Linking regional extreme sea level variability in North-Western Europe to large scale climate modes

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1 Overview

- Sea level extremes are becoming **more frequent and intense** with climate change, posing a threat to coastal communities
- In North-Western Europe, distinct regions of **similar variability** of daily maximum sea level can be distinguished
- These local regions are influenced and connected to large scale pressure decreases, and **teleconnections** like the North Atlantic Oscillation

2 Introduction

Extreme sea level (ESL) pose a big threat of coastal flooding, and their frequency and intensity are expected to increase in the future[1], due to increasing storm frequency and weather extremes.

Here, the spatiotemporal variability of ESL is researched, linking large scale physical processes and climate teleconnections to local sea level variability.

- **Sea level:** daily maximum of the Coastal Dataset for the Evaluation of Climate Impact (CODEC)[3] dataset from 1979 to 2018
- **Weather variables:** daily mean of ERA5[4]
- **Teleconnections**: monthly indices[5]

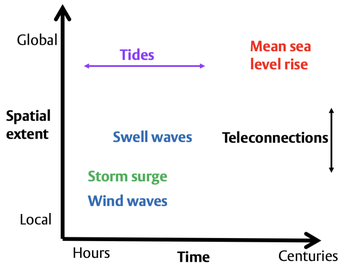


Figure 1: Schematic of contributors to extreme sea level height, with varying spatial and temporal extent, inspired from CSIRO[2]

1. What are the local regions of extreme sea level variability in the North Sea?
2. What are the processes and weather drivers for each regional cluster?
3. How are global teleconnections linked to local sea level variability?

3 EOF results

Emperical Orthogonal Functions (EOF) Analysis was done on the detided and deseasonalised daily maximum values of sea level, where the first **four modes explain over 90% of the variance** in the data.

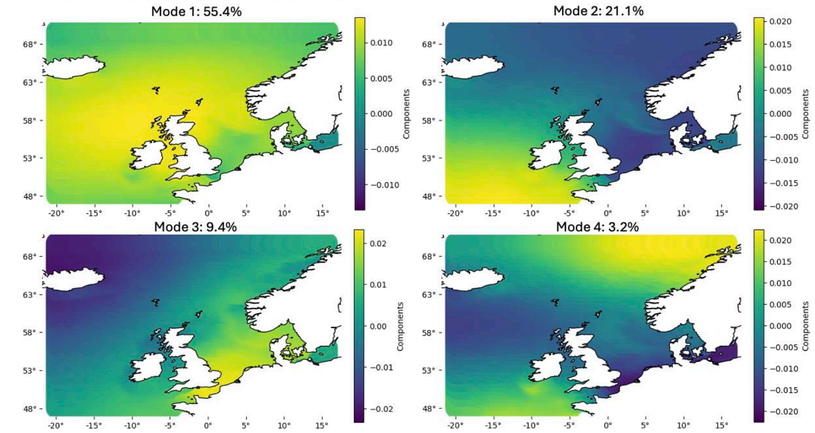


Figure 2: First four Empirical Orthogonal Function modes on the daily maximum de-tided sea level CODEC dataset[3]

4 Regions of variability

An ensemble of Gaussian Mixture Models was used, with soft voting, to assess regions of similar detided sea level variability. This is based on a method by Poropat et al. (2024)[6]. For relative performance, the silhouette score and elbow method were used. Six distinct regions were outlined, when seven of the first EOF modes were used as input.

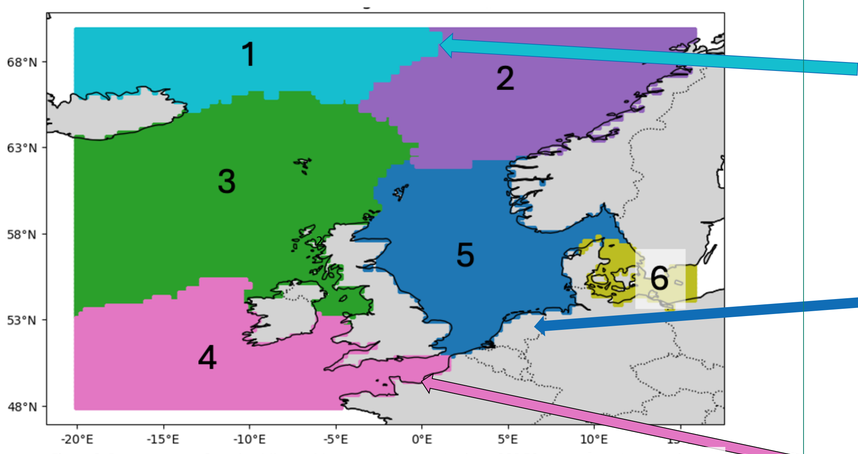


Figure 3: Best ensemble Gaussian Mixture Model result for the de-tided CODEC dataset[3], evaluated using the silhouette score and elbow method. The clusters can be characterised as follows:

