A European study of the marine extreme water level on coastal flooding

Melisa Menendez*, Alexandra Toimil, Hector Lobeto, Maria Suarez-Bilbao, Camila De Sa Cotrim, Ana J. Abascal, Iñigo Losada

* menendezm@unican.es

CoCliCo
coastal climate core services

Extreme water level and coastal flooding in Europe

Waves crash against a seawall in Prestwick, Scotland, in 2014

La Rochelle (France 2010)

High water in Venice, Italy, Oct. 29, 2018

Los Alcázares (Murcia 2020)

San Sebastian (2014)

Coastal flooding in Aberystwyth, Wales, 2013

Gijón (Asturias, Spain, 2014)

Flood_Hamburg (2022)

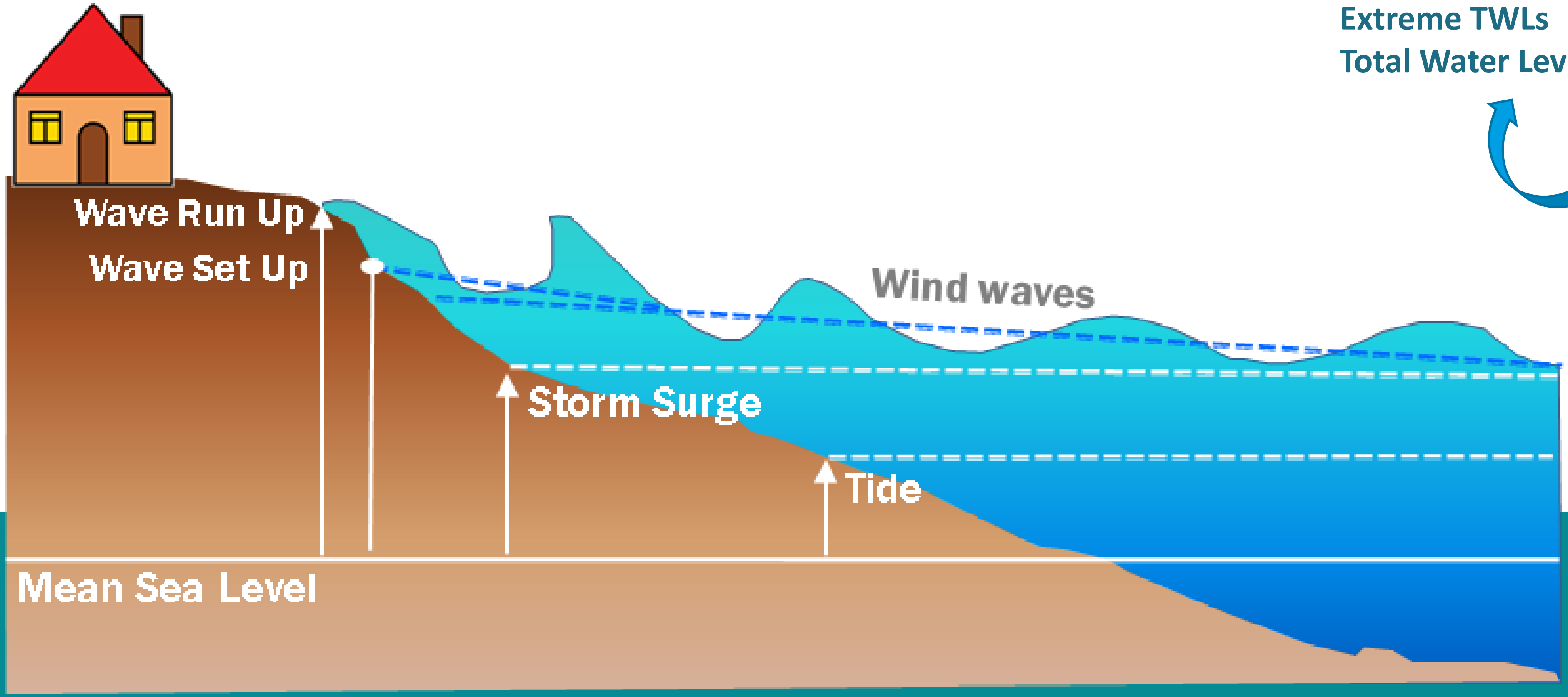
Goals of the study:

- The **development of high-resolution marine datasets** providing mean and extreme climate conditions **for the historical and projected changes** covering the European coast.
- Develop a coastal **Total Water Level dataset** to be used as **boundary conditions for the flood models.**
- Modelling the flood and getting **flood maps**

Coastal
Flooding
Erosion

Extreme TWLs
Total Water Levels

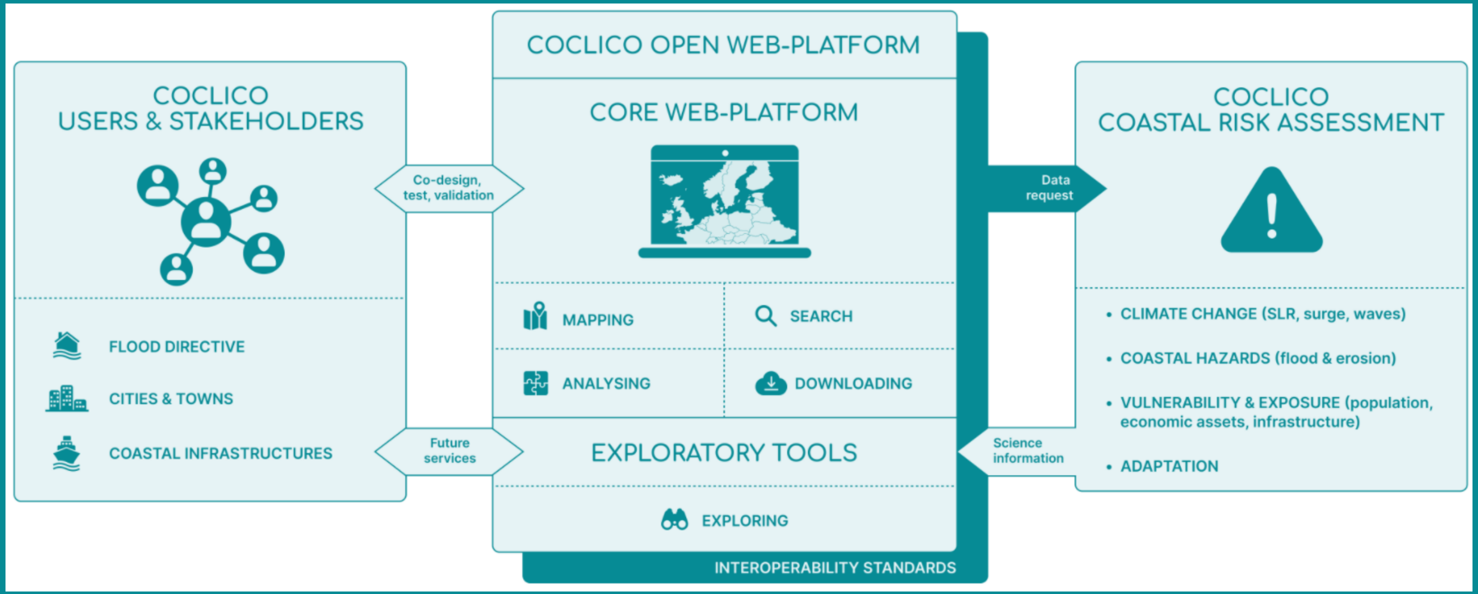
Waves
Still Water Level
Vertical land motions



CoCliCo
coastal climate core services

CoCliCo
Coastal Climate Core Services

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101003598



WEBSITE:
https://coclicoservices.eu
TWITTER:
https://twitter.com/CoCliCoServices
LINKEDIN:
https://www.linkedin.com/company/coclicoservices

The CoCliCo project is a Horizon Europe project, led by **Goneri le Cozannet** (BRGM)

brgm Géosciences pour une Terre durable · CAU · Global Climate Forum · Mercator Ocean International · Sayers and Partners · IHcantabria · Guerilla Creative · Aristotle University of Thessaloniki · VU Vrije Universiteit Amsterdam · UEA University of East Anglia · Deltares Enabling Delta Life · ENEA · vizzuality. · LGi sustainable innovation · cnrs · federlogistica · ICLEI Local Governments for Sustainability

CoCliCo
coastal climate core services

❖ A European study of the marine extreme water level on coastal flooding

Development of a pan-European high-resolution historical database

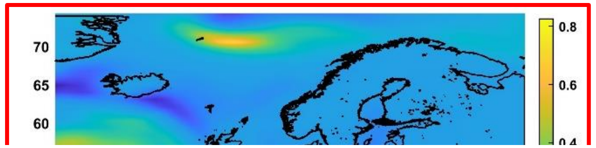
i. Storm surge hindcast
ii. Wave hindcast
iii. Total Water level reconstruction along the European coast
iv. Extreme TWL estimation
v. Modelling the coastal flooding

Development of pan-European regional climate projections

i. The selected CMIP6 climate models
ii. Mean sea level rise scenarios
iii. Storm surge projections
iv. Wave climate projections
v. Total Water level time series projections along the European coast
vi. Extreme TWL estimation
vii. Modelling the coastal flooding

Development of a pan-European high-resolution historical database

Historical simulation of the **STORM SURGE** (meteorological sea level component).



Numerical Model: Regional Ocean Modeling System (ROMS). A free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation with a split-explicit time-stepping algorithm.

It uses a horizontal curvilinear Arakawa C grid and vertical stretched terrain-following coordinates.

Two simulations are run (with/without astronomical tide) in order to test the non-linear interactions of tide vs. surge:

Forcings: ERA5 atmospheric Surface winds and SLP

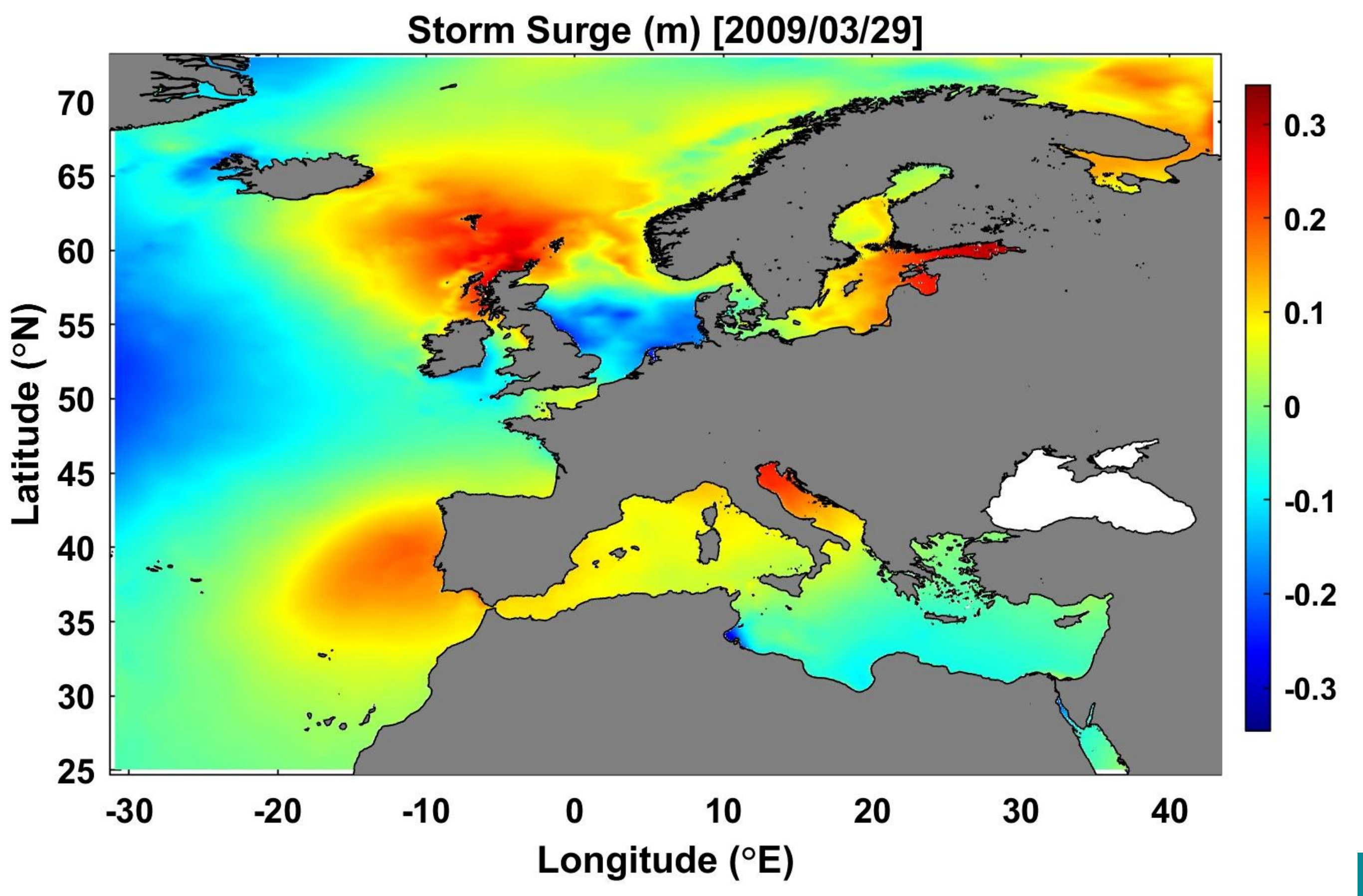
Boundary & initial conditions: The inverted barometer effect is imposed at the open boundaries of the domain

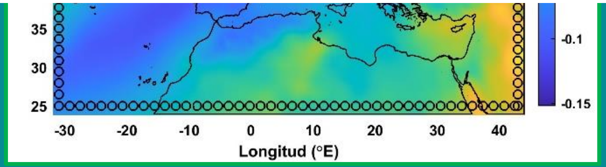
Modeled period: 1995 – 2022

Horizontal resolution: 5 km – 11 km

Temporal resolution: 1 h

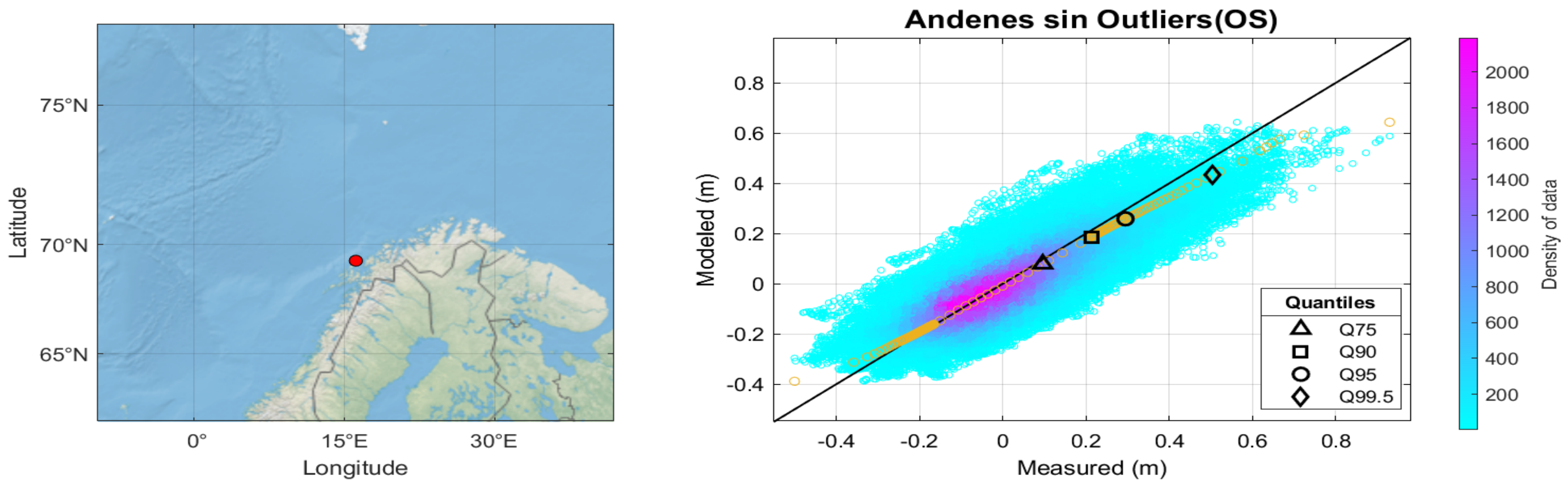
Output: hourly time series of the storm surge (NTR)





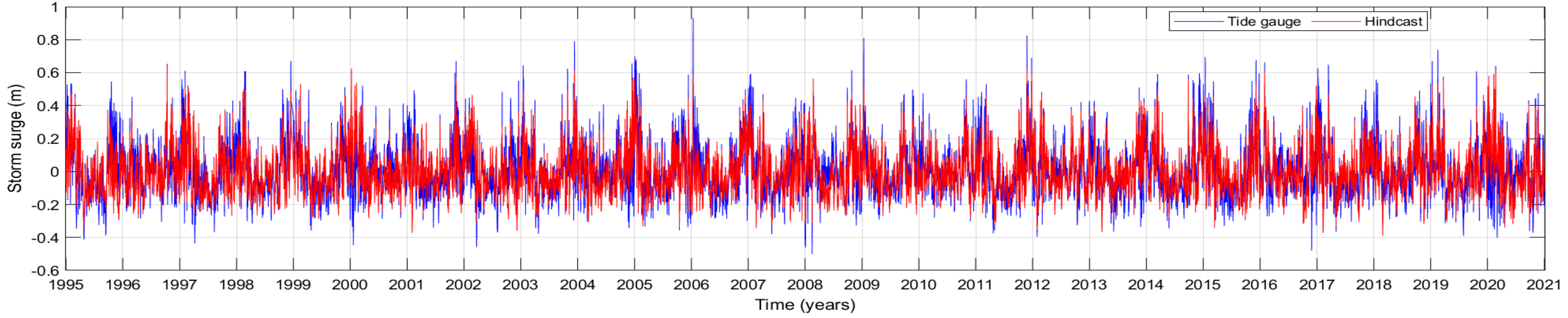
Development of a pan-European high-resolution historical database

Historical simulation of the **STORM SURGE** (meteorological sea level component).



