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Climate change impacts at port scale

T3.4 Analysis of climate change impacts at port scale

Deliverable – E 3.4.1 – Port of Aveiro

30th January 2021

Executive Summary

The European Union (EU) Strategy on Adaptation to Climate Change, launched in 2013, has encouraged all EU Member States to adopt comprehensive adaptation strategies, including also cross-border issues (EC, 2013c). The evaluation of the EU Adaptation Strategy undertaken by the European Commission (EC) showed that the EU Strategy on Adaptation to Climate Change has stimulated some actions on cross-border climate risks between Member States, in particular river basins and Alpine areas, but further action is needed (EC, 2018d). It reiterates the relevant role that transnational (as well as cross-border and interregional) programmes, co-financed by the Cohesion or Regional Policy, play in promoting cooperation projects on CCA, including those developed in the frame of the EU macro-regional strategies. Furthermore, Climate-ADAPT supports cooperation across European countries and regions by fostering exchange of knowledge and experiences and supporting the setting-up of transnational governance structures to jointly cope with common challenges.

Within the institutional framework described above, each country in the SUDOE area has developed a general strategy for adaptation to climate change. It must be highlighted that countries in the SUDOE area have significant socio-economic activity on the coast (tourism, fishing, navigation, etc).

This deliverable has the results of the activities carried out in WP3, for the Port of Aveiro, where a methodology to identify and evaluate the impacts of changing meteocean processes in ports was developed. The remaining ports selected in the project will have specific reports for them.

This deliverable particularly addresses the activities carried out in the task T3.4, which is built on the analysis carried out in the previous tasks (T3.1, T3.2 and T3.3). An analysis of the impacts of climate changes on the metocean processes in the Port of Aveiro is presented, in terms of the expected change in the parameters which are relevant for the port.

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20 October 2022	Update atmospheric parameters analysis	César Paradinas Blázquez
4 November 2022	Update sea parameters analysis	Paulo Chambel Leitão
9 November 2022	Version ready for dissemination	José Chambel Leitão

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Abbreviations

EU	European Union
GVA	Gross value added
IPCC	Intergovernmental Panel on Climate Change
GPMB	Grand Port Maritime de Bordeaux
WP	Work Package
RCP	Representative Concentration Pathways
SSP	Shared Socio-economic Pathways
IAPH	International Association of Ports and Harbours
UNCTAD	United Nations Conference on Trade and Development
AAPA	American Association of Port Authorities
MSL	Mean Sea Level
RP	Return Period
RMSE	Root Mean Square Error

1 PROJECT OVERVIEW

1.1 Motivation

Ports are crucial to a national economy and their importance will increase due to the expected increase in international trade. As an example, the Port of Valencia provides the Valencian economy with a Gross Added Value of 2,500 million euros, a figure equivalent to 2.39% of the Gross Domestic Product of the Valencian Community and generates 38,866 jobs that represent 2.09% of its employment.

Ports are susceptible to the effects of climate change such as variations in waves, sea level rise and heat waves. In this context, the ports of the SUDOE space face the common challenge of adapting to the effects of climate change to avoid having to stop operations. With today's just-in-time production models, the total or partial closure of ports would affect industry and freight distribution centres.

On the other hand, it should be noted that the effects of climate change in the Mediterranean ports of the SUDOE space are different from those of other ports located in the Atlantic Ocean or in the Cantabrian Sea, so it is important to cooperate and seek synergies between regions facing similar challenges. ECCLIPSE aims to respond to a need that cannot be addressed solely from a national perspective.

It is therefore necessary for ports to implement effective climate change adaptation strategies. Such strategies require tools that allow a deep understanding of the impacts of climate change at a local scale, as opposed to current models that due to their globality and wide temporal range are not effective in decision-making.

ECCLIPSE will analyse the impact of climate change in ports, develop tools and models for early prediction, contribute to raising awareness of the impact of climate change and define transnational strategies for prevention and action in the SUDOE space that can minimize their effects.

1.2 ECCLIPSE Objectives

The objective of ECCLIPSE is to develop a common framework for assessing the impacts associated with climate change and the adaptation to such impacts of ports in the SUDOE space.

The main project results will be the following:

- The development and implementation of a common methodology will make it possible to assure the consistency of the results to be obtained for each port by using the same scientific and technical criteria so that the conclusions drawn for the entire port network are consistent. This also makes it easier to extend the application to other European ports.
- ECCLIPSE will provide the mechanisms for designing and implementing the measures to adapt ports to climate change. These measures will have a common scientific basis for the whole European port network.

- Finally, the results of the climate projections will be stored in a climate database by port, which will allow the study of the evolution of the climate change impact in specific locations when planning and designing new port infrastructures

2 INTRODUCTION

Based on the criteria proposed in Deliverable 3.3.1, simulations were carried out to assess climate change impact on navigation, port operation and infrastructure design. This was done for a list of metocean parameters agreed with the three port authorities involved in the project: Port of Aveiro, Port of Bordeaux and Port of Valencia.

Not only the parameters were defined but also the relevant threshold values and the statistical processing that should be done.

Based on that information, several numerical models and algorithms were used to reach a description for each parameter in five conditions:

- Baseline or present situation;
- RCP 4.5 mid-century scenario (2040-2060);
- RCP 8.5 mid-century scenario (2040-2060);
- RCP 4.5 end-of-century scenario (2080-2100);
- RCP 8.5 end-of-century scenario (2080-2100);

Results are organized in different Reports per Port Authority where all the parameters are addressed. The present Report is for the Port of Aveiro.

3 Port of Aveiro

3.1 General description

The Port of Aveiro is located at (40º 39'N, 8º 45'W), on the western coast of the Iberian Peninsula, with its hinterland on the central and northern Portugal and central Spain. The Port is located in the entrance of Ria de Aveiro (see Figure 1), a coastal lagoon where the tidal propagation shapes the hydrodynamic conditions in the entrance and navigation channels of the Port.

It is a multifunctional port, operating primarily for the service of various sectors of industry in the central region of Portugal.

The port entrance is 1.5 miles from the North Sector terminals (facilities 1 to 7 in Figure 2) and 4.5 miles from the South Sector terminals (facilities 8 and 9 in Figure 2).

Currently, the Port of Aveiro can dock vessels with the following characteristics:

- Average draft of up to 9.75 m;
- Maximum length: up to 200 m.

Further information can be seen at https://portodeaveiro.pt/.

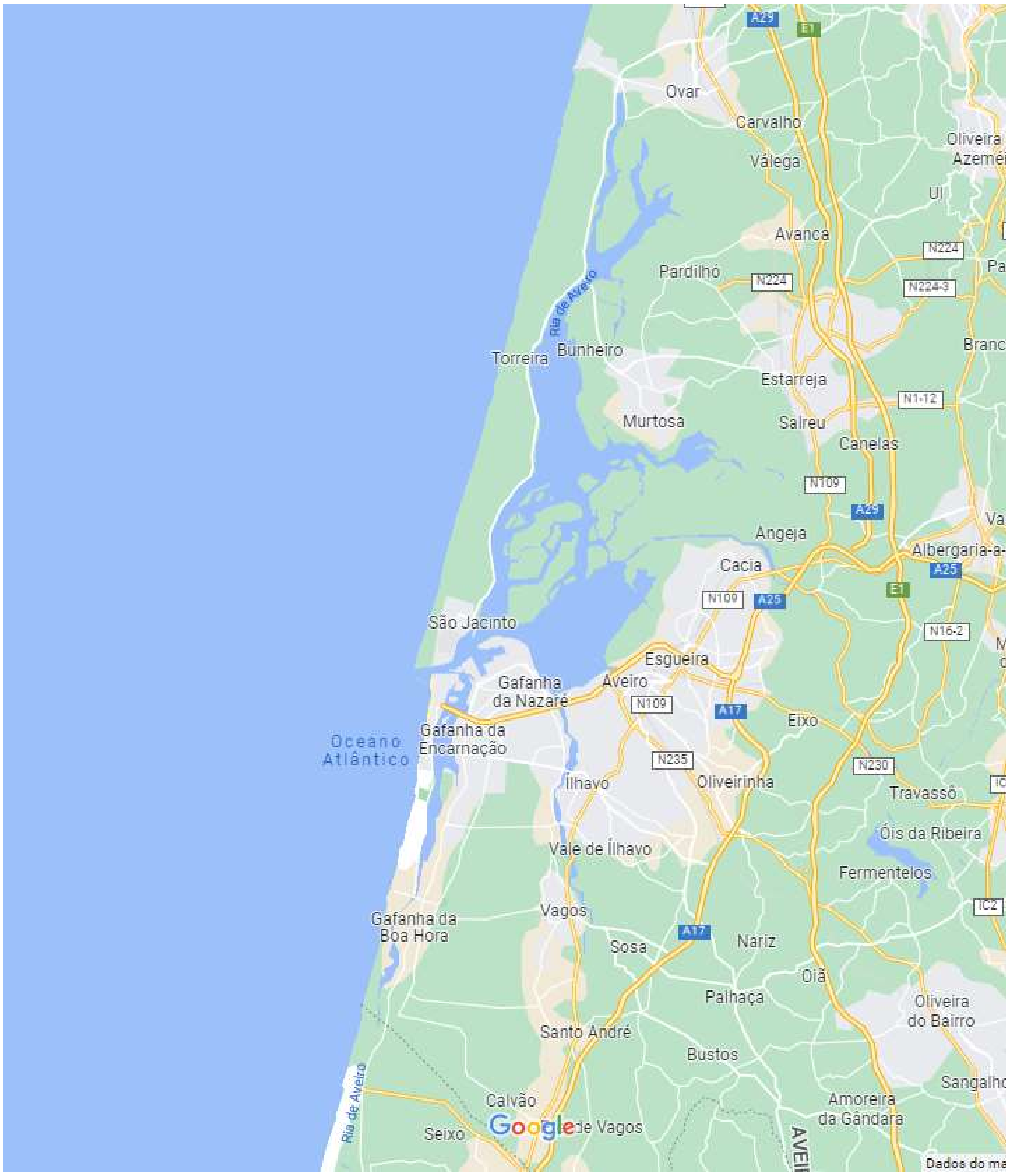


Figure 1 - General view of Ria de Aveiro

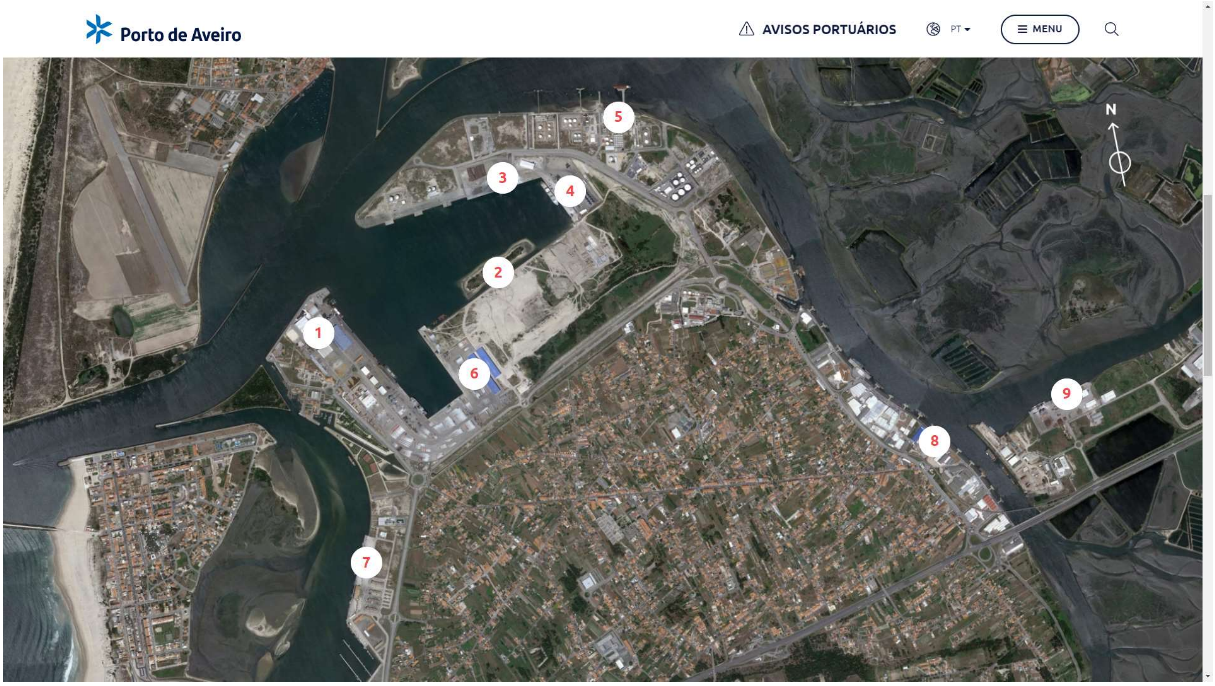


Figure 2 - Facilities at the Port of Aveiro

3.2 Metocean Parameters

Table 1 has a description of the metocean parameters deemed relevant for the Port of Aveiro, as described in Deliverable 3.3.1. The generic processing methods are also described in Table 1. Tools that were used and the resulting climate change forecasts for the Port of Aveiro are detailed in the following sections.

Table 1 –Relevant metocean parameters for Port of Aveiro, as defined in Deliverable 3.3.1

	Currents	Waves	Wind	Sea level	Visibility
Restrictions to navigation					
Description	The currents generated near the inlet are mainly driven by tide. It has been identified that the mean water level is crucial to determine the tidal prism and as consequence the intensity of the currents. Two thresholds of current velocity have been established: (1) Above 1 knot for ships over 150 m length and 9.0 m draft; (2) Above 4 Knot for ships over 135 m length and 7.5 m draft.	Port of Aveiro is located inside the Ria de Aveiro and is well protected from swell, however the pilot's operation (boarding vessel at sea) is impacted by the waves. During periods of Hs above 4 meters pilots do not board vessels at sea.	Strong winds also affect ship's entrance and exit. The Port adopts two thresholds: (1) 30 knots for vessels larger than 135 meters; (2) 40 knots for all vessels.	--	Visibility shorter than 500 m restricts the entrance of ships longer than 135 meters.
Processing	Evaluate the navigation windows available with currents below 1 knot, based on high resolution modelling for the navigation channel.	Basic wave statistics and evaluate events where Hs exceeds 4 m, their duration and frequency.	Basic wind statistics and evaluate events where wind exceeds 30 and 40 knots, their duration and frequency.	--	Evaluate events (duration and frequency) where visibility is lower than 500m, using a visibility proxy (difference between air temperature and dew point).
Operational Threshold					
Description	--	--	Land operations limited by winds higher than 54.4 knots. Exception: Beyond 28.8 km/h the operation with solid bulk in North Terminal could be suspended by the Port Authority if the wind direction is from SSO (180º to 225º) or NNW (315º to 360º).	--	It may occur due to fog or heavy rainfall. Visibility shorter than 200 m restricts road traffic operations.
Processing	--	--	Basic wind statistics and evaluate events where wind exceeds 28.8 and 54.4 knots, their duration and frequency. Evaluate if wind direction is expected to change above 28.8 knots, their duration and frequency.	--	Evaluate events (duration and frequency) where visibility is lower than 200m, using a visibility proxy (difference between air temperature and dew point).
Infrastructure's thresholds design					
Description	--	Wave climate change leading to higher or more frequent damages in harbour protection structures	--	Sea level increase: (1) impacts in low level dock structures; (2) reduces rainwater drainage capacity in low land areas	--
Processing	--	Wave climate statistics and extreme event analysis	--	Extreme events of sea level (including tide, meteorology and mean sea level)	--

3.3 Currents

The currents baseline and climate change impact on these were based in Hidromod´s experience in implementing hydrodynamic models in Ria de Aveiro, complemented with IDAD's knowledge (which works in close cooperation with the University of Aveiro).

3.3.1 Modelling strategy

IDAD was sub-contracted to propose the best strategy to simulate accurately the tide level and currents in Ria de Aveiro with a particular focus in the Porto of Aveiro area.

The following spatial discretization was proposed by IDAD:

- curvilinear structured grid;
- 477x1254 cells and 135644 elements;
- Spatial resolution ranges from 20-50 m inside the lagoon to 60-250 m in the platform region.

IDAD also provided a very complete bathymetric data set (Figure 3). Additionally, implemented and validated a first version of the hydrodynamic model.

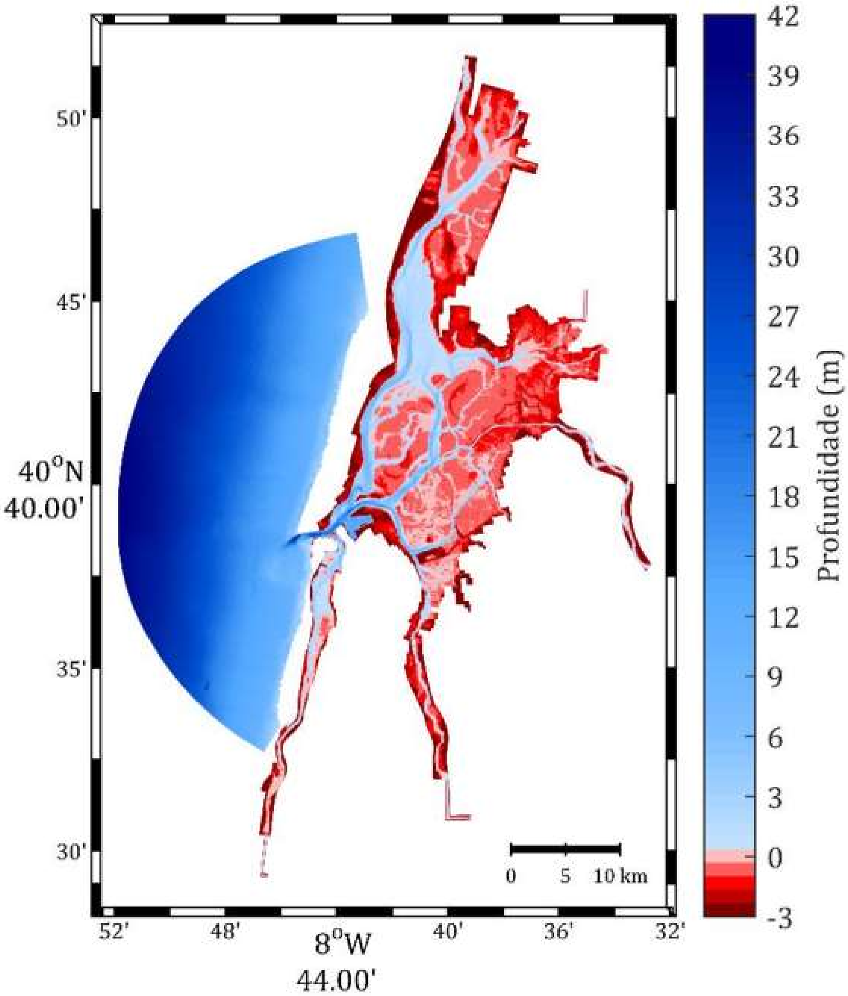


Figure 3 – Bathymetric data interpolated to the curvilinear grid (source : IDAD).

