A methodology to evaluate the impacts of climate change in a coastal system

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Which is the shape of the equilibrium planform of this beach?

We need to define the local wave climate: long-term distribution

Predominant Waves
(Mean energy flux)

N 12º E
N 2º E

CP 1
CP 2

α_{min}

Po_2
Po_1
How many hours in a year the agitation inside the harbor is higher than 30 cm?

We need to define the local wave climate: long-term distribution
What should be the size of the blocks of this rubblemound breakwater?

We need to define the local wave climate: long-term extreme value distribution
How frequent does the breaching of this beach take place?

We need to define the local wave climate: long-term extreme value distribution
Impacts of Climate Change in a Coastal System

We are aware of recent trends of sea level...

Is Wave Climate being affected by Climate Change?
Impacts of Climate Change in a Coastal System

Objective: Evaluation of Climate Change Impact on coastal areas

Analysis and evaluation of climate change impacts on beaches, estuaries, lagoons, deltas and dune morphodynamics; coastal erosion; flooding risk assessment and impacts on the functionality and stability of coastal infrastructures.

To take into account

- Sea level rise
- Wave climate trends: long-term distribution and extreme value distribution: Hs, W, θ, SS

Historical analysis of long-term trends
Outline

1. Introduction

2. Methodology to obtain regional vulnerability indices

3. Methodology to assess detailed studies

4. Conclusions
2. Methodology to obtain regional vulnerability indices

“Effects of the climate change on the Spanish coast” (2002-2004)

Funded by the Spanish Agency of Climate Change (Ministerio de Medio Ambiente, SPAIN)

Phase I: To evaluate wave climate and sea level changes along the littoral

Phase II: To evaluate changes in the coast: beaches, ports, estuaries,…

Phase III: To establish strategies
2. Methodology to obtain regional vulnerability indices

Phase I
- Data bases
- Calibration
- Statistical models
  - Long-term trends
  - Climate variability

Phase II
- Vulnerability indices
- Theoretical effects of climate change in coastal areas

Phase III
- Integrated Coastal Zone Management + Adaptation strategies
2. Methodology to obtain regional vulnerability indices

**Average Direction of mean energy flux**

**Long-term trend of Direction of mean energy flux**

\[ \Delta \theta_{FE} \ (^{\circ}/\text{year}) \]
2. Methodology to obtain regional vulnerability indices

Long-term trend in SWH exceeded once every 50 years

$\Delta H$

$m/year$
2. Methodology to obtain regional vulnerability indices

\[ W = kH^3 \]
\[ \delta W = 3kH^2 \delta H \]
\[ \frac{\delta W}{W} = 3 \frac{\delta H}{H} \]

**Rubble-mound block sizes variation**

**REPRESENTATIVE DATA (2050)**

<table>
<thead>
<tr>
<th>Galician North Coast and Canarian North coast</th>
<th>Mediterranean coast</th>
<th>Cadiz Gulf</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑ 40 %</td>
<td>-10/10 %</td>
<td>↓ 40 %</td>
</tr>
</tbody>
</table>

*Non depth-limited wave!*
Regional vulnerability indices..... usually in deep water
Outline

1. Introduction

2. Methodology to obtain regional vulnerability indices

3. Methodology to assess detailed studies

4. Conclusions
3. Methodology to assess detailed studies
Impacts of Climate Change in a Coastal System

3. Methodology to assess detailed studies

Data bases

Calibration

Statistical models

Long-term trends
Climate variability

Vulnerability indices

Dynamic downscaling
Wave propagation models
Spatial scale $\sim O(m)$

Statistical downscaling
Classification algorithms
Time scale (1 hour)

Theoretical effects of climate change in coastal areas

Integrated Coastal Zone Management + Adaptation strategies
3. Methodology to assess detailed studies

Update of wave reanalysis data

Forcing: NCEP/NCAR winds and ice coverage
WaveWatch-III Version 2.22
3. Methodology to assess detailed studies
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Calibration of wave reanalysis data bases (Tomas et al, 2008, CSR)

-- Deep-water Buoy
-- Calibrated Reanalysis
3. Methodology to assess detailed studies

**Reanalysis node**

Wave propagation processes:
Refraction + shoaling + diffraction + breaking + wind generation

**Deep water time series**

44 years x 8766 sea states (hours)/year = 385,704 propagations!!
Impacts of Climate Change in a Coastal System

3. Methodology to assess detailed studies

Classification: **Self Organizing Maps**

Kohonen (2001)

Each sea state:

\[(H_{s1}, T_{m1}, \theta_1, H_{s2}, T_{m2}, \theta_2)_i\]

Deep-water reanalysis node (SIMAR-44)

Deep-water reanalysis node (SIMAR-44)

Time (h)

0 5 10 15 20


Deep-water reanalysis node (SIMAR-44)
3. Methodology to assess detailed studies. **Self Organizing Maps**

**Sea states classification = Statistical downscaling**

- Frequency of occurrence of each sea state: $H_c$
- Total energy of each sea state: $H_{sc}$
- $H_s$, $T_m$, $\theta$ of the sea and swell components

The diagram illustrates the methodology for assessing detailed studies using Self Organizing Maps for sea state classification through statistical downscaling.
3. Methodology to assess detailed studies.

