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Tool for the regionalization of climate change in SUDOE coastal-port environments

T3.3 Adjustment of the method to the requirements of climate change impact models

Deliverable – E 3.3.1

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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 addresses the activities carried out in the WP3, with the objectives of to develop and implement a methodology to identify and evaluate the impacts of future changing of meteocean processes on ports using the tree ports selected in the project as pilot tests for the developed methodology.

This deliverable particularly addresses the activities carried out in the task T3.3, which is built on the analysis carried out in the previous tasks (T3.1 and T3.2) with the goal of present a methodology to identify and analyse the impacts of future changes of meteocean processes on ports.

This deliverable is structured in 8 chapters: Chapter 1 provides an introduction to the ECCLIPSE project and main objectives. Chapter 2 covers the scope and motivation of this deliverable. Chapter 3 summarizes the results of the previous task with a description of the climate information needs and types of problems likely to be affected by climate change. Chapter 4 present how to generate information regarding the present conditions while Chapter 5 presents a similar analysis but addressing future projections. In Chapter 6 the present and future projections are compared whit the conclusions presented in Chapter 7. Additional information regarding future projections and scenarios are present in Annex.

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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

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

The scope and motivation of this deliverable is to describe a tool as sequence of steps to perform an evaluation of possible impacts of future climate on coastal-port environments. The sequence of steps to be presented here can be divided into the following:

1. Identify sensible assets and activities that can be impacted by metocean related processes; Example activities and assets are:
    a. Operation window
    b. Downtime
    c. Structural suitability
2. For each problem, the relevant metocean processes need to be identified, for instance:
    a. Operation window might be dependent on wave agitation and/or current.
3. Once the processes have been identified, it is important to determine the degree of complexity of the information needed to be analysed for each process. For this step, a strong background on the meteorological and hydrodynamics of the region under investigation is mandatory. For instance:
    a. Port of Aveiro has an operation window problem that occurs mainly due to the strong tidal currents generated near the estuary entrance. The peculiar geometries of the channels and the inter-tidal flats forces the use of high-resolution numerical modelling (yet depth integrated) to correctly represent tidal propagation into the estuary. So does the port of Bordeaux, which is characterised by the amplification of the tide/surge driven water level signal at the entrance of the estuary and whose water levels should be studied through the use of high-resolution numerical modelling (2D depth integrated for the maritime boundary conditions and 3D too inside the estuary).
    b. Waves are also relevant at port of Aveiro or at the mouth of the Gironde estuary (Le Verdon), however, due to its location waves are only relevant in open waters, on the ocean side, where regional (meso-scale) wave models would provide sufficient information.

4. Along with the definition of the degree of complexity of the information needed for the analysis of each process, the type of analysis also needs to be defined. That will vary according to the process itself and to the type of asset/activity it is impacting upon. For instance:
    a. Intense wave agitation causes downtime at port of Aveiro where a significant wave height threshold for operation exists where values above it would result in the stoppage of navigation. Based on that association it is possible to determine that the effects of waves (process) on the downtime (activity) can be analysed in terms of:
        i. Frequency of occurrence of events above threshold. In other words, how frequent are the waves above a pre-defined threshold?
        ii. Time scale (duration) of the events. Once the waves have reached a threshold, how long it stays above it? With respect to the future, are the storms stronger (higher waves) but shorter in duration? Or are the extreme waves smaller but the duration of events longer?
    b. While duration and frequency of occurrence is crucial for operation purpose, mean and extreme values tend to be significant for infrastructural purposes.
        i. Extreme wave analysis is crucial for the design of coastal structures, an increase on the expected extreme waves in the future due to climate change may result on changes in the design of new structures as well as an adaptation of the existing ones.

2.1 Spatial and temporal scales

The analysis design in item 4 (above) are to be considered for present conditions and future projections so their results would form the basis to drive conclusions about the future climate impact on coastal ports. Furthermore, the correct definition of spatial and temporal scales needs to be determined for each process and considered for both present and future projections. When considering numerical simulations, the specificities of the spatial scales are probably determined by the type of modelling approach defined, while the temporal scale would be more dependent on the type of process and how it is interpreted.

3 Climate Information Needs

3.1 Existing conditions

In the deliverable 2.4.1 the threshold limits associated to climate-related parameters have been established and divided into three main areas: **navigation, ports operation and infrastructure design.** For each port, the process of classifying the problems and thresholds was based on:

- Identification of critical asset, operations or systems.
- historical impact of extreme weather events.
- identification of the climate risk thresholds that entail a risk to the exposed vulnerable elements of the ports.
- Definition of the specific indicators (based on frequency and intensity) of exceedance of the thresholds.

A summary to the classification made in the previous report is presented below:

3.2 Restrictions to navigation

3.2.1 Port of Aveiro

At Port of Aveiro the key impacts to navigation are related to regions close to the inlet where entry and exit manoeuvres are limited by:

- Current:
    - 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:
        - Above 1 knot for ships over 150 m length and 9.0 m draft.
        - Above 4 Knot for ships over 135 m length and 7.5 m draft.
    - **Processing: evaluate the navigation windows available with currents below 1 knot, based on high resolution modelling for the navigation channel**
- Waves:
    - 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 H_s above 4 meters pilots do not board vessels at sea.
    - **Processing: Basic wave statistics and evaluate events where Hs exceeds 4 m, their duration and frequency.**
- Wind:

  - Strong winds also affect ship's entrance and exit. The Port adopts two thresholds:
    - 30 knots for vessels larger than 135 meters.
    - 40 knots for all vessels.
  - **Processing: Basic wind statistics and evaluate events where wind exceeds 30 and 40 knots, their duration and frequency.**
- Low visibility:
    - Visibility shorter than 500 m restricts the entrance of ships longer than 135 meters.
  - **Processing: evaluate events (duration and frequency) where visibility is lower than 500m, using a visibility proxy (difference between air temperature and dew point).**
- Dredging operation:
    - Restricts navigation for 290 hours every year.
  - **Despite the evolution of sediment transport modelling of the past decades, the state of the art of coastal morphodynamics modelling has not reached the stage of representing satisfactory long term 2D sediment transport. Furthermore, such analysis if carried out would demand extensive high-resolution numerical modelling which is out of reach of the project.**

3.2.2 Port of Bordeaux

At Port of Bordeaux the key impacts to navigation are respectively related to regions close to the mouth of the Gironde estuary (Le Verdon), but also those located in the central part of the estuary (Pauillac and Blaye) and finally on the Garonne river (Ambès, Grattenica, Bassens and Bordeaux).