3.3.2 Validation

In a first step the tide level model results were compared in 10 tidal gauge stations for a one-month simulation (July 2019). In the Aveiro mouth station (Barra) the model presents a root mean square error (RMSE) of 4 cm and a correlation of 0.99 (Figure 4). This station represents the tide level variability in the downstream limit of the port area (North sector, Figure 2). The second station closest to the port area (South sector, Figure 2) is located 5 km upstream (Vista Alegre, Canal do Boco). In this station the model presents a RMSE of 14 cm and a correlation of 0.96 (Figure 4). A RMSE around ~5-10 cm can be assumed for the entire port area (Figure 2). The model accuracy tends to decrease upstream because the model errors associated with the tide propagation from Ria's mouth to inner areas accumulates and also because the bathymetry becomes more complex (e.g. narrow channels, larger intertidal areas). Even so the overall accuracy is quite good with a 16 cm RMSE average and an average correlation of 0.96 (Figure 4).

Figure 4 – RMSE and correlation of the hydrodynamic model tide levels in 10 stations for a one month simulation (July 2019).

In a second step the model was compared with velocity measurements (4 points) along 1 day in June 2019 (Figure 5). The station closest to the port area is located 1.5 km upstream of the North sector (Costa Nova, Canal de Mira). In this point the model presents an RMSE of 0.07 m/s

(9%) and a correlation of 0.96 (Figure 5). The average RMSE for all 4 stations was 0.13 m/s and the average correlation 0.81. Also, in the case of the velocities the error increases upstream. The overall accuracy can be considered quite good.

A critical navigation restriction for the port operation are the currents in the channel between the port entrance (or Ria's mouth) and the North Sector terminals. However, in this area there is no current meter data available. To overcome this lack of data, the Aveiro harbour pilot service maintains a register of observed currents velocity for this area. The observation method is based in the ship position and the relative velocity of the ship to the water. The observations show a clear maximum of 5.5 nots in spring tides under average river flow conditions. The maximum velocity model results are consistent with this observed limit (Figure 6).

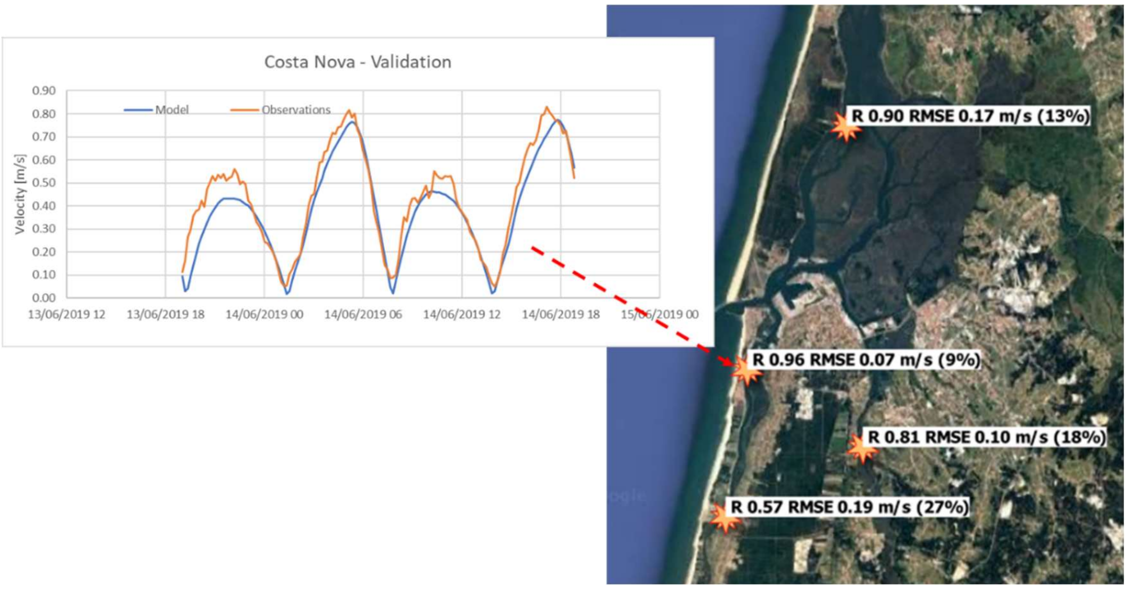


Figure 5 – RMSE and correlation of the hydrodynamic model velocities in 4 stations along 1 day (June 2019).

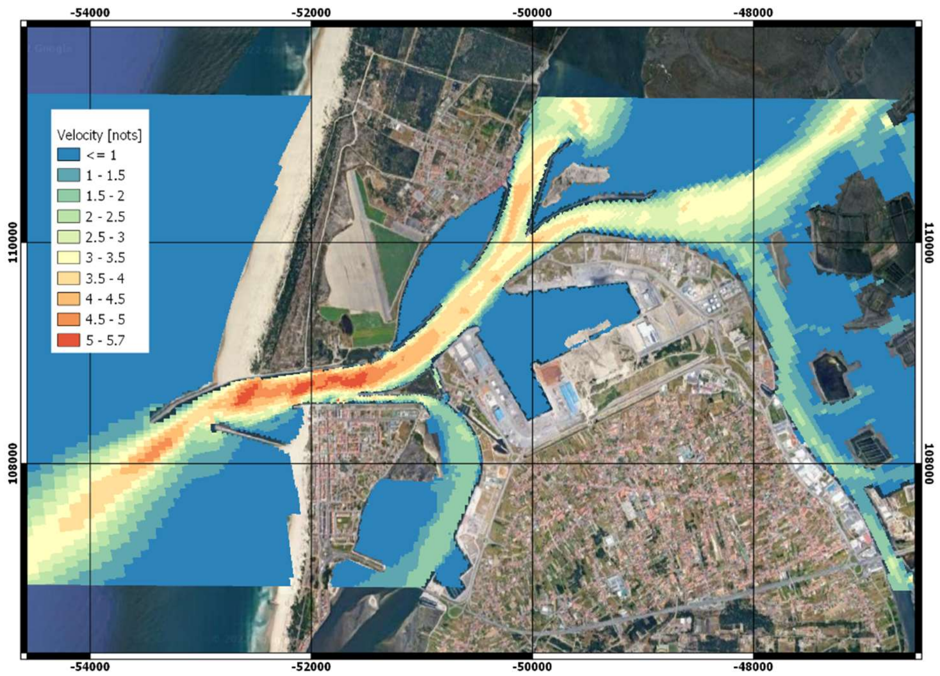


Figure 6 - Maximum velocity (July 2019).

3.3.3 Results

The analysis of model results was focused on the time interval (or window) in which currents are below a specific velocity threshold. Two thresholds were considered: 1 not (limit for the larger ships) and 4 nots (limit for smaller ships). The unit assumed for this parameter (time window) was hours per day. The parameter was computed for each model cell for spring and neap tide conditions. The baseline was defined assuming the present mean sea level (MSL). For baseline conditions the time window below 1 not, in neap tide conditions, has minimum values of the order of 6 [hours/day] (Figure 7). For spring tide minimum values are of the order of 3 [hours/day] (Figure 8). For the 4 nots threshold under neap tide conditions currents intensity is always below the threshold (24 [hour/day], Figure 9). For spring tide conditions, the time window minimum values are of the order of 14 [hours/day] (Figure 10).

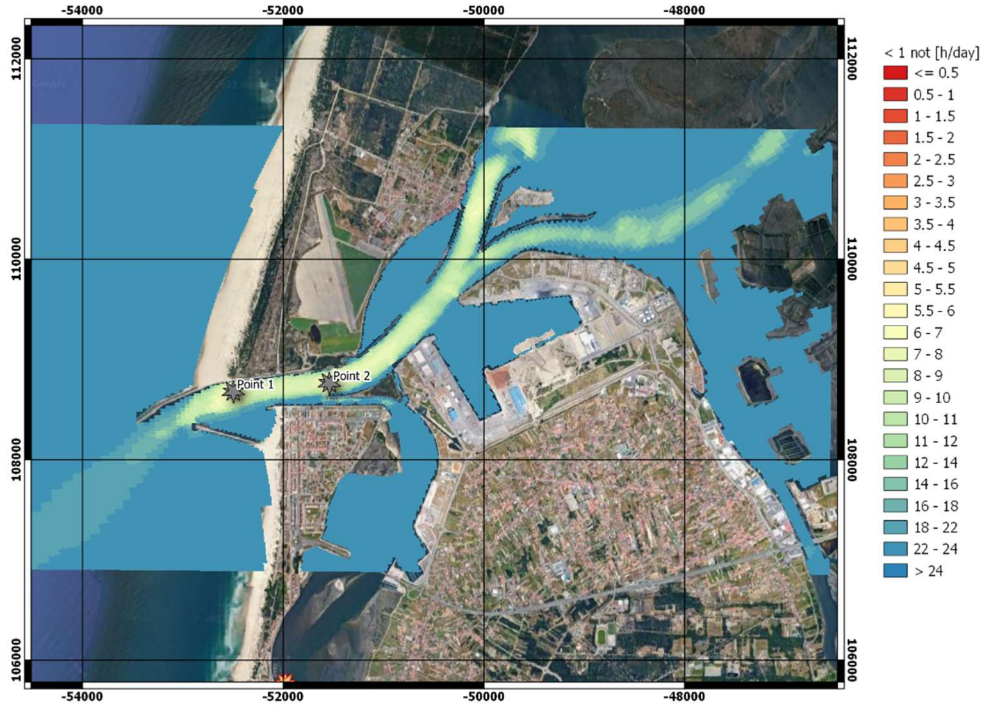


Figure 7 – Baseline – Currents under neap tide conditions – Time window < 1 not.

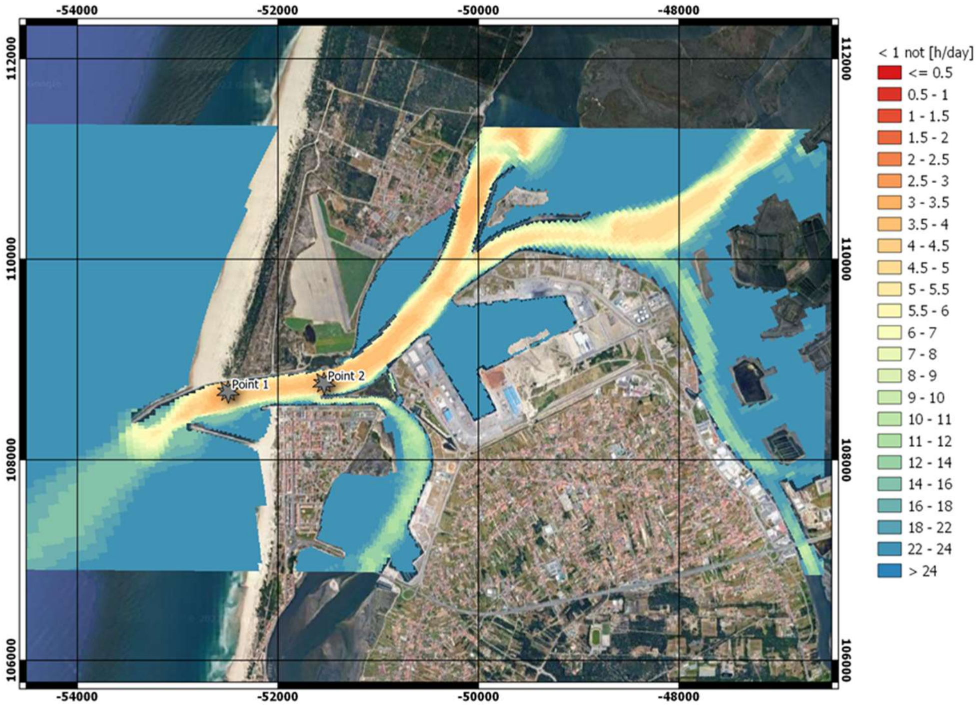


Figure 8 – Baseline – Currents under spring tide conditions – Time window < 1 not.

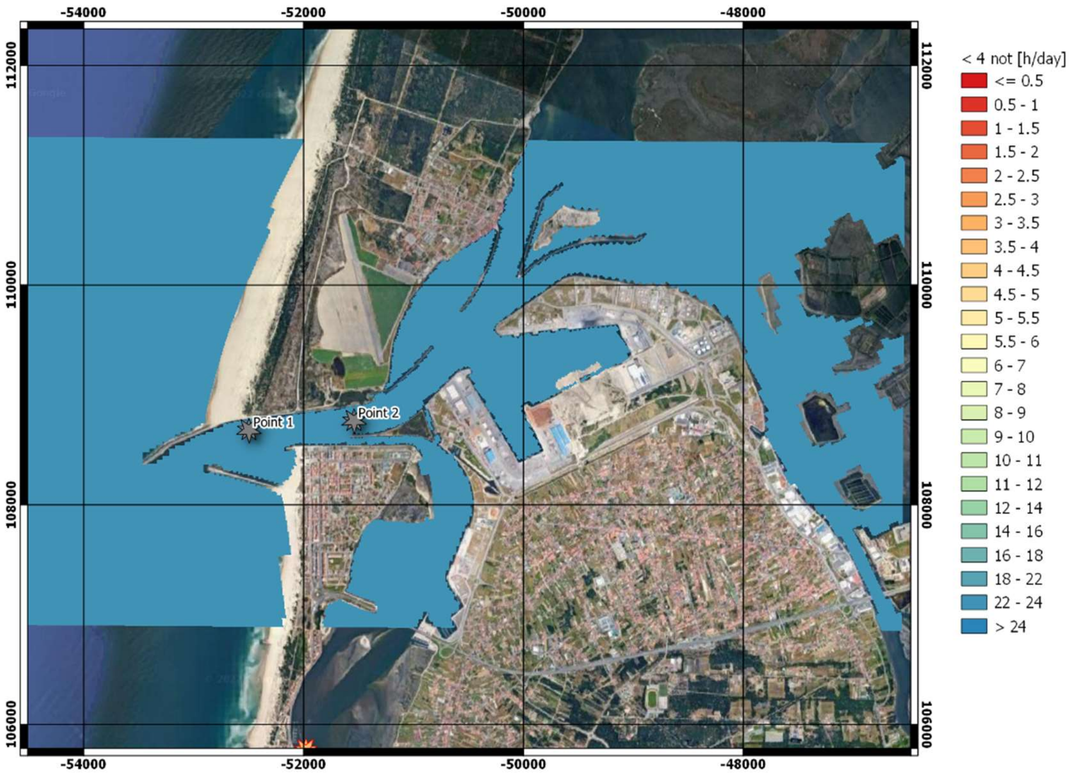


Figure 9 – Baseline – Currents under neap tide conditions – Time window < 4 nots

Figure 10 – Baseline – Currents under spring tide conditions – Time window < 4 nots

The model minimum time window values occur, in a persistent way, in two points named Point 1 and Point 2 (Figure 7 and Figure 8). To estimate climate change projections for the time window parameter, the model was run for MSL rise projections proposed by the IPCC 5 (Table 2).

Table 2 - Climate change induced mean sea level rise range (Adapted from Oppenheimer et al., 2019)

IPCC 5 Scenarios	Global Mean Sea Level [m]
RCP 4.5 (2040-2060)	0.19-0.34
RCP 8.5 (2040-2060)	0.23-0.40
RCP 4.5 (2080-2100)	0.34-0.64
RCP 8.5 (2080-2100)	0.51-0.92

The climate change projections for the time window parameter in Point 1 and Point 2, and for spring and neap tide conditions is presented in Table 3 (for the 1 not threshold) and Table 4 (for the 4 nots threshold).

For the 1 not threshold a reduction from ~3 [h/day] (baseline) to ~2 [h/day] is expected in a 100 years' horizon, for spring tide conditions. A maximum reduction from ~7 [h/day] to ~4 [h/day] is expected under neap tide conditions for the same time horizon. For the 4 nots threshold, a maximum reduction from ~14 [h/day] to ~9 [h/day] is expected again for the 100 years horizon. For the neap tide conditions, the currents intensity is always below the 4 nots threshold (time window = 24 [hour/day]) for all tested MSL rise scenarios.

3.3.4 Restrictions to Navigation

Given the results showed above, there is a clear tendency of time window reduction for safe navigation (see Table 3 and Table 4).

Table 3 - Baseline vs Climate Change Projections - Time window with currents < 1 not

Window of operation < 1 not	Present [h/day]	RCP 4.5 (2040-2060) [h/day]	RCP 8.5 (2040-2060) [h/day]	RCP 4.5 (2080-2100) [h/day]	RCP 8.5 (2080-2100) [h/day]
Point 1 - Spring Tide	3.2	2.8 - 3.0	2.7 - 2.9	2.5 - 2.8	2.2 - 2.6
Point 2 - Spring Tide	3.3	2.8 - 3.0	2.7 - 2.9	2.4 - 2.8	2.1 - 2.6
Point 1 - Neap Tide	6.5	5.5 - 5.9	5.4 - 5.8	4.8 - 5.5	4.3 - 5.1
Point 2 - Neap Tide	6.8	5.7 - 6.1	5.5 - 6.0	4.8 - 5.7	4.3 - 5.2

Table 4 - Baseline vs Climate Change Projections - Time window with currents < 4 nots

Window of operation < 4 nots	Present [h/day]	RCP 4.5 (2040-2060) [h/day]	RCP 8.5 (2040-2060) [h/day]	RCP 4.5 (2080-2100) [h/day]	RCP 8.5 (2080-2100) [h/day]
Point 1 - Spring Tide	14.2	12.1 - 12.9	11.8 - 12.7	10.6 - 12.1	9.3 - 11.2
Point 2 - Spring Tide	18.2	14.8 -16.1	14.3 - 15.8	12.5 - 14.8	10.6 - 13.5
Point 1 - Neap Tide	24.0	24.0	24.0	24.0	24.0
Point 2 - Neap Tide	24.0	24.0	24.0	24.0	24.0

3.4 Sea Level

Climate change effects on mean sea level inside Ria de Aveiro was evaluated as the combined result of changes in MSL, storm surges and astronomic tide.

3.4.1 Mean Sea Level

In Antunes (2019) the variation of mean sea level (MSL) registered in the Cascais tidal gauge since 1880 is shown (Figure 11).

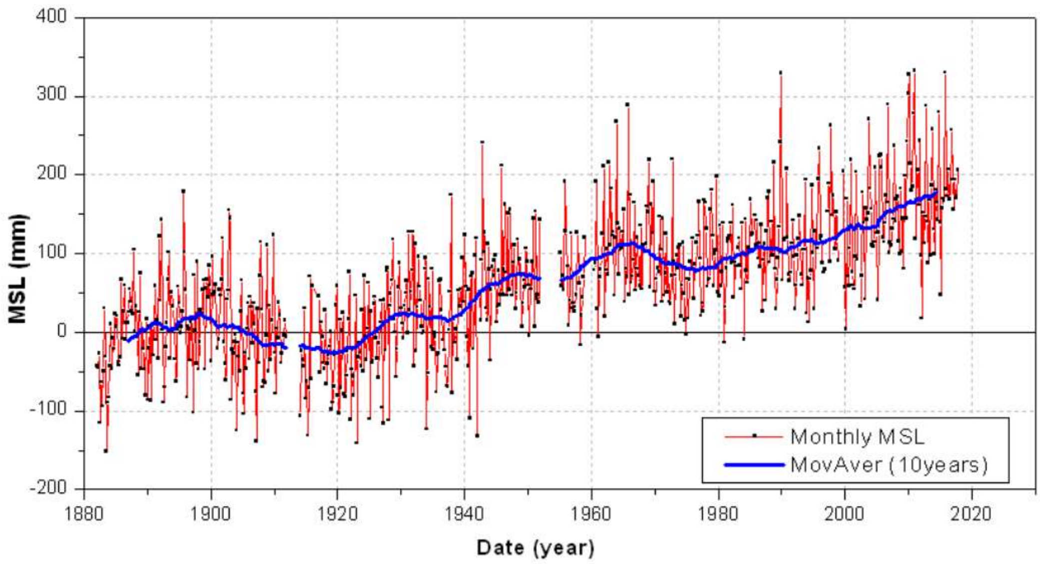


Figure 11 - Cascais tidal gauge secular series of monthly MSL, from 1882 to 2017, relative to the national vertical datum, and a moving average (MovAver) of the 10-year base period (adopted from Antunes, 2019)

Cascais tidal gauge data shows very similar sea level rise rates (Figure 11) when compared with the ones retrieved by global mean sea level models (Antunes, 2019). The median values and likely ranges for projections of global mean sea level (GMSL) rise in meters relative to 1986–2005 for the two scenarios of interest (RCP 4.5 and RCP 8.5) are presented in Table 2. Based in the work of Antunes (2019) the mean sea level rise scenarios for the Aveiro port were assumed equal to the global projections present in Table 2.