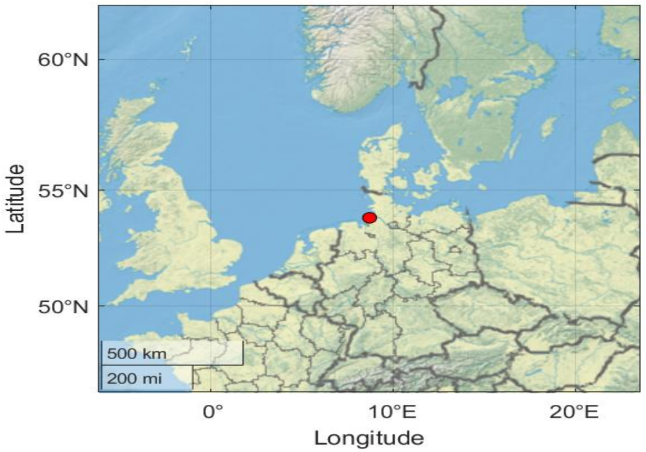
Location: Andenes
Hindcast: ERA5
years: 1995 - 2020

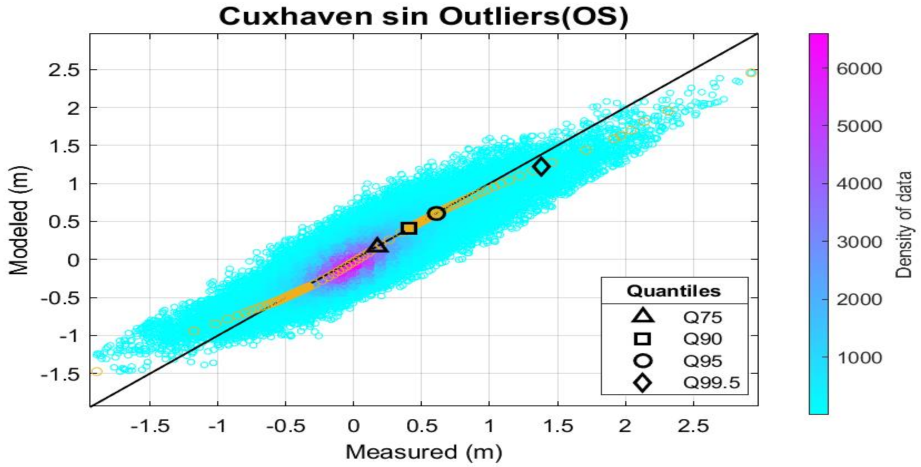
Statistical indicators:
Nobs: 227008
R2 = 0.75
Rho = 0.87
RMSE = 0.09m
Bias = -0.0096689 m
Corr = 0.83
Skill index = 0.9



Development of a pan-European high-resolution historical database

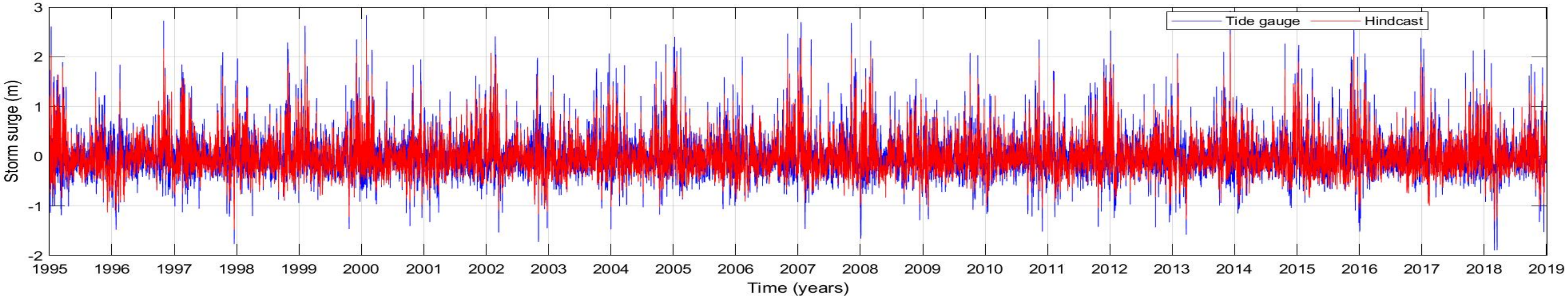
Historical simulation of the **STORM SURGE** (meteorological sea level component).





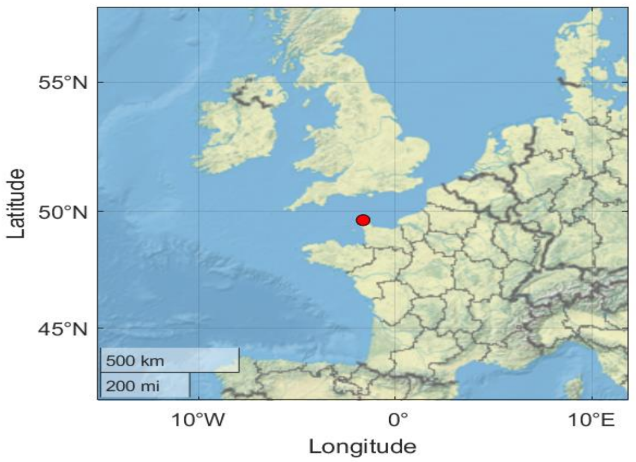
Location: Cuxhaven
Hindcast: ERA5
years: 1995 - 2018

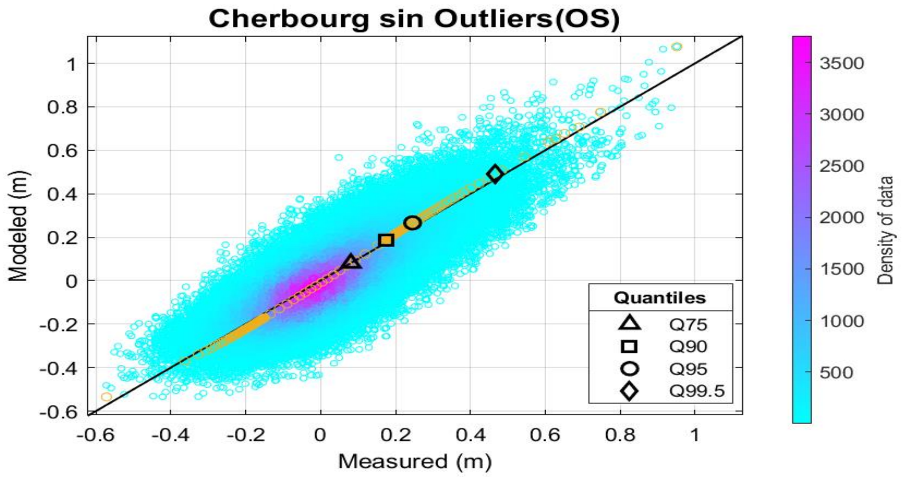
Statistical indicators:
Nobs: 210199
R2 = 0.78
Rho = 0.88
RMSE = 0.18m
Bias = -0.021583 m
Corr = 0.85
Skill index = 0.92



Development of a pan-European high-resolution historical database

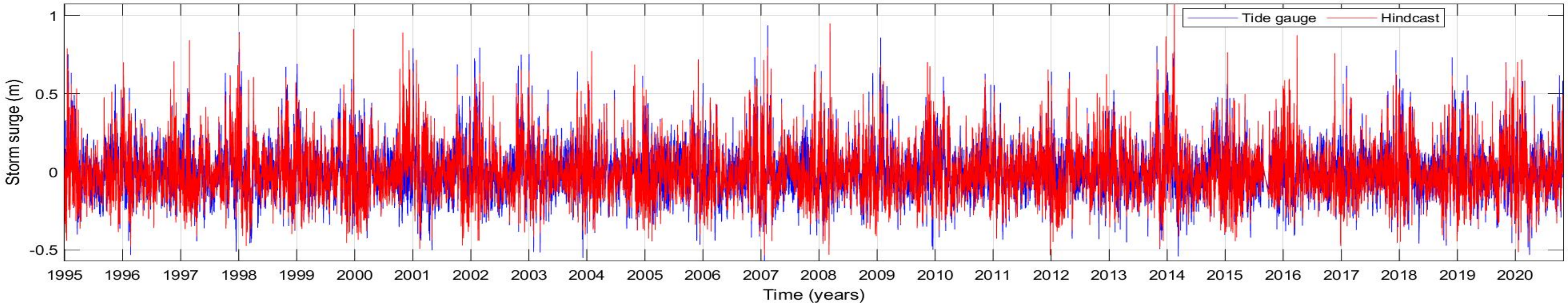
Historical simulation of the **STORM SURGE** (meteorological sea level component).





Location: Cherbourg
Hindcast: ERA5
years: 1995 - 2020

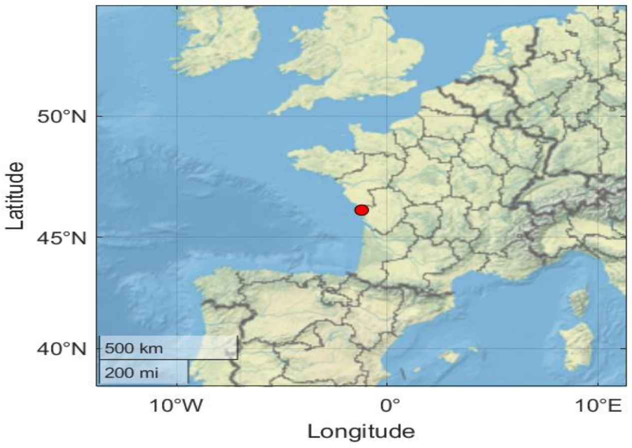
Statistical indicators:
Nobs: 223901
R2 = 0.68
Rho = 0.82
RMSE = 0.09m
Bias = -0.0072535 m
Corr = 0.79
Skill index = 0.88

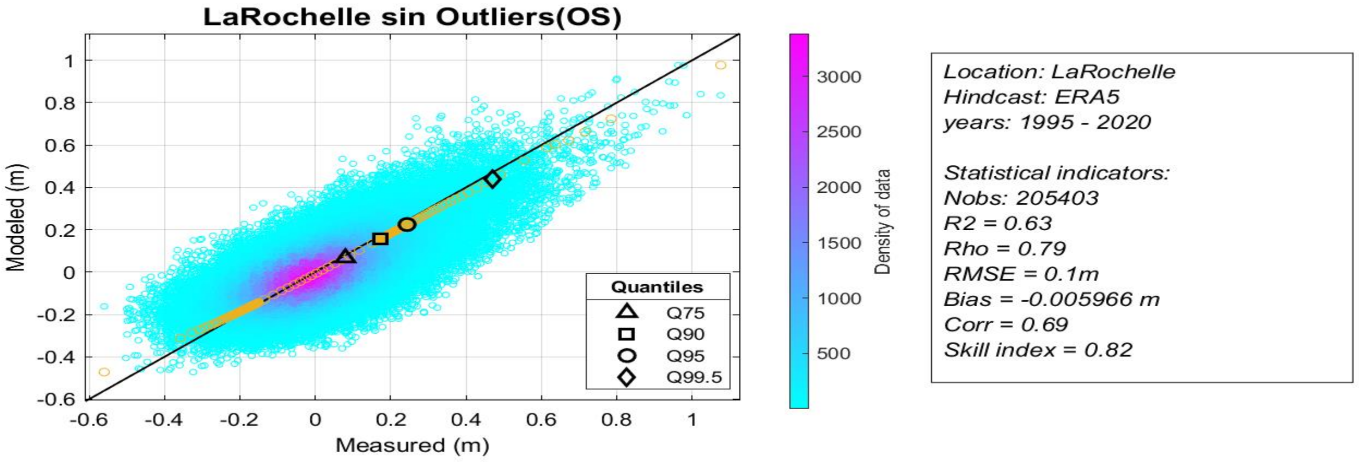


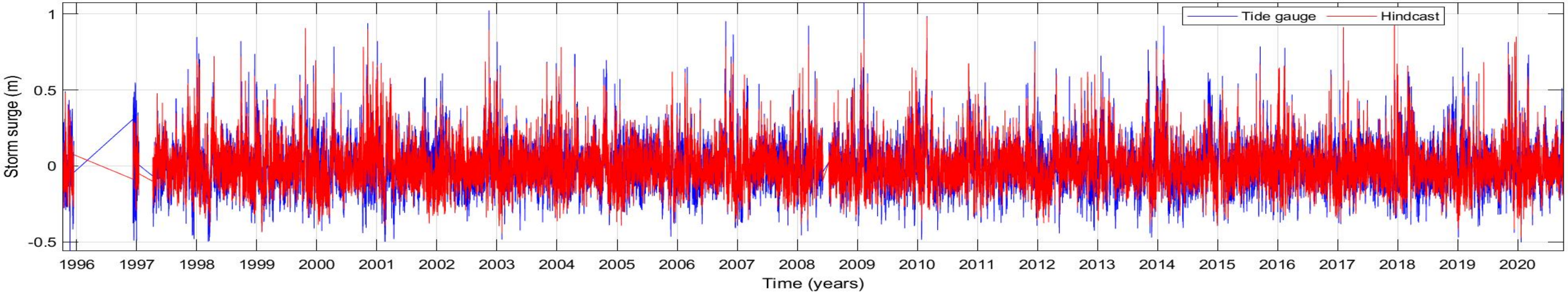
CoCliCo
coastal climate core services

Development of a pan-European high-resolution historical database

Historical simulation of the **STORM SURGE** (meteorological sea level component).

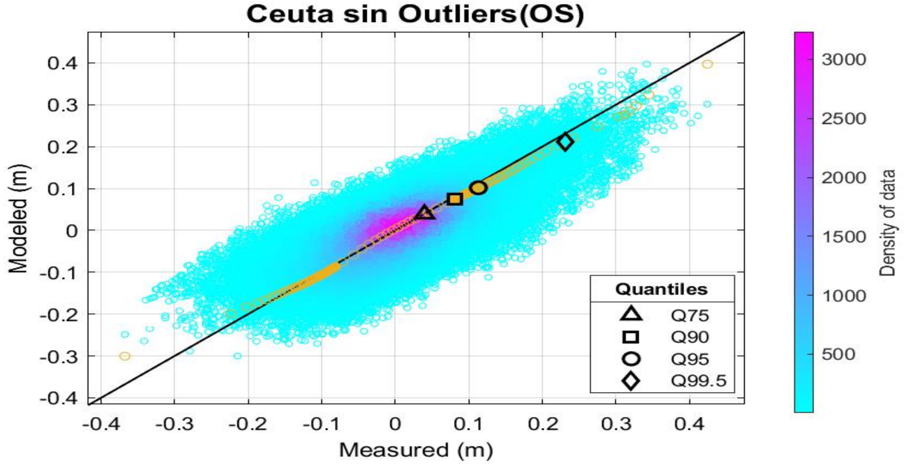






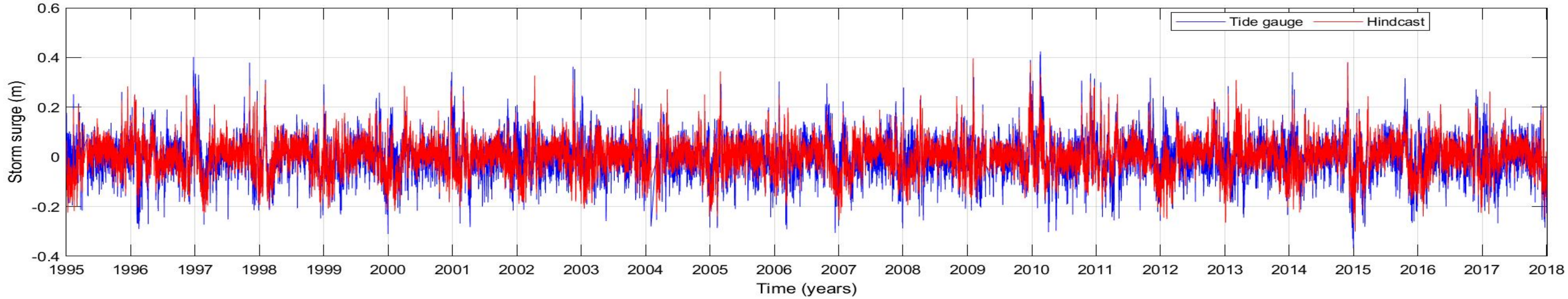
Development of a pan-European high-resolution historical database

Historical simulation of the **STORM SURGE** (meteorological sea level component).