Although the closure of the port to navigation for climatic reasons is exceptional, climatic hazards have a real impact on nautical access conditions or even the shutdowns of the Bassens Terminal, on the Garonne river.

The navigation in terms of entry and exit manoeuvre is limited by the following climate conditions:

- Current:
  - The currents generated near the mouth of the estuary are mainly driven by tides and surge levels, themselves resulting from time-space dependent meteorological forcings such as wind and pressure fields. Near the port entrance currents are both generated by tides and surges together with the Garonne river flow at the upstream part of the Gironde estuary. The entry and exit manoeuvres of ships are hampered by the increased intensity of currents. Currents also interfere in docking and steering at the end of the flow and / or slack (reverse).
    - The current velocity threshold was established above 5 knots.

  - **Processing: evaluate the navigation windows available with currents below 5 knots, based on 3D high resolution modelling of hydrodynamics for the navigation channel**
- Waves:
  - The pilot's operation is affected by the wave height in open sea waters at the mouth of the Gironde estuary (Le Verdon). When the H_s is exceeding 3 m, pilots are taken aboard the ship by using a helicopter. However, this service is not fully available at any time.
    - During periods of H_s above 3 meters, pilots do not board vessels at sea.
  - **Processing: Basic wave statistics and evaluate events where Hs exceeds 3 m, their duration and frequency.**
- Wind:
  - The negative effect of winds at the Port of Bordeaux are not significant. However, the following wind thresholds were established:
    - Above 20 knots for vessels crossing the Jacques-Chaban-Delmas Bridge, mainly passengers traffic.
    - Above 30 knots the use of tugs is mandatory.
  - **Processing: Basic wind statistics and evaluate events where wind exceeds 20 and 30 knots, their duration and frequency.**
- Low visibility:
    - Visibility shorter than 1 000 m restricts the entrance of ships crossing Jacques-Chaban-Delmas and/or Stone Bridge.
  - **Processing: evaluate events (duration and frequency) where visibility is lower than 1000m, using a visibility proxy (difference between air temperature and dew point).**
- Dredging operation:
  - Limitations caused by dredging operation are relevant at the port of Bordeaux. The Port Authority eventually issues an authorization for upstream to thresholds (flow in Bordeaux > 300 m^3/s and dissolved oxygen > 0,5g /l, water temperature <25 °).
    - Restricted navigation for 7 000 hours corresponding to the main dredging operation to extract 9 million m^3 of sediment every year.
    - Similarly, as for the port of Aveiro, it is assessed that the 3D sediment transport is not mature enough and too costly to predict the morphodynamic evolution. It is rather proposed to select the salinity intrusion as a proxy of the location of the turbidity maximum and associated increase in dredging need. To achieve this goal, a 3D hydrodynamics numerical model is used fed by a storm surge numerical model and a tide model at the maritime boundary condition and a conceptual hydrological for the

prediction of discharges at the upstream part of the Dordogne and Garonne rivers.

3.2.3 Port Authority of Valencia

At the ports managed by the Port Authority of Valencia (Gandía, Sagunto and Valencia) the main restrictions are related to extreme weather events caused by wind and/or waves. Special restrictions apply to the bulk liquid traffics. The navigation is limited by the following climate conditions:

- Waves:
    - The seaports ports of Gandía, Sagunto and Valencia are strongly affected by the waves. The following thresholds have been stablished for each port.
        - Gandía: Above 4.5 m the port is closed to navigation.
        - Sagunto: Above 3.5 m the port is closed to navigation.
        - Valencia: Above 4.5 m the port is closed to navigation.

- Wind:
    - Strong winds also affect ship's entrance and exit, as well as the vessel manoeuvring inside the port. The Port Authority adopts the following wind speed threshold for the three ports:
        - Above 14 m/s (27.5 knots) the port is closed to navigation.
        - Above 9 m/s (17.7 knot) the port is closed to navigation for Q_{flex}, Q_{max} and spherical tank vessels.
        - Above 10 m/s (19.6 knot) the port is closed to navigation for vessels over 200 000 m^3 capacity.
- Low visibility:
    - The Port Authority adopts the following visibility threshold, mainly caused by fog, for the three ports:
        - Visibility shorter than 1 800 m the port is closed to navigation.

3.3 Operational Threshold

3.3.1 Port of Aveiro

At Port of Aveiro two parameters are identified as critical for operation the wind (intensity and direction) and visibility.

- Wind:
    - 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 (180° to 225°) or NNW (315° to 360°).

  - **Processing: Basic wind statistics and evaluate events where wind exceeds defined threshold, their duration and frequency.**
- Low visibility:
  - It may occur due to fog or heavy rainfall.
    - Visibility shorter than 200 m restricts road traffic operations.
  - **Processing: evaluate events (duration and frequency) where visibility is lower than 500m, using a visibility proxy (difference between air temperature and dew point).**

3.3.2 Port of Bordeaux

Port operations at the Grand Port Maritime of Bordeaux are limited or restricted depending on the traffic operated at the different terminals from the mouth of the Gironde estuary (Le Verdon) to Bordeaux, at the upstream part of the Garonne river (7 specialised terminals). The main climate variables that affect the port operations are wind speed, air and water temperature, low flowrates of the Garonne and Dordogne rivers and floods caused by the quay overtopping due to the rising tide in combination with storm surges. The road traffic is also limited by the reduction of visibility caused by fog and rainfall.

- Wind:
  - Load/unload and land operations limited by winds higher than 72 km/h in solid bulk and container terminals.
  - **Processing: Basic wind statistics and evaluation of events where wind exceeds defined threshold (72 km/h), both in duration and frequency.**
- Floods:
  - Overtopping affects load/unload and land operations by tide coefficient of 110 associated with surges of 20 cm to 40 cm.
  - Exception: Flooding only affects land operation in liquid bulk traffics (Blaye and Bassens).
  - **Processing: analysis of water levels statistics and evaluation of events where overtoppings occur in liquid bulk terminals both in frequency and duration, using surge levels and hydrodynamic numerical tools.**
- Low flow rates and resulting water temperatures
  - Water temperature < 25°, dissolved oxygen not lower than 5 mg/l during 5 days or not lower than 3 mq/l.
- Temperature/heat waves :
  - Land operations limited: 33°C – 40°C.
  - **Processing: Basic temperature statistics and evaluation of the events where temperatures are higher than 33°C both in frequency and duration.**
- Low visibility:
  - It may occur due to fog or heavy rainfall or fog.
    - Visibility shorter than 200 restricts road traffic operations.