1 Arctic Waters | 2 Norwegian Sea | 3 Central North Atlantic | 4 Eastern North Atlantic | 5 North Sea | 6 Baltic Sea

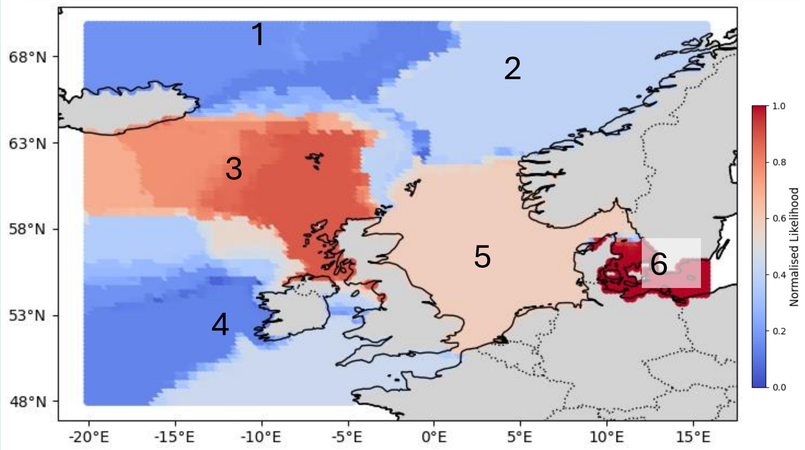


Figure 4: Normalised likelihood results from the ensemble model, showing high likelihood for points belonging to the Baltic cluster 6, as well as a clear centre in cluster 3. Surprisingly, the ensemble fits least well for the cluster 1 and cluster 4.

References

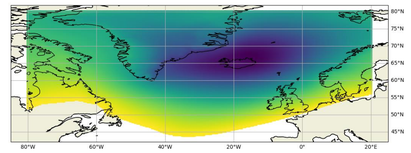
1. Tebaldi, Claudia, et al. "Extreme sea levels at different global warming levels." *Nature Climate Change* 11.9 (2021): 746-751.
2. Commonwealth Scientific and Industrial Research Organisation. "Causes of Extreme Sea Levels." *CSIRO*, https://research.csiro.au/slrwavescoast/extremes/causes-extreme-sea-levels/. Accessed 18 Apr. 2025
3. Muis, Sanne, et al. "A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections." *Frontiers in Marine Science* 7 (2020): 263
4. Hersbach, Hans, et al. "The ERA5 global reanalysis." *Quarterly journal of the royal meteorological society* 146.730 (2020): 1999-2049
5. National Oceanic and Atmospheric Administration. "Teleconnection Indices: Introduction." *Climate Prediction Center*, https://www.cpc.ncep.noaa.gov/data/teledoc/teleintro.shtml. Accessed 18 Apr. 2025.
6. Poropat, Lea, et al. "Unsupervised classification of the northwestern European seas based on satellite altimetry data." *Ocean Science* 20.1 (2024): 201-215

5 Links to climate variables

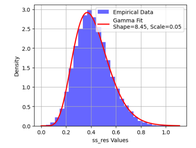
Using composite analysis and linear regression with ERA5 daily mean variables, a pattern in mean sea level pressure could be seen for each cluster.

- ESL in cluster 5 was paired with low pressure up north, compared to more localised pressure decrease in cluster 1
- No significance was found for the significant wave height composites
- Gamma distributions fit the weighted average sea level distributions

Cluster 1: Arctic Waters Cluster

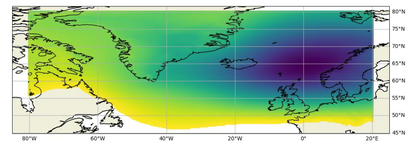


Correlation Arctic Oscillation: 0.61
Correlation North Atlantic Oscillation: 0.56

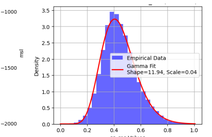


Characteristics:
Lowest mean
Lest kurtosis

Cluster 5: North Sea Cluster

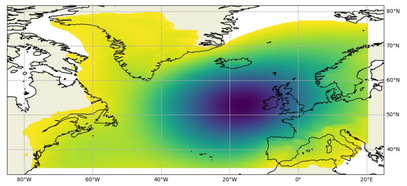


Correlation Arctic Oscillation: 0.44
Correlation North Atlantic Oscillation: 0.28

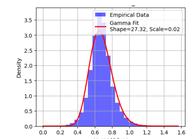


Characteristics:
Highest skewness and kurtosis

Cluster 4: Eastern North Atlantic Cluster



Correlation Arctic Oscillation: -0.21
Correlation North Atlantic Oscillation: -0.18



Characteristics:
Highest mean
2nd largest kurtosis

6 Summary

- **Six distinct regions** of daily maximum sea level height variability can be distinguished in North-Western Europe
- The average variability in the Northern most clusters correspond to variability in the **North Atlantic Oscillation and the Arctic Oscillation,** which is inverse to the variability closer to the West Atlantic.
- The tendency for extremes is highest in the North Sea, likely due to **bathymetry interactions**

7 Future work

- Understand physical processes and phenomenology better of ESL occurrences
- Link teleconnections correlations to causality
- Improve understanding of the non-linear tidal-sea level interactions

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