Wave propagation = Dynamic downscaling
Impacts of Climate Change in a Coastal System
3. Methodology to assess detailed studies

**Propagation Coefficients**

\[ K_{hp(q)} = \frac{H_{sp(q)}}{H_{s(q)}} \]
3. Methodology to assess detailed studies

- Deep water time series
- Local time series

-- Shallow water Buoy
-- Calibrated Reanalysis + Propagation
3. Methodology to assess detailed studies

**Regression model** (Menendez et al, this session; Mendez et al, 2006 JGR)

Seasonality + Long-term Trends

\[
\begin{align*}
\mu(t) &= [\beta_0 + \beta_1 \cos(2\pi t) + \beta_2 \sin(2\pi t)] e^{\beta_{LT} t} \\
\psi(t) &= \alpha_0 + \alpha_1 \cos(2\pi t) + \alpha_2 \sin(2\pi t) \\
\xi_0 &
\end{align*}
\]
Example of Adaptation

Example: Sea level rise at 2050 $\delta \eta = 15$ cm
+ increase of storminess at 2050 (wave height $\delta H = 80$ cm)
3. Methodology to assess detailed studies

High Resolution Numerical Model
Impacts of Climate Change in a Coastal System

3. Methodology to assess detailed studies

Example of Adaptation

Increase of overtopping

Higher crown-wall (2 m)

Objective: reestablish operations, reliability and security current conditions
Action: higher crown wall

2 m x 10 m x 3500 m = 70000 m³ ...
Concrete: 60€/m³
4.2 M€
4. Conclusions

• Impact assessment of climate change on coastal areas depends directly on changes on atmospheric and ocean forcings.

• The effect of these forcings on coastal areas is highly dependent on local characteristics.

• The main agent considered during the last decades has been sea level rise. Wave climate, storm surges, winds and currents have also to be considered.

• High resolution information is required to address impact assessment and adaptation measures.

• We propose a combination of dynamic, statistical downscaling and time-dependent statistical models.
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Impacts of Climate Change in a Coastal System

**SOM**

Data

\[ x_1 = (x_1, x_2, x_3, \ldots, x_n) \]
\[ x_2 = (x_1, x_2, x_3, \ldots, x_n) \]
\[ x_i = (x_1, x_2, x_3, \ldots, x_n) \]
\[ x_p = (x_1, x_2, x_3, \ldots, x_n) \]

Data vector

\[
\begin{array}{cccc}
\cdots & \cdots & \cdots & \cdots \\
\end{array}
\]

Training algorithm

\[
\sum_{k=1,\ldots,M} d(C_k) = \sum_{k=1,\ldots,M} \sum_{x_i \in C_k} \| x_i - v_k \|^2
\]

\[ M = 9 \]

\[ c_5 = (2, 2) \]

\[ v_5 = (v_{51}, \ldots, v_{5n}) \]

Scheme of 3x3 two-dimensional self-organizing map

C1  C2  C3
    |
C4  C5  C6
    |
C7  C8  C9
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**SOM**

**Data Vector**

\[ x_i = (x_1, x_2, x_3, \ldots, x_n)_i \]

**Reference Vector**

\[ v_k = (v_1, v_2, v_3, \ldots, v_n)_k \]

**Winner centroid:**

\[ \| v_{w(i)} - x_i \| = \min_k \{ \| v_k - x_i \|, k = 1, \ldots, M \} \]

**Adjustment of the winner centroid and its neighbours**

\[ v_k = v_k + \alpha h(\omega(i), k)(x_i - v_k), k = 1, \ldots, M \]
Unimodal characterization

Deep-water reanalysis point (SIMAR-44)

Data
\[ x_1 = (H_s, T_m, \theta)_1 \]
\[ x_2 = (H_s, T_m, \theta)_2 \]
\[ x_P = (H_s, T_m, \theta)_P \]
\[ P \approx 400000 \]

SOM Sizes: \( k = [25 \ 49 \ 100 \ 196 \ 324 \ 400 \ 529 \ 625] \)
5. Clasificación de estados de mar

Redes neuronales autoorganizativas

Clasificación mediante K-medias
Unimodal characterization

Mean energy flux direction Error

\[ \Delta \theta = \theta_{FE_{retroanálisis}} - \theta_{FE_{centroides}} \]