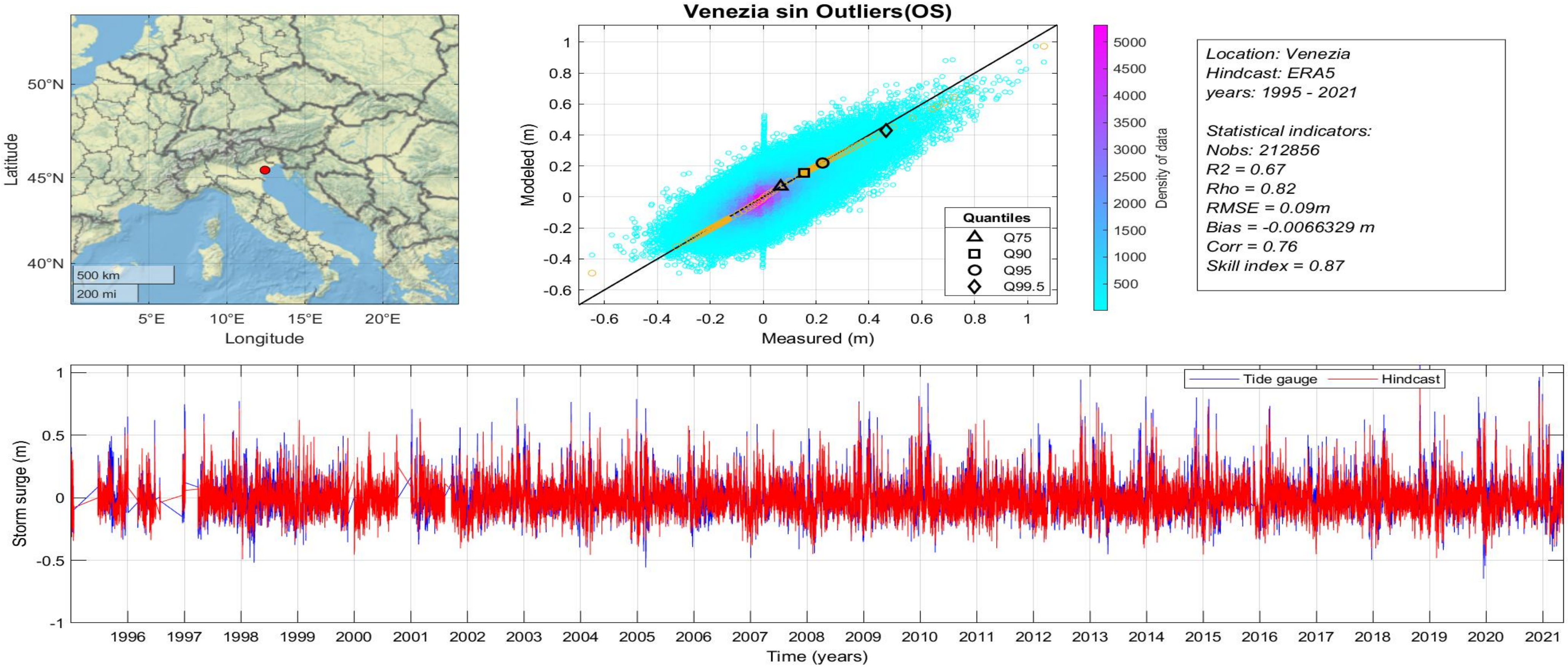
Location: Ceuta
Hindcast: ERA5
years: 1995 - 2017

Statistical indicators:
Nobs: 199964
R2 = 0.64
Rho = 0.8
RMSE = 0.05m
Bias = -0.00092396 m
Corr = 0.71
Skill index = 0.84



Development of a pan-European high-resolution historical database

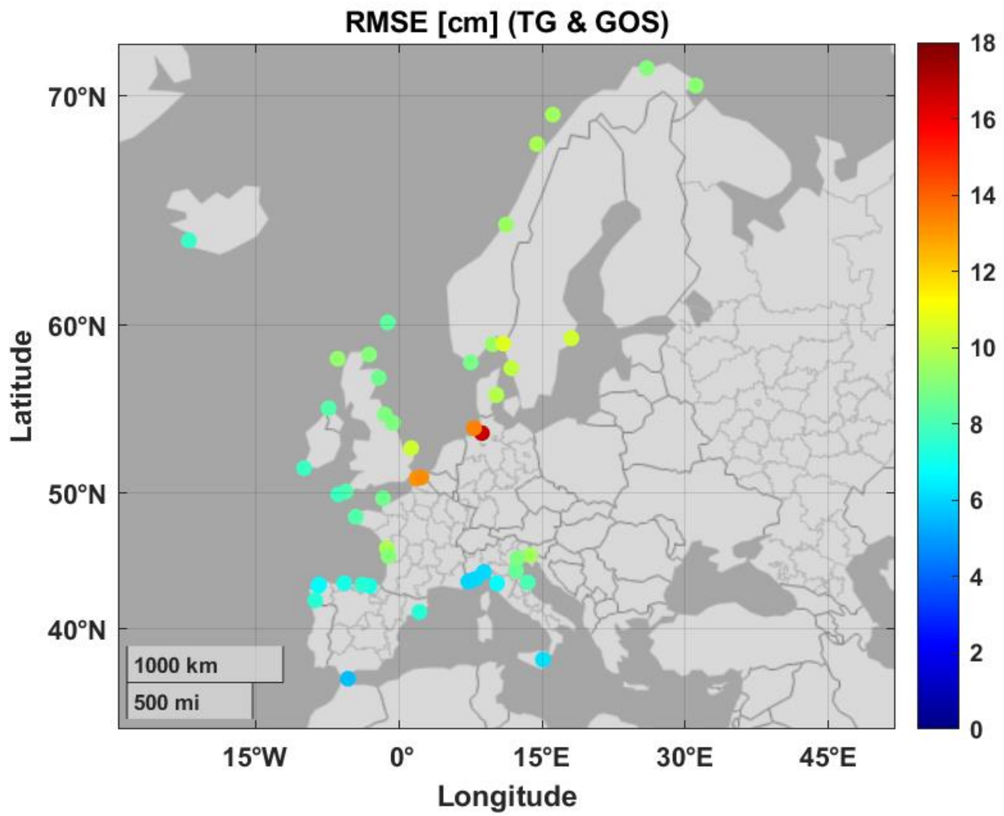
Historical simulation of the **STORM SURGE** (meteorological sea level component).

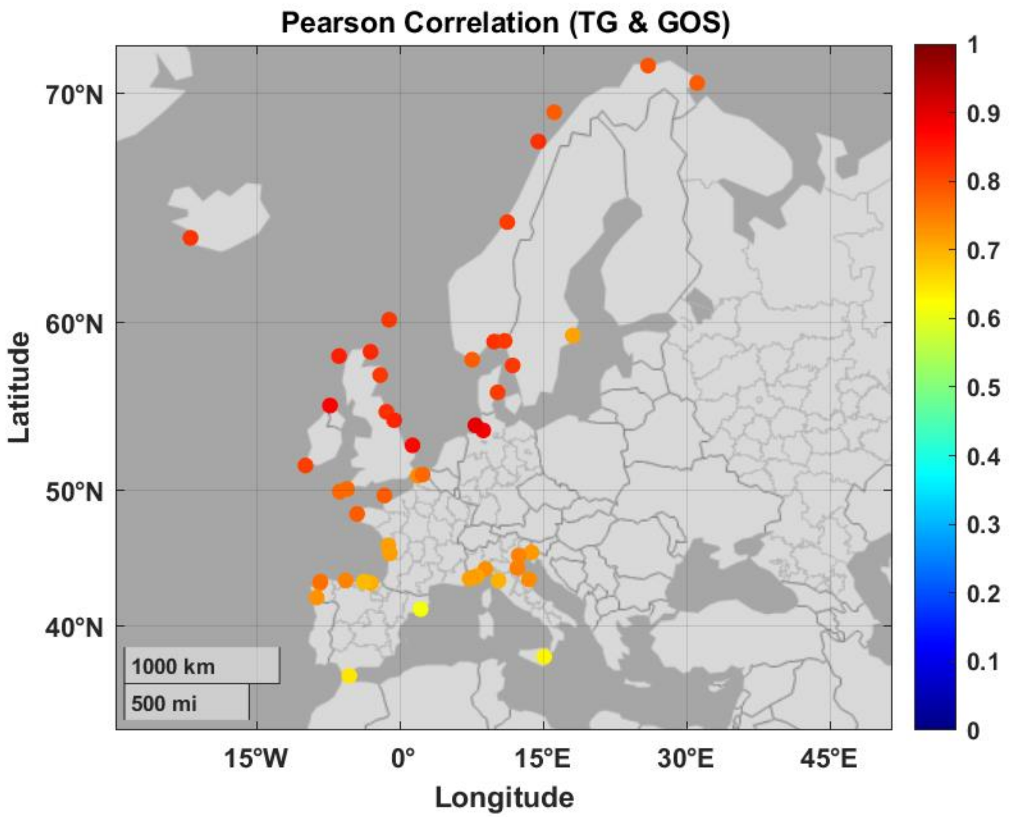


CoCliCo
coastal climate core services

Development of a pan-European high-resolution historical database

Historical simulation of the **STORM SURGE** (meteorological sea level component).





❖ A European study of the marine extreme water level on coastal flooding

Development of a pan-European high-resolution historical database

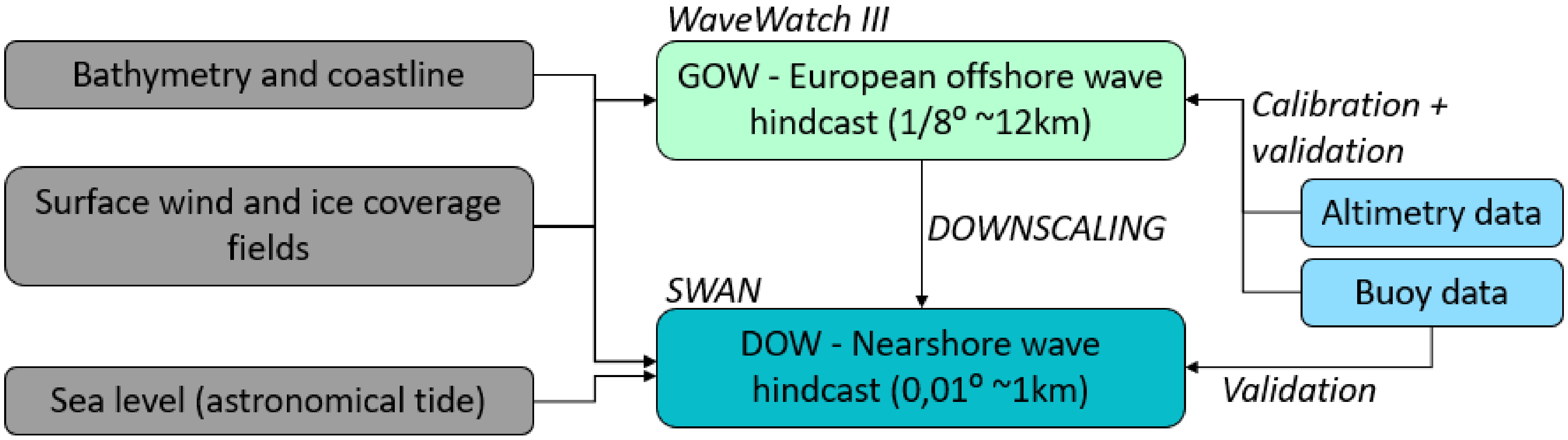
i. Storm surge hindcast
ii. Wave hindcast
iii. Total Water level reconstruction along the European coast
iv. Extreme TWL estimation
v. Modelling the coastal flooding

Development of pan-European regional climate projections

i. The selected CMIP6 climate models
ii. Mean sea level rise scenarios
iii. Storm surge projections
iv. Wave climate projections
v. Total Water level time series projections along the European coast
vi. Extreme TWL estimation
vii. Modelling the coastal flooding

Development of a pan-European high-resolution historical database

Historical simulation of the **WAVES** (wind generated waves)



- **Approach**
  - **Dynamical downscaling:** WaveWatch III v.7.00.
  - **Hybrid (statistical-dynamical) downscaling:** SWAN model version 41.45
- **Forcing models**
  - **ERA5** reanalysis surface wind fields + ice coverage fields.
- **Temporal period of simulations**
  - **Hindcast:** 1985-2022
- **Simulation outputs**
  - Integrated sea state wave parameters (i.e., H_s, T_m, Dir_m). Hourly resolution.
  - Spectral partitions
  - Local selected directional spectra data

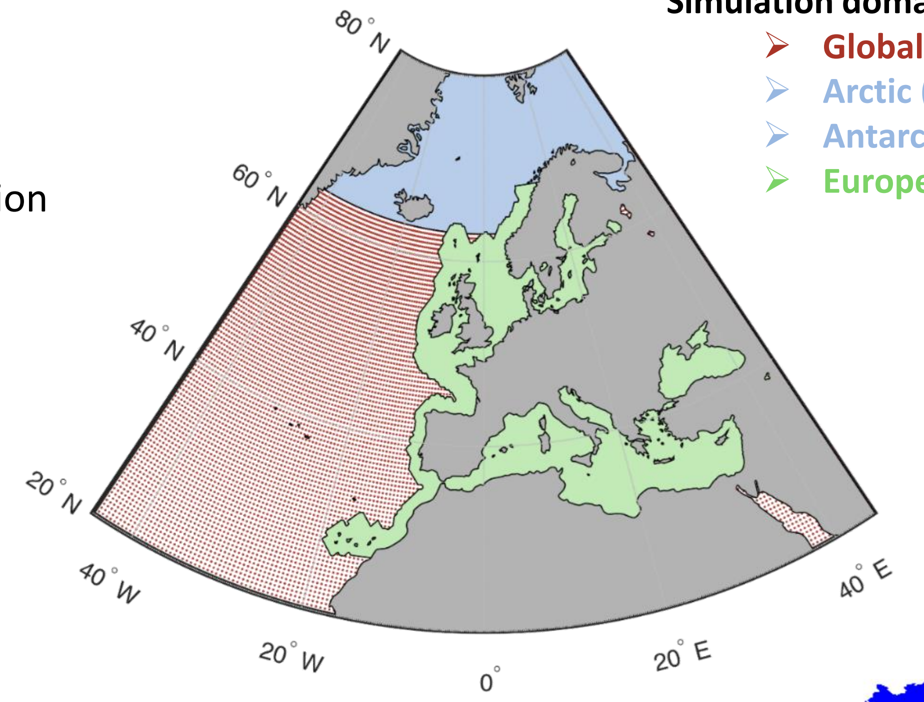
Development of a pan-European high-resolution historical database

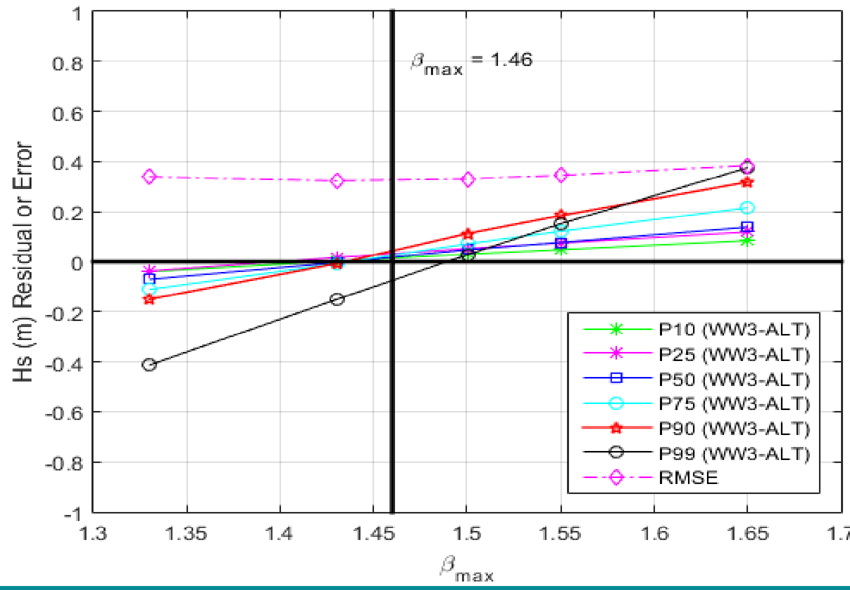
Historical simulation of the **WAVES**

- **Model:** WaveWatch III v.7.00.
  - ➢ Setup: ST4 parameterization.
  - ➢ Altimetry-based calibration of the atmosphere-ocean interaction tuning parameter (wave-growth parameter, β_{max}).
  - ➢ Multi-grid (IRI: irregular, regular, irregular)
  - ➢ Higher resolution near the European coastline

Simulation domains:

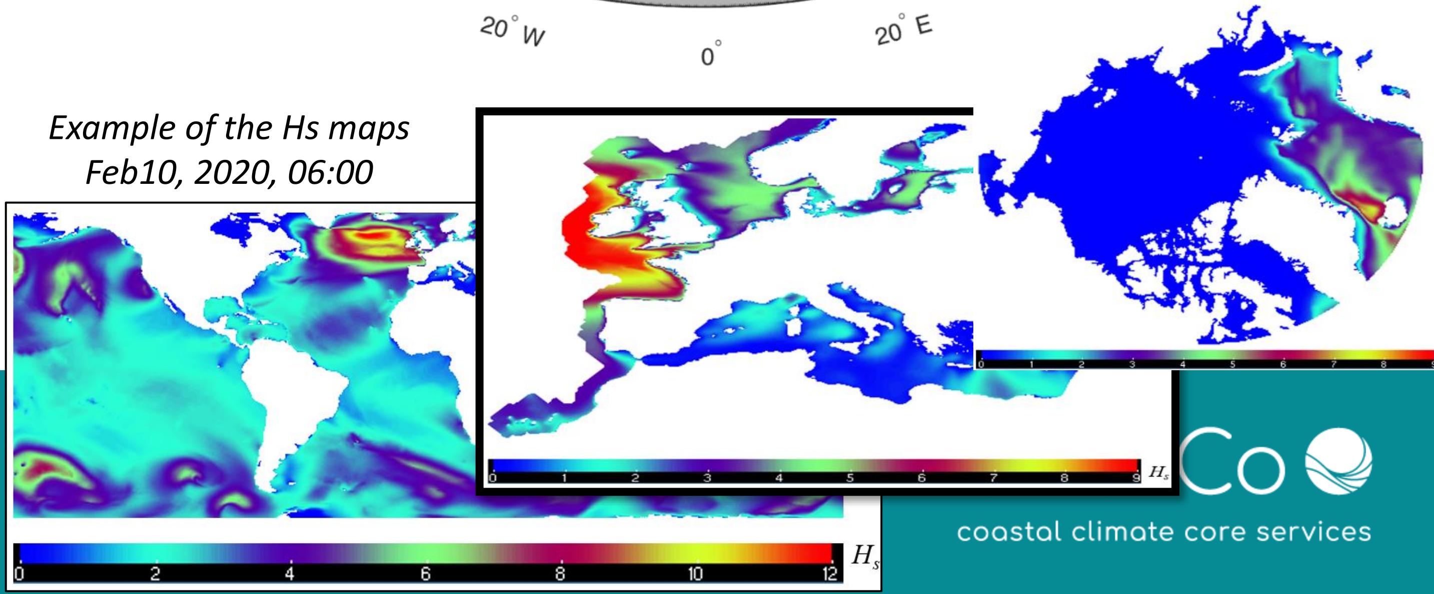
- ➢ Global (0.5° resolution)
- ➢ Arctic (~18km)
- ➢ Antarctic (~18km)
- ➢ Europe (1/8°, ~12km)





Calibration of WW3 model using ERA5 wind fields based on modifying β_{max} and comparing the model results with altimeter observations of H_s for the year 2010 for the European seas and the North Atlantic basin . The optimum βmax value is specified by the vertical black line.