3.4.2 Storm Surge

The baseline and climate scenarios projections of the storm surge extremes were quantified using the Portuguese Coast Operational Modelling System (PCOMS)[1] model. Deltares Global Tide and Surge Model (GTSM)[2] results available in the Copernicus Climate Change Service (https://climate.copernicus.eu, Yan et al., 2020) were also used. The GTSM results only consider one atmospheric forcing solution for the climate scenarios. The methodology develop in the ECCLIPSE project recommends the use of three atmospheric forcing solutions to allow an

[1]PCOMS (Portuguese Coast Operational Modelling System) is an implementation of the MOHID model (www.mohid.com) run in forecast mode for the continental Portuguese coast (Mateus et al., 2012).
[2] Deltares Global Tide and Surge Model (GTSM) version 3.0 is used together with regional climate forcing and sea level rise initial conditions. The regional climate forcing employed was the HIRHAM5 model from the Danish Meteorological Institute (DMI), a member of the EURO-CORDEX climate model ensemble, which is downscaled from the global climate model EC-EARTH.

estimation of the uncertainty for each climate scenario. For this reason, the PCOMS model was run in the framework of the ECCLIPSE project considering three atmospheric forcing solutions for each climate scenario (RCP 4.5 and RCP 8.5).

3.4.2.1 Storm surge - Modelling Strategy

To assess the impact of climate change over storm surges, the PCOMS model was run with three atmospheric forcings from 2040 to 2100 and for the two Representative Concentration Pathway (RCP) scenarios, RCP 4.5 and RCP 8.5, totalling 6 simulations. In **¡Error! No se encuentra el origen de la referencia.** the designation assigned to each simulation, the simulated period, and the corresponding atmospheric forcing are presented. For each atmospheric forcing in **¡Error! No se encuentra el origen de la referencia.** the Regional Climate Model (RCM) used to perform the dynamic downscaling, the Global Climate Model (GCM) where the regional model is nested, and the RCP climate scenarios are also presented.

Table 5 – List of datasets used to calculate return period, simulated period and respective RCMs, GCM and RCP scenarios (atmospheric forcing : https://climate.copernicus.eu)

Name	Simulated period	Atmospheric forcing		
		GCM	RCM	RCP scenarios
PCOMS (CNRM)	2040-2100	CNRM-CERFACS-CNRM-CM5	ALADIN63	RCP4.5
PCOMS (IPSL)	2040-2100	IPSL-IPSL-CM5A-MR	SMHI-RCA4	RCP4.5
PCOMS (MOHC)	2040-2100	MOHC-HadGEM2-ES	DMI-HIRHAM5	RCP4.5
PCOMS (CNRM)	2040-2100	CNRM-CERFACS-CNRM-CM5	ALADIN63	RCP8.5
PCOMS (IPSL)	2040-2100	IPSL-IPSL-CM5A-MR	SMHI-RCA4	RCP8.5
PCOMS (MOHC)	2040-2100	MOHC-HadGEM2-ES	DMI-HIRHAM5	RCP8.5
GTSM (EC)	2041-2070	EC-EARTH	HIRHAM5	RCP8.5
GTSM (EC)	2071-2100	EC-EARTH	HIRHAM5	RCP4.5

PCOMS and GTSM simulations from 1979 to 2017 were used to define the baseline. Both models were forced with the ERA5 atmospheric reanalysis (Table 6). The ERA5 and the GTSM results were download from Copernicus Climate Change Service. The simulation period (38 years) allows a consistent extreme storm surge analysis. This analysis is considered to be representative of the present situation.

Table 6 - List of datasets used to calculate return period for the past time (1979-2017)

ID	Time	Atmospheric forcing
PCOMS (ERA5:1979-2017)	1979-2017	ERA5 reanalysis
GTSM (ERA5:1979-2017)	1979-2017	ERA5 reanalysis

The PCOMS storm surge was assumed equal to the total sea level model results less the astronomic tide. The astronomic tide was estimated using the t-tide analysis matlab tool (Pawlowicz et al., 2002). In the case of GTSM the storm surge results were already available in the Copernicus Climate Change Service. The analysis of extremes was applied to the storm surge time series of both models (PCOMS and GTSM). The concept of extreme events is very relevant for risk analysis in different areas of coastal engineering. To an extreme value is associated a specific frequency of occurrence. This frequency is usually expressed using the concept of return period (RP), which can be interpreted as the average interval of occurrence between events. Another way is to consider the frequency as probability of occurrence of a given event along 1 year. For example, an extreme event with a return period of 100 years has a 1% probability of occurring in 1 year. Return periods of extreme storm surge were calculated following the "*Peaks Over Thresehold*" methodology described in Mathiesen et al (1994).

3.4.2.2 Storm Surge – Validation

The GTSM (Muis et al., 2016, Muis et al., 2018, Wang et al., 2021) and PCOMS (Mateus et al., 2012, Bartolomeu et al., 2018, Leitão et al., 2018) model validation was done extensively in the framework of several scientific publications. However, the GTSM is a global scale model while PCOMS is a coastal scale one. The GTSM uses data assimilation while PCOMS does not. The numerical approaches have also some differences (e.g. GTSM – unstructured grid, PCOMS – structured grid). Having these differences in mind a comparison of the storm surge results of each model for a 3 years period (2015-2017) for 7 tidal gauges located along the Portuguese coast was done (Figure 12). The GTSM present a slightly better performance with a lower RMSE average (5.3 cm GTSM and 5.9 cm PCOMS) and a higher correlation average (0.81 GTSM and 0.73 PCOMS). For the Aveiro tidal gauge GTSM model presents a RMSE of 6.3 cm and PCOMS 7.1 cm. The GTSM correlation is 0.79 and the PCOMS one is 0.69. These differences, particularly the RMSE ones, can be considered small consequently the ability of both models to simulate storm surges was assumed similar.

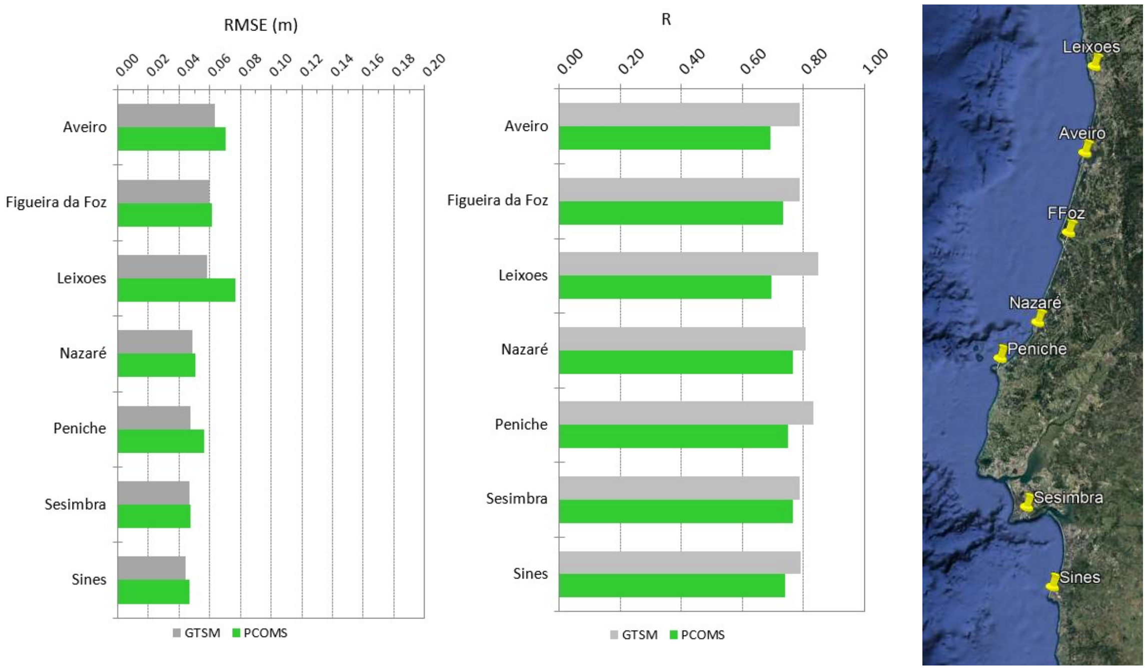


Figure 12 – Storm surge validation of PCOMS and GTSM models for the period from 01/01/2015 to 01/01/2018.

3.4.2.3 Storm Surge – Results

The baseline storm surge calculated with two models (PCOMS and GTSM) using the meteorological boundary conditions of ERA5 reanalysis (between 1979 and 2017) gave the results shown in Table 7. The results are very similar. For the return period of 50 and 100 years the results are equal, for the return periods of 5, 10 and 25 PCOMS presents results only 1 cm above the GTSM. Only for the return period of 2 years the PCOMS results are 2 cm above GTSM results. This similarity is consistent with the validation presented above. The average of the two model results was considered as the baseline of the storm surges extremes.

Table 7 – Baseline storm surge extremes for the period of 1979-2017

Return period [years]	GTSM (ERA5: 1979-2017) [m]	PCOMS (ERA5: 1979-2017) [m]	Average [m]
2	0.42	0.44	0.43
5	0.53	0.54	0.54
10	0.60	0.61	0.61
25	0.69	0.70	0.70
50	0.76	0.76	0.76
100	0.83	0.83	0.83

The storm surge extremes computed for the climate change scenarios of interested are presented in Table 8 for different return periods. For each return period, RCP scenario and time window of analysis 4 extreme values were considered (PCOMS (CNRM), PCOMS (IPSL), PCOMS (MOHC), GTSM (EC) see **¡Error! No se encuentra el origen de la referencia.**). To simplify the results analysis for each set of 4 extreme values is only presented the minimum and maximum values. This way is present in each table cell (return period x scenario) an interval of values (min-max) to show the incertitude of the projections.

Table 8 – Baseline (or present) versus Climate Change Projections for storm surge

Return period	Present [m]	RCP 4.5 (2041-2070) [m]	RCP 8.5 (2041-2070) [m]	RCP 4.5 (2071-2100) [m]	RCP 8.5 (2071-2100) [m]
2	0.43	0.39 - 0.47	0.39 - 0.47	0.44 - 0.49	0.4 - 0.46
5	0.54	0.47 - 0.57	0.46 - 0.58	0.51 - 0.59	0.48 - 0.58
10	0.61	0.52 - 0.64	0.51 - 0.65	0.55 - 0.65	0.53 - 0.66
25	0.70	0.58 - 0.72	0.57 - 0.74	0.61 - 0.73	0.59 - 0.76
50	0.76	0.62 - 0.79	0.61 - 0.81	0.66 - 0.8	0.63 - 0.84
100	0.83	0.67 - 0.85	0.65 - 0.87	0.7 - 0.86	0.67 - 0.91

3.4.3 Astronomic tide

The dampening effect of the astronomic tidal wave as it enters Ria de Aveiro was evaluated with the MOHID numerical model. This model implementation and validation was already presented in the "Currents" section. In Figure 13 the spring high tide level relative to the present

MSL spatial variability is presented. This model result was done assuming in the open boundary a spring tide with a height of 3.1 m and the present MSL. The main conclusion is that high tide level inside the Ria is about 20 cm less in the navigation and docking areas than it is outside (coastal area). This decrease is due to the intense velocity present along the Ria de Aveiro entrance channel and consequent increase of the bottom shear stress in this area.

With the rise in mean sea level, the dampening effect will be higher due to increased velocities (see "Currents" section) generating higher bottom shear stress and consequently more energy dissipation. Spring high tide level (relative to the respective MSL) hydrodynamic model results for different MSL for a point in the navigation area are shown in Figure 14. These results present a clear reduction of the spring high tide level with the increase of the MSL. However, this reduction stops for a MSL above 120 m. Above this limit the spring high tide level converges asymptotically for a constant value of 1.24 m.

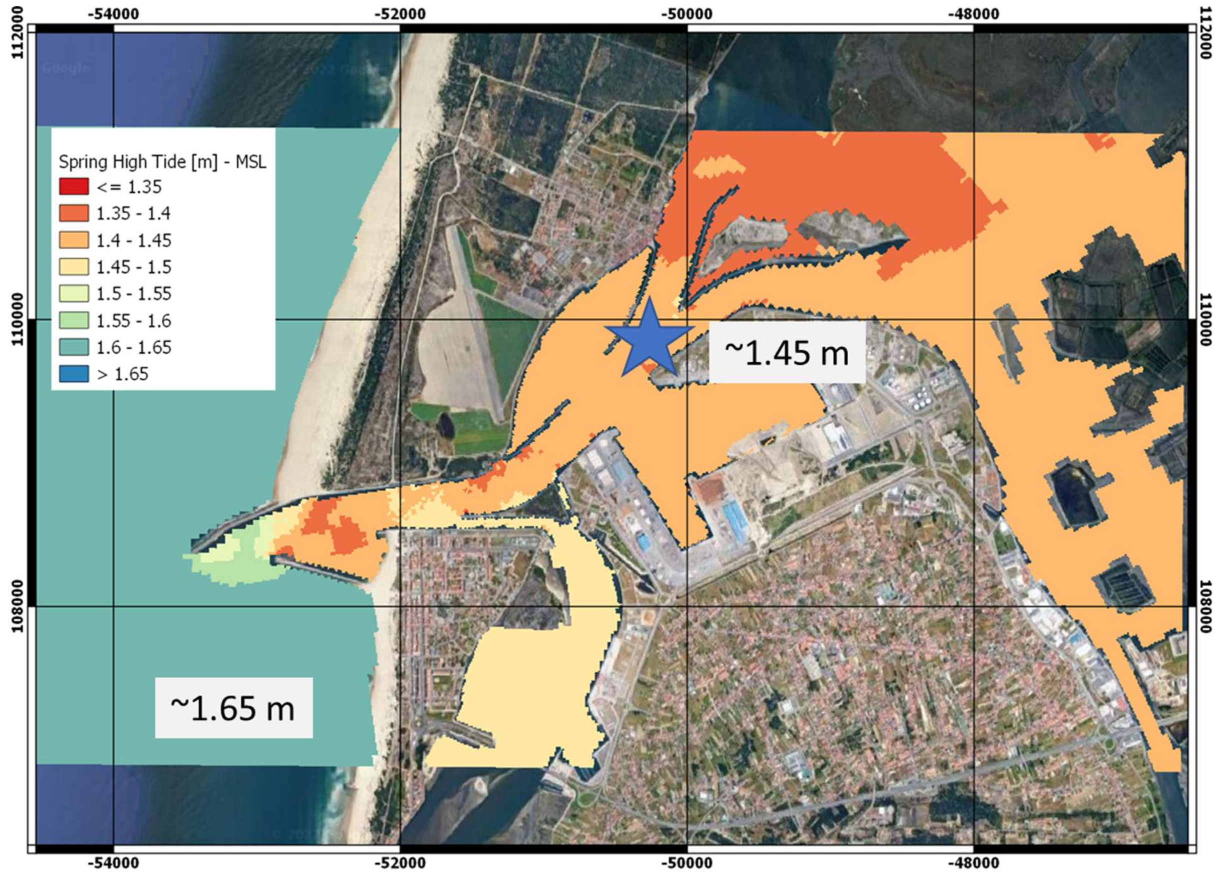


Figure 13 – Astronomic high tide level relative to the present coastal mean sea level for spring tide conditions. The blue star marks the point where the decrease of the tide level for a spring high tide function of MSL rise was computed (Figure 14).

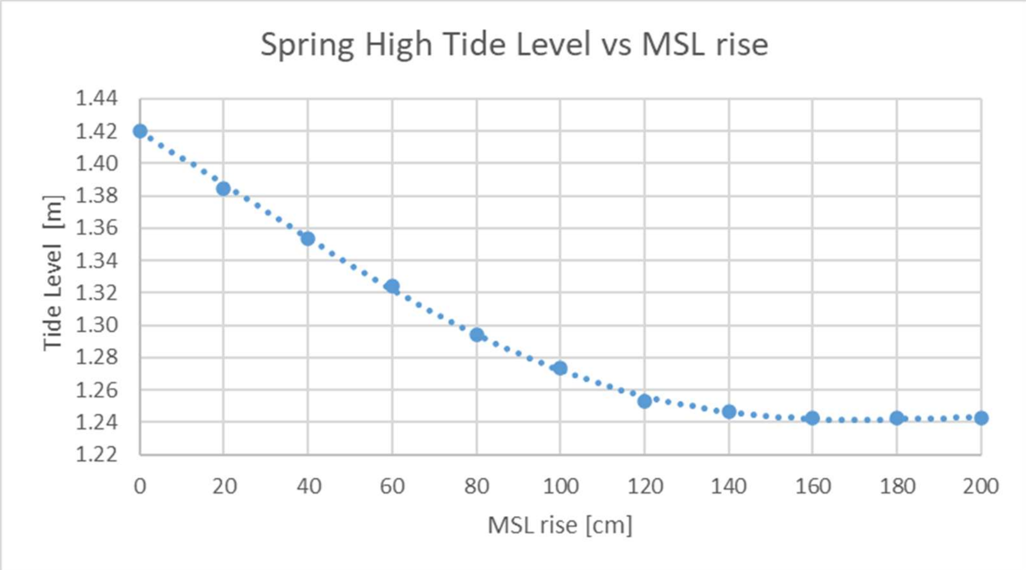


Figure 14 – Variation of the spring high tide level (relative to the respective MSL) function of the MSL rise for a point located in the Aveiro Port (blue start - Figure 13).

3.4.4 Total sea level change

The total sea level changes due to the MSL, storm surge and astronomic tide changes described earlier are resumed in Table 9. It is assumed that the present MSL in the coast relative to the hydrographic zero is 2.26 m. The total sea level baseline for a 2 years return period (4.11 m, Table 9) is obtained adding to the present MSL (2.26 m), the present spring high tide level (1.42 m, Figure 14) and the storm surge with a RP of 2 years (0.43 m, Table 8). The remaining values of Table 9 are obtained adding to the present mean sea level (2.26 m) the MSL rise (Table 2), storm surge (Table 8) and astronomic tide (Figure 14) projections.

The extreme tide levels projections relative to present situation (Table 10) tend to be 5-15 cm below the MSL IPCC 5 projections (Table 11). This is mainly due to the decrease of the spring high tide level with the increase of the MSL describe above. Additionally, the storm surge levels projections present mild variations relative to the baseline (Table 8).