Longitudinal transport relative Error

\[ E_Q(\%) = \left( \frac{Q_{retroanálisis} - Q_{centroides}}{Q_{retroanálisis}} \right) \cdot 100 \]

Quantification Error

\[ E = \frac{\sum_{k=1}^{M} d(C_k)}{P} = \frac{\sum_{k=1}^{M} \sum_{x_i \in C_k} \|x_i - v_k\|}{P} \]
Unimodal characterization

Reanalysis data: $P \approx 400000$

$$\theta_{FE_{\text{reanalysis}}} = \arctg \frac{\sum_{i=1}^{P} H_{si}^2 \cdot T_{mi} \cdot \text{sen}(\theta_i)}{\sum_{i=1}^{q} H_{si}^2 \cdot T_{mi} \cdot \cos(\theta_i)}$$

$$Q_{\text{reanalysis}} = \sum_{i=1}^{P} H_{si}^2 \cdot T_{mi}^{1.5} \cdot \left(\text{sen} \theta_i\right)^{0.6}$$

Clusters SOM: $M = 25, 49, \ldots, 625$

$$\theta_{FE_{\text{centroids}}} = \arctg \frac{\sum_{i=1}^{M} H_{si}^2 \cdot T_{mi} \cdot \text{sen}(\theta_i) \cdot f_i}{\sum_{i=1}^{M} H_{si}^2 \cdot T_{mi} \cdot \cos(\theta_i) \cdot f_i}$$

$$Q_{\text{centroids}} = \sum_{i=1}^{M} H_{si}^2 \cdot T_{mi}^{1.5} \cdot \left(\text{sen} \theta_i\right)^{0.6} \cdot f_i$$
4. Methodology to assess detailed studies

Sardinero beaches
Magdalena beach
Puntal beach
4. Methodology to assess detailed studies
4. Methodology to assess detailed studies

**Impact**: Reduction of 30% occupational Area

**Objective**: reestablish current situation

**Action**: Beach nourishment

8 m x 2500 m x 10 m

Sand 10€/m³

2 M€
5. Projection of Coastal Dynamics to the XXI century

**Historical analysis of long-term trends**

- **1950**
- **2008**
- **2100**

**Projection to XXI century**

- **1950**
- **2008**
- **2100**
5. Projection of Coastal Dynamics to the XXI century

Impacts of Climate Change in a Coastal System

1950 2007 2100

Wind waves and Storm surge? River discharge?

(AOGCM - Atmosphere-Ocean General Circulation Model)

Climatic System

Astronomical Forcings
GHG Forcings

...in the ocean...

Temperature
Wind SLP

...in the littoral

Rainfall

Waves Storm Surge

River discharge
5. Projection of Coastal Dynamics to the XXI century

6-hourly SLP data bases available

CCSM-NCAR (Community Climate System Model - National Center for Atmospheric Research, USA)
CNRM-MeteoFrance (Centre National de Recherches Meteorologiques, Francia)
CERA, World Data Center for Climate (Max-Planck-Institute for Meteorology, Alemania)
CGCM 3.1 (Environment Canada)
Impacts of Climate Change in a Coastal System

5. Projection of Coastal Dynamics to the XXI century

Phase I

- Data bases: Scenario A2, A1B, B1, ...
- Calibration
- Statistical models
- Long-term trends, Climate variability

Phase II

- Vulnerability indices
- Theoretical effects of climate change in coastal areas

Phase III

- Integrated Coastal Zone Management – Adaptation strategies
5. Projection of Coastal Dynamics to the XXI century

**To take into account:**

Hurricane projections in the XXI century (statistical and dynamic downscaling)

For each scenario…
- Different models
- Different ensembles

Probabilistic approach… ensemble projections
Impacts of Climate Change in a Coastal System

1. Data bases: atmosphere, ocean and hydrology

- Instrumental (buoys, radar, tidal/rainfall gauges, flow measurements,..)
- Visual data (ships)
- Hindcast data (WWWIII / WAM models)
- Satellite data (altimeters)
1. Data bases: atmosphere, ocean and hydrology

Summing up..

**Numerical model**

- Good quantitatively
- Sparse in space
- Long records
- Extreme values are not adequate

**Satellite**

- Good quantitatively
- Sparse in time
- Well-spatially distributed
- Short records (10 years)

**Buoy**

- Good quantitatively
- Shallow water buoys affected by propagation
- Sparse in space and time, gaps
- Short records (in general)

**Visual data**

- Good qualitatively
- Good directional information
- Sparse in space
- Long records
- Extreme values are not adequate
3. Methodology to assess detailed studies

WAVE REANALYSIS DATA SIMAR – 44 DATA BASE

definition of the sea state:

1. $H_s$, $T_p$, $\theta$
2. $H_{s1}$, $T_{m1}$, $\theta_1$, $H_{s2}$, $T_{m2}$, $\theta_2$