Example of the Hs maps
Feb10, 2020, 06:00



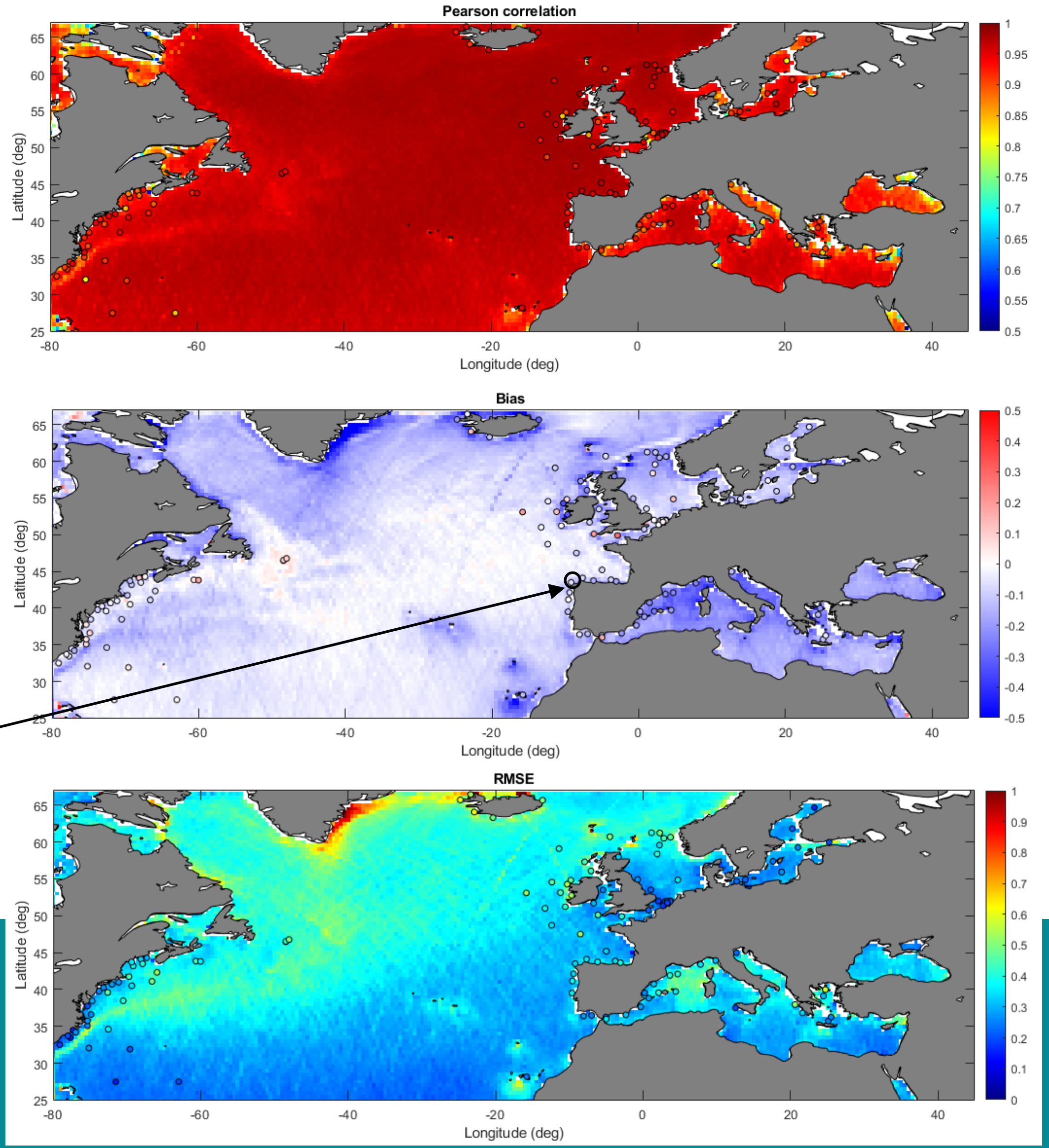
coastal climate core services

Development of a pan-European high-resolution historical database

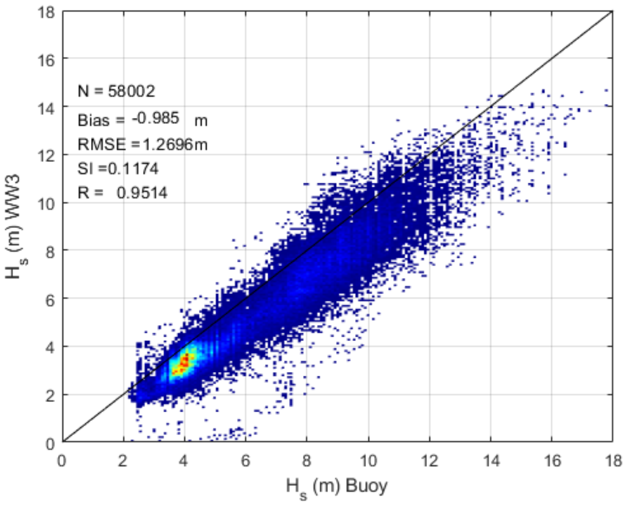
Historical simulation of the **WAVES**

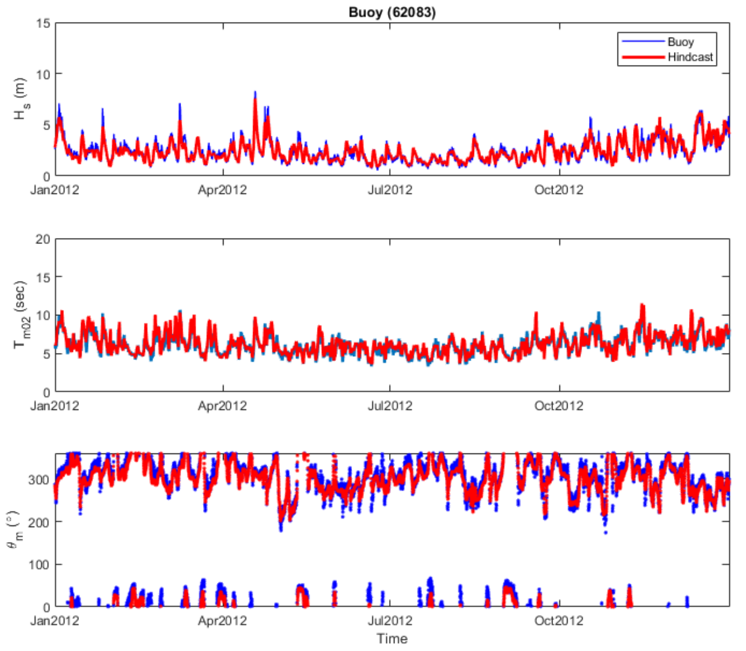
Validation

The wave hindcast has been validated against altimetry and buoys



Buoy Villano-Sisargas (NW Spain)





Validation of all buoy data above 99.5th Hs in the NE Atlantic

Development of a pan-European high-resolution historical database

Historical simulation of the **WAVES**

A **Hybrid methodology to downscale waves to coastal areas** (Camus et al. 2013)

Historical databases

↓

Selection of cases

↓

Propagation

↓

Time series reconstruction

↓

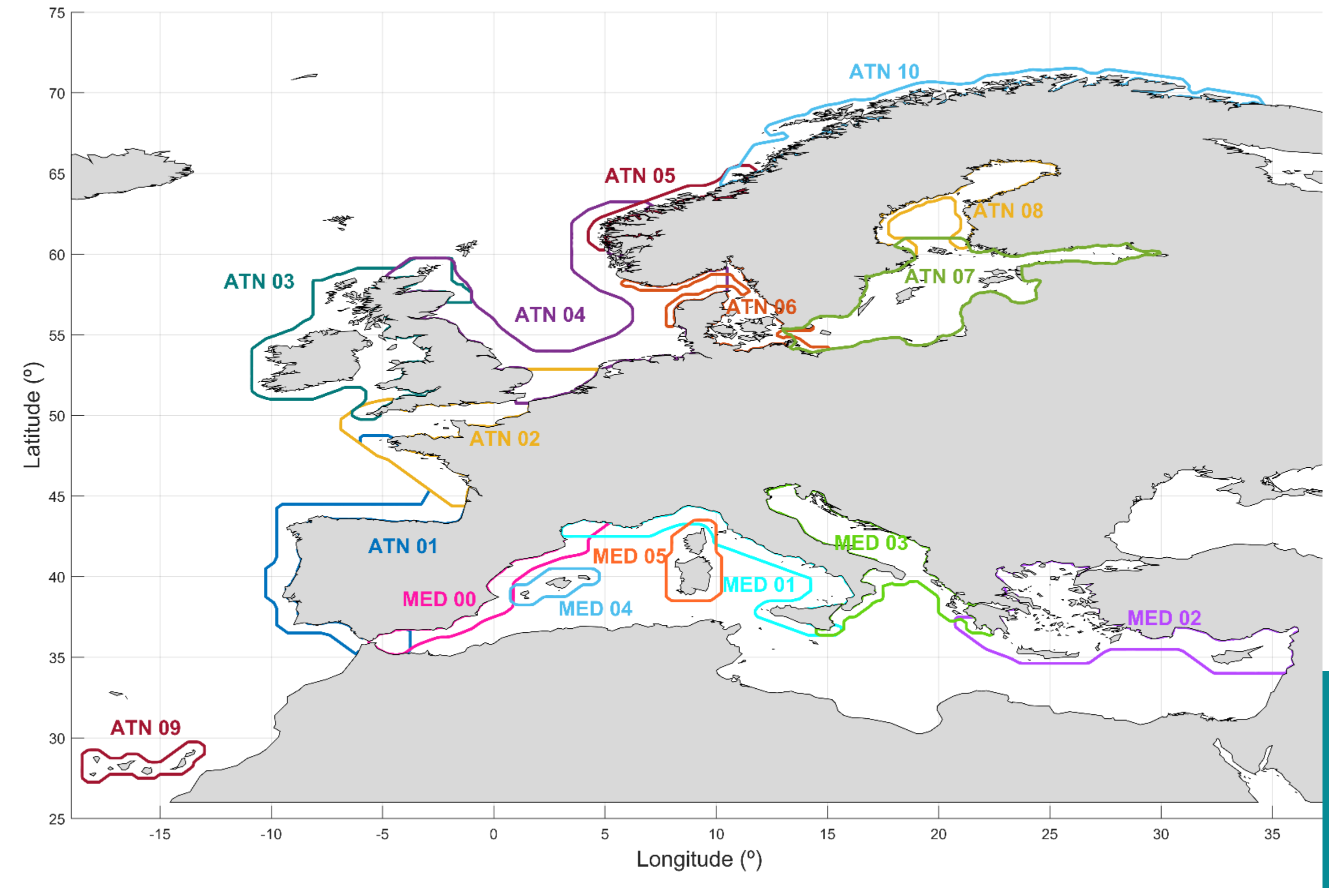
Validation

↓

Wave time series at coastal locations

Nearshore wave hindcast

- **16 unstructured computational domains** all along the European coastline
- Spatial resolution: from 1/8º (offshore) to **1km nearshore**



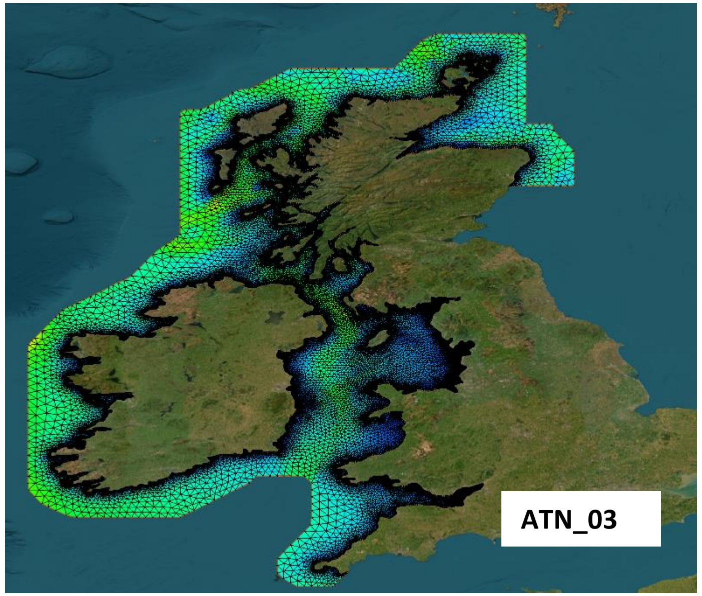
Development of a pan-European high-resolution historical database