Table 9 – Estimated range for the extreme sea level events for the navigation and dock area of the port of Aveiro

Return period [years]	Present	RCP 4.5 (2040-2060) [m]		RCP 8.5 (2040-2060) [m]		RCP 4.5 (2080-2100) [m]		RCP 8.5 (2080-2100) [m]	
2	4.11	4.20	4.42	4.21	4.45	4.37	4.68	4.47	4.89
5	4.22	4.28	4.52	4.28	4.56	4.44	4.78	4.55	5.01
10	4.29	4.33	4.59	4.33	4.63	4.48	4.84	4.60	5.09
25	4.38	4.39	4.67	4.39	4.72	4.54	4.92	4.66	5.19
50	4.44	4.43	4.74	4.43	4.79	4.59	4.99	4.70	5.27
100	4.51	4.48	4.80	4.47	4.85	4.63	5.05	4.74	5.34

Table 10 – Estimated range for the extreme sea level events change relative to the present situation for the navigation and dock area of the port of Aveiro

Return period [years]	RCP 4.5 (2040-2060) [m]		RCP 8.5 (2040-2060) [m]		RCP 4.5 (2080-2100) [m]		RCP 8.5 (2080-2100) [m]	
2	0.09	0.31	0.10	0.34	0.26	0.57	0.36	0.78
5	0.06	0.30	0.06	0.34	0.22	0.56	0.33	0.79
10	0.04	0.30	0.04	0.34	0.19	0.55	0.31	0.80
25	0.01	0.29	0.01	0.34	0.16	0.54	0.28	0.81
50	-0.01	0.30	-0.01	0.35	0.15	0.55	0.26	0.83
100	-0.03	0.29	-0.04	0.34	0.12	0.54	0.23	0.83

Table 11 - Climate change induced mean sea level rise range IPCC5 projections (Adapted from Oppenheimer et al., 2019)

IPCC 5	RCP 4.5 (2040-2060) [m]		RCP 8.5 (2040-2060) [m]		RCP 4.5 (2080-2100) [m]		RCP 8.5 (2080-2100) [m]	
MSL rise	0.19	0.34	0.23	0.4	0.34	0.64	0.51	0.92

3.4.5 River flow contribution to sea level

The contribution of the river flow for extreme sea level in the port area was not considered in this report. Sea level validation of major floods in Ria de Aveiro would require an effort which is out of the scope of this project. Also, other authors have studied this topic (e.g., Ribeiro, et al., 2021) and an eventual merge with the values presented above may be done in the future.

3.4.6 Infrastructure's thresholds design

The sea level rise in the Port of Aveiro was considered to: (1) impact low level dock structures; (2) reduce rainwater drainage capacity in low land areas. The values in Table 9 are a good support for the design of those structures.

3.5 Waves

3.5.1 Generic evaluation

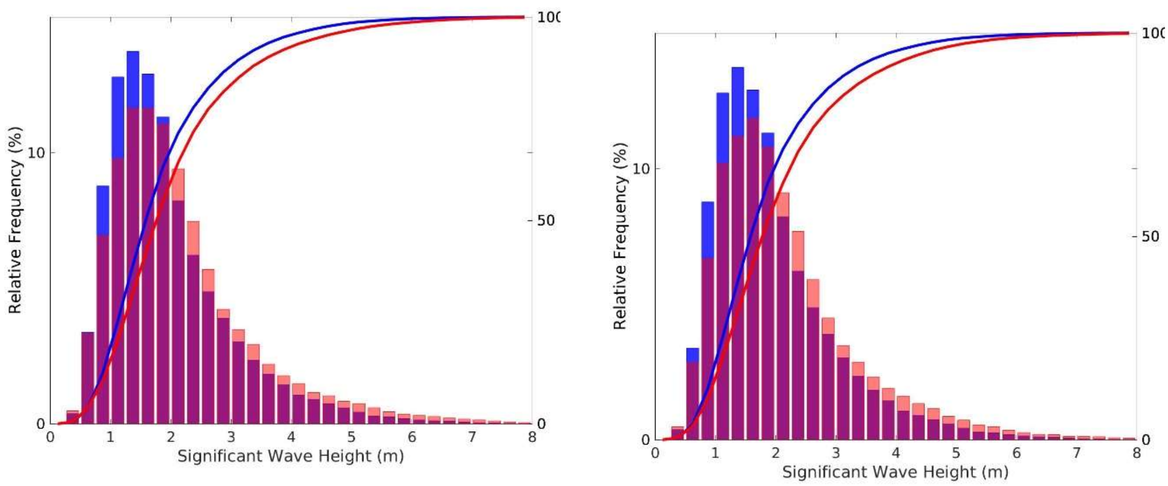
The impacts of waves on port's operability and infrastructures are analysed by evaluating present conditions with mid and end century climate projections, with the same methodology being applied to all time series.

The datasets considered for the analysis are tranches of 20 years of wave modelling results (using the ECMWF's Wave Model) for the present (Reanalysis) and mid and end century projections for RCP 4.5 and 8.5. The extraction point from the model is about 15 km West from The entrance of the Ria de Aveiro (see Figure 15). For these simulations the wind predictions were extracted from the HIRHAM5 regional climate model downscaled from the global climate model EC-EARTH (available at https://cds.climate.copernicus.eu/).

Figure 15 – Site where data from ECMWF's Wave Model was extracted

The impact of waves on the Aveiro Port operability can be evaluated by analysing the significant wave height (parameter usually used to define operational thresholds). As shown in Figure 16 and Figure 17, both future projections indicate a left shift in the wave height distribution (towards higher amplitudes). The larger differences between present and future projection are observed for the end-century RCP 4.5. Similar results are shown in Figure 18 where the tendency of Hs suggests an increase towards the end of the century for RCP 4.5 and a decrease for RCP 8.5. Nevertheless, on average both climate scenarios show higher wave bulk parameters (eg., Hs, Hmax, Tp) when compared to present values (Table 12).

(a) (b)



I (d)

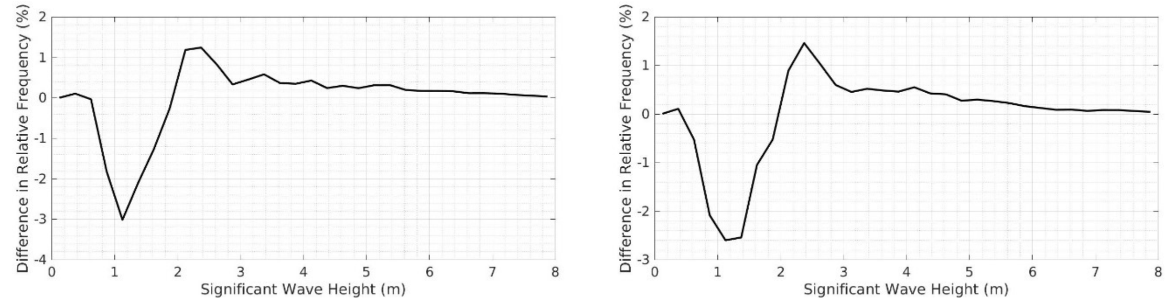
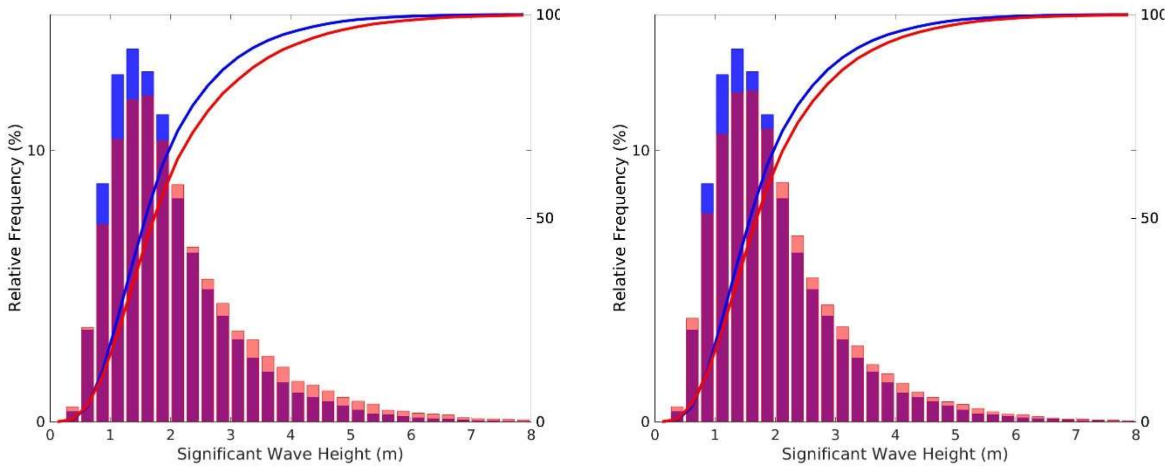


Figure 16: Frequency of occurrence of significant wave height for the present (blue) and mid-century (2040-2060) climate projections (red). (a) RCP 4.5 (b) difference in relative frequency present and RCP4.5), (c) RCP8.5 and (d) difference in relative frequency (present and RCP8.5)

(a) (b)



(c) (d)

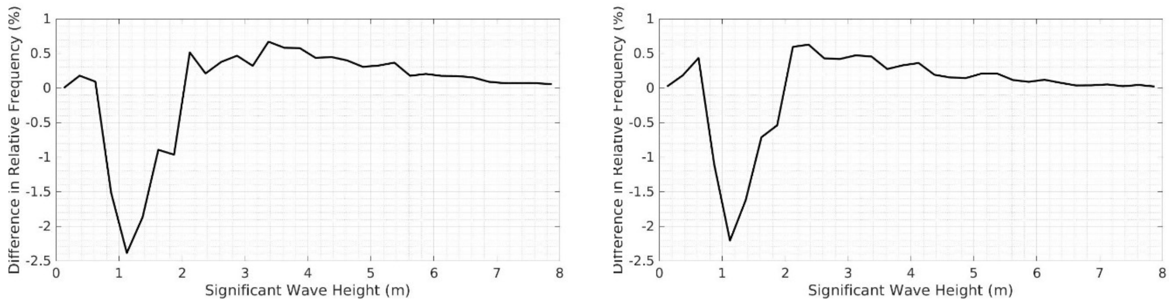


Figure 17: Frequency of occurrence of significant wave height for the present (blue) and end-century (2080-2100) climate projections (red). (a) RCP 4.5 (b) difference in relative frequency (present and RCP4.5), (c) RCP8.5 and (d) difference in relative frequency (present and RCP8.5).

Table 12: Bulk wave parameters, Aveiro coast.

	Present	RCP 4.5 (2040-2060)	RCP 8.5 (2040-2060)	RCP 4.5 (2080-2100)	RCP 8.5 (2080-2100)
Hs mean (m)	1.95	2.16	2.19	2.18	2.09
Tp mean (s)	11.17	11.31	11.24	11.27	11.11
Hs 90% (m)	3.3	3.73	3.77	3.84	3.59
Hs 95 % (m)	4.0	4.60	4.57	4.69	4.38
Hs max (m)	9.36	10.85	10.30	11.86	12.08

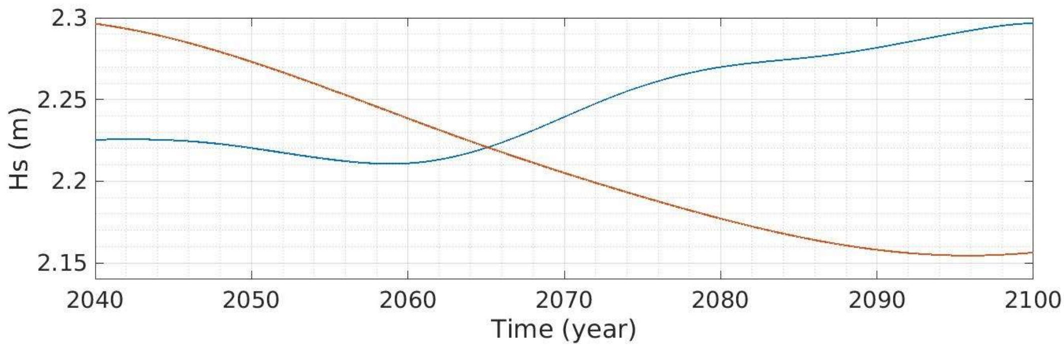


Figure 18: Significant wave height tendencies for the climate projections RCP 4.5 (blue) and RCP 8.5 (red).

3.5.2 Restrictions to navigation

The analysis of events above a threshold for the future projections suggests that the main change between present and future climate is the frequency of occurrence of events that tends to increase significantly (Table 13). For all simulations the mean duration of events (Hs above 4 meters) is similar in the order of 1.15 days (about 28 hours), however the mean interval duration shifts from 22 days (present) to 13-14 days (projections). Those results suggest that the main impact of waves for navigation at Port of Aveiro is the increase in the frequency of downtime.

Table 13: Events of Hs> 4m and interval between events

Scenario	Present	RCP 4.5 (2040-2060)	RCP 8.5 (2040-2060)	RCP 4.5 (2080-2100)	RCP 8.5 (2080-2100)
Number of events	**312**	**485**	**507**	**478**	**440**
Mean Event duration (days)	**1.15**	**1.21**	**1.20**	**1.30**	**1.14**
Mean Interval between events (days)	**22.2**	**13.8**	**13.2**	**13.8**	**14.9**

3.5.3 Infrastructure's thresholds design

Infrastructures are designed using a "Design Wave" which may have a 100-years return period or similar. The selection of the proper Design Wave is not addressed here. What is in fact done is to use the maximum value obtained for the significant wave height (Hs max), in the analysed scenarios, as a proxy of the Design Wave. Future changes in HS max should fairly represent changes in the Design Wave.

An increase in Hs max is forecasted for the climate change scenarios, as presented in Table 12. For the mid-century scenario, an increase between 10 and 16% is expected, while for the end of the century, the increase is close to 30%.

3.6 Atmospheric data sources

According to the list of identified variables of interest, a diverse set of weather observations had to be gathered to proceed with the calculations of their climatic changes, also doing the same for other derived variables. Due to the different nature of the measurements to be gathered (mean wind, wind gusts, temperature, precipitation, dew point…) and of the entities in charge of doing so, not all weather stations offer all the variables. Therefore, data for the development of the calculations in the case study had to be gathered from multiple sources and locations, detailed hereafter:

- IPMA (*Instituto Português do Mar e da Atmosfera*): the Portuguese national institute for meteorological forecasting, the IPMA, offers a remarkable net of weather stations distributed throughout the whole hydrological basin of Aveiro (Figure 19), with measurements of different variables depending on the stations considered. As has been done in the other ECCLIPSE cases, **all these stations have been considered** (after different validations and quality testing) for the calculations that have taken place. When studying and displaying the results, each station was treated separately and then the cluster of them (the whole Aveiro region), depending on the variable and the interest in getting a projection for the region (i.e.: temperature) or the location (i.e.: wind), to that way get a better understanding of all the behaviours. For this case, and after a thorough analysis, the observation point at the city of Aveiro itself, **IPMA station, has been taken as the representative observation** of the Port of Aveiro (Figure 20 with its location).

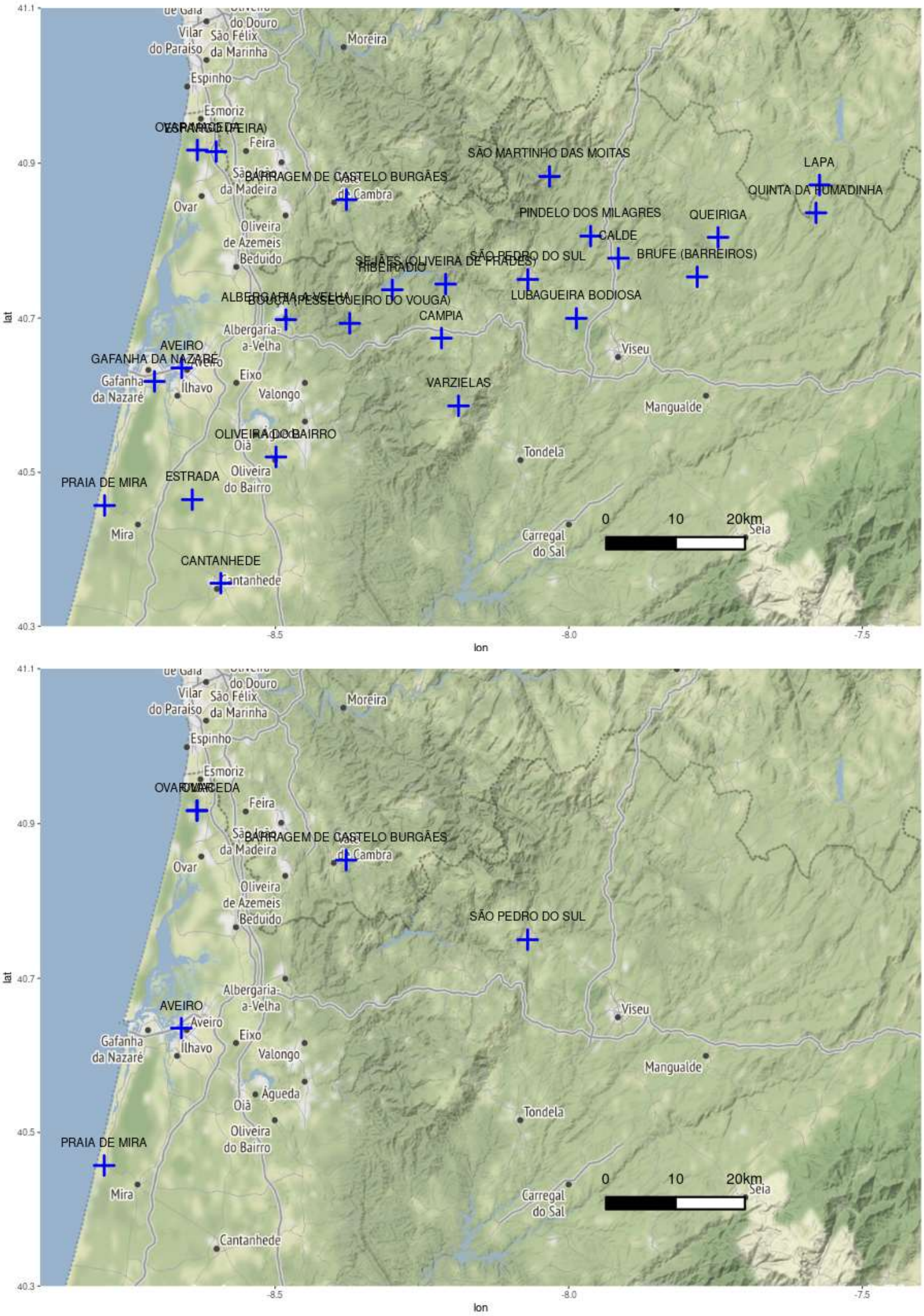


Figure 19 - Location of all the IPMA weather observations in the area considered. Precipitation observations belong to the upper image; temperature to the bottom one.