    - **Processing: evaluate events (duration and frequency) where visibility is lower than 200m, using a visibility proxy (difference between air temperature and dew point).**

3.3.3 Port Authority of Valencia

The climate thresholds established for the port operation at the ports managed by the Port Authority of Valencia (Gandía, Sagunto and Valencia) are summarised below. Port operations are strongly affected by wind speed. The threshold varies between terminals depending on the traffic handled. Currently, the impact of port agitation is insignificant, however this phenomenon is expected to be greater in the future due to the effects of climate change. The temperature is expected to have a negative evolution, with an increase of heat waves and extreme temperatures, which affect the health of port workers and the efficiency of electrical devices, while increasing the energy consumption. The road traffic is also limited by the reduction of visibility caused by fog and rainfall.

- Wind:
    - Load/unload operation. The following thresholds apply by dedicated terminal:
        - Solid bulk: 5.5 m/s (19.8 km/h)
        - Liquid bulk: 16 m/s (57.6 km/h)
        - Container terminals: 20.8 m/s (75 km/h)
    - Land operation. The following thresholds apply by dedicated terminal:
        - Solid bulk: 9.7 m/s (35 km/h)
        - Liquid bulk: 25 m/s (90 km/h)
        - Container terminals: 20.8 m/s (75 km/h)
- Port agitation:
    - The theoretical thresholds are obtained from the guideline ROM 3.1. Recommendations for the Design and construction of Ports, Approach Channels and Harbour Basins, issued by Puertos del Estado:
        - Solid bulk: Agitation wave < 0.8 m
        - Liquid bulk: Agitation wave < 1m
        - Container: Agitation wave < 0.3 m
        - Passenger/ro-ro: Agitation wave < 0.3 m
- Temperature/heat waves:
    - Land operations limited: 33°C with a relative humidity of 30 %
- Low visibility
    - It may occur due to fog or heavy rainfall:
        - Visibility shorter than 200 m restricts road traffic operations.

3.4 Infrastructure's thresholds design

3.4.1 Port of Aveiro

The following are the main processes likely to impact port's infrastructures:

- Sea level increase:
    - impacts in low level dock structures
    - reducing rainwater drainage capacity in low land areas~
    - **Processing: Extreme events of sea level (including tide, meteorology and mean sea level)**
- Wave climate change leading to:
    - higher or more frequent damages in harbour protection structures
    - **Processing: Wave climate statistics and extreme event analysis**
- Change in sediment transport patterns resulting in decreased channel and inner waters depths:
    - leading to increase dredging requirements.
    - **Despite the evolution of sediment transport modelling presented of the past decades, the state of the art of coastal morphodynamics modelling has not reach the stage of representing satisfactory long term 2D sediment transport. Furthermore, such analysis if carried out would demand extensive high-resolution numerical modelling which is out of reach of the project.**

3.4.2 Port of Bordeaux

The climate-related hazards identified in Bordeaux port are:

- Flooding:
    - Depending on the predicted tide level, storm surges (which result from wind and pressure time/space dependent forcings) and river flows resulting on global water levels along the Gironde estuary (from the mouth of the estuary at Le Verdon to Bordeaux, on the Garonne river).
    - For the near, middle and far future, including the mean sea level rise
    - **Processing: statistical analysis of the global water levels quantiles (including tide, surge levels and mean sea level) corresponding to extreme events (including tide, meteorology and mean sea level) using 2D numerical modelling at Le Verdon and 3D numerical modelling inside the Gironde estuary towards Bordeaux, on the Garonne river.**
- Sedimentary dynamics modification:
    - Depending on the river flow, the turbidity maximum can be installed at Bordeaux (low flow) or closer to the mouth (high flow) and increase dredging requirements. Increase of water temperature may also constrain the release operation.

  - **Processing: 3D numerical hydrodynamic modelling inside the Gironde estuary towards Bordeaux, on the Garonne river to analyse the evolution of salinity.**
- Port agitation:
  - Agitation of the port waters due either to the penetration of the swell in the mouth of the Gironde or to wavelets. It appears that the most marked agitation is caused by wavelets, particularly by winds coming from the south-east, an origin which gives the wind a significant 'fetch' (of the order of 20 to 25 km). The measured heights of wavelets range between 0,50 m and 1,50 m while those of the swell are generally between 0,80 m and 1,00 m.
- Wind:
  - Wind action at Le Verdon-sur-Mer, located at the entrance of estuary, must be considered as a risk in cases where overstressing causes a moored vessel to break its ropes and collide with the quay, causing damage to fenders and bollards, including to the quay.
  - **Processing: basic wind statistics and evaluation of events where wind intensity exceeds a defined threshold together with a specific wind direction, both in duration and frequency.**

3.4.3 Port of Valencia

The climatic and maritime factors to be considered for their effects on the infrastructures of the ports of Valencia, Sagunto and Gandía are as follows:

- Sea level:
  - The following data refer to the project for the Northern Extension of the Port of Valencia in 2007, the latest one. Other previous works at the ports of Valencia, Sagunto and Gandía were calculated using empirical formulae, without laboratory tests and with less reliable oceanographic data and shorter series. The design parameters for the latest extension have been better adjusted and the breakwater blocks are smaller, leaving the other works on the safe side in terms of surges.
    The ROM for breakwater works recommends a return period of 457 years:

Table 1. Sea level considering astronomical tide and meteorological surge

	Astronomical tide	**Meteorological surge**	**Sea level**
Living equinoctial high tide	0.27 m (port zero)	0.73 m	0.27 + 0.73 = 1 m
Living equinoctial low tide	- 0.14 m (port zero)	- 0.45 m	- 0.14 – 0.45 = - 0.59 m

Source: Construction project of for the expansion of the Port of Valencia 2007. Annex Nr 3. Maritime Climate Study

The latter are the values that were used in the project as they are on the safety side. However, for the purpose of dimensioning the works it was considered that it is very conservative to consider that during the design storm (generally associated with low pressure fronts), an over-elevation of -0,45 m, associated with a high-pressure front with a return period equal to the design period (R = 475,5 m). Therefore, the minimum level of calculation is:

N_{min} (living equinoctial low tide) = -0,14 m (P.Z.)

