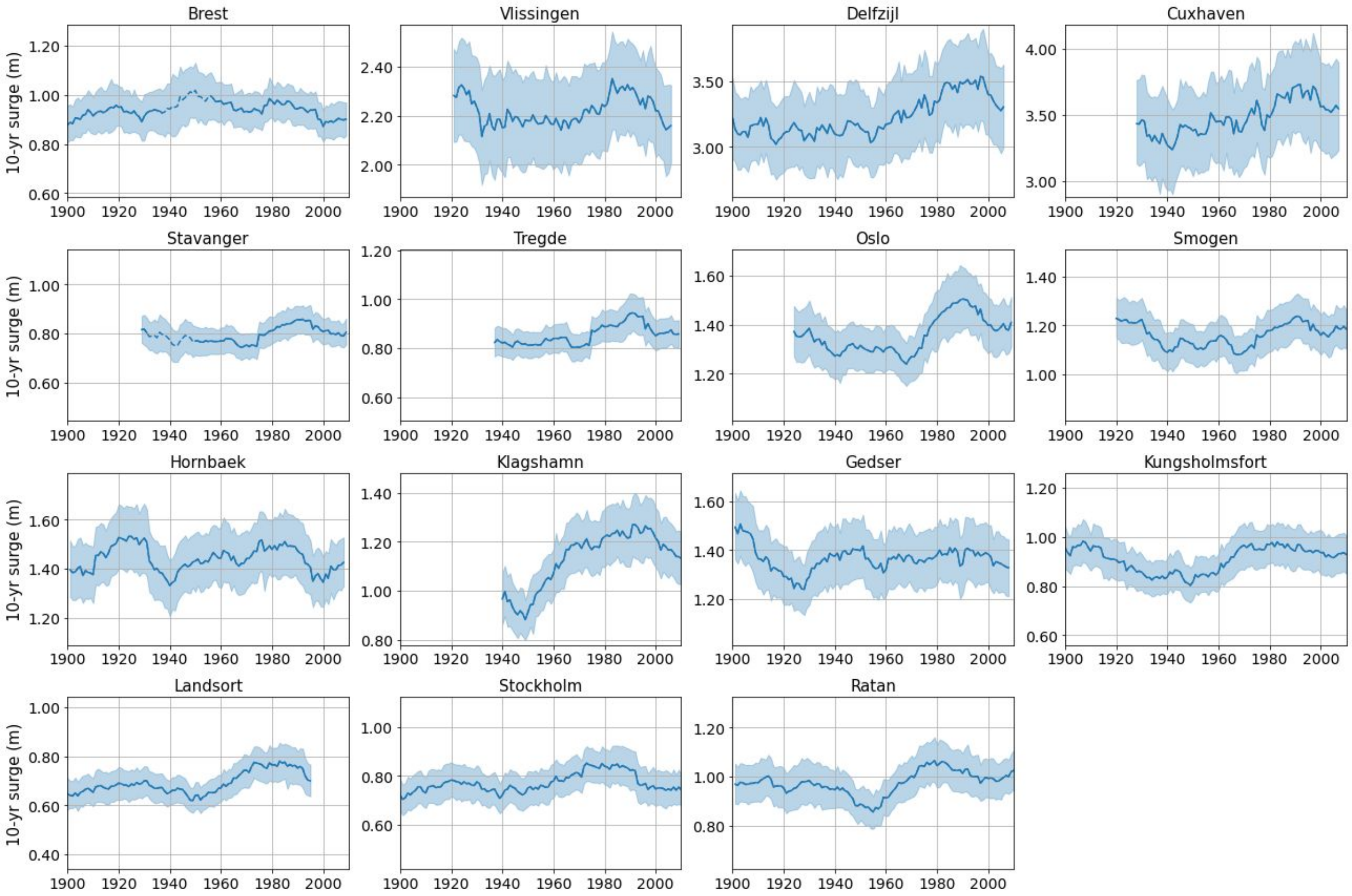
Appendix 3: Annual and semi-annual cycles in μ