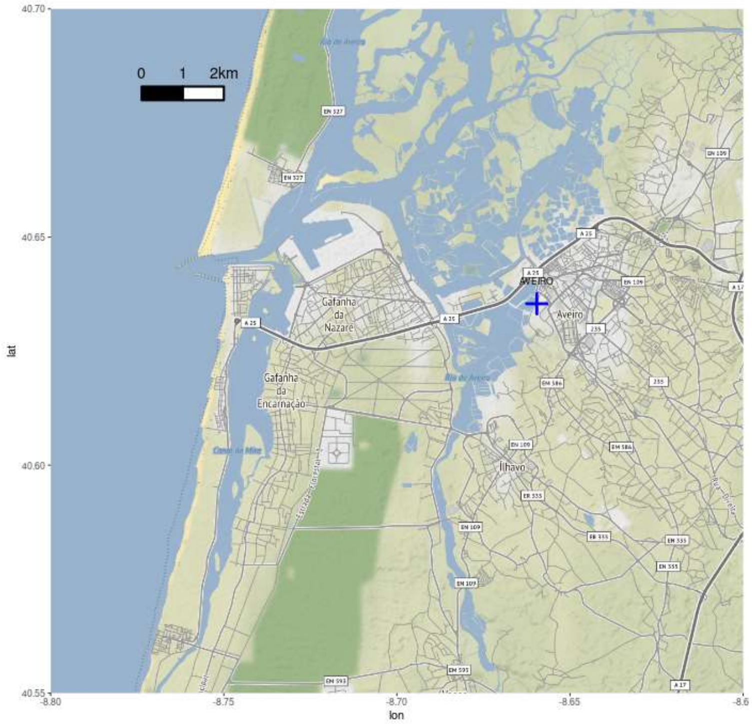


Figure 20 - Location of the IPMA meteorological station in Aveiro

- *Puertos del Estado (PdE)*, the national institute from Spain for the meteorological forecasting of the seas, has an initiative, SIMAR, in which a large grid of points for the Mediterranean and the Atlantic seas are simulated for trying to simulate the wind at that point. One of these points (id 1045063, used here as **SIMAR AVEIRO**) is near Aveiro (Figure 21), so it can be used as values inside the Atlantic Ocean but close to the shore. The data are mean daily values. It needs to be mentioned that, after a homogeneity test of the data series, a change of trend was observed in the year 2005 (maybe due to some update in the simulation processes of PdE), so **the series was split into two: 1045063A (1958-2005) and 1045063B (2005-2020)**, to be analysed separately.

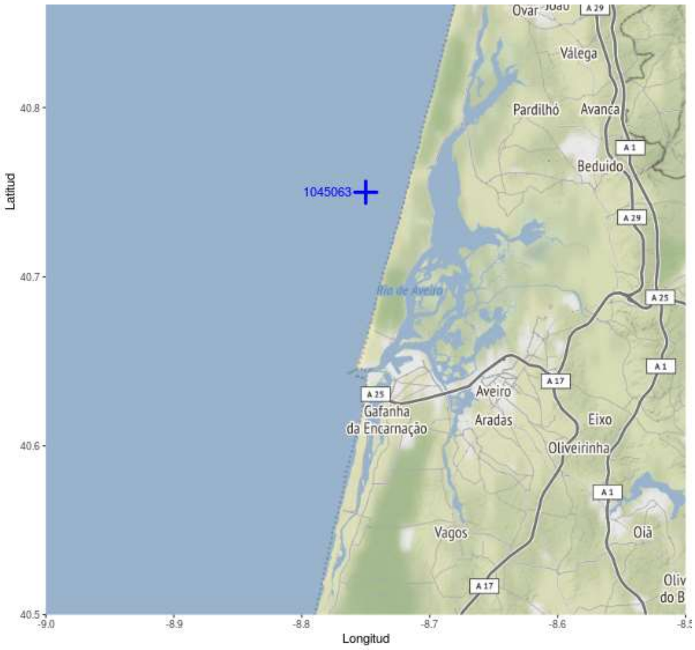


Figure 21- Location of the SIMAR meteorological simulation point near Aveiro.

3.7 Wind

3.7.1 Study of the wind under climate change

Wind is one of the most difficult meteorological variables to be studied when dealing with future climate change variations. Due to its own nature, a result of multiple factors such as orography, local thermal variations, pressure gradients, or other weather phenomena, the future study of wind is not as straightforward as temperature could be, and future changes in pressure centers and other atmospheric patterns that determine wind's strength and direction is still today prone to high uncertainties.

Nevertheless, the statistical downscaling that has been performed here (FICLIMA method, *Ribalaygua et al., 2013*) allows a much finer scale analyses, considering local variations of wind already registered in weather observations, and thus obtaining more trustworthy future projections. It is still good advice to take into account the aforementioned difficulty to work with the wind when interpreting the next results.

3.7.2 Conclusions for mean daily wind

The figures obtained to depict the results (Figure 22) show two future plumes, one per each RCP. They represent the confidence interval (quantiles 10th and 90th) to show the uncertainty obtained by plotting the results of the 10 used models, while the thick line represents the median. Black shadowed area stands for Historical values, set at 0 in present days to better assess future changes.

Conclusions for mean daily wind under climate change scenarios show **no appreciable changes** in the daily wind under any scenario. The median of the simulations for the 10 used climate models (the thick line) shows small oscillations around 0 and the confidence intervals (the shadowed areas) also show small oscillations. The conclusion thus is that there are not going to be significant changes in the mean daily wind under the two studied climate change scenarios.

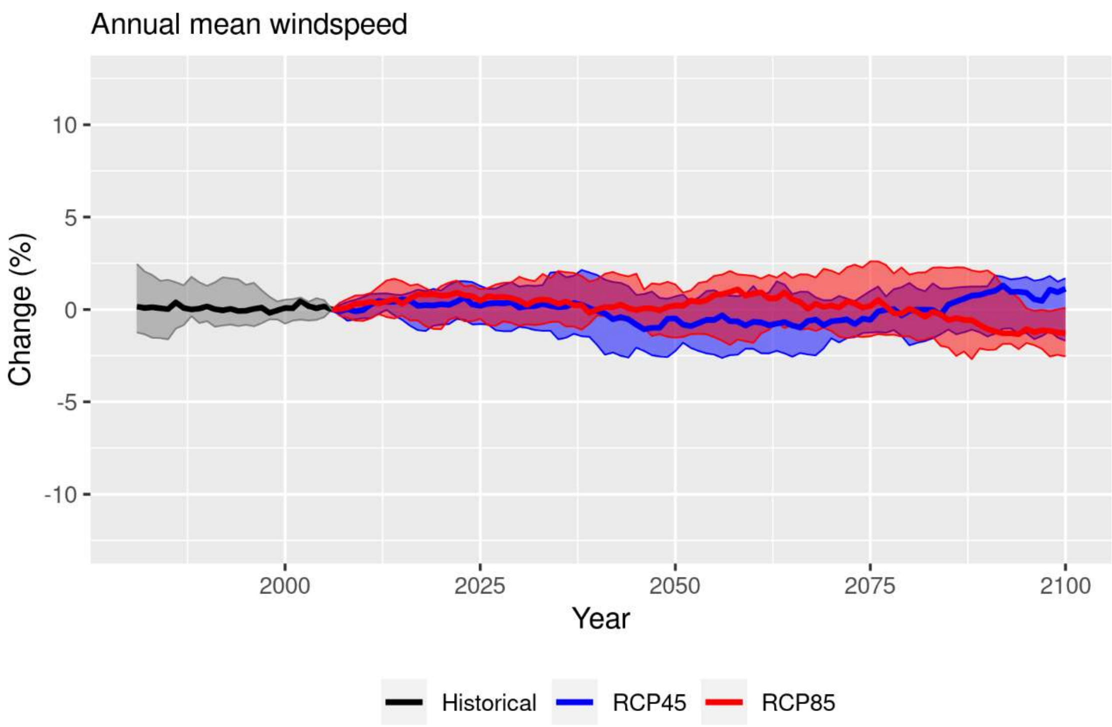


Figure 22 – Future relative change in percentage of mean daily wind against the past

Table 14. Summary of results of Annual Mean Wind. Uncertainty range between brackets. Shaded boxes mean changes are significant.

	RCP 4.5			RCP 8.5		
	2016-2040	2041-2070	2071-2100	2016-2040	2041-2070	2071-2100
Port of Aveiro	0% (-2/+2.5)	-1% (-2/+1)	1% (-2/2)	0% (-1.5/+2)	0% (-2/2)	-2% (-2.5/0)

3.7.3 Conclusions for extreme winds - Mean wind

One of the key objectives of this work is to study the possible changes in operational thresholds that affect the normal operation of the Port of Aveiro. As these thresholds are provided from real observed situations, they probably are associated with wind gusts and not with mean daily values, which are the values measured in the case of the Port of Aveiro. That's why a double approach to the thresholds has been made:

1. Taking identified thresholds as static values. The identified operational thresholds will be used as limiting values, with a quantile (in the climatic distribution) associated, checking if this quantile of the data to which they belong has any significant changes. Thus, if 55,5 km/h is currently in the 70th quantile and in the future in the 60th quantile, this wind value will become more frequent, but if it is in the 80th quantile it will be less usual.
2. Using symmetrical reasoning. This is, not using a threshold as a starting point, but a set of Return Periods of extreme wind values, meaning that which wind value is associated with a certain Return Period can be checked, and how this value changes with future climate projections. As an example, if an associated wind of 100 km/h is estimated for a 20-year return period (the maximum expected wind that happens in a climate window of 20 years), if in the future the associated wind is 120 km/h it can be concluded that the extreme winds are going to be higher.

Knowing that the thresholds in the case of the Port of Aveiro are 28.8, 54.5, 55.5, and 74.1 km/h (Figure 23, Figure 24, and Figure 25 – the 55.5 km/h value has been omitted, as it is quite similar to the 54.5 km/h), it can be seen that (pay attention to the y-axis scale) **these thresholds won't suffer from remarkable variations** in their associated quantiles in the future (if so, small decreases in frequency could be produced by the end of the century for the 28.8 km/h value). It can be therefore concluded that, for this SIMAR point, there are **not going to be significant changes**. A summary of the results can be found in Table 15 after the next figures.

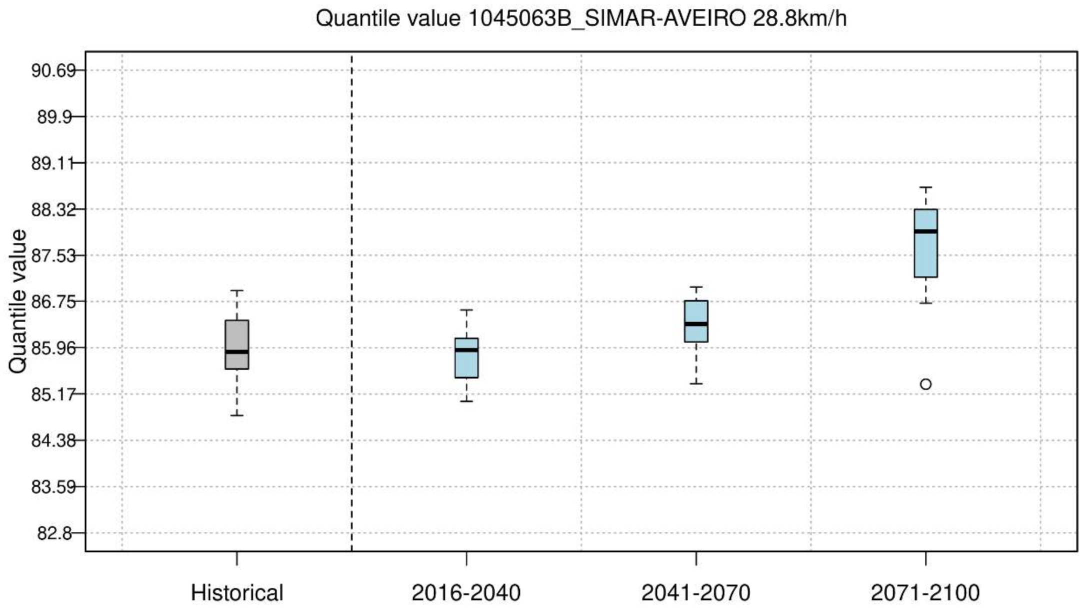


Figure 23 - For the SIMAR meteorological simulation point near Aveiro, changes in the quantile value associated with the 28,8 km/h threshold.

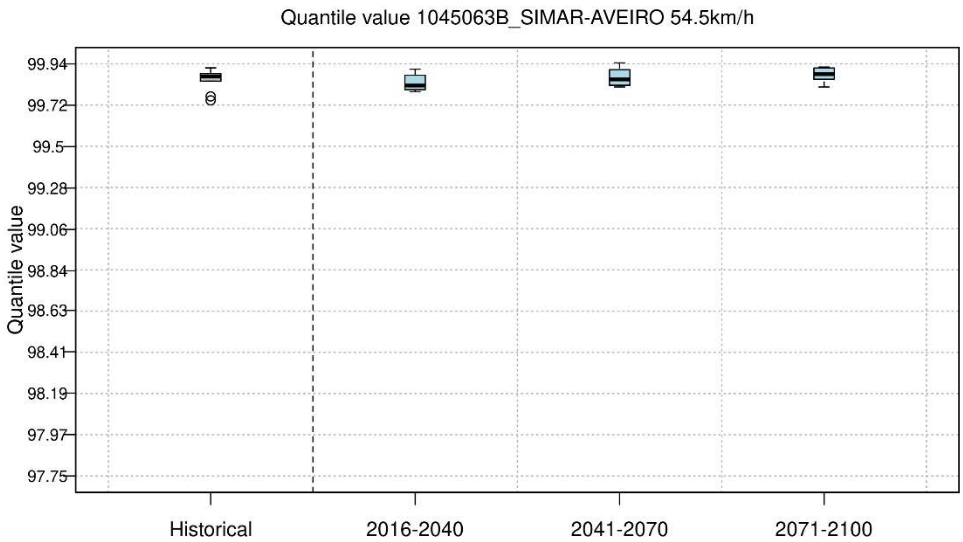


Figure 24 - For the SIMAR meteorological simulation point near Aveiro, changes in the quantile value associated with the 54,5 km/h threshold.

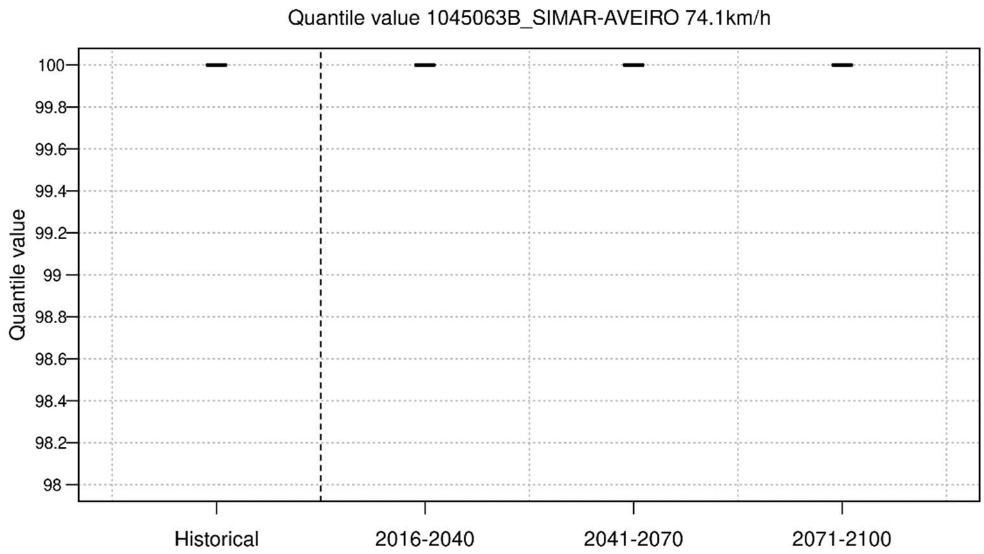


Figure 25 - For the SIMAR meteorological simulation point near Aveiro, changes in the quantile value associated with the 74,1 km/h threshold.

Table 15. Summary of results of Extreme Mean Wind, considering quantiles associated with identified thresholds. Shaded boxes mean changes are significant.

Quantile values	SIMAR-AVEIRO station (idem for IPMA)			
	Historical	2016-2040	2041-2070	2071-2100
Median value for 28.8 km/h	85.90	85.96	86.40	88.00
Median value for 54.5 km/h	99.82	99.78	99.82	99.86
Median value for 74.1 km/h	99.99	99.99	99.99	99.99

Results obtained from the analysis of the changes in the thresholds under climate change for the **IPMA** meteorological station are statistically identical to those of the SIMAR station, and thus pictures are not shown. Changes in these thresholds are therefore **not significant**.

Moving now the results obtained for the other approach, the one working with Return Periods. Possible changes for the SIMAR meteorological simulation point are calculated considering 5, 20, and 100-year return period winds (Figure 26, Figure 27 and Figure 28). As it can be seen (as always, please pay special attention to the y-axis scale), the values associated with these return periods **don't have significant changes** in the future. The **same conclusion can be said for the IPMA** meteorological station (pictures therefore not shown): none of the associated values to the return periods has significant changes in the future.

The final conclusion is that neither the mean daily wind nor the extreme mean daily winds are going to have significant changes in the future.

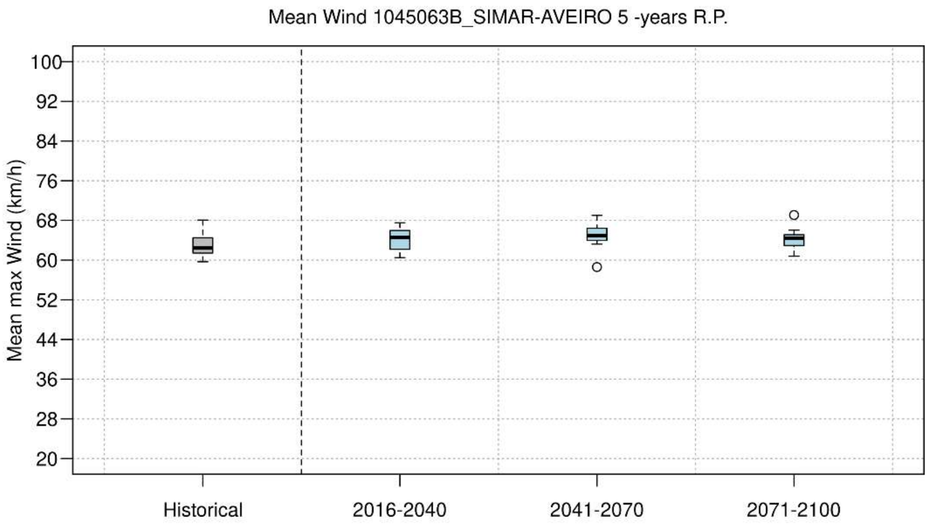


Figure 26 - For the SIMAR meteorological simulation point near Aveiro, changes in the value associated with a mean daily wind with a return period of 5 years.