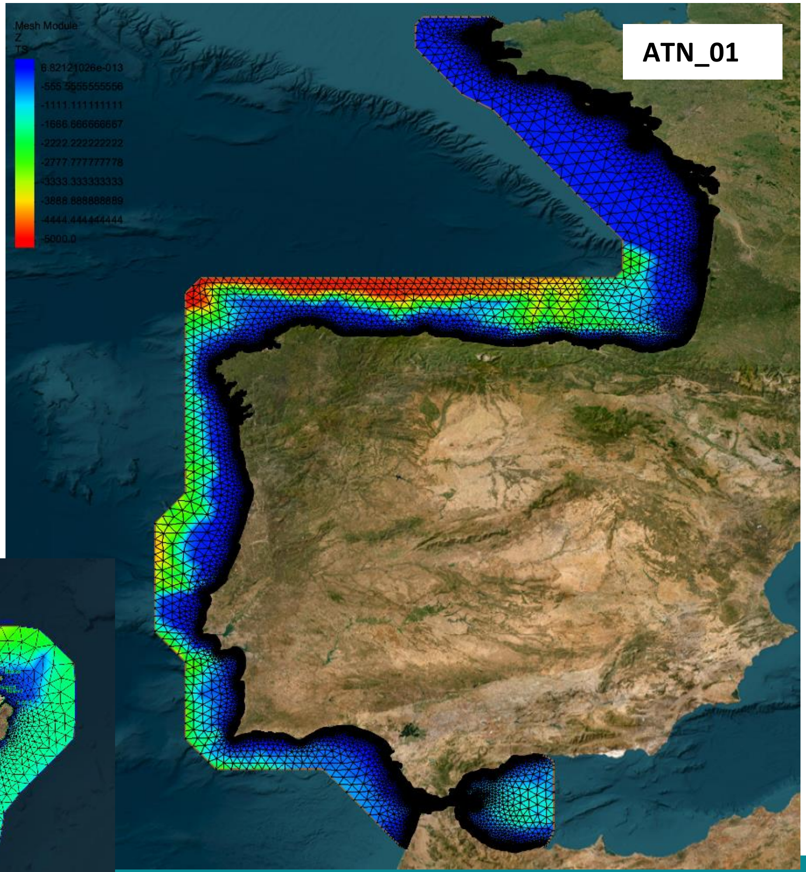
Historical simulation of the **WAVES**

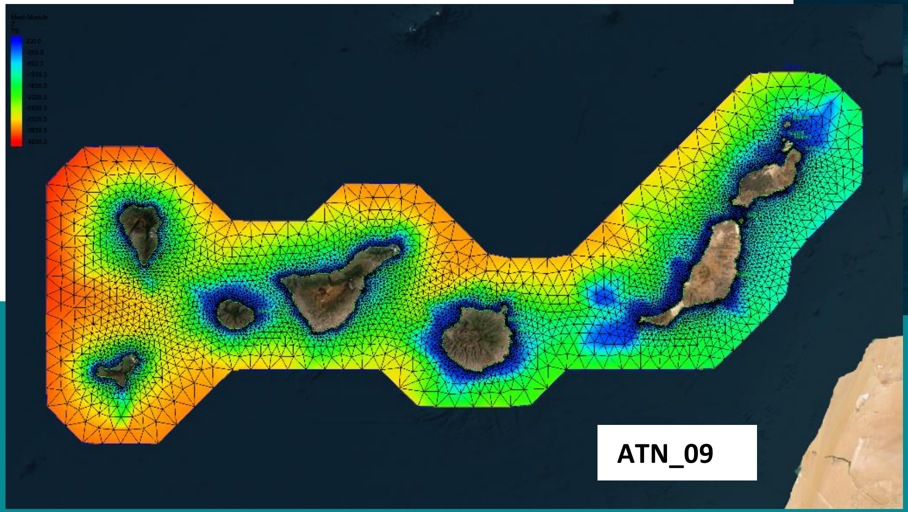
Nearshore wave hindcast

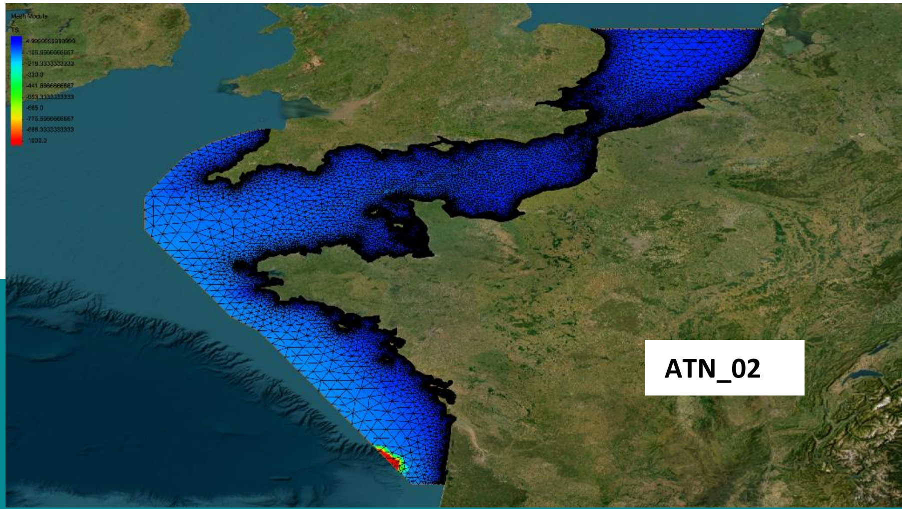
Numerical domains

- **Atlantic** domains





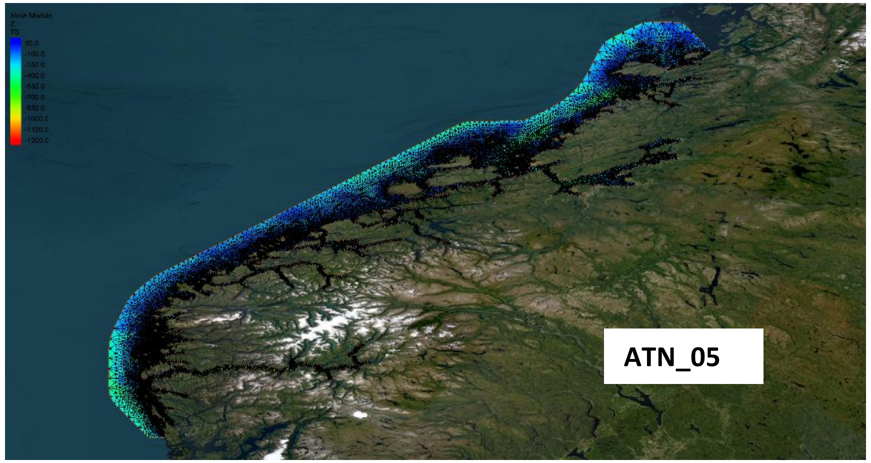


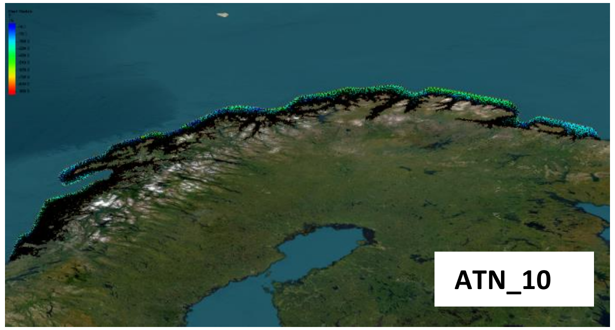


Development of a pan-European high-resolution historical database

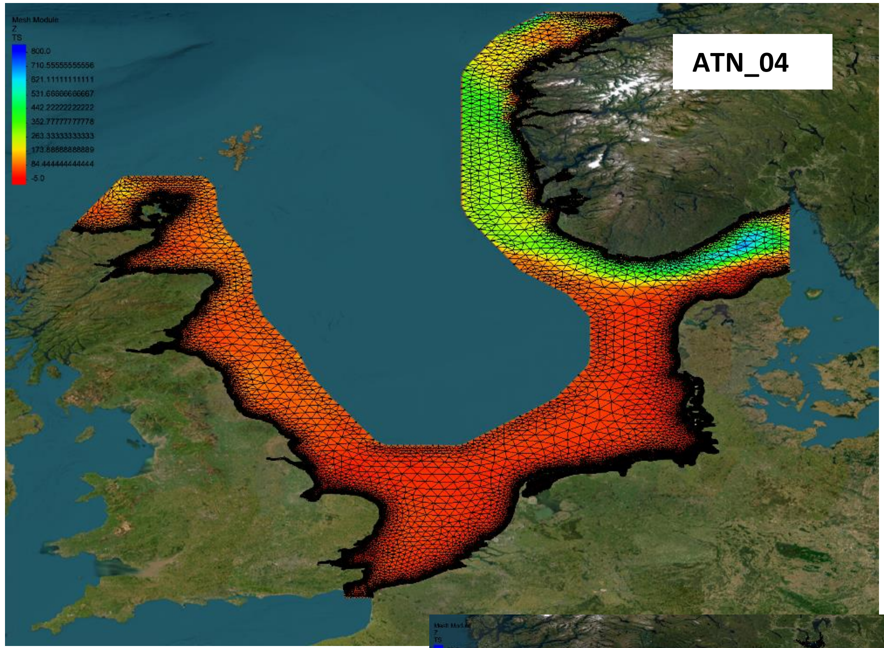
Historical simulation of the **WAVES**

- **Norwegian Sea** domains

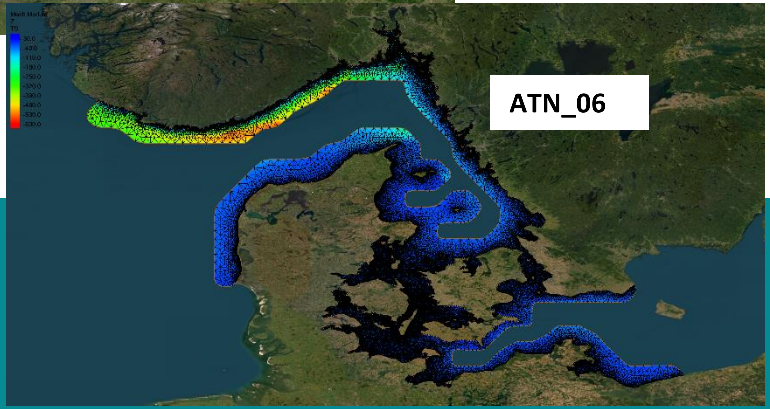


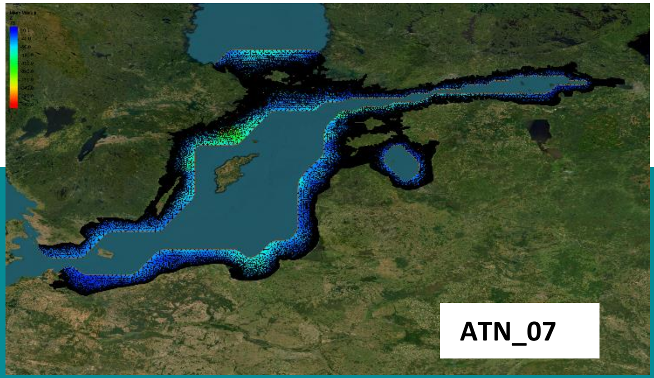


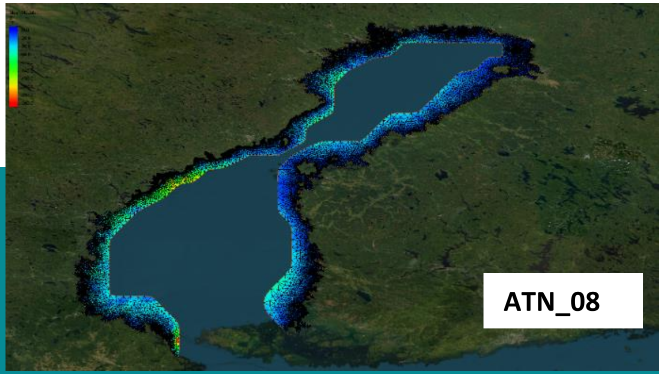
- **North Sea** domain



- **Baltic Sea** domains



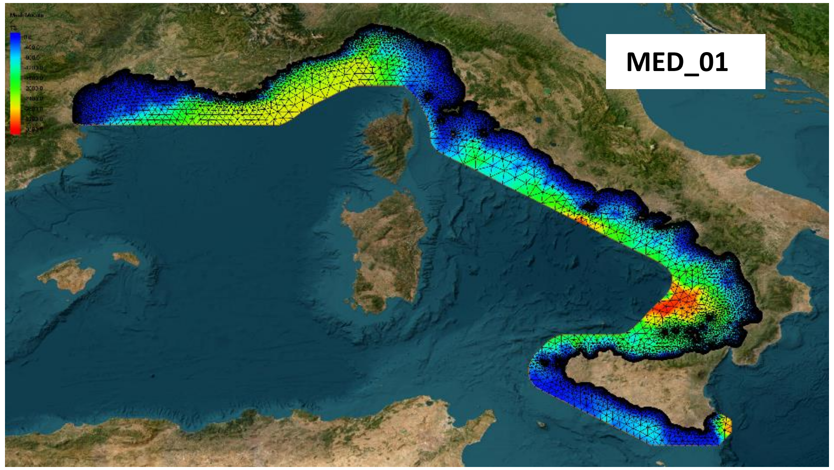


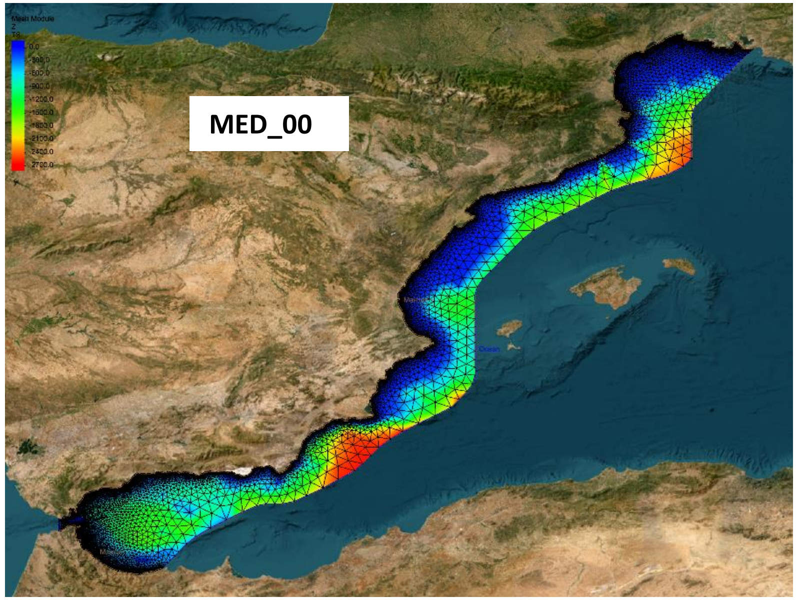


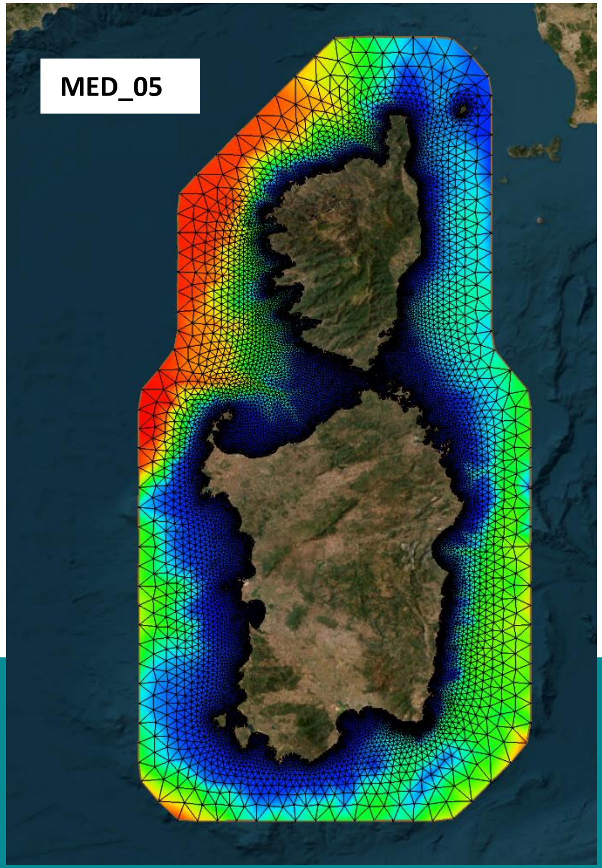
Development of a pan-European high-resolution historical database

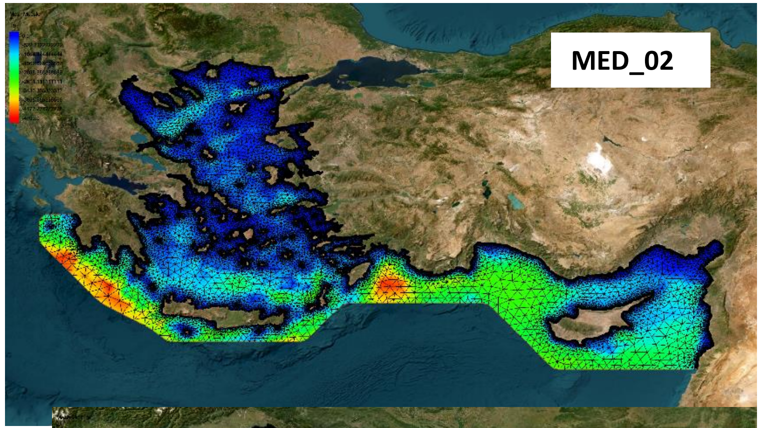
Historical simulation of the **WAVES**

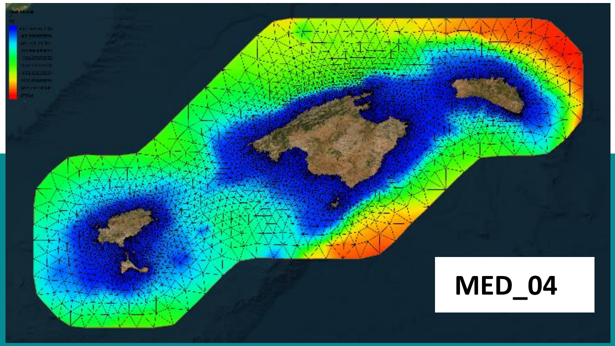
- **Mediterranean Sea** numerical domains











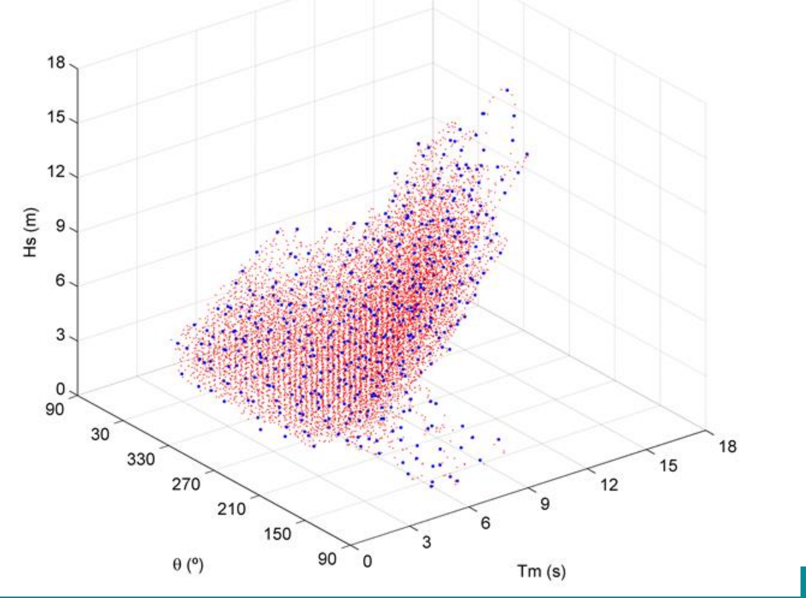
Development of a pan-European high-resolution historical database

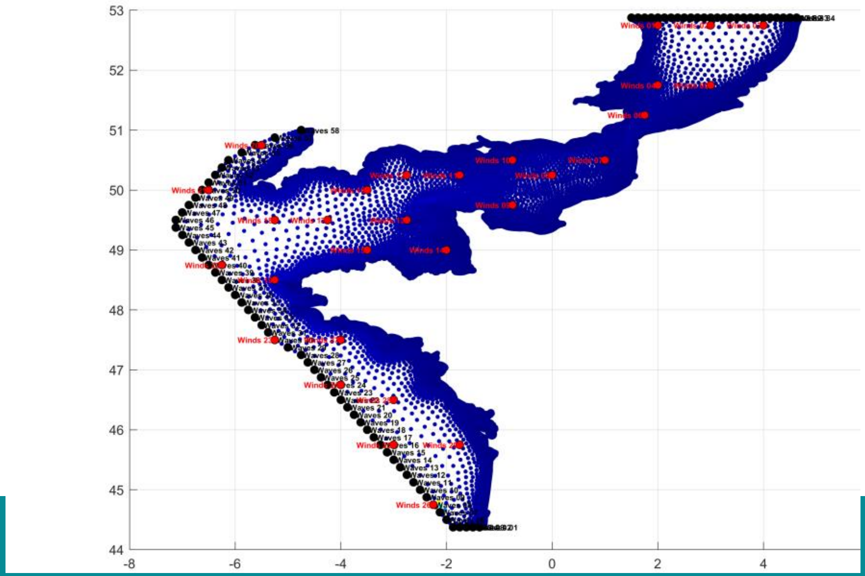
Historical simulation of the **WAVES**

Classification of cases to be numerically simulated

- Principal component analysis (PCA) is applied to the standardized variables for each grid point considered in the selection process.
- Selection technique: **maximum dissimilarity selection algorithm (MDA),** in order to obtain a representative subset of sea states in deep water areas
- Applied to **wave, wind** and **ice coverage parameters** (northern European domains only)
- Number of sea states selected at each domain: **1000 cases to nearshore wave are propagated**

Example of selected Hs, Tm and Dir cases for a grid-point





Example of the English Channel domain (ATN_02) selected grid points to obtain the 1000 cases

- *Wind points*
- *Sea state wave parameters grid- points*

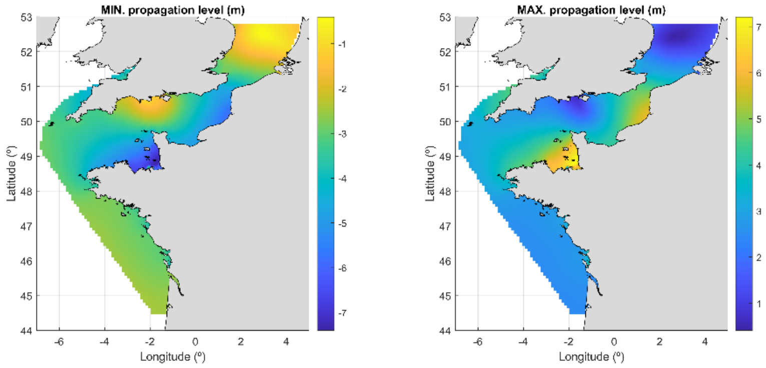
Development of a pan-European high-resolution historical database

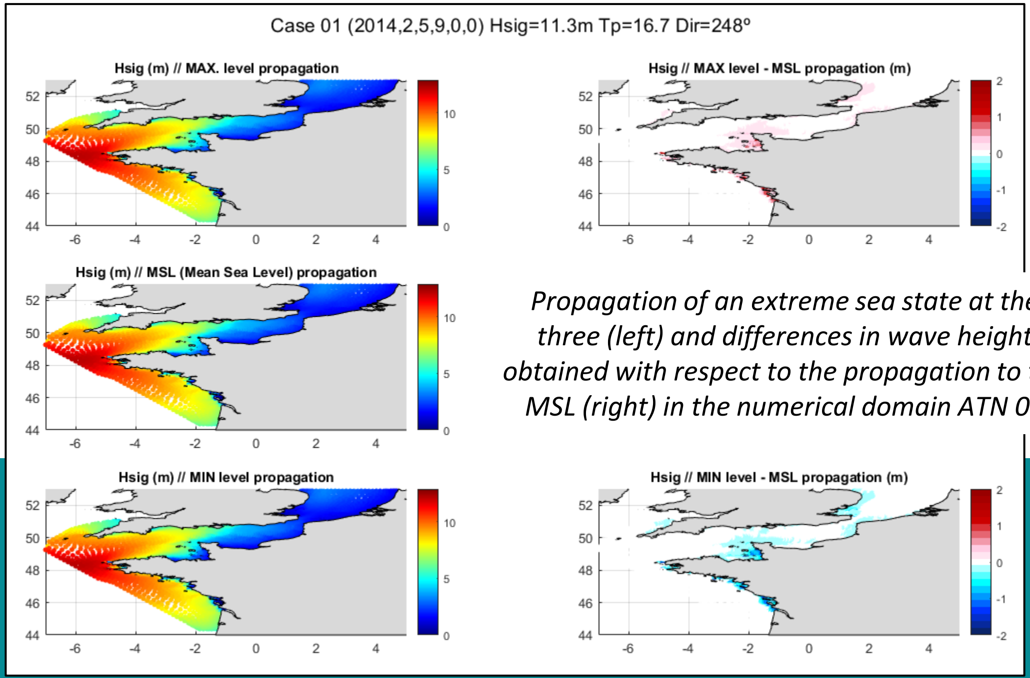
Historical simulation of the **WAVES**

Propagation and model configuration

Coastal wave sensibility to sea level

- Three propagation levels were configured in meso-tidal and macrotidal domains (ATN_01, ATN_02, ATN_03, ATN_04 and ATN_09) corresponding to the MSL, minimum and maximum levels of a complete nodal cycle of the astronomical tide