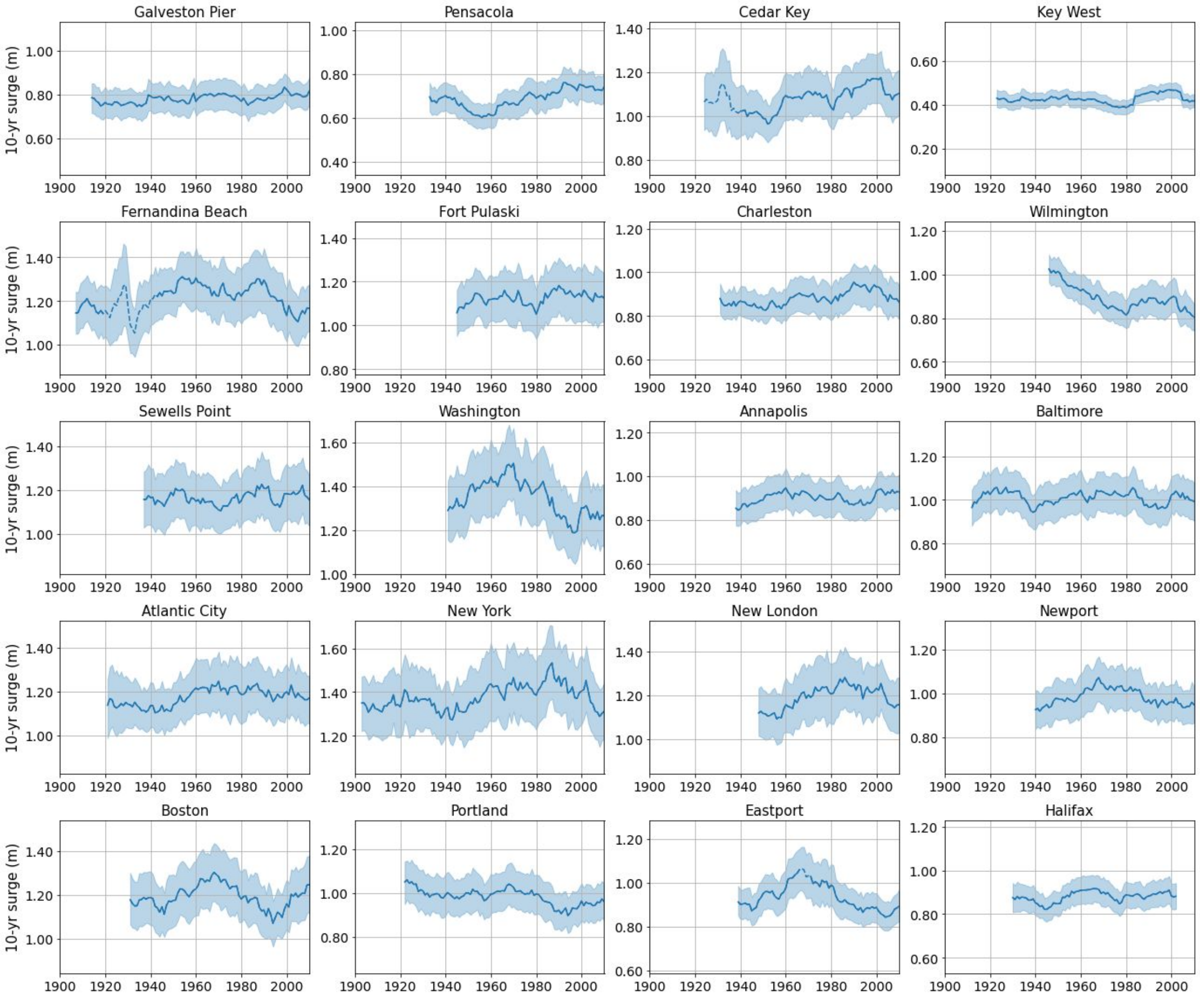
Appendix 4: Performance of the model, relatively to the mean peak surge