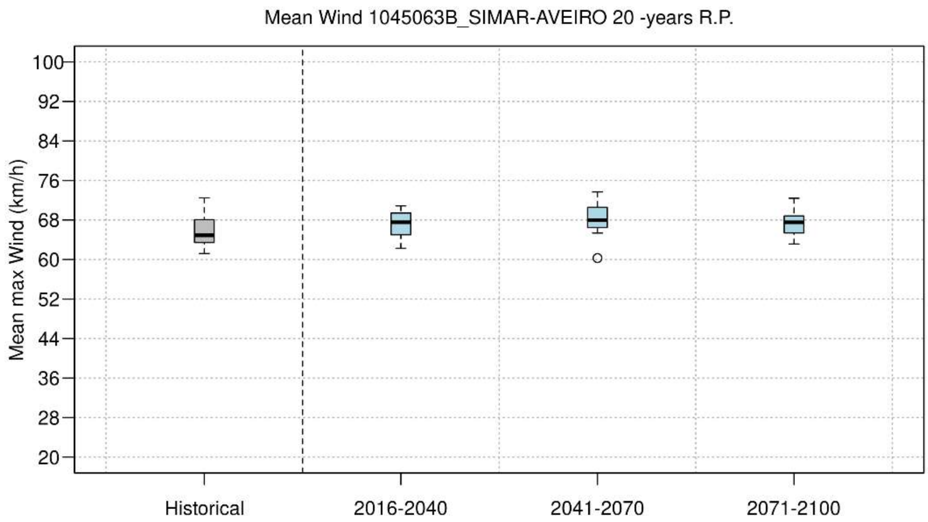


Figure 27 - For the SIMAR meteorological simulation point near Aveiro, changes in the value associated with a mean daily wind with a return period of 20 years.

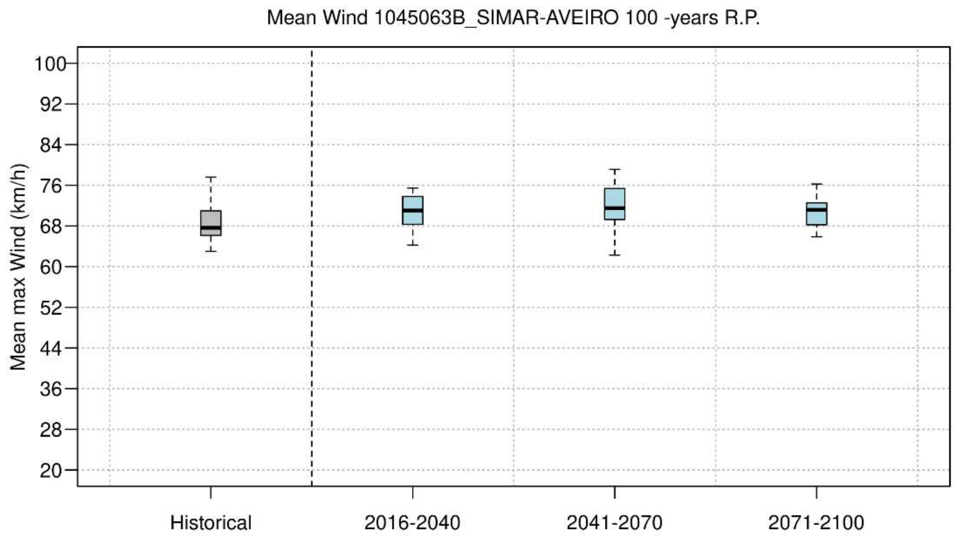


Figure 28 - For the SIMAR meteorological simulation point near Aveiro, changes in the value associated with a mean daily wind with a return period of 100 years.

Table 16. Summary of results of Extreme Mean Wind, considering variations in wind values associated with established Return Periods. Shaded boxes mean changes are significant.

Quantile values	SIMAR-AVEIRO station (idem for IPMA)			
	Historical	2016-2040	2041-2070	2071-2100
Median 5-y RP (km/h)	62	64	64	64
Median 20-y RP (km/h)	64	68	68	68
Median 100-y RP (km/h)	68	73	73	72

3.8 Visibility - Fog

It is very difficult to use climate change studies to try to study a variable such as visibility, which can be determined by multiple meteorological phenomena (fog, rain, haze, dust clouds, ...), all of them of great complexity. It is however identified as one of the main concerns for the Port of Aveiro. In this regard, it needs to be remarked that the presence of fog can be studied and projected (with limitations), but only its presence or appearance in this case, not its intensity. In other words, the number of foggy days can be projected, but this does not imply knowing for how long will this fog stay in the area or its thickness for limiting the visibility, since only mean daily values are available.

Following this point, fog's presence leads to the closure of the port, with the consequent economic impact. It is one of the concerns of the Port of Aveiro, as it is specified in DEL 3.3.1, with a restriction to the access of ships (longer than 135m) for visibility below 500m, and even closing road activities if falling under 200m.

In order to determine if on a specific day the visibility will be limited by the presence of fog, observed past historical days were studied and four meteorological variables were considered for simulating foggy days:

- wind, both in its zonal and meridional dimensions
- maximum temperature
- minimum temperature
- dewpoint temperature (as a proxy for relative humidity).

Since observed data of foggy days is not available as a measure, ERA5-Land data (a reanalysis of the past) will be used for simulating those days. The original ERA5-Land data of wind, maximum and minimum temperature, and dewpoint temperature has been used, then interpolated to the reanalysis grid, and then the number of foggy days has been calculated. Note that the daily interpolation would be computationally very time-consuming, so the foggy days were directly calculated for some thirty-year periods (Historical in the past and 2016-2040, 2041-2070, 2071-2100 in the future) and then the results interpolated.

This way the relative increase in the number of fog days can be obtained in each future period with respect to the historical one (Figure 29). Now, the 10th, 50th, and 90th percentiles are calculated to obtain the median value and a range of possible values to plot uncertainty. Before extracting any conclusion, note again that calculating the number of foggy days is very complex as it depends on different meteorological variables, which makes the results obtained not as trustworthy as those obtained directly by statistical downscaling (temperature, precipitation, wind). What this implies is that even if the results indicate a very strong signal (statistically significant), they should still be treated with great caution.

As can be seen in the figure of the results, and for any of the studied scenarios, there is no clear signal of increase or decrease in the median (the thick line) of the simulated data for every climate model, and the confidence intervals (the shadowed areas) cover both positive and negative values. Only by the end of the century did the medians show a slight decrease (especially for the RCP8.5 scenario), but the confidence intervals continue showing positive and negative values, which prevents from drawing a clear conclusion on changes in the number of foggy days.

So the final conclusion of this study for the visibility under climate change scenarios is that **any significant conclusions can be taken about the increase or decrease** in the number of foggy days. A summary of the results can be found in Table 17.

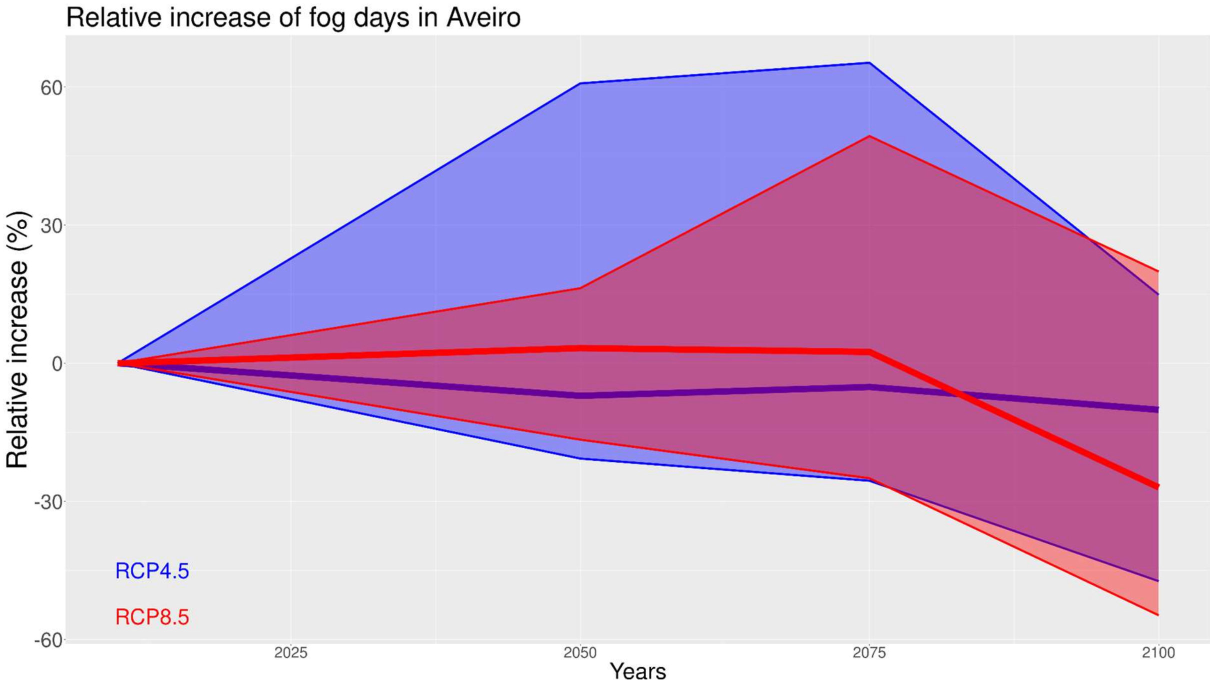


Figure 29 - Relative changes (in %) of foggy days in ***Aveiro****.*

Table 17. Summary of results of Annual Foggy days. Uncertainty range between brackets. Shaded boxes mean changes are significant.

	RCP 4.5			RCP 8.5		
	2016-2040	2041-2070	2071-2100	2016-2040	2041-2070	2071-2100
Gironde Estuary	-8% (-20/+60)	-5% (-25/+65)	-8% (-45/+20)	+3% (-15/+10)	+3% (-25/+50)	-30% (-55/+20)

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4. ANNEX

Variables not addressed in the main part of this document were also obtained for the case study of the Port of Aveiro, and can be found in this section. Following the advice from Aveiro stakeholders, and continuing with the calculation dynamic that has been followed for the other case studies, a different set of variables has been also projected into the future for Aveiro's case study. Despite these variables not being identified in DEL 3.3.1 as main concerns for Port of Aveiro, their calculations have been also produced and their results are added here as an annex. The idea of this is that they can be taken into account too and consider the added value that these results can suppose for other activities and future resilience measures in the Port of Aveiro.

4.1. Precipitation

Precipitation is a variable that is indeed mentioned in DEL 3.3.1 as a phenomenon affecting visibility in the port, but not considered interesting enough to be treated as the main concern. Nevertheless, since it was calculated, results for it are attached hereafter for their consideration. In this regard, even though rainfall is considered a limiting factor for visibility in other cases (Valencia, Bordeaux), the direct link between rainfall and visibility is not treated or calculated either here or in the other ports. So, to approach this topic, the future expected changes in extreme rainfall events have been calculated as these are directly related to downpours and a strong reduction of visibility in the areas of study.

The climate of the Port of Aveiro is an oceanic temperate climate (Köppen Cfb), marked by its situation in the western Atlantic shore of the Iberian Peninsula, where low pressures send frontal systems that enter the region, with most of the precipitation that falls in Aveiro all year round being linked to them. This type of precipitation in Aveiro is usually moderate, but can get quite intense thanks to its latitude, ocean temperature, and orographic forcing inland. Very active frontal systems can produce accumulations of more than 50 mm in one day, which also poses a risk to visibility at Port installations. Thunderstorm activity in Aveiro is quite sparse, mostly associated with embedded activity in the frontal systems; although in summer some heavy showers can reach the location from inland with cut-off lows situations.

Therefore, before going into detail about extreme rainfall events associated with certain return periods, the expected changes in the total annual rainfall of the Port of Aveiro have also been calculated, as well as the seasonal ones so as to get a better view of the future behavior of the precipitations in the area. For all these calculations, and to make results more coherent and robust, **all the stations in the area have been taken into account** to that way incorporate as much data as possible into these projections.

4.1.1 Annual and seasonal rainfall

First, an analysis of the results coming from annual rainfall will be done, followed by a more detailed one of the seasonal. The next figures show two future plumes, one per each RCP. They represent the confidence interval (quantiles 10^{th} and 90^{th}) to show the uncertainty obtained by plotting the results of the 10 used models, while the thick line represents the median. Black shadowed area stands for Historical values, set at 0 in present days to better assess future changes.

Analysing now annual future variations for the Port of Aveiro, annual rainfall expected changes **show no significant signal** (Figure 30). Both RCPs oscillate around 0% of change, with an uncertainty that grows until the year 2030, staying quite remarkable after that. However, these results belong to an annual scale, and there could be a strong difference between seasons that could explain this uncertainty. To have a better approach to what is expected in the future, seasonal results are discussed next.

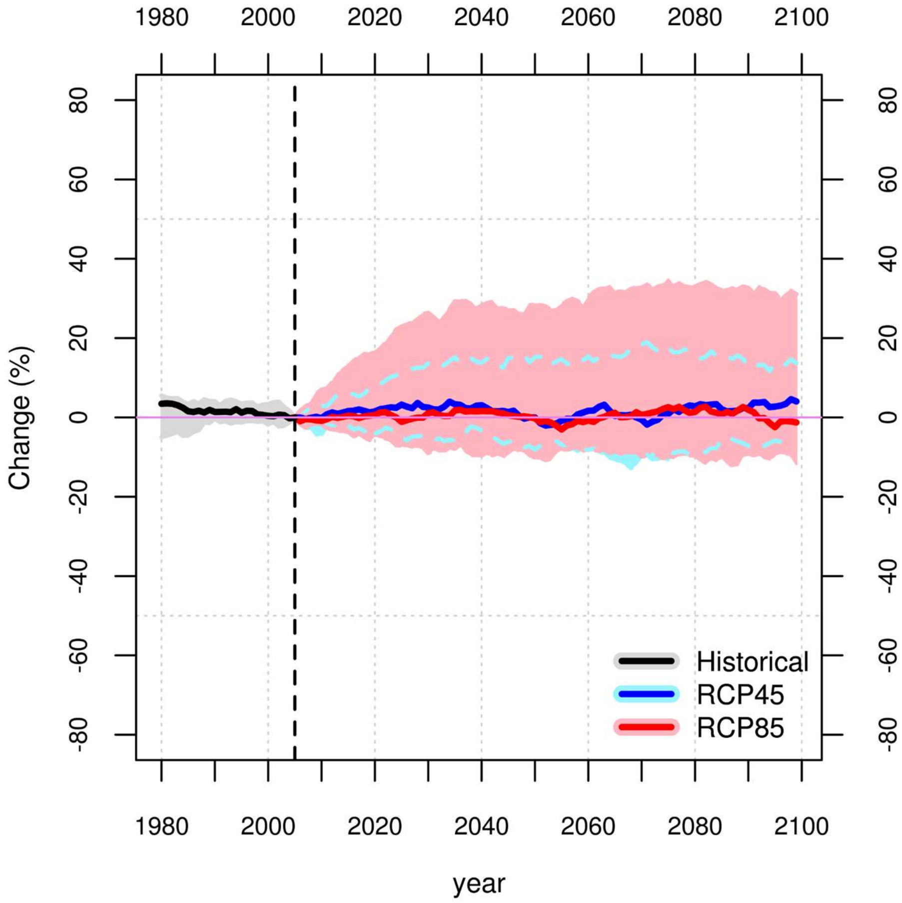

Figure 30- For the ***Port of Aveiro****, relative changes in the value of annual mean rainfall.*

Table 18. Summary of changes in Annual Mean Rainfall. Uncertainty range between brackets. Shaded boxes mean changes are significant.

	RCP 4.5			RCP 8.5		
	2016-2040	2041-2070	2071-2100	2016-2040	2041-2070	2071-2100
Port of Aveiro	+2 % (-5/+15	0% (-15/+20)	+5% (-5/+15)	+2% (-10/+25)	0% (-15/+30)	0% (-15/+30)

Checking now seasonal results (in Figure 31) it can be seen that the outcomes for Spring and Summer, although with great uncertainty (especially Summer), do not show any significant changes with respect to the historical baseline; medians from both RCPs practically stay stuck to the 0 line or their linked uncertainty grows to a point where it doesn't point to any trend whatsoever. In the case of **winter and autumn**, nevertheless, a signal can be seen, and for both cases, the **changes could be considered significant**. For winter, climate projections tend to simulate a small yet significant increase in the rainfall for that season, around +10% for the middle of the century, and up to +20% by the end of it. Uncertainty remains quite large for Winter, but all of it points towards increases. In the case of autumn, on the contrary, results point towards slight but significant reductions in the amounts of rainfall for the period, with results indicating a reduction of down to -15/20% for the rest of the century.

It could be therefore concluded, with enough significance, that future annual expected changes in rainfall are linked to big uncertainties associated with the probable changes, of contrary sign, of winter and autumn rainfall, while no significant changes are estimated in the rest of the seasons. This expected **increase in winter rainfall and decrease in autumn** could be linked to future changes in the atmospheric circulation, with Summer months lasting longer and a delay in the arrival of autumn precipitations, while in winter a change of low-pressure patterns plus warmer temperatures helping rain to be more efficient could lead to this projected increase. **This could produce a more frequent reduction of visibility in the port areas in the winter months.**

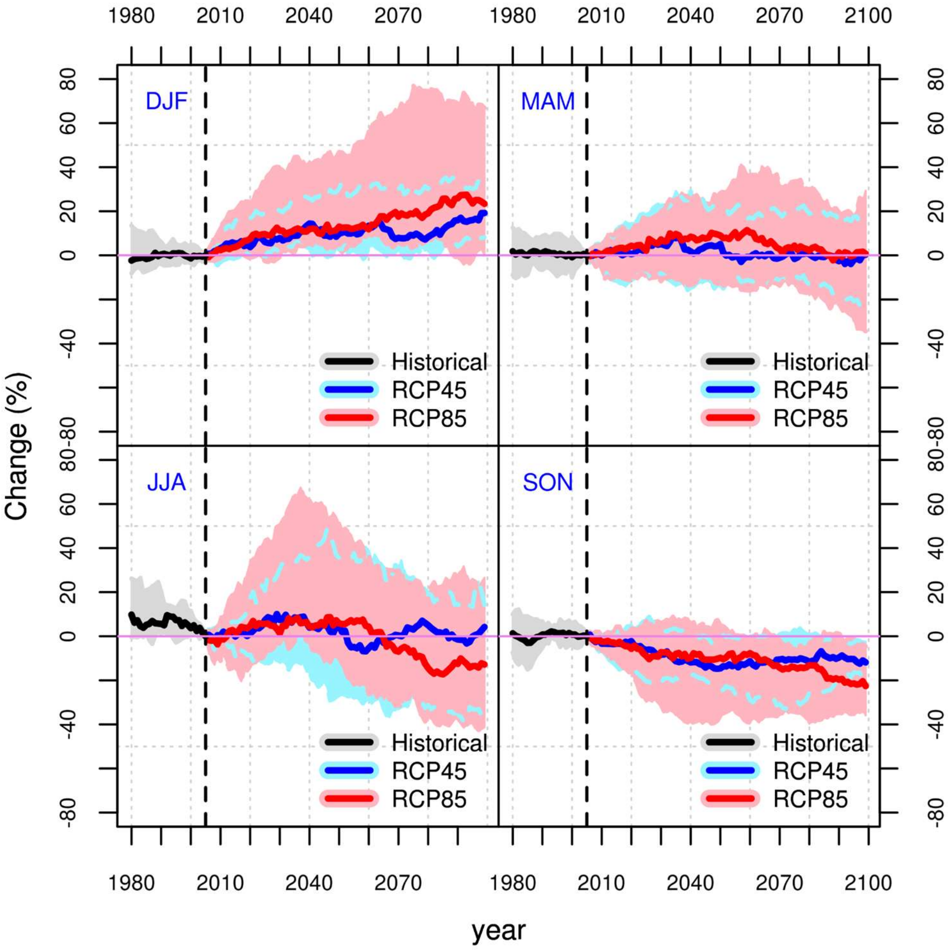

*Figure 31 - For the **Port of Aveiro**, relative changes in seasonal rainfall, considered for each season of the year starting from Winter (December-January-February).*

Table 19 - Summary of changes in Seasonal Mean Rainfall. Uncertainty range between brackets. Shaded boxes mean changes are significant.