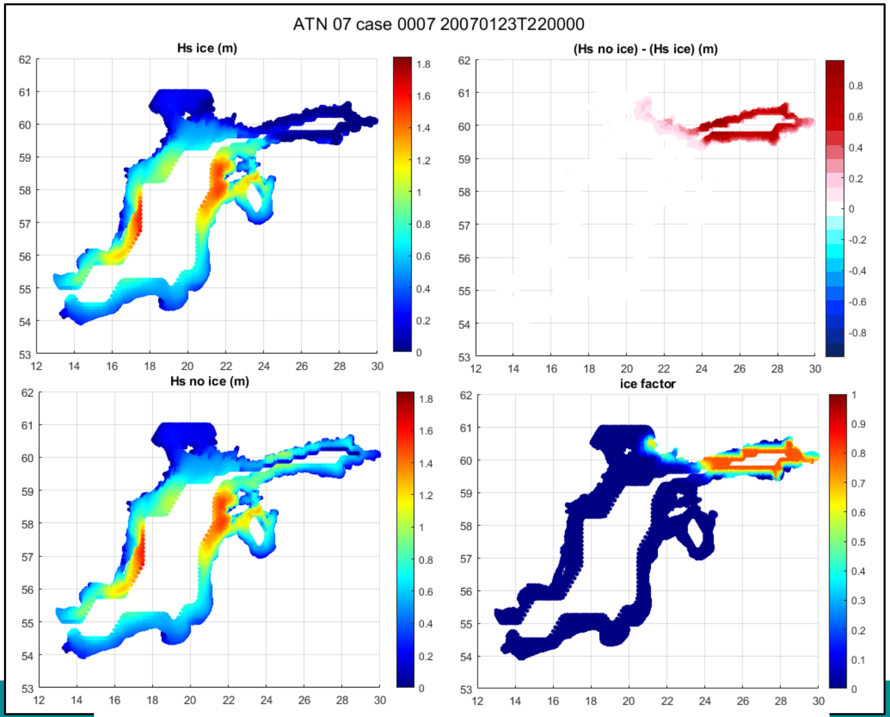




Propagation of an extreme sea state at the three (left) and differences in wave height obtained with respect to the propagation to the MSL (right) in the numerical domain ATN 02

Wave dissipation due to sea ice

- Wave dissipation due to sea ice was activated in the simulations of ATN_05, ATN_06, ATN_07, ATN_08 and ATN_10 domains



Sensitivity analysis of the marine ice effect on waves at the ATN 07 in the Baltic Sea

Development of a pan-European high-resolution historical database

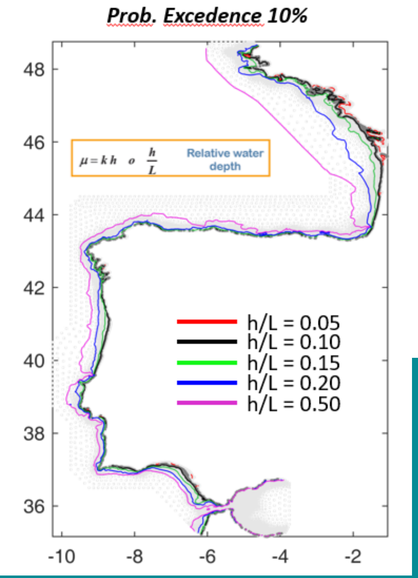
Historical simulation of the **WAVES**

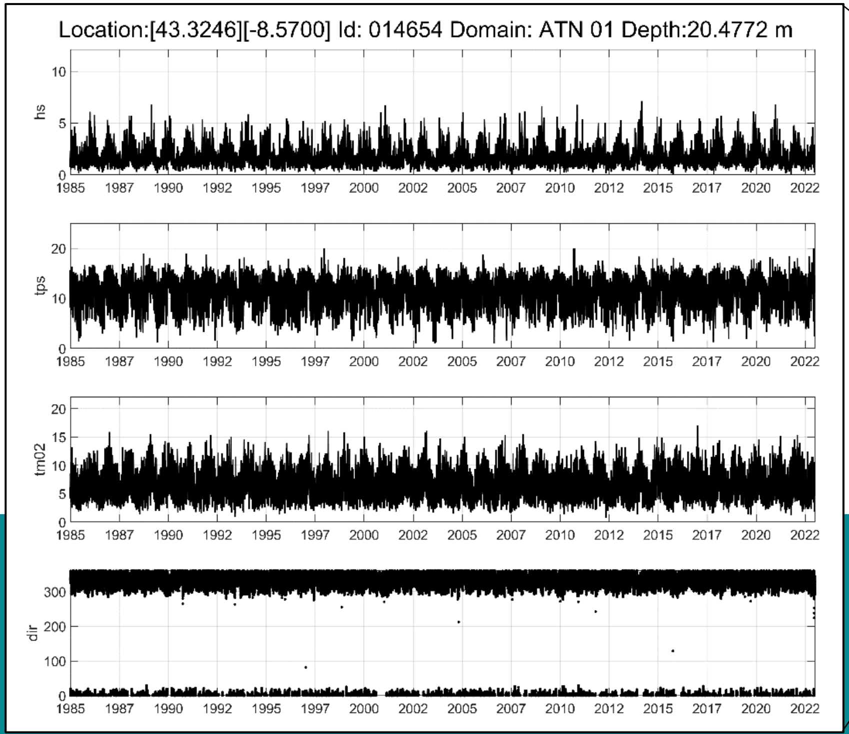
Reconstruction of time series at each coastal location (with ~1km resolution)

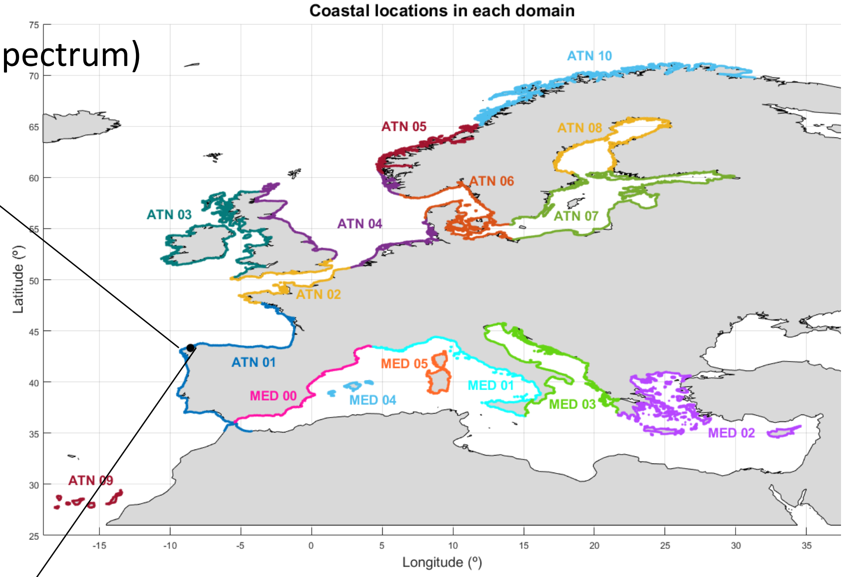
The time series of the propagated sea state parameters at a particular location on shallow waters are reconstructed using a non-linear interpolation technique based on **radial basis functions (RBFs)**, providing excellent results in a high dimensional space with scattered data as occurs in the 1000 selected cases.

Hourly time series (1985-2022) of sea state parameters were reconstructed at ~**60.000 coastal locations** (relative water depth' of 0,10) along the european coast:

- ✓ Hs: significant wave height
- ✓ Tps: smooth peak period (Obtained from a parabolic fit of the discretized peak of wave frequency spectrum)
- ✓ Tm02: mean zero-crossing period
- ✓ Dirm: mean wave direction





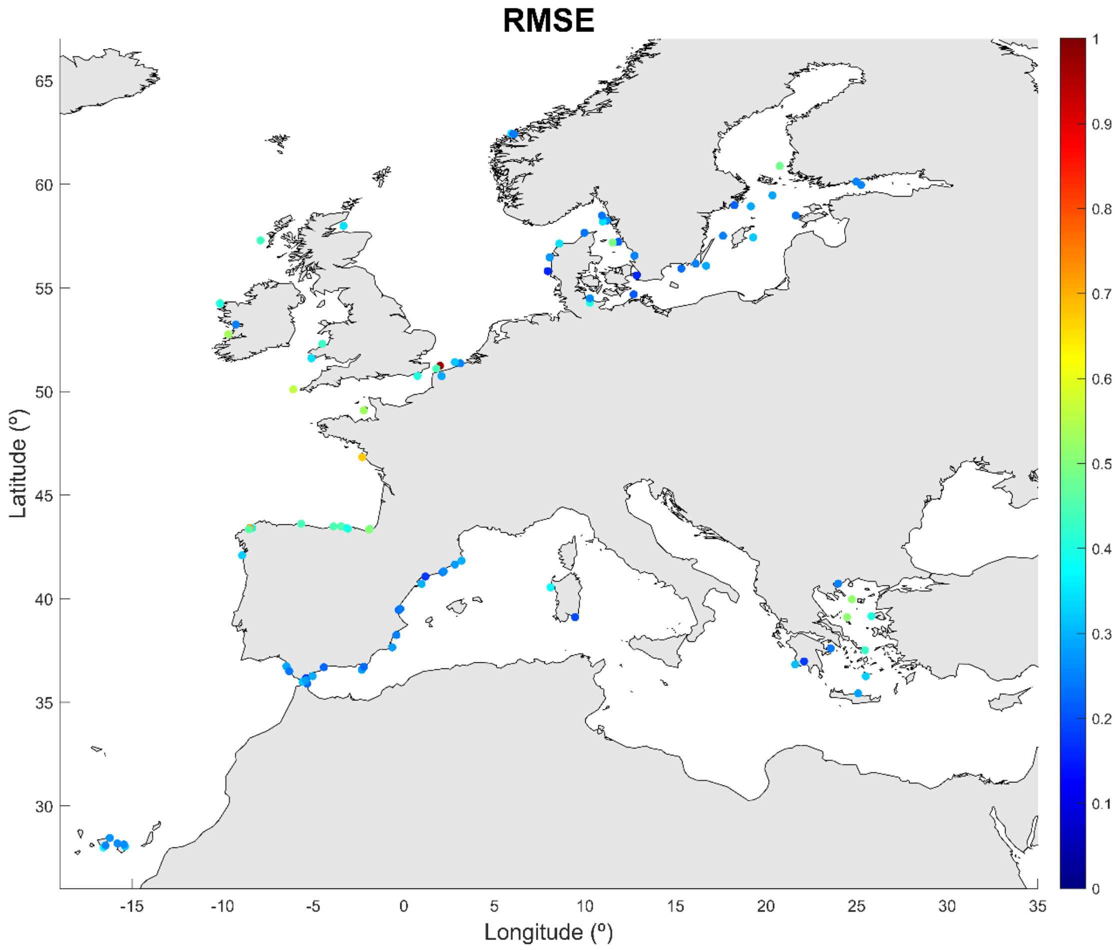


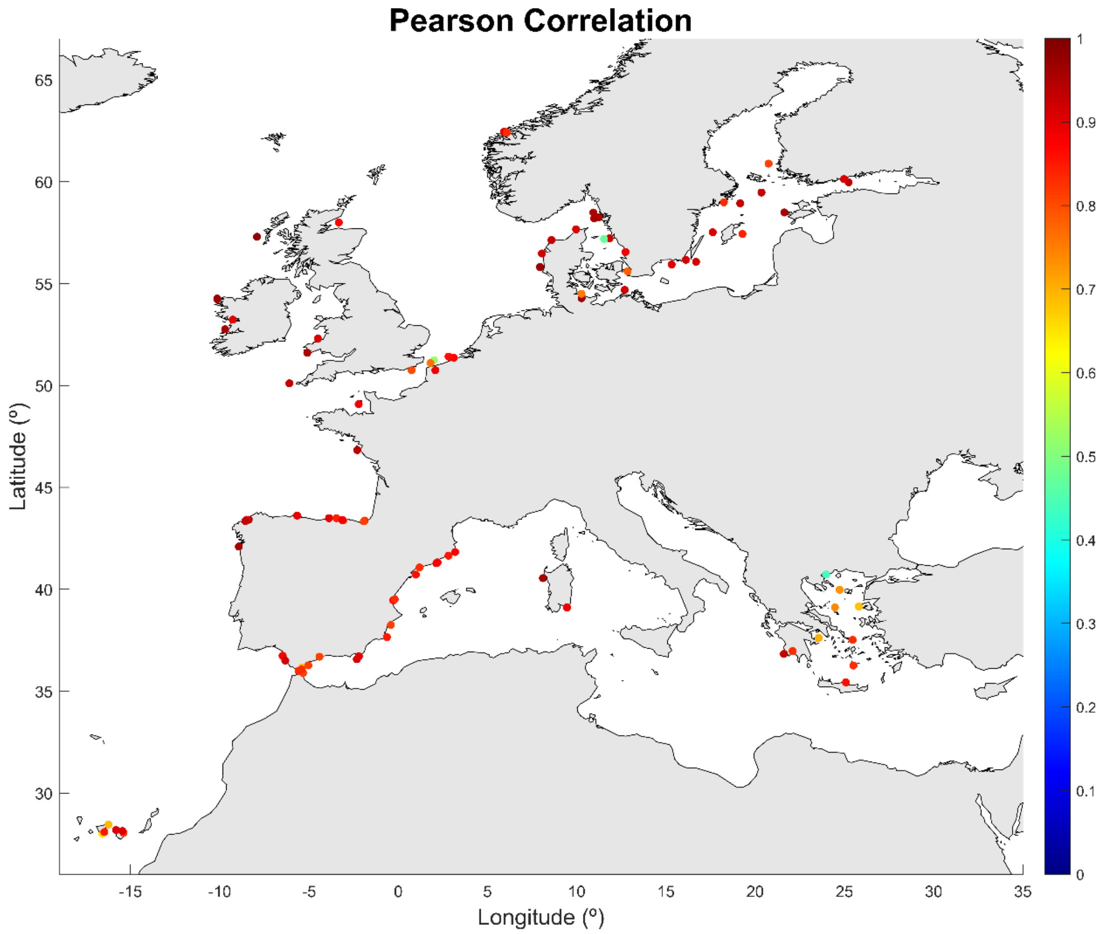
coastal climate core services

Development of a pan-European high-resolution historical database

Historical simulation of the **WAVES**

Validation with coastal wave buoys





❖ A European study of the marine extreme water level on coastal flooding

Development of a pan-European high-resolution historical database

i. Storm surge hindcast
ii. Wave hindcast
iii. Total Water level reconstruction along the European coast
iv. Extreme TWL estimation
v. Modelling the coastal flooding

Development of pan-European regional climate projections

i. The selected CMIP6 climate models
ii. Mean sea level rise scenarios
iii. Storm surge projections
iv. Wave climate projections
v. Total Water level time series projections along the European coast
vi. Extreme TWL estimation
vii. Modelling the coastal flooding

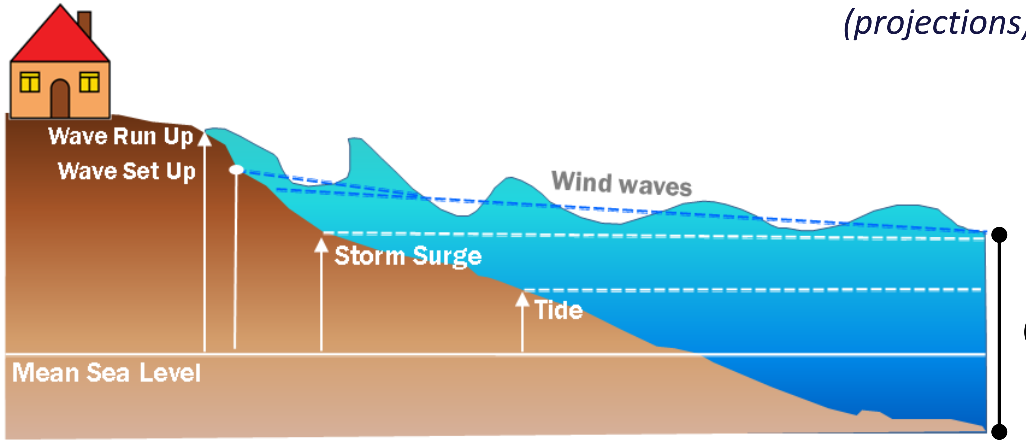
Development of a pan-European high-resolution historical database

- Estimation of **TOTAL WATER LEVEL** hourly time series

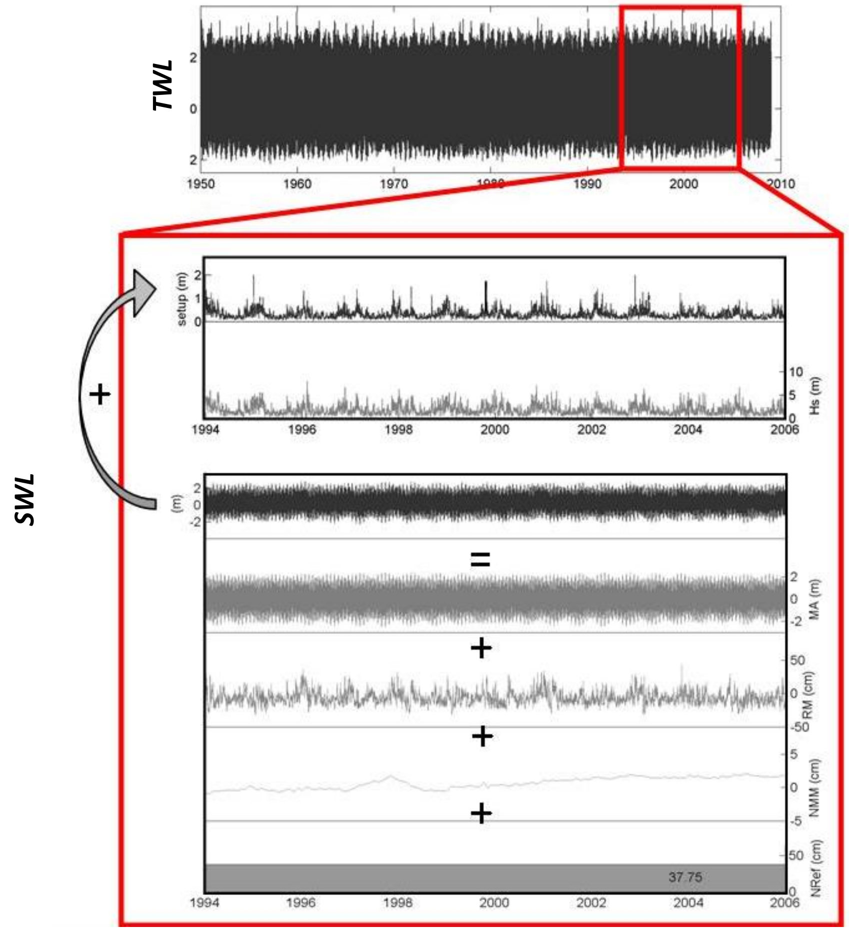
Total Water Level (TWL) = SEA LEVEL + WAVES