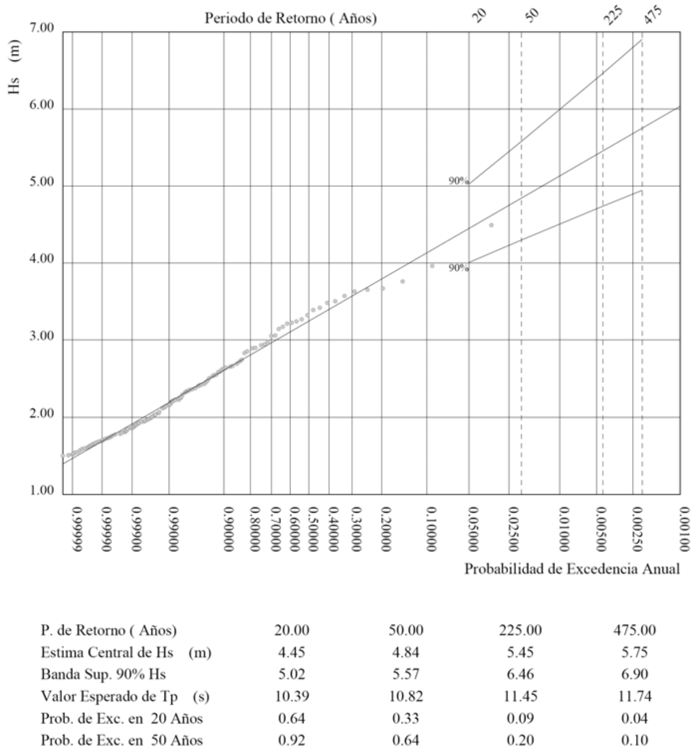
- Average swell regime:
    - The average regime is directly related to what are called mean operating conditions. Not all directions of the rose can affect study area. The range of directions is limited by the geometric configuration of the coast. Consequently, the only waves likely to affect the area are those from the NE, ENE and SE directions. The following table presents the swell characteristics used in the agitation study, which are those associated with an exceedance probability of 200 hours/year for each direction of interest (NE to SE). This value corresponds to the maximum inoperability interval recommended by ROM 3.1-99 for commercial ports.

Table 2. Average swell regime

Direction	Prob. Sector (%)	Hs (m)	Tp(s)
NE	12,68	3.10	8.8
ENE	16,38	3.11	8.9
E	12,75	2.42	7.9
ESE	11,22	1.64	6.8
SE	10,29	1.25	3.2

Source: Construction project of for the expansion of the Port of Valencia 2007. Annex Nr 3. Maritime Climate Study

- Extreme swell regime:
    - The following figure presents the scalar extremal regime of the Valencia buoy including both the central estimate and the 90% confidence band.



P. de Retorno (Años)	20.00	50.00	225.00	475.00
Estima Central de Hs (m)	4.45	4.84	5.45	5.75
Banda Sup. 90% Hs	5.02	5.57	6.46	6.90
Valor Esperado de Tp (s)	10.39	10.82	11.45	11.74
Prob. de Exc. en 20 Años	0.64	0.33	0.09	0.04
Prob. de Exc. en 50 Años	0.92	0.64	0.20	0.10

Figure 1. Extreme swell regime of the buoy of Valencia

Source: Construction project of for the expansion of the Port of Valencia 2007. Annex Nr 3. Maritime Climate Study

a return period of 475,06 years corresponds, according to the extreme graph of the Valencia buoy, to a design wave height Hs = 5,75 m in the central estimate and Hs = 6,90 m in the 90% confidence band.

For central estimation:

Table 3. Design wave heights. Return period R=475 years, central estimation.

Direction	**NE**	**ENE**	**E**	**ESE**	**SE**	**Máximum**
$H_{s,\ buoy}$	5,75 m	5,75 m	5,75 m	5,75 m	5,75 m	---
K_{a}	1,0	1,0	0,9	0,8	0,7	---
$H_{s,\ buoy,\ dir}$	5,75 m	5,75 m	5,18 m	4,60 m	4,03 m	5,75 m
$\mathbf{T_{p}}$	**11,8 s**	**11,8 s**	**11,2 s**	**10,6 s**	**10,0 s**	**11,8 s**
$K_{r,buoy}$	0,7637	0,7853	0,9525	0,9119	0,8749	---
$\mathbf{H_{s,0}}$	**7,53 m**	**7,32 m**	**5,43 m**	**5,04 m**	**4,60 m**	**7,53 m**

Source: Construction project of for the expansion of the Port of Valencia 2007. Annex Nr 3. Maritime Climate Study

For the 90% confidence band:

Table 4. Design wave heights. Return period R=475 years, 90% confidence band

Direction	NE	ENE	E	ESE	SE	Maximum
$H_{s, buoy}$	6,9 m	6,9 m	6,9 m	6,9 m	6,9 m	---
K_{a}	1,0	1,0	0,9	0,8	0,7	---
$H_{s, buoy, dir}$	6,9 m	6,9 m	6,21 m	5,52 m	4,83 m	6,90 m
T_{p}	**12,9 s**	**12,9 s**	**12,3 s**	**11,6 s**	**10,9 s**	**12,9 s**
$K_{r,buoy}$	0,7562	0,7725	0,9574	0,9060	0,8371	---
$H_{s,0}$	**9,12 m**	**8,93 m**	**6,49 m**	**6,09 m**	**5,77 m**	**9,12 m**

Source: Construction project of for the expansion of the Port of Valencia 2007. Annex Nr 3. Maritime Climate Study

4 Baseline Conditions

IPCC defines the Baseline as "(…) the state against which change is measured." A fair comparison of future climatic scenarios against the present state of environmental parameters depends on a correct characterisation of the climatological baseline.

To characterize the baseline of climatic parameters relevant to the coastal-port environment, adequate data is required. The issues to be considered when selecting the climatological baseline include the types of data needed (question addressed in the previous section), the length of the baseline period, the sources of data and how they can be compared consistently with the climate change scenarios.

The climatological information required for baseline analysis is defined in terms of:

- Climatic parameters: according to what is described in section 3 (Climate Information Needs) of this document, several meteorological and oceanographic parameters were selected that are relevant to the restrictions on navigation, port operations and infrastructure management.
- Spatial scale: together with the definition of the variables, the spatial scale at which the analysis is performed is also defined. Since the analysis of climate change is made, for example, in a calculation grid with 50 km of resolution, for a given parameter, the spatial scale of that parameter in the baseline must be representative of calculation cells with 50 km. This spatial representativeness must be assessed in a specific way for each parameter.
- Temporal resolution: As mentioned in the spatial scale, the temporal resolution of the parameters to be analysed must be consistent with the scale for which the climate changes forecast for the same parameter are analysed; being daily averages or monthly averages, they should be compared with the same types of values calculated for the baseline.
- Calculation period: The usual climatological reference period is a "normal" period of 30 years, as defined by the World Meteorological Organization (WMO). When values are not available for this period, these cases are specified.