	RCP 4.5			RCP 8.5		
	2016-2040	2041-2070	2071-2100	2016-2040	2041-2070	2071-2100
Port of Aveiro (winter)	+10% (0/+25)	+10% (0/+30)	+20% (+5/+30)	+10% (0/+40)	+20% (+5/+60)	+25% (0/+70)
Port of Aveiro (spring)	+5% (-15/+25)	0% (-10/+20)	0% (-20/+20)	+10% (-15/+20)	+10% (-15/+30)	0% (-35/+30)
Port of Aveiro (summer)	+10% (-10/+30)	0% (-40/+30)	0% (-40/+20)	+5% (-5/+60)	0% (-30/+30)	-10% (-40/+25)
Port of Aveiro (autumn)	-10% (-20/0)	-10% (-30/0)	-10% (-20/0)	-10% (-40/+10)	-10% (-40/0)	-20% (-35/0)

4.1.2 Extreme rainfall events

In this section will be tried to go a step further by not only sticking to the results of the previous section which, as was seen, studies the future behavior of total annual/seasonal mean rainfall, but diving deeper into the results of specific events of extreme rainfall. These are also of concern to the case study, occurring in spring/summer linked to the pass of thunderstorms or in winter to extremely active fronts, and by studying them it could be concluded if they could become more frequent or intense, and pose a higher risk to the port operability.

For this section, all stations have also been used, but now each one separately to try this way to identificate any possible particularity in the future behavior of extreme rainfall at each location. After checking the results, again the **IPMA** station at Aveiro is taken as the representative for the port area. Also, the same Return Periods (RP) for the obtention of results are taken: 5, 20, and 100-year, projecting them in three climatic future periods: 2016-2040, 2041-2070, and 2071-2100.

In the left part of the figures, it can be observed the historical values in gray, obtained with the corrected (with observations) historical simulations of each of the models used. In the right part in light blue, on the other hand, it can be checked the three simulated values for each of the time periods, again, obtained with the corrected models depicted with boxplots.

Results in this case of Port of Aveiro point to a **significant moderate increase in the expected rainfall associated with these extreme precipitation events** linked to the RPs studied. Taking a look at the plotted results for IPMA, it can be seen that for all the RPs used (5, 20, and 100-year), the increase is totally significant, with the median of each boxplot way above that of the historical baseline, as well as all the associated uncertainties (represented with the boxplot itself). This confirms that the increase signal is to be taken into account. Besides, the observed trend propagates with time, with greater rainfall expected amounts by the end of the century. Accumulated relative increases by the end of the century reach up to **25-40%** from baseline values for all RPs medians. These results are coherent with the future warmer scenarios where bigger water availability and energy in the atmosphere would increase the potential for heavier precipitation, both with thunderstorm summer events or persistent and extremely active winter frontal systems; thus **posing a greater risk for future visibility reduction** in the Port. A summary of the results can be found in Table 20.

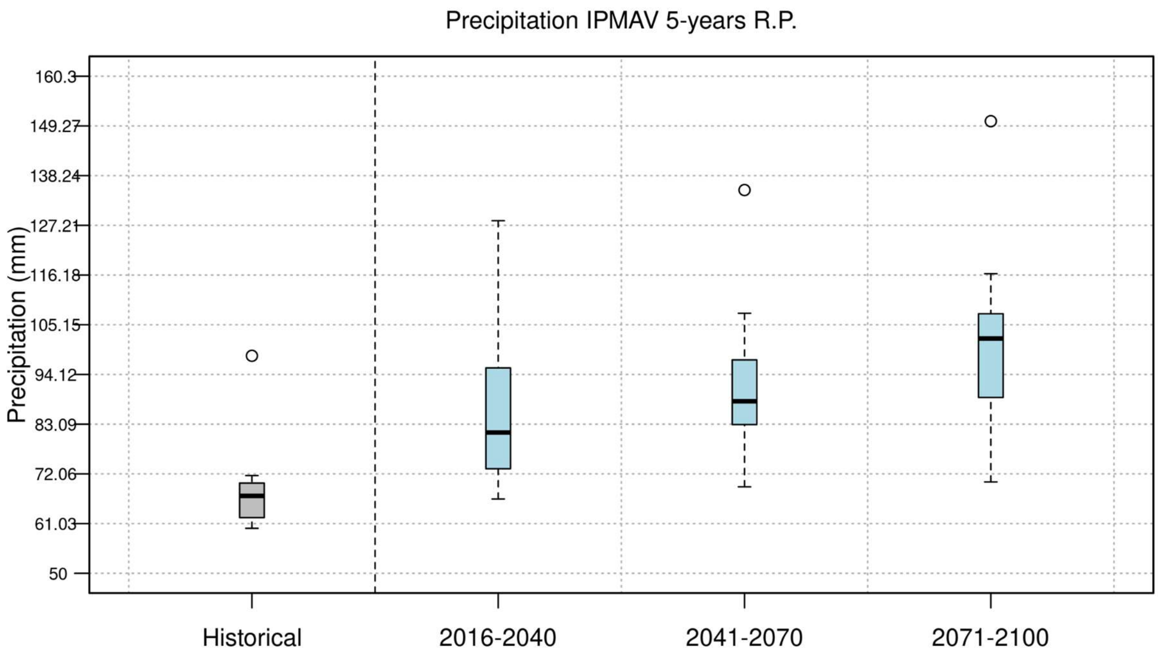

*Figure 32 - For the **Port of Aveiro**, changes in mm for the future values of the extreme rainfall events associated with a Return Period of 5 years.*

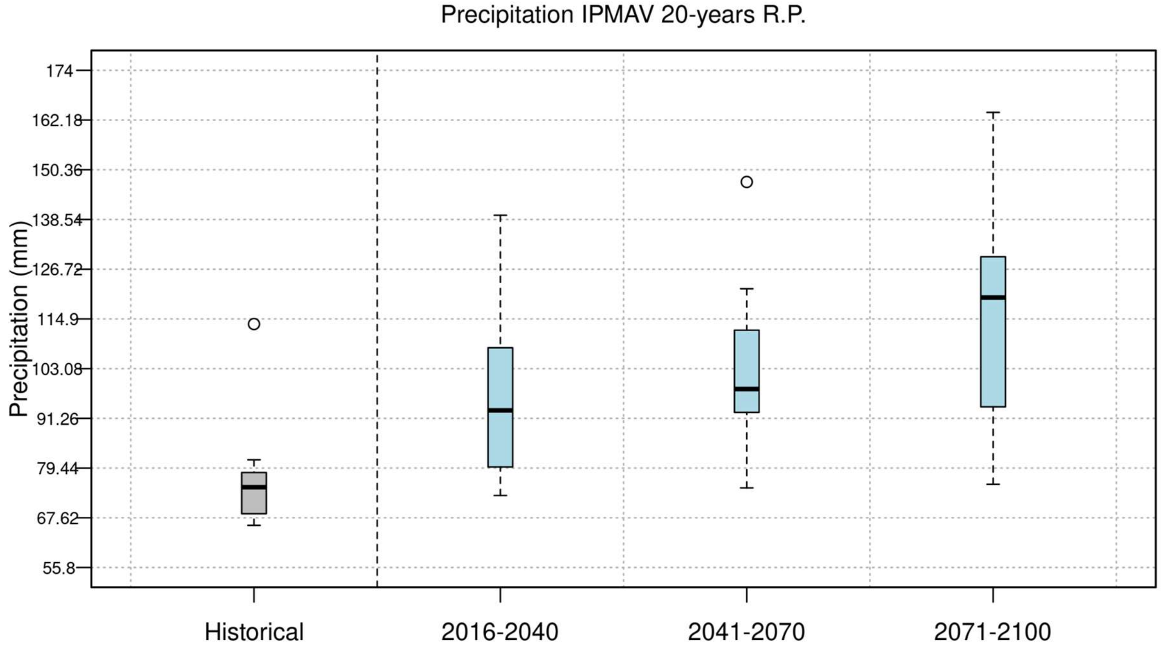

*Figure 33 - For the **Port of Aveiro**, changes in mm for the future values of the extreme rainfall events associated with a Return Period of 20 years.*

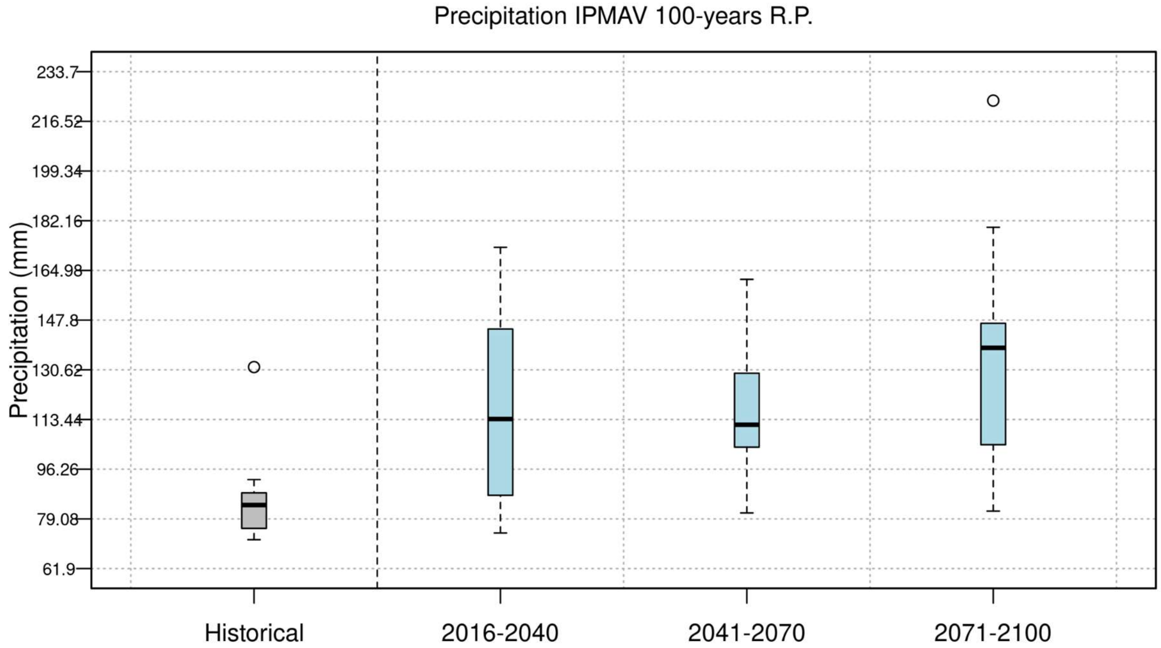

*Figure 34 - For the **Port of Aveiro**, changes in mm for the future values of the extreme rainfall events associated with a Return Period of 100 years.*

Table 20 - Summary of results of Extreme Rainfall, considering variations in rainfall values associated with established Return Periods. Shaded boxes mean changes are significant.

	IPMA - Port of Aveiro			
	Historical	2016-2040	2041-2070	2071-2100
Median 5-y RP (mm)	66	80	88	100
Median 20-y RP (mm)	75	92	95	120
Median 100-y RP (mm)	85	114	112	138

4.2. Temperature

The Aveiro District, in whose coastal region the Port of Aveiro is located, is bathed in all of its western shore by the Atlantic Ocean, and is under the regular influence of north and westerly winds associated with both sea breezes and with the general atmospheric circulation. This situation, especially with north winds in summer and the consequent coastal upwelling of cold waters, makes Aveiro temperatures to be usually quite mild throughout the year. However, sometimes this pattern is disrupted by the movement of the Azorian High, leading to the entrance of inland wind and the appearance of heat events. When this situation occurs in summer, wind arrives from the inner parts of the Iberian Peninsula, pushing hot air masses across the country and descending them to coastal heights, which produces a Föehn effect associated with extremely high temperatures and very dry air. If the wind is strong enough this effect can persist even on the shore itself, erasing local shore breezes, and keeping day and night temperatures way above normal values. The present warming climate conditions are already causing severe heatwaves to impact the region these past years.

To check future variations of temperature in Aveiro city, the expected changes in the annual mean temperature have been calculated, as well as the seasonal ones so as to get a better view of the future behavior of the temperature variations in the area and their possible linked impacts for each season. In this regard, considering the natural distribution and behavior of temperature in the region, it was analyzed the future expected evolution of temperature in the whole area (including all the stations gathered to make the basis more robust). The next figures show two future plumes, one per each RCP. They represent the confidence interval (quantiles 10^{th} and 90^{th}) to show the uncertainty obtained by plotting the results of the 10 used models, while the thick line represents the median. Black shadowed area stands for Historical values, set at 0 in present days to better assess future changes.

As can be seen in the next Figure 35, the expected changes (**increases**) in future mean values of Maximum Temperature in the whole region are **evident and significant**, with differences between RCPs, with increases for RCP 4.5 that would flatten by the end of the century up to +2ºC, but with higher changes for **RCP 8.5, where are remarkable, up to 3.5ºC.** It needs to be mentioned that nowadays RCP 4.5 is almost exceeded, so it would be by far the most "optimistic" scenario at the moment.

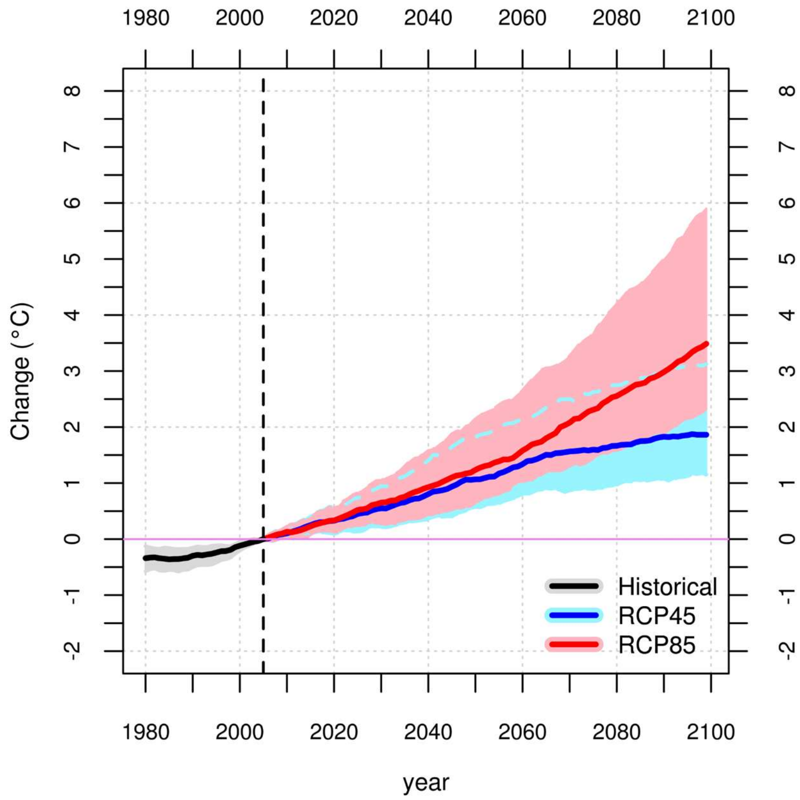

*Figure 35 - For **ALL STATIONS** (whole case study area), future expected change of Mean Annual Maximum Temperature for both RCP.*

Table 21 - Summary of changes in Annual Mean Temperature. Uncertainty range between brackets. Shaded boxes mean changes are significant.

	RCP 4.5			RCP 8.5		
	2016-2040	2041-2070	2071-2100	2016-2040	2041-2070	2071-2100
Port of Aveiro (° C)	+0.75 (+0.5/+1.25)	+1.75 (+1/+2.5)	+2 (+1/+3)	+1 (+0.75/+1.5)	+2 (+1.25/+4)	+3.5 (+2.5/+6)

Moving to the results at a **seasonal** scale (Figure 36), it can be observed that there is a difference from one season to another. Of course, following the previous result at an annual scale, all the expected future variations at the seasonal scale, as can be seen, are **increases**, but the magnitude of them differs from one to the other.

For the RCP 4.5, expected increases are smaller and quite similar, about +2°C by the end of the century for the whole area, except for winter where it would stay at +1°C. Again, RCP 4.5 is almost too optimistic nowadays, so it is better to focus on **RCP 8.5,** where the trends are quite strong, with uncertainty (spread) widening progressively with time, but still keeping a significant signal all the way. Results here show that increases for **spring, summer, and autumn go up to +3-3.5°C by the end of the century**, except for winter, with milder increases (+2.5°C). Summer results show the biggest uncertainty, with the **worst-case scenario reaching even +7.5°C**, probably due to an expected change in wind pattern that could make Atlantic influence disappear; this would pose a huge risk for nature and livelihoods in the area. A summary of the results can be found in the next table.

Table 22 - Summary of changes in Seasonal Mean Temperature. Uncertainty range between brackets. Shaded boxes mean changes are significant.