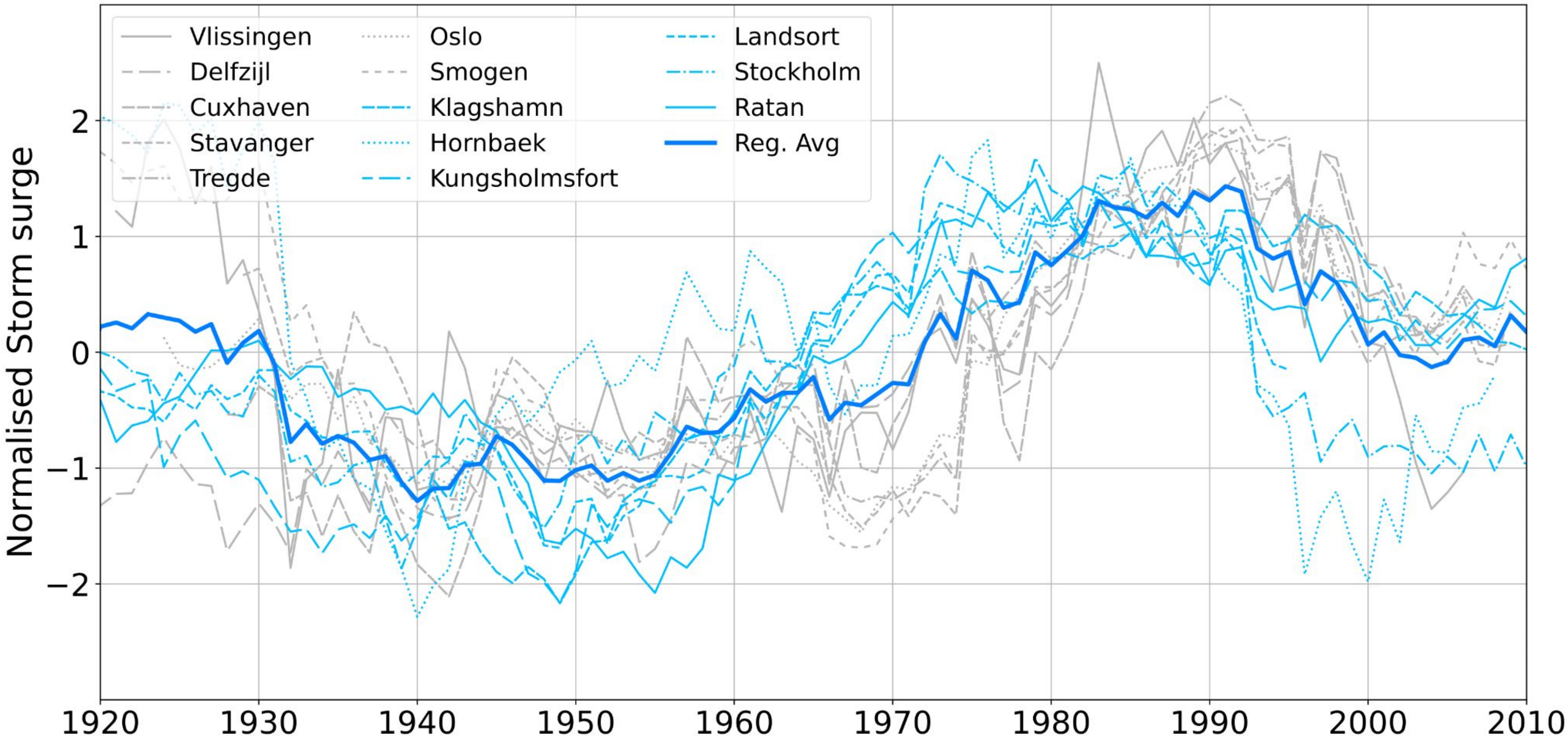
Appendix 5: 10-yr return levels at the 35 tide gauges