4.1 Average Baseline Climate Information

A correct definition of baseline conditions is a crucial part of the analysis, therefore a clear connection between the processes and affected asset/activity needs to be determined previously and represented through the methodological analysis.

Based on the previous report (deliverable 2.4.1) summarized in the previous chapter, it is possible to infer that the most important issues foreseen by port operators are impacts on operability. In other words, how long will the port be inoperant (or partially operant) due to climate related processes? Since the impacts and types of processes may vary significantly, it is important to establish key relations between physical processes and related problems to correctly address its impacts.

1. Determine whether the associated metocean process can be classified as an event (e.g., heat wave, storm surge, waves generated by a large weather system) or are "permanent" changes as mean sea level or mean air temperature.
2. For event like processes, the next step is to determine what is an event. That may also vary according to the type of process and the reader should always refer to the literature to find suitable methodologies.
    a. Events can be determined by the upper and down crossing of a threshold (Figure 2).
3. Once events are characterized, what is their frequency of occurrence?
    a. How often do unfavourable events occur (thresholds exceedance frequency)?
4. Time scale of the events
    a. What is the time scale of the events? And what is the interval between them? Both in time of duration and interval of occurrence (Figure 2).

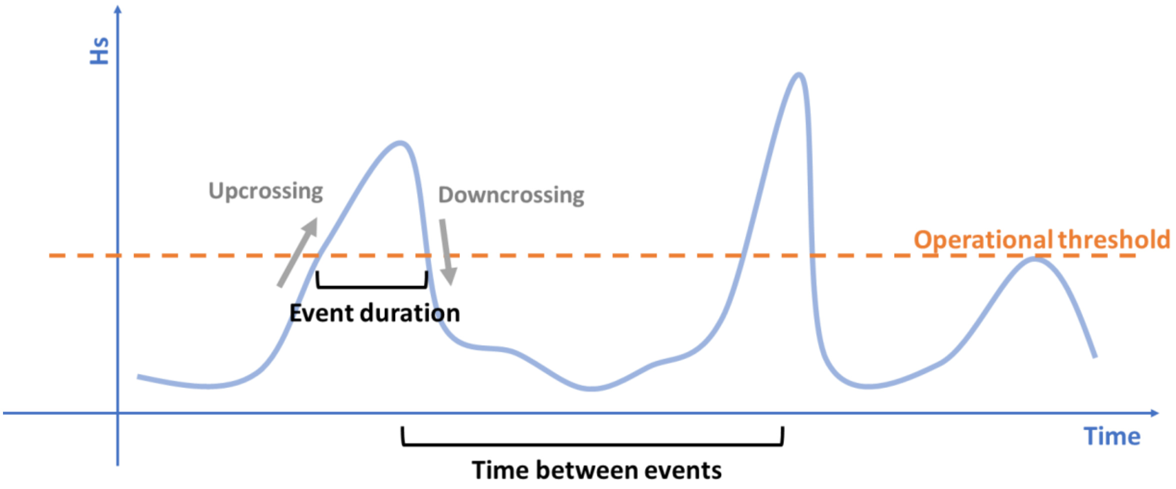


Figure 2: Schematic representation of wave events occurring above an operational threshold, where the event duration is determined by the up and down crossing of the threshold. Time between events defined by the interval between maxima.

While the above parameters are valid to most metocean parameters, each process may need additional parameters.

1. Coastal ports are often designed to protect their entrance to the most frequent and severe wave directions. Therefore, it is expected that changes in wave direction may also have significant impact on port's operability (Figure 3).

Figure 3: Hypothetical example of change in wave direction with respect to coastal ports structures

4.1.1 Example: Wave events above threshold in Port of Aveiro

To represent the current pattern of wave events at the coastal zone of Aveiro (Figure 4), 20 years of numerical results obtained from simulations computed using the ECMWF's Wave Model (SAW) are used (data available in https://cds.climate.copernicus.eu). The model is also used to reproduce two future climate scenarios RCP 4.5 and 8.5, further discussed below.

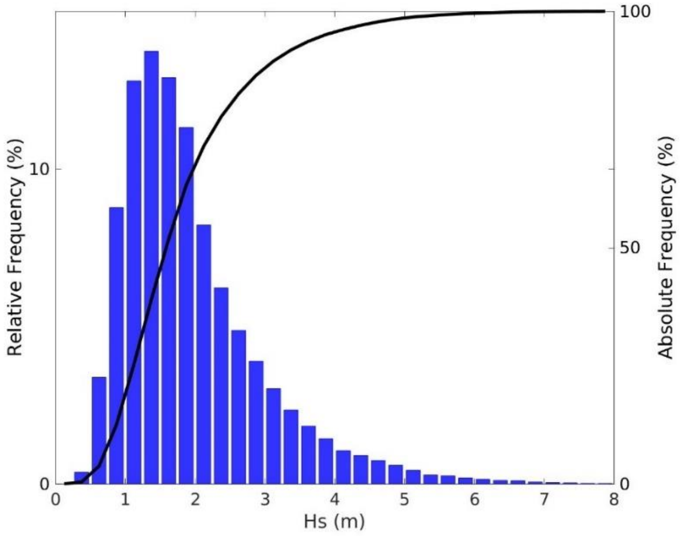


Figure 4: Significant Wave Height distribution historical/present dataset.

At Port of Aveiro navigation is ceased when waves reach Hs above 4 meters, by applying the threshold crossing methodology discussed previously each wave event and interval can be individualized (Figure 5) and its statistics analysed (see section).

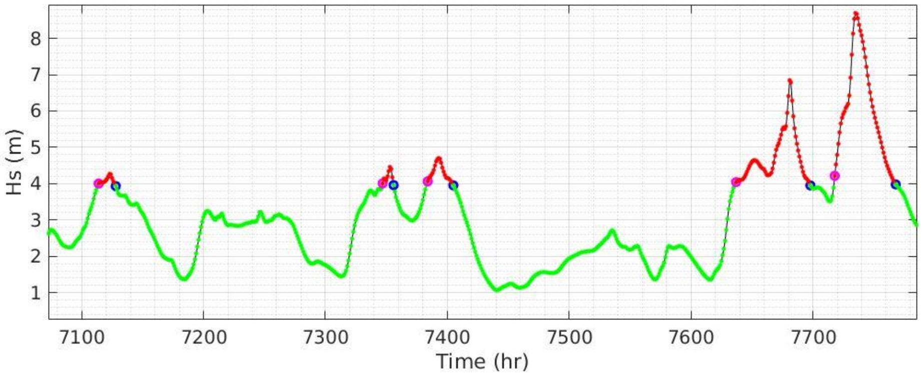


Figure 5: Time series of significant wave height highlighting events above threshold (red dots) and interval between events (green dots).