SEA LEVEL:
- **Astronomical tide**
- **Storm surge**
- **Mean sea level Rise** *(projections)*

WAVES:
- **Set-up**

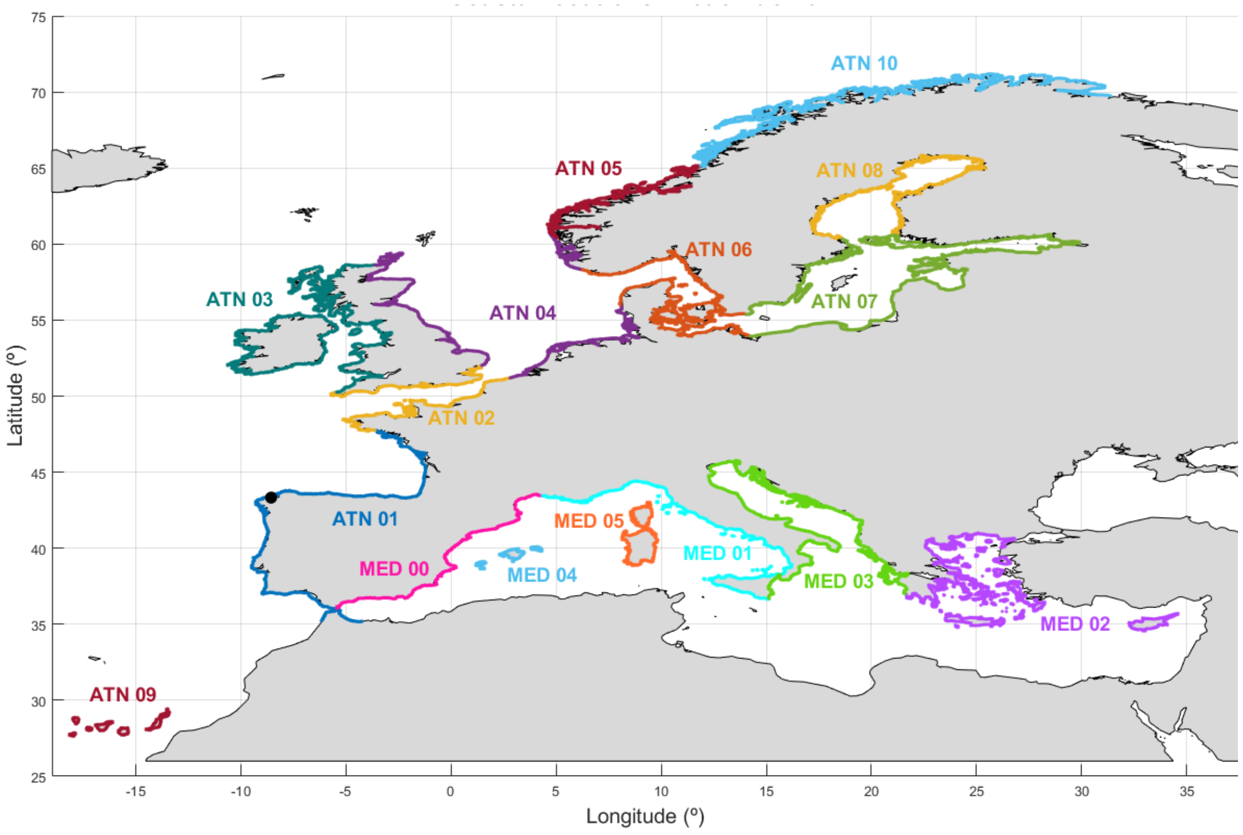


Still Water Level (SWL, sea level variations)



Development of a pan-European high-resolution historical database

- Estimation of **TOTAL WATER LEVEL** hourly time series



- **HISTORICAL APPROACH**

Colllection of the *hourly time series* (1985-2022) for more than 50.000 coastal European locations

Variables:

❖ Astronomical tide:

Astronomical tide hourly time series are generated using 15 harmonic constituents derived from TPXO9 model (after checking tide models/data coastal quality by comparing against tide-gauge records). TPO9 spatial resolution near the coast: ~3km.

❖ Storm surge:

Hourly time series from the developed European hindcast

❖ Sea state parameters:

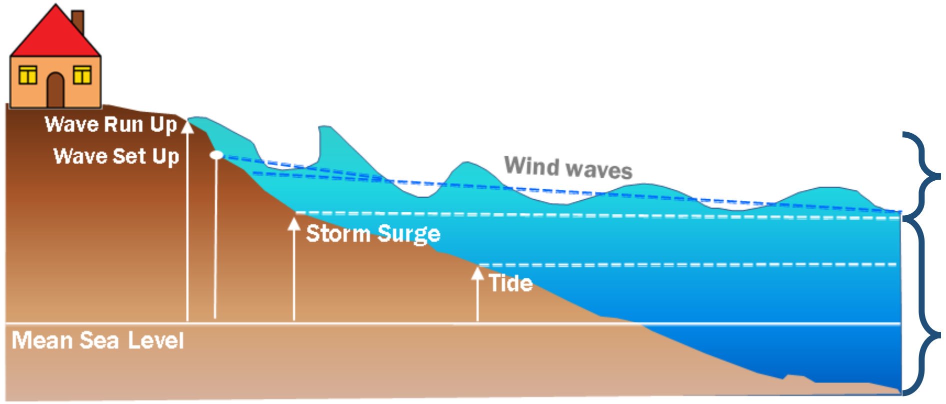
Hourly time series of:

- Hs: significant wave height
- Tps: smooth peak period (Obtained from a parabolic fit of the discretized peak of wave frequency spectrum)
- Tm02: mean zero-crossing period
- Dirm: mean wave direction

CoCliCo coastal climate core services

Development of a pan-European high-resolution historical database

- Estimation of **TOTAL WATER LEVEL** hourly time series



Wave contribution → Static wave setup, Dynamic wave setup, Wave runup

Static wave setup → Static wave setup
Dynamic wave setup → Infragravity swash
Wave runup → Incident swash

Still water level (SWL) = MSL + astronomical tide + storm surge

(Foreshore Slope)

Sunamura (1984)
and normalizing it as Melet et al. (2020)
Spatially and temporally variable

$$\tan\alpha = \frac{0.12}{(H_b/g^{0.5}D^{0.5}T)^{0.5}}$$

tan α = foreshore slope
H_b = wave breaking height
g = gravity
D = sediment grain size
T = wave period

Wave Setup
Stockdon et al. (2006)

Infragravity swash

$$S_{IG} = 0.06(H_0L_0)^{1/2}$$

S_{IG} = infragravity swash
H_0 = wave height
L_0 = wavelength

Static wave setup

$$<\eta> = 0.35\beta_f(H_0L_0)^{1/2}$$

η = static wave setup
B = foreshore slope
T = wave period

CoCliCo
coastal climate core services

Development of a pan-European high-resolution historical database

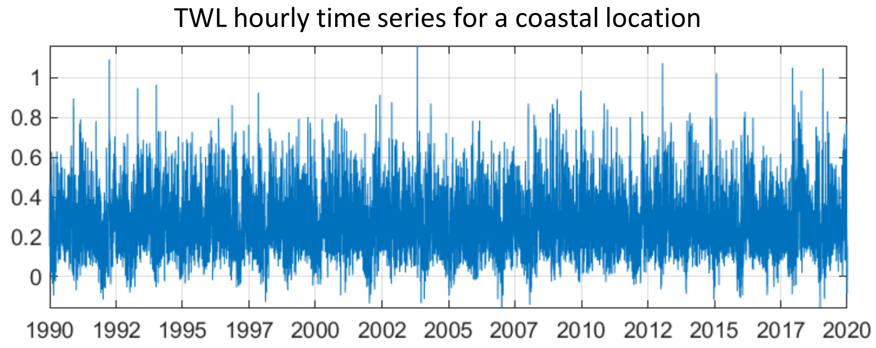
- Estimation of **TOTAL WATER LEVEL** hourly time series

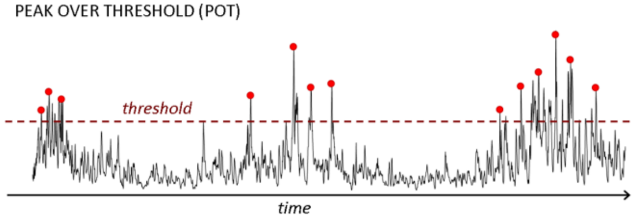
For each coastal locatoin TWL hourly time series..

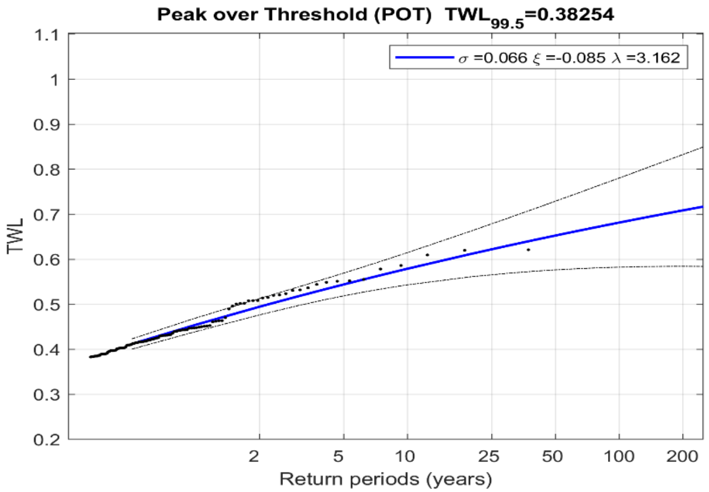
a) Selection of the extreme Events
   - Identify the ***lowest anual maxima as threshold*** of the POT method
   - Collect the Peak (maximum) and duration of each storm

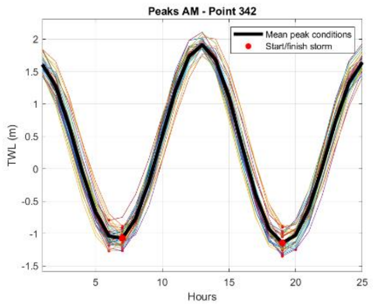
b) Fitting to the GPD-Poisson statistical extreme value model
   - Estimation of the 1, 100 and 1000 yr return TWL values
   - Shape and duration of the storm associated to the return levels

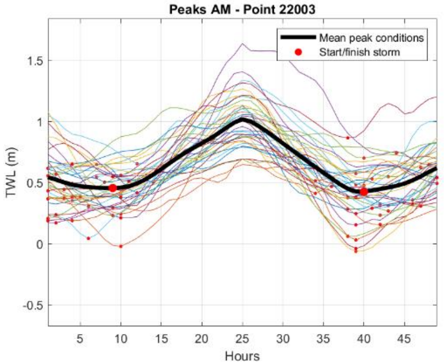
triangle
- *12h tidal dominance*
- *Modeling duration: storm surge-wave dominance*

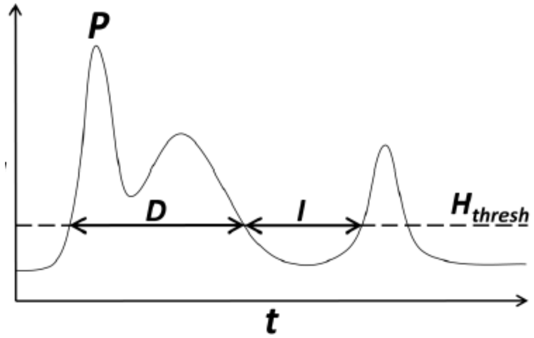












CoCliCo
coastal climate core services

❖ A European study of the marine extreme water level on coastal flooding

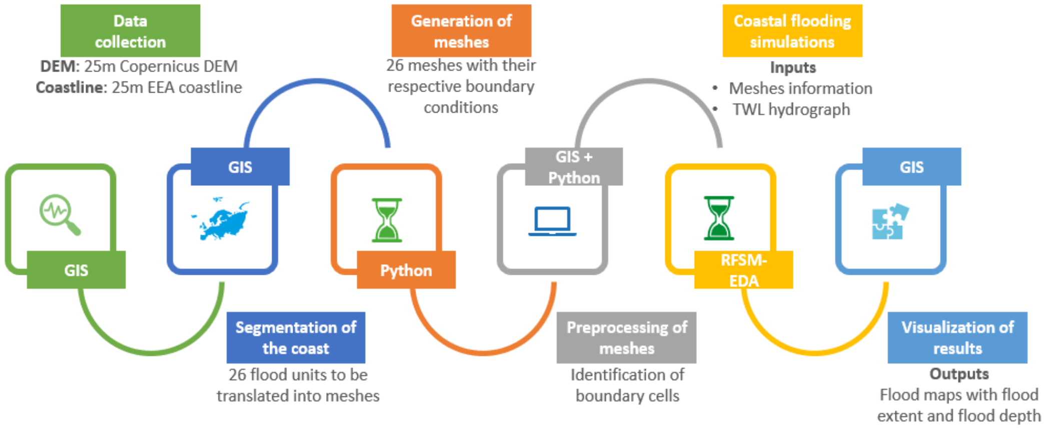
Development of a pan-European high-resolution historical database

i. Storm surge hindcast
ii. Wave hindcast
iii. Total Water level reconstruction along the European coast
iv. Extreme TWL estimation
v. Modelling the coastal flooding

Development of pan-European regional climate projections

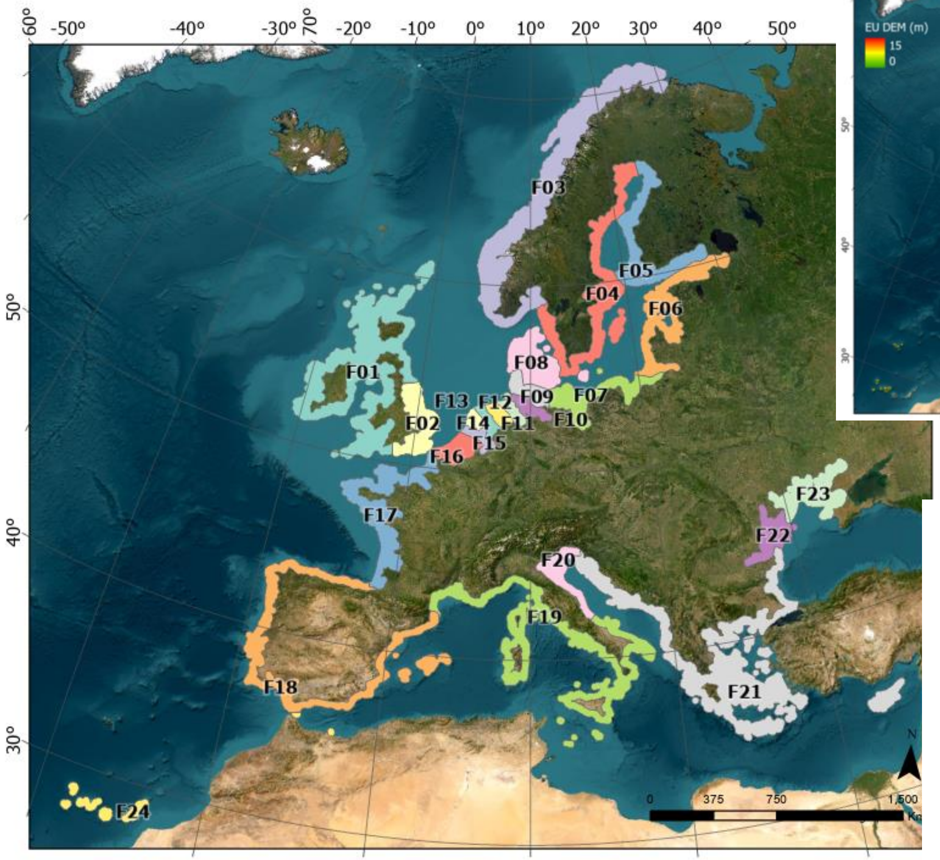
i. The selected CMIP6 climate models
ii. Mean sea level rise scenarios
iii. Storm surge projections
iv. Wave climate projections
v. Total Water level time series projections along the European coast
vi. Extreme TWL estimation
vii. Modelling the coastal flooding

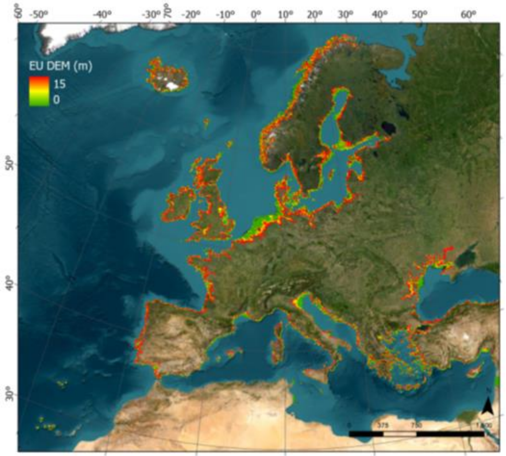
- Coastal **FLOOD MODELLING** Approach



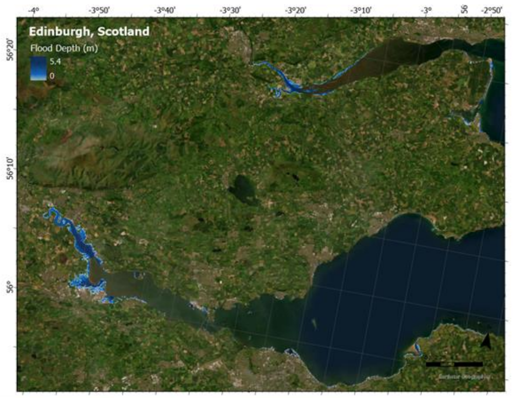
EU-DEM (25 m of resolution) & coastal segmentation