	RCP 4.5			RCP 8.5		
	2016-2040	2041-2070	2071-2100	2016-2040	2041-2070	2071-2100
Port of Aveiro (winter - °C)	+0.5 (+0/+1)	+1 (+0.5/+1.5)	+1.25 (+0.75/+2)	+0.5 (+0.25/+1)	+1.5 (+0.75/+2.25)	+2.5 (+1.75/+3.5)
Port of Aveiro (spring - °C)	+1 (+0.25/+1.5)	+1.75 (+1/+3)	+2.25 (+1.25/+3.5)	+1 (+0.5/+1.5)	+2 (+1.5/+4)	+3.75 (+2.5/+6)
Port of Aveiro (summer - °C)	+1 (+0.25/+2)	+1.5 (+0.5/+3)	+2 (+1/+4)	+1 (+0.25/+2)	+2.25 (+1.5/+4.5)	+3.5 (+2/+7.5)
Port of Aveiro (autumn - °C)	+1 (+0.5/+2)	+2 (+1/+3)	+2.25 (+1.5/+4)	+1 (+0.5/+2)	+2.5 (+1.75/+4)	+4 (+3/+6.5)

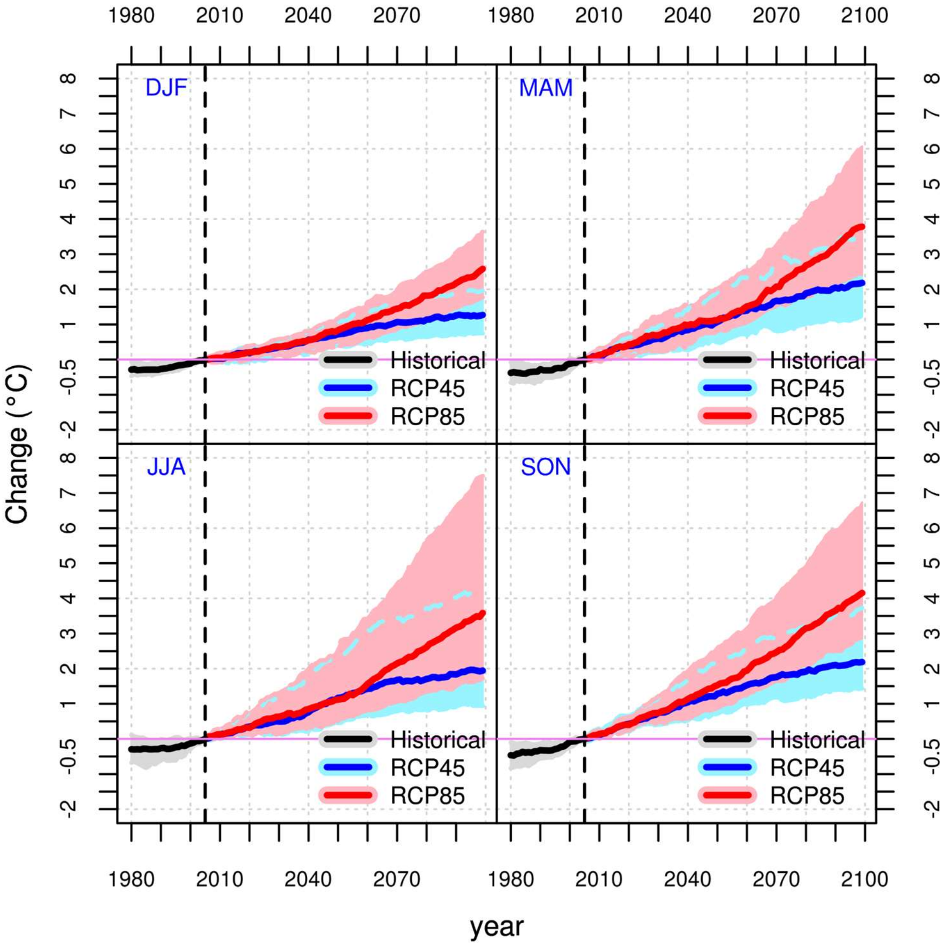

*Figure 36 - For **ALL STATIONS** (whole case study area), future expected change of Mean Seasonal Maximum Temperature for both RCP.*

4.1.3 Heatwaves

The previous results link that section with the next results in this one, which are all calculations obtained for heatwaves in the Port of Aveiro. The values that are about to be discussed for the Port of Aveiro concern two different properties of the heatwaves, used to characterize their behavior (intensity and length), and two other parameters characterizing heatwave presence in the climate (frequency and heatwave days):

- Intensity: described as the maximum (peak) temperature reached during the duration of the heatwave.
- Maximum length: number of consecutive days a heatwave could last.
- Frequency: number of heatwave events (depending on the description used) per year.
- Heatwave days: sum of the total number of days, non-consecutive (from all heatwave events), falling under the heatwave description

There are several descriptions for a heatwave event, having each country (depending on their climate and impact) a different one. In this case for the Port of Aveiro, the following description has been made to try to suit what's been looked for in this project:

1. **FIC heatwave description.** With the objective of having a heatwave description that could really match the extreme temperature situations that ECCLIPSE seeks to tackle, and identified in DEL 3.3.1, an ad-hoc heatwave description was created. This description, defined as "FIC", merges other descriptions like WMO or AEMet and adds extra value considering that extreme temperature situation posing a risk for operating occur mainly in summer. Therefore, this description for FIC heatwave would be: *a heatwave is considered to happen whenever at least three consecutive days register maximum temperatures above percentile 95% of its maximum temperature data series for the months of April to September of the 1976-2005 period"*. This description has the benefit that it forces temperature values to be among the highest possible for a heatwave to appear. Therefore, FIC heatwaves only happen for extreme situations, and mostly occur around the summer months, posing thus its appearance as a true risk and hazard for outside activities and health

In brief, all results point towards an **extremer future scenario where temperatures under a strong warming scenario would reach values unprecedented**, and heatwaves would turn into a phenomenon of extreme impact in the region considering their projected significative increases in all its characteristics. Following now with more detailed results for each of the variables studied. <u>It is to be remarked that all changes and discussions from here on are always referred to heatwave values defined for the baseline period.</u> A summary of the results can be found at the end in Table 23.

- Starting with the discussion of results and heatwave properties, for the case of **Intensity** (Figure 37) it can be seen that both RCP show a scenario where the maximum temperature associated with the peak of a heatwave is meant to increase. RCP 4.5 show a softer increase, tending to flatline by the end of the century up to an increase of +2°C. **RCP 8.5, on the other hand, keeps rising until the end of the century up to +4°C in its median**, and with an uncertainty that increases with time but stays within fair values, which points out that results for this RCP are **completely significant**.

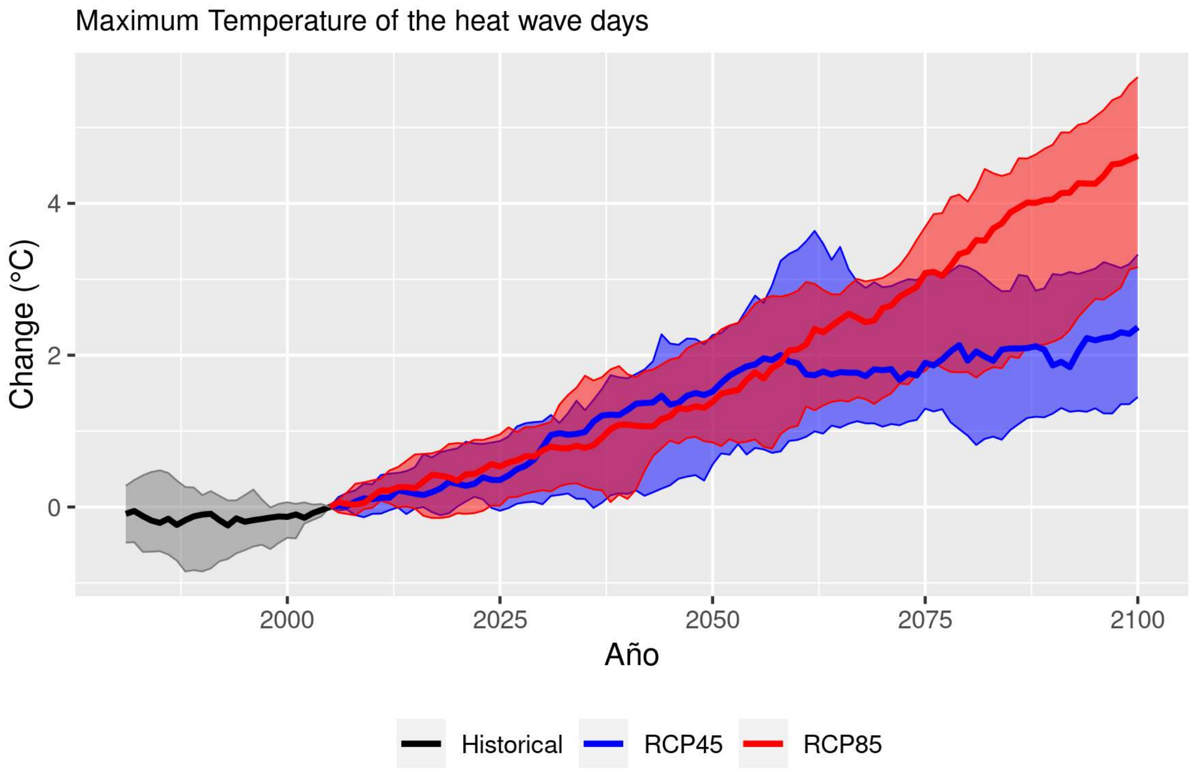

Figure 37 - For the ***Port of Aveiro****, changes in the Maximum Temperature values (or* ***Intensity****) expected for the days under a Heatwave with respect to present "normal" values.*

- Continuing with **maximum length** (Figure 38), its respective figure shows that values **will increase with time in a significant way**. For the historical period, the maximum length of a heatwave stays around 5 days, and until the year 2050 both RCP evolve in a similar way up to around 7 days. The expected notable change would come after this point, where RCP 4.5 goes up to a maximum length of around 10 days… but **RCP 8.5, although with great uncertainty, moves its median up to 15 days**, with the spread covering from +10 up to +30 in the worst-case scenario. **The increment signal is significant**. The median future value would suppose an **increment of 300%**, which considering that the "dog days" in this part of France last for about 40-50 days (nowadays), could suppose that by the end of the century **a single heatwave could cover even a third of the summer**.

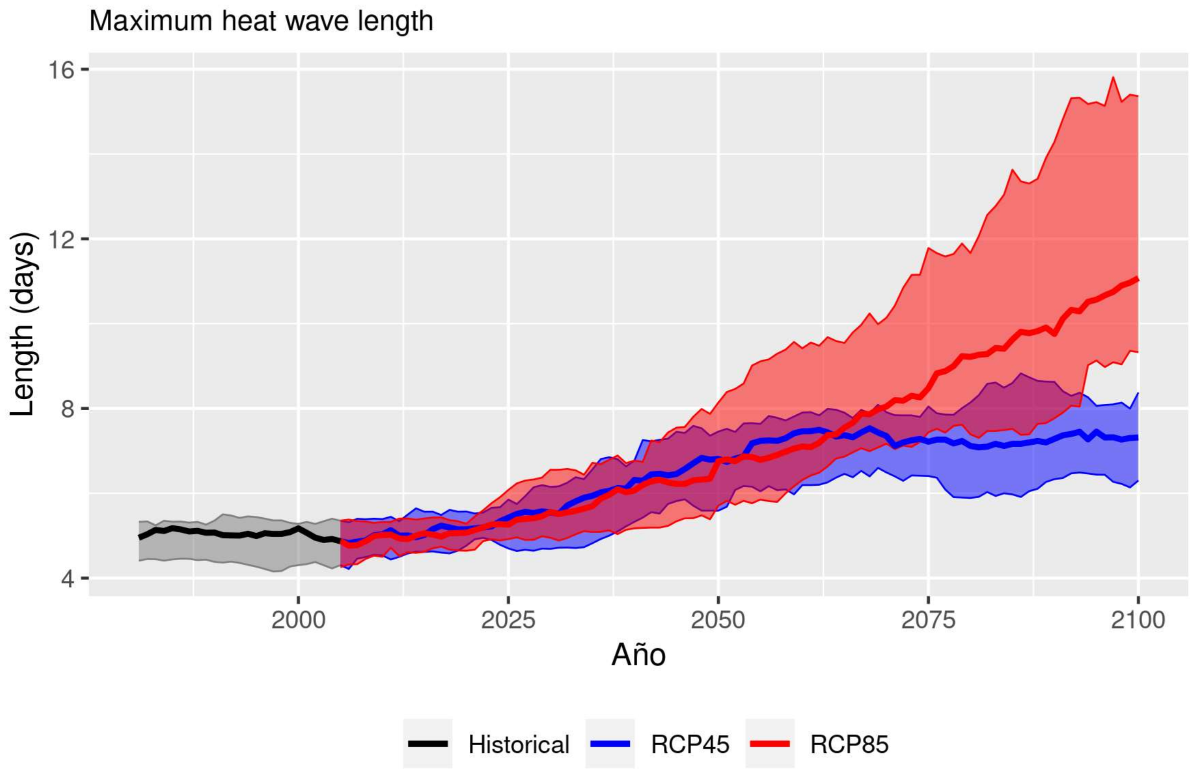

*Figure 38 - For the **Port of Aveiro**, mean number of days each Heatwave event may last in the future (**Length**).*

- Regarding heatwave variabilities in the climate, for **frequency,** there is not much difference between RCPs until the end of the century practically, which could be taken as proof of the already happening warming trend. Anyway, historical values show that normally there is around one heatwave per year, and both RCPs show a similar evolution until 2070, up to 3 heatwaves. From there, RCP 8.5 gets a greater increasing trend, rising up to more than 6 heatwaves per year (median value), with moderate uncertainty and significant signal. Therefore, **the increasing trend is clear and significant**, with future values **rising from 1 event to 5 to 7 events per summer**.

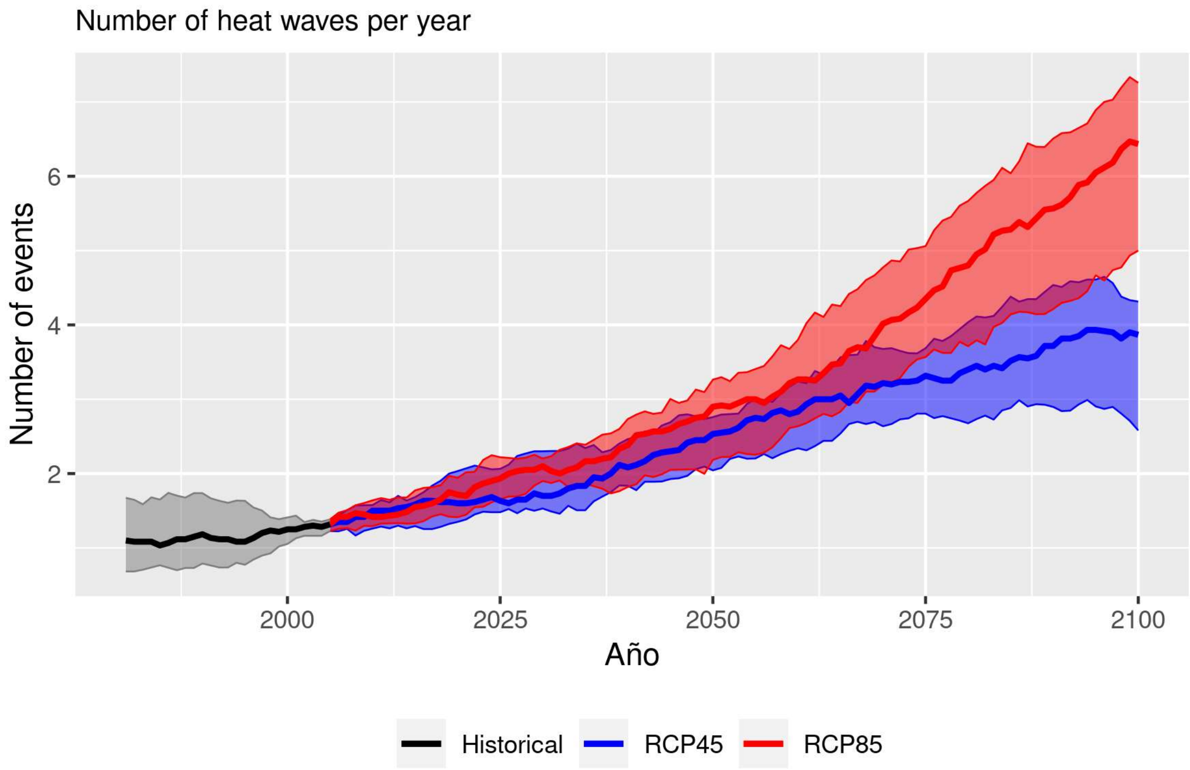

*Figure 39 - For the **Port of Aveiro**, number of Heatwave events (**Frequency**) expected for the future.*

- Last, for the **heatwave days**, this variable displays the total number of extreme temperature days, linked to heatwaves, that could happen throughout the year.. Historical values are placed around 5, and like in the other variables, until 2050 both RCP show a similar trend increasing up to 12-13, and then taking different paths. **RCP 8.5**, which corresponds to the worst-case scenario, rises **its median up to around 40 heatwave days, a massive and significant increase**, with the spread from models going from +25 up to +50.

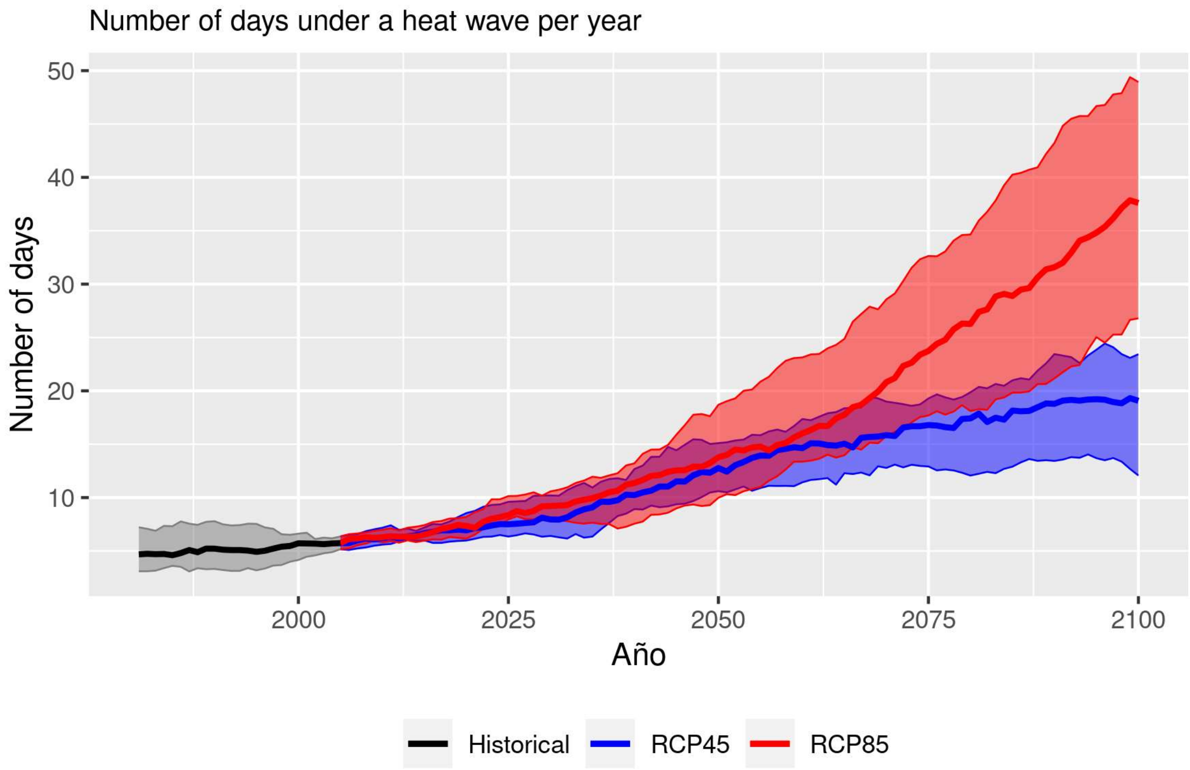

*Figure 40 - For the **Port of Aveiro**, number of total days (per year) under a heatwave event.*

*Table 23 - Summary of results of the changes in heatwave characteristics in the **Port of Aveiro**. Uncertainty range between brackets. Shaded boxes mean changes are significant.*

	Historical	RCP 4.5			RCP 8.5		
		2016-2040	2041-2070	2071-2100	2016-2040	2041-2070	2071-2100
Change in Intensity (°C)	31.5	+1.5 (+0.5/+2.2)	+1.8 (+1/+3)	+2.3 (+1.8/+3.2)	+1.3 (+1/+2)	+2.5 (+1.5/+3)	+4.5 (+3/+5.5)
Max. length (days)	5	6.5 (4.8/7.5)	7.7 (6.2/8)	7.5 (6/8.2)	6.5 (4.5/7.5)	8 (7.5/9)	11 (9.5/15.5)
Frequency (nº events)	1.2	2 (1.8/2.2)	3.2 (2.6/3.7)	4 (2.5/4.2)	2.2 (1.8/2.6)	4 (3.2/4.8)	6.5 (5/7.2)
Heatwave days	5	11 (9/30)	16 (13/19)	19 (12/24)	13 (8/32)	20 (15/27)	37 (27/49)