4.1.2 Example: Currents above threshold at Port of Aveiro

For coastal ports located inside estuaries with significant tidal prism currents at its entrance can create hazardous conditions posing risk to navigation. Port of Aveiro is an example where current velocities are the main metocean process affecting its operability. With the projected increase in mean sea level the tidal prism at Ria the Aveiro is likely to follow the same trend. As a result, an increase in the velocities at the entrance are expected to reduce the periods of operation (current velocities below 1 m/s).

Since mean sea level is not characterized as an event-like process the analysis differ from what is presented above. Instead of searching for intensity and frequency of occurrence of events, high-resolution hydrodynamic simulations were performed to evaluate the impact of the discrete increase in mean sea level. The results are interpreted in terms of duration of currents with intensities below operational limits as exemplified in Figure 6.

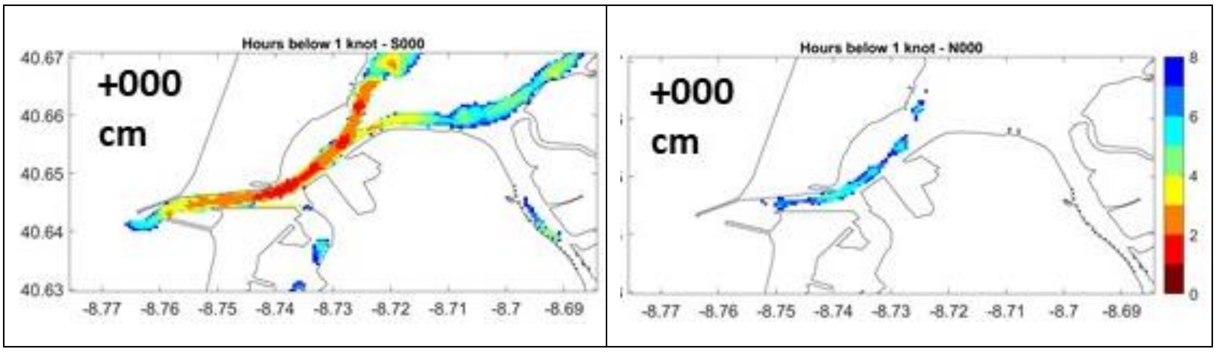


Figure 6: Number of hours with currents below threshold (1 knot) for spring tide (left) and neap tide (right) for the current mean sea level.

4.2 Baseline Extreme Events

While operational problems tend to be linked to the duration and frequency of occurrence of events, other areas such as infrastructure are strongly linked to extreme values. For those, processes are analysed in terms of likelihood of occurrence. For extreme events, a methodology called "Extreme Value Analysis" is often used and is based on a probabilistic distribution fitting of the extreme events. Different methodologies exist to determine what extreme events are and how to find the best distribution probabilities. The reader should refer to the most relevant literature such as FEMA (2016), Mathiesen et. al (1994).

4.2.1 Baseline Extreme Events: Water levels at Port of Aveiro

Figure 7 shows an example of the result of the Extreme Value Analysis applied to water levels at the coastal region of Aveiro. 38 years (1979 – 2017) of total water level (tide + storm surge) extracted from ERA5 reanalysis where the Peaks Over Threshold methodology was applied for event and peak selection.

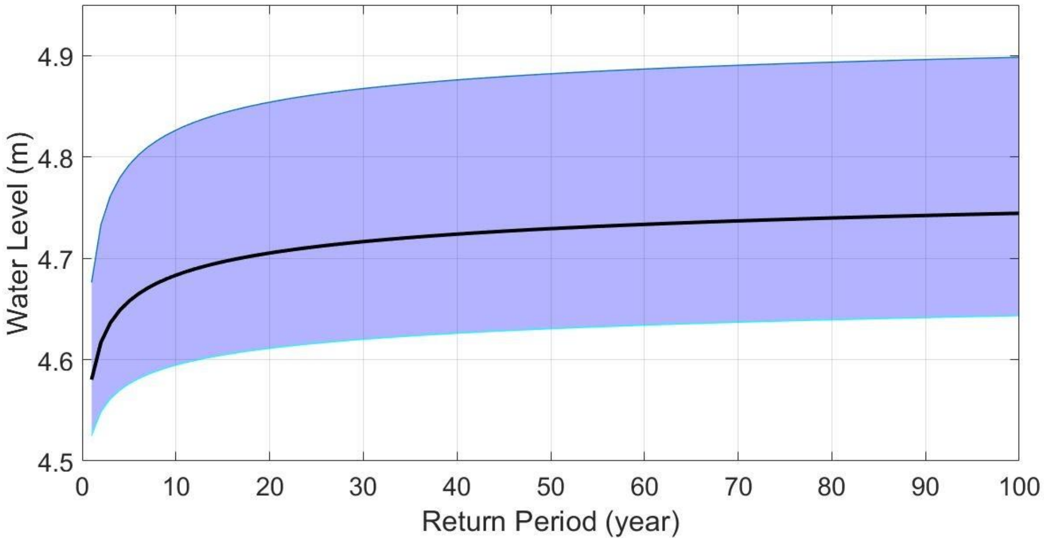


Figure 7: Peaks Over Threshold analysis applied to water level at the coastal region of Aveiro. Blue shaded area is the upper and lower limits of the expected values considering a 95% confidence interval.

5 Future Climate Conditions

5.1 Datasets

The most basic need to study the effects of climate change on any environment is to be able to find a model that represents well the climate. The most powerful tool for climate simulation are the Climate Models (CMs) that are often divided into Global Climate Models (GCMs) that are spatially coarser models covering the entire globe; and Regional Climate Models (RCMs) that are spatially refined models usually applied at continent scale. These numerical models represent the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes. The climate system can be represented by models of varying degrees of complexity; that is, for each component or set of components, it is possible to identify a spectrum or hierarchy of models that differ in aspects such as the number of spatial dimensions, the degree of explicit representation of physical, chemical or biological processes, or the degree of use of empirical settings.

The consideration and quantification of the uncertainties inherent in any climate simulation is one of the fields in which the scientific community is making the greatest efforts. There are several technical options for dealing with this problem, but all of them involve the use of as many projections as possible. If possible, one should work with a few tens of projections, obtained from several CMs. The more similar the projections obtained from different CMs are for a particular location or region, the less uncertainty in the expected future climate for that location. This kind of strategy is usually called a *model ensemble*, as described in https://climateinformation.org.