Appendix 5: 10-yr return levels at the 35 tide gauges

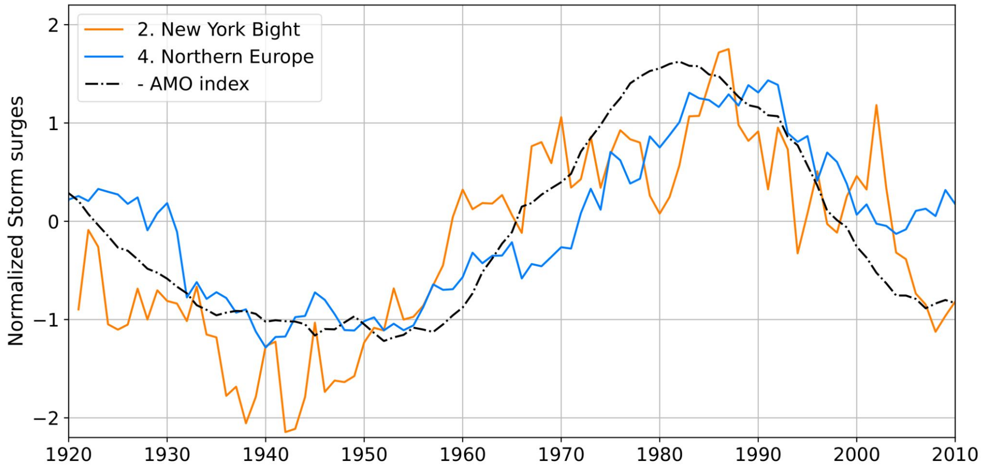


Appendix 6: Baltic Sea sub-zone, different physics

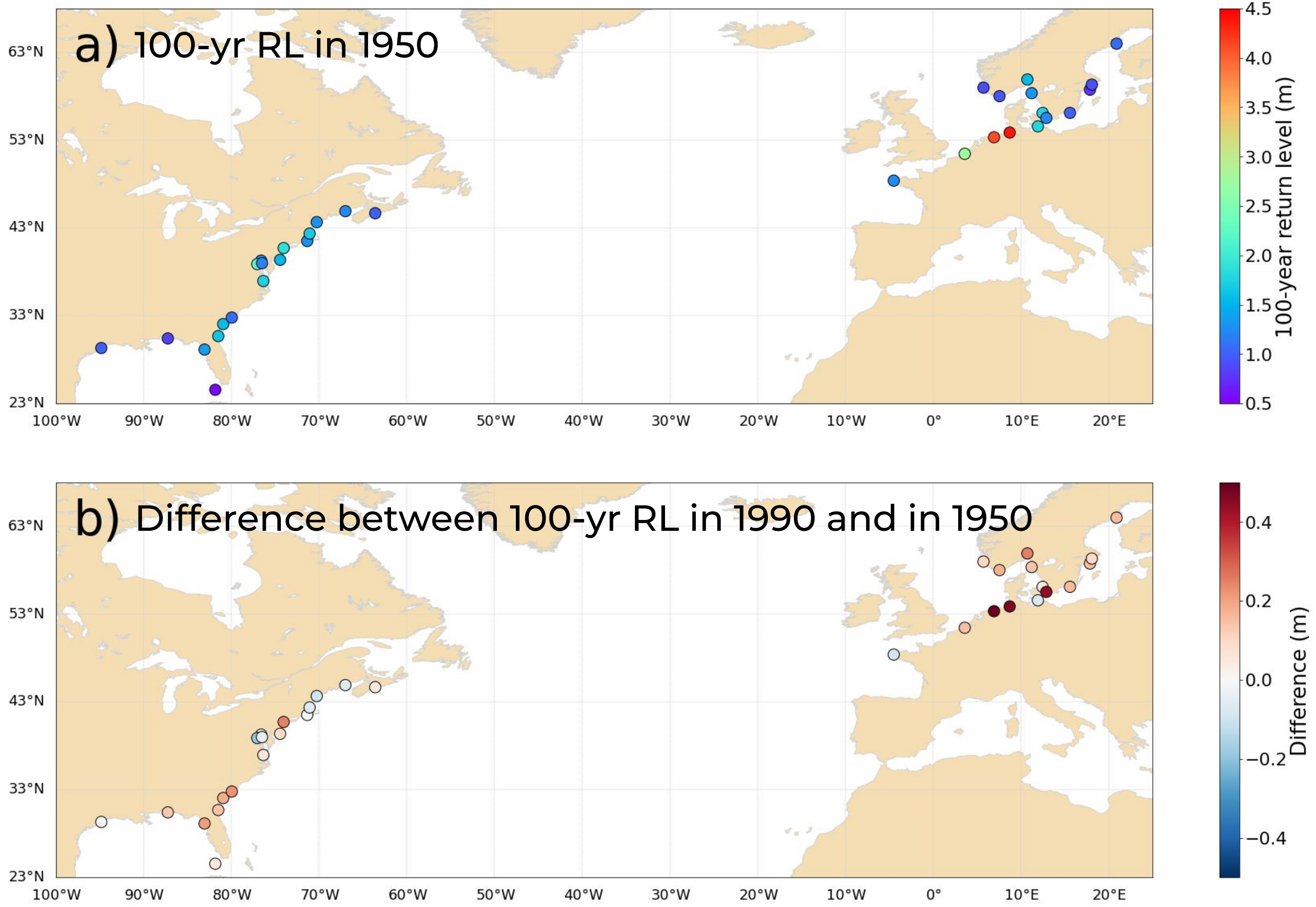


Appendix 7: Correlations with NAO and AMO indices

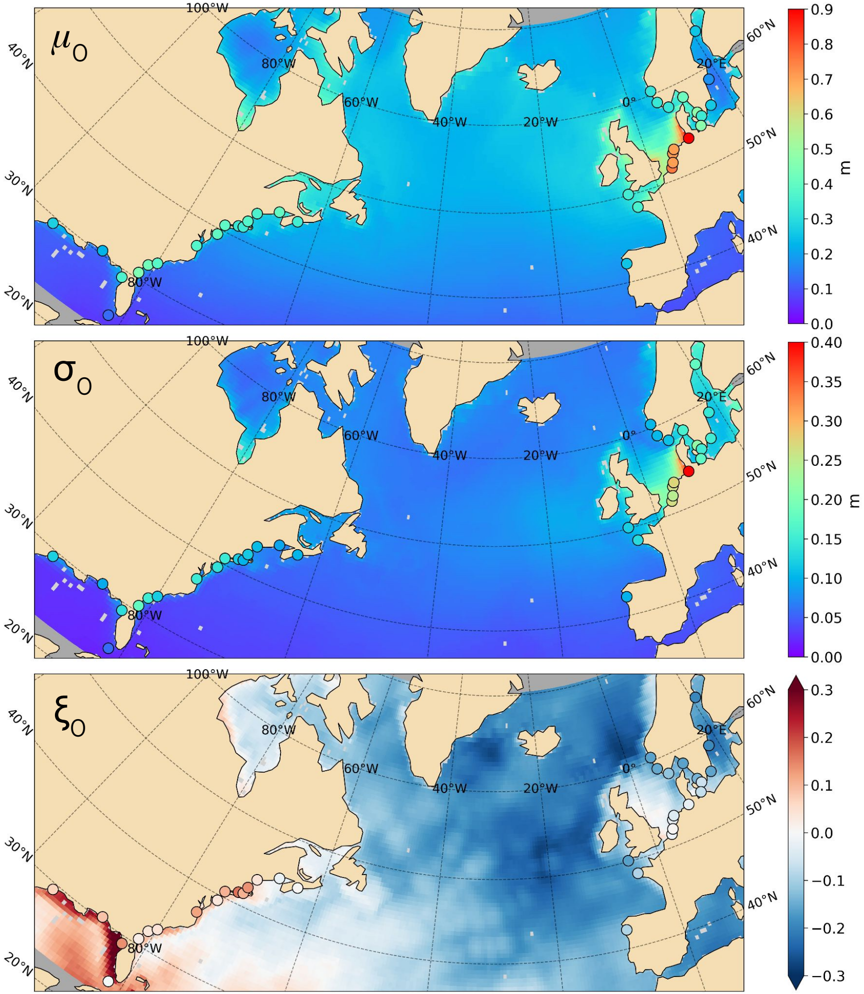
Region	r_{NAO}	p_{NAO}	r_{AMO}	p_{AMO}
Northern U.S.	-0.44	0.05	-0.06	0.41
New York Bight	0.26	0.40	-0.79	0.04
Southern U.S.	0.61	0.19	-0.47	0.30
Northern Europe	0.75	0.10	-0.85	0.02



Appendix 8: Changes in return levels between 1950 and 1990



Appendix 9: Constant parameters, with σ_0



Appendix 10: Individual surge events and density plots