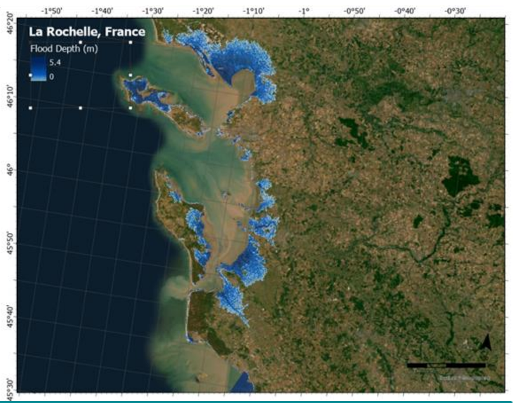
26 flood units





Examples of flood maps on different European coastal areas (boundary conditions: ~5m TWL , 12 hours)

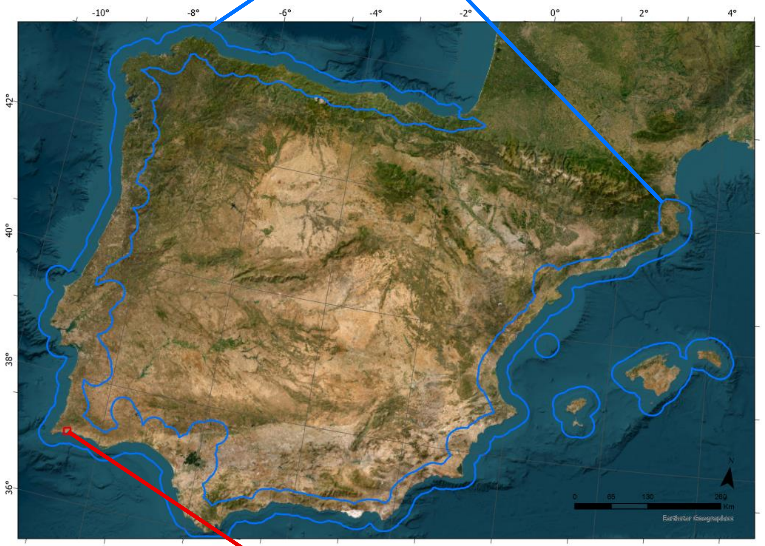




coastal climate core services

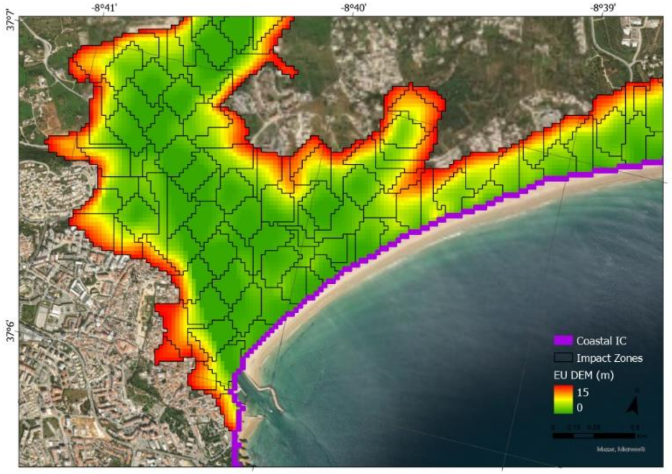
- Coastal **FLOOD MODELLING** Approach

FU25F18 – Iberian Peninsula

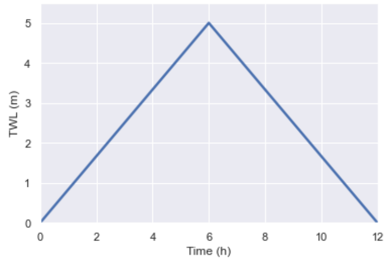


E.g., Lagos, Portugal

1. DEM + Mesh + Boundary Cells



2. Total Water Level (TWL) hydrographs



3. Spatial distribution of Manning roughness coefficient

FLOOD MODELLING OUTPUTS

Flood maps and information on:

- Maximum flood depth at each cell
- Average velocity at each cell
- Flooded area

RFSM-EDA model:

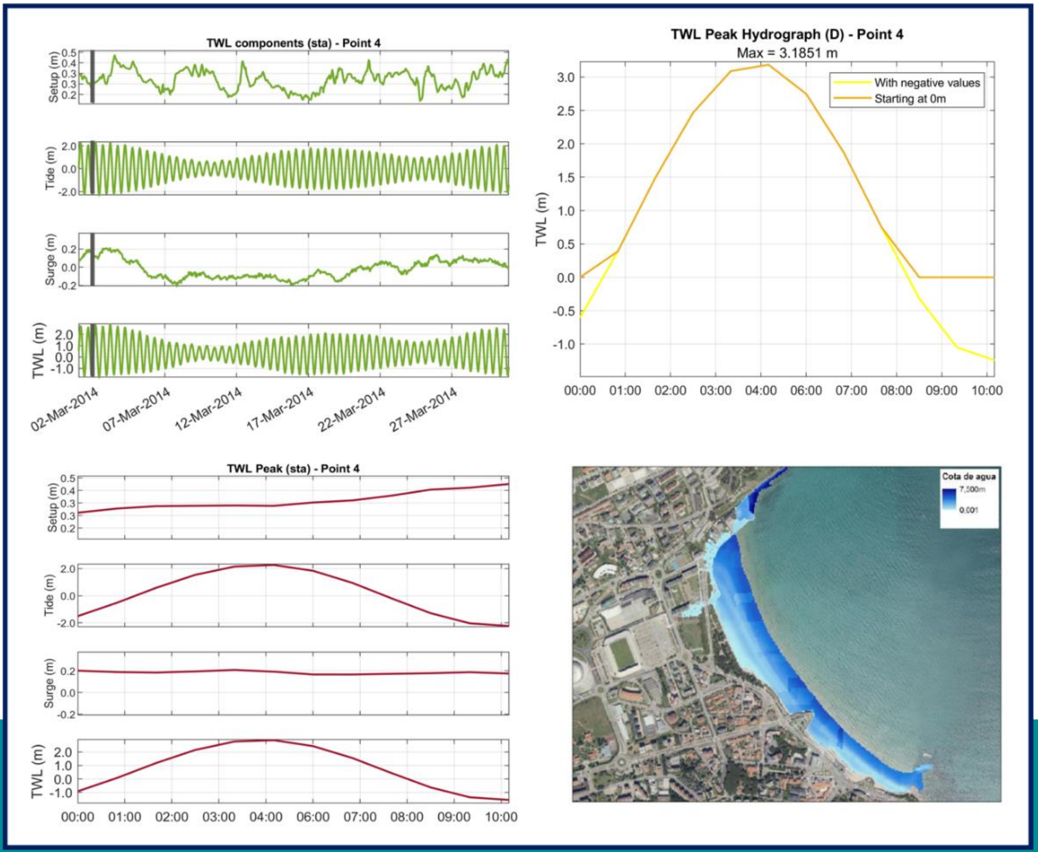
Simplified Solving shallow water equations (saint benant eq.). Cell storage method. Irregular cells adjusted to the DMT.

CoCliCo coastal climate core services

- Coastal **FLOOD MODELLING** Approach

European historical flood events:
Validation of the flood outcomes

Location	Storm	Source	HR DEM
Santander (Spain)	Storm – 03/03/2014	Published report	5 m (IGN)
Brouage (France)	Xynthia – 28/02/2010	Breilh et al. (2013)	1 m (IGN) resampled to 3 m
Rimini (Italy)	Storm – 15/11/2002	Koks et al. (2022)	2 m (Geoportale Emilia – Romagna)
Sicily (Italy)	Zorbas – 27-28/09/2018	Scicchitano et al. (2021)	2 m (provided by Roberto Iacono)
Murcia (Spain)	Gloria – 19-23/01/2019	Published report	2 m (IGN + Government of Murcia)
Solent (UK)	Storm – 10/03/2008	Wadey (2012, 2013)	2 m (DEFRA) resampled to 3 m
Ter Heijde (NL)	Potential dike break	de Moel et al. (2012)	5 m (PDOK)
Katwijk (NL)	Potential dike break	de Moel et al. (2012)	5 m (PDOK)
Scheli Fjord (Germany)	Storm – 02/01/2019	Kiesel et al. (2023)	10 m (Copernicus)
Gâvres (France)	Storm - 02/01/2014	ECFAS	1 m (IGN) resampled to 3 m
Vila do Conde (Portugal)	Christina – 06/01/2014	ECFAS	DGT (Direção-Geral do Território) - 2m



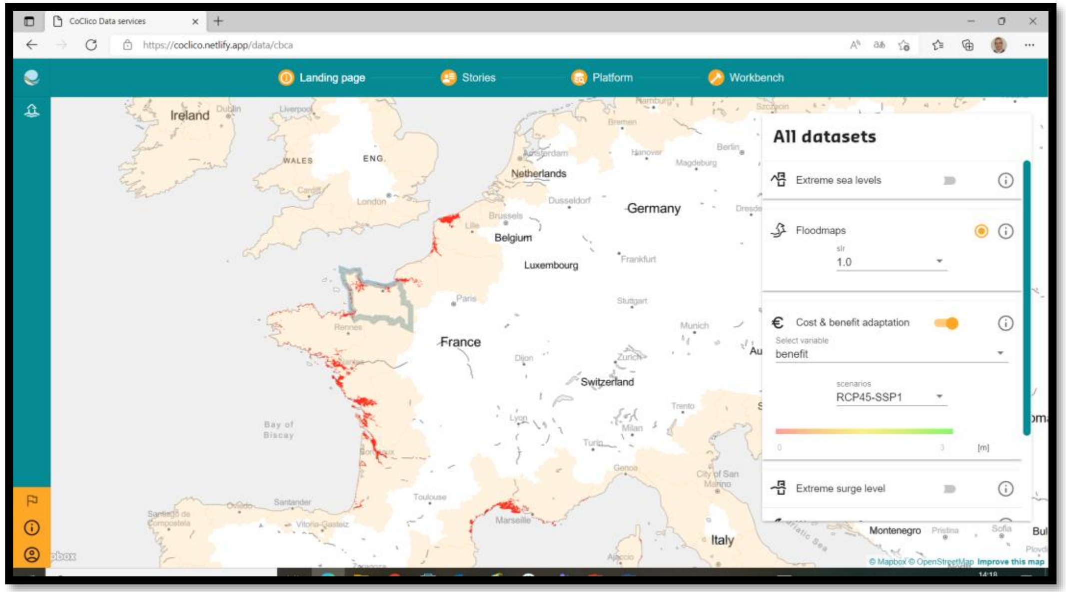
Sensitivity analysis to:

- the influence of the foreshore slope,
- the wave setup formulation,
- the 2D flood model,
- the resolution of the DEM

CoCliCo
coastal climate core services

The Fast Track Platform

The Full Track Platform



Implementation in progress!

CoCliCo
coastal climate core services

❖ A European study of the marine extreme water level on coastal flooding

Development of a pan-European high-resolution historical database

i. Storm surge hindcast
ii. Wave hindcast
iii. Total Water level reconstruction along the European coast
iv. Extreme TWL estimation
v. Modelling the coastal flooding

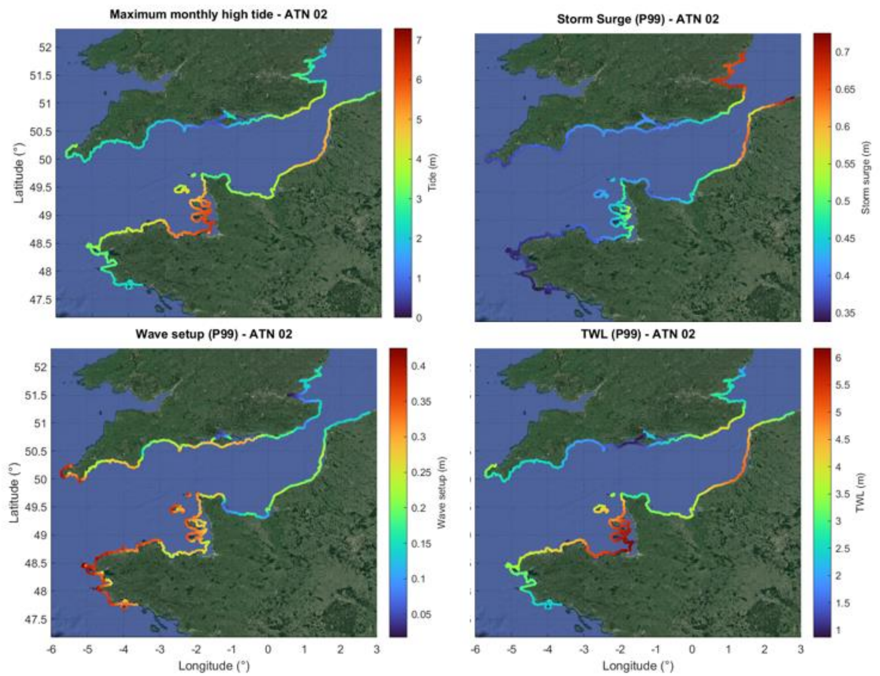
Development of pan-European regional climate projections

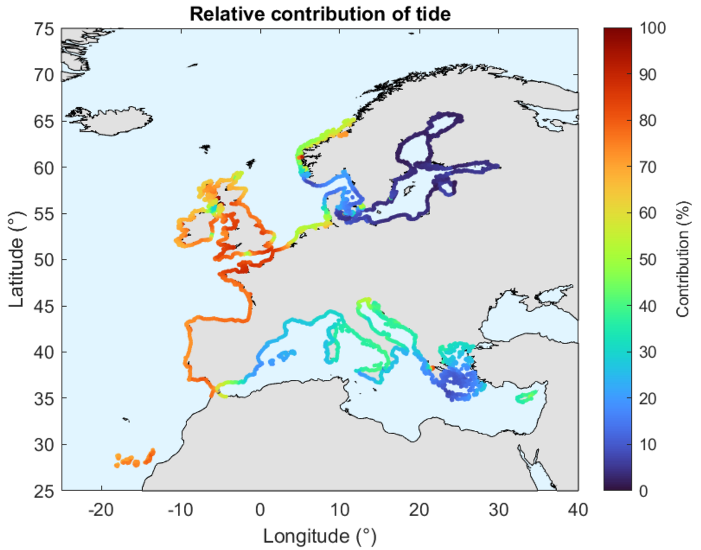
i. The selected CMIP6 climate models
ii. Mean sea level rise scenarios
iii. Storm surge projections
iv. Wave climate projections
v. Total Water level time series projections along the European coast
vi. Extreme TWL estimation
vii. Modelling the coastal flooding

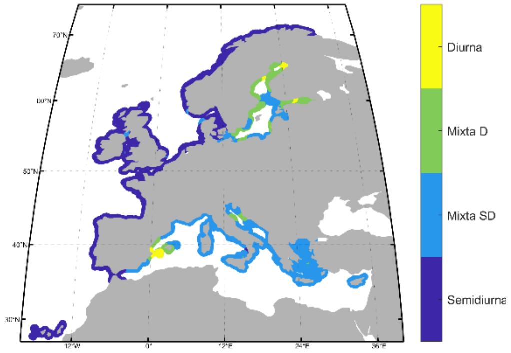
❖ Production of geospatial layers of sea-level dynamics, total water levels and flood maps

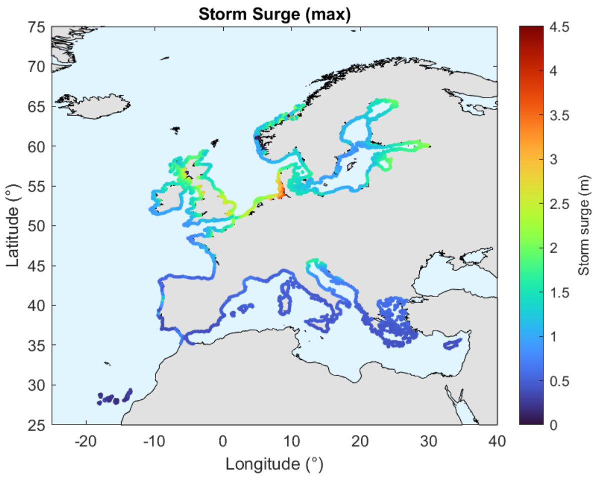
The geo-spatial layers are being implemented in the CoCliCo Full-Track web-platform.

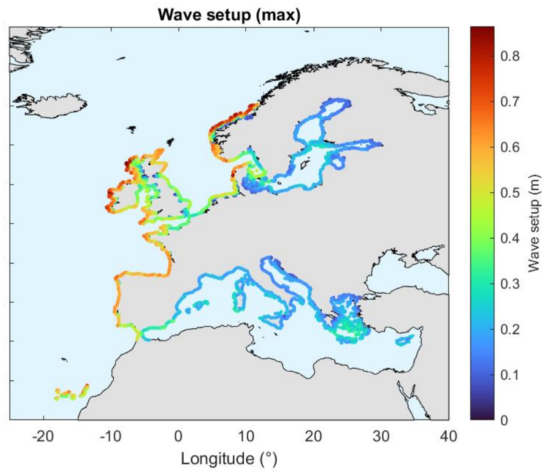
1. Tidal range
2. Tidal type (diurnal, semidiurnal..)
3. 99% percentile of the Storm surge
4. 99% percentile of the wave setup
5. 99% percentile of the TWL
6. Contribution of the Wave Setup to the extreme TWL
7. Contribution of the Storm surge to the extreme TWL
8. Coastal TWL associated to the 1, 100 and 1000 years return period
9. MSLrise associated to each future target year (e.g. 2050, 2100, 2150)
10. % of change of the extreme TWL(1, 100, and 1000 yrs) for each future target year and return period
11. Historical flood Hazard map associated to 1, 100, and 1000 yrs TWL
12. Future CC changes in coastal floding











A European study of the marine extreme water level on coastal flooding

Thanks for your attention!

Melisa Menendez*, Alexandra Toimil, Hector Lobeto, Maria Suarez-Bilbao, Camila De Sa Cotrim, Ana J. Abascal, Iñigo Losada

* menendezm@unican.es

CoCliCo
coastal climate core services