Evaluating the effects of each and every one of the projections can be too laborious. For example, running a complex hydrological model dozens of times (once with each projection) may be unfeasible because of the computational cost and the effort required to interpret their outputs. Therefore, for a correct quantification of uncertainty, it is necessary to apply specific methodologies that allow it to be adequately managed. One of the most common options is to order the projections and select a subset of them that will correctly represent the variability between them: for example, one from the central part of the range of possibilities corresponding to a medium change, another from the high part corresponding to a larger change, and another from the low part corresponding to a smaller change. Once that selection is made, the effects can be evaluated. In the example presented above, by running the complex hydrologic model considering the selected subset it is possible to get an better understanding of the range of possible effects.

The above is a mere simplification as it contains some theoretical-technical complexities. For example, if the effects to be evaluated are related to water availability, the projections should be ordered according not only considering one parameter, but rather a combination of parameters such as temperature and precipitations.

5.1.1 The need for downscaling

CMs are able to simulate very satisfactorily the general atmospheric circulation, but due to their resolution (order of 100 km) they are not able to reproduce smaller scale atmospheric phenomena relate to local climatology. In order to overcome this and other limitations of CMs, downscaling techniques are used. These techniques consist of adapting the outputs provided by CMs to the local scale. There are two main downscaling approaches: statistical and dynamical, each with its own advantages and limitations (Table 5).

Table 5: Differences between dynamical and statistical downscaling. (Source: Patz, et al., 2005)

	Benefits	**Drawbacks**	**Applications**
Dynamical downscaling	• Simulates climate mechanisms • No *apriori* assumptions about how current and future climate are related • ‘State of the science’ tools • Continually advancing computersare making RCMs faster andcheaper to run • Encourages collaborations between climate scientists	• Expensive, in terms of computer resources and professional expertise • Results may be sensitive to uncertain parameterisations • Biases in the GCM (providing boundary conditions) may propagate to regional scale • Output from models may notbe in a format well-suited to analysis—additional dataprocessing often required	• Studies associated with climate extremes and non linear variability, as health • Data-poor areas • Connecting outcomes with climate processes • Include land-use impacts on climate or health outcomes

Statistical downscaling	• Much cheaper (runs quickly ondesktop computers with free software). • Builds on the statistical expertise common among researchers. • May correct for biases in GCM. • Allows for the assessment of climate results over a range of GCMs and emission scenarios.	• Assumes relationships between local and large-scale climate remain constant • Does not capture climate mechanisms • Not well suited to capturing variance or extreme events.	• Climate means, and variability with some limitations • Data-rich regions, especially Northern Hemisphere mid-latitudes • Compare present with projected climate in a consistent framework • Test a range of inputs • Variable scales, down to individual measurement sites

The dynamic downscaling increases its resolution of the dynamic models over the region of interest. It can be done in two ways, either with a "zooming" technique of the CM grid itself or by nesting a Limited Area Model (LAM) in the boundary conditions provided by the CM. These are called Regional Climate Models (RCM). They have a stronger physical basis (although they also use statistical relationships in the parameterizations). They have the disadvantage of a very high computational cost, making their application to a wide set of projections (combining CM and GHG concentration scenarios) very complicated, which is a major limitation for the correct consideration and quantification of uncertainties.

The statistical downscaling approaches obtain empirical relationships between large-scale variables from CMs and high-resolution (surface) variables. They have a much lower computational cost (which allows them to be applied to a multitude of CMs and emission scenarios), but suffer from an implicit uncertainty resulting from accepting the hypothesis that the relationships between predictors and predictands detected in the past are valid in the future. Indeed, the statistical relationships between low-resolution atmospheric fields and surface variables at the local scale are always imperfect and may be non-stationary, which means that, even if these relationships hold true in the present climate, they are not necessarily true in a future climate (this is known as the stationarity problem).

5.1.1.1 VERIFICATION OF THE DOWNSCALING METHODOLOGY

Before simulating the future climate, it is necessary to verify that the tools used for this purpose work properly in the study area by correctly simulating the observed past climate. For this purpose, it is necessary to carry out complete and robust verification analyses of the downscaling methodologies used, and validation of the CMs to be downscaled. For the different variables, the errors with which the methodology and each CM simulate the observed climate at each location must be known.

The verification starts by applying the downscaling methodology to the so-called atmospheric reanalyses, which are representations of the state of the atmosphere (the predictors) on each day of a certain reference period (e.g. from 1979 to the present). The latest reanalyses have quite detailed resolutions, but it would be of no use for a tool to obtain good results when the predictors have that resolution, if it is then going to be applied to the MC outputs, with low resolution (around 100 km), so the spatial and temporal resolution of the reanalysis must be relaxed to those offered by the MCs.

Verification must be tackled in depth, not only for mean values but also for extremes (90th or 95th percentiles of precipitation and daily temperatures, number of consecutive days without rain...), and at all time scales: climatic (30 years), decadal, annual, monthly, and even daily. The latter is very important, because if the tool simulates well the changes between one day and the next, it means that the physical links between predictors and predictands are being captured, physical links that will not change even in a context of climate change (purely empirical relationships can change), and therefore, it means that we are combating, at least theoretically, the main problem of statistical downscaling, the so-called non-stationarity problem, which questions whether the predictor/predictand relationships established in the past will be stationary (will hold in the future).

Once the downscaling methodology has been successfully verified, each CM to be regionalized is *validated* by downscaling its control outputs, called Historical (for the period 1960-2015, for example). By comparing the simulations thus obtained with the observed climate, the extent to which the CM is adequately representing the observed climate is assessed. This validation must also be performed at the local scale – in fact, previous studies have shown that some CMs could work adequately in a certain area of a territory, but not in another. The results of this validation of each CM (also for each variable and for each point of the territory) are also used in the quantification of uncertainties: the better the validation results of a CM, the lower the uncertainties in the simulations of that CM.

5.1.2 Use case: the ECCLIPSE Project

Which climate models to use in a climate change study? How many to choose? With what spatial resolution? And with what spatial resolution? Let's see, as an example, which models have been used in the ECCLIPSE project and with what characteristics, and why those models.

5.1.2.1 Used GCMs

In the ECCLIPSE project 10 GCMs have been selected for making a statistical downscaling at the provided meteorological stations. There is no particular reason in choosing 10 models but the fact there are not many models that provide data on a daily time scale – in general, the results of climate models are distributed on a monthly scale, therefore, among the (of the order of) 40 climate models with available results, only (of the order of) 10 have them on a daily scale. Table 6 shows the list of the 10 climate models used in the ECCLIPSE project.

Table 6: List of climate models used in the ECCLIPSE project.

[redacted]	[redacted]	[redacted]
ACCESS1-0	1,25°x1,875° daily	Commonwealth Scientific and Industrial Research Organisation (CSIRO) & Bureau of Meteorology, Australia.
GFDL-ESM2M	2°x2,5° daily	National Oceanic and Atmospheric Administration (NOAA), E.E.U.U.
CanESM2	2,8°x2,8° daily	Canadian Centre for Climate Modeling and Analysis (CC-CMA), Canadá.
CNRM-CM5	1,4°x1,4° daily	CNRM (Centre National de Recherches Meteorologiques), Meteo-France, Francia.
BCC-CSM1-1	1,4°x1,4° daily	Beijing Climate Center (BCC), China Meteorological Administration, China.
HADGEM2-CC	1,87°x1,25° daily	Met Office Hadley Center, United Kingdom.
MIROC-ESM-CHEM	2,8°x2,8° daily	Japan Agency for marine-Earth Science and Technology (JAMSTEC), Atmosphere and Ocean Research Institute (AORI), and National Institute for Environmental Studies (NIES), Japan.
MPI-ESM-MR	1,8°x1,8° daily	Max-Planck Institute for Meteorology (MPI-M), Germany.
MRI-CGCM3	1,2°x1,2°	Meteorological Research Institute (MRI), Japan.

	daily	
NorESM1-M	2,5°x1,9° daily	Norwegian Climate Centre (NCC), Norway.

It is not mandatory to use 10 models in a project and it is not mandatory that those 10 models are precisely these ones. However, it is important to use as many models as possible, since the more models, the better uncertainty will be quantified. In this case, 10 models with daily information give us enough information for quantifying the uncertainty of the changes and about the extreme values (the reason why daily scale information is used).

In this project, the climate model data were mainly used for simulating precipitation and temperature via statistical downscaling. It is important to remember that all the data from these models (and the other models associated with the studies described here) are free and freely available for using in any other project.

5.1.2.2 Used RCMs

One of the objectives of the ECCLIPSE project was to obtain wave simulations in order to reproduce their possible effects on harbors. But to perform these simulations we needed to start from sub-daily values (ideally, 3-hourly, and if not possible, 6-hourly) on a much finer grid, at least near the coast, a different data source was needed since the GCMs give results in the order of 1° (about 100 km) and very rarely sub-daily values.

What was done was to use data from different RCMs, which allowed to have data at low spatial and temporal resolutions in order to launch the numerical processes of wave simulation based on the original data from those RCMs. The RCMs used have been generated as part of the EURO-CORDEX project (Coordinated Downscaling Experiment - European Domain) (https://www.euro-cordex.net/) a project that is, in its own words,

> EURO-CORDEX is the European branch of the international CORDEX initiative, which is a program sponsored by the World Climate Research Program (WRCP) to organize an internationally coordinated framework to produce improved regional climate change projections for all land regions world-wide. The CORDEX-results will serve as input for climate change impact and adaptation studies within the timeline of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) and beyond.

Please note EURO-CORDEX is a scientific initiative that provides free data of several RCMs that can be used for several different projects

What was made in the ECCLIPSE project was to use as many RCMs as possible but imposing a sub-daily temporal scale. At the end, three of the provided RCMs were selected – they are detailed in the table 7, where we can see the GCM where they are nested, the RCM used for making the dynamical downscaling and the research centre that has developed the RCM.

Table 7: List of RCMs used in the ECCLIPSE project.

GCM	RCM	Research Center
CNRM-CERFACS-CNRM-CM5	ALADIN63	CNRM (Centre national de Recherches Météorologique), France
IPSL-IPSL-CM5A-MR	SMHI-RCA4	Rossby Centre regional atmospheric model, SMHI (Sveriges Meteorologiska och Hydrologiska Institut), Sweden
MOHC-HadGEM2-ES	DMI-HIRHAM5	DMI (Danish Meteorological Institute), Denmark

As mentioned previously, it is not mandatory to use 3 regional models in a project and it is not mandatory that those 3 models are precisely these ones. What is mandatory is to use as many models as possible. For the ECCLIPSE project only 3 models with the characteristics needed were found.

5.1.2.3 Consistency between GCMs and RCMs

Which strategy should be followed, that of using the GCMs and subjecting them to statistical downscaling or should one opt to use the direct output of an RCM such as those provided by EURO-CORDEX? And if both are used, as in the ECCLIPSE project, what kind of relationship can be established between the two studies?

There is no single answer to these questions. The important thing is to get as much information as possible that fits the requirements (spatial and temporal resolution). Using the statistical downscaling of a GCM will allow us to obtain very local results but limited to the fact of having observed data, although, yes, with less error than with an RCM. An RCM, on the other hand, allows us to obtain results in areas where there are no observed data with low temporal resolution, although there may be few RCMs with the requirements needed and the error will be greater than with statistical downscaling.

For example, in the case of the ECCLIPSE project, precipitation predictions are generated based on statistical downscaling of GCMs, and those predictions are the basis for the study of changes in precipitation regimes, both average and extreme precipitation. Alternatively, the hydrological contribution of the basins in which a port may be (especially in the case of estuaries) it is necessary to cover a large area with precipitation results, and for that a fine grid (of small spatial resolution) such as that of an RCM is more than adequate.

As discussed previously, since the main goal is to compare predictions with present conditions it is important that the selection of the climate projections datasets takes in consideration the types on datasets (spatial and temporal scales) used to determine the baseline values.

5.2 Climate Change Projections – Average Values

The examples to be shown are relative to the climatic variables of precipitation, maximum temperature and minimum temperature, and have been carried out for scenarios associated with the 5th IPCC Assessment Report - in fact, such a study has only been carried out for the core scenarios of that Report, i.e. RCP4.5 and RCP8.5 (see . What we are going to see are the results of the application of statistical downscaling for the observed data of the three ports under study in this project for the 10 used climate models associated with the 5th Assessment Report.

The purpose of showing these results is to serve as an example for other possible future projects studying the impact of climate change on other possible civil structures in the SUDOE area - and any other area, in its more generic form. Not all projects should use the same variables nor their graphical representation should be the same, but the concepts (the verification of the downscaling methodology, the validation of the models, the representation of the simulated future changes under different scenarios, the selection of the statistics to be used) will be the same whatever the project to be carried out and we believe that all these examples will help to define the direction to follow in each possible project.

5.2.1 Port of Aveiro

5.2.1.1 Precipitation

First we are going to see some graphical representations of the verification of the statistical downscaling methodology of precipitation with the meteorological observatories of the Aveiro area. Recall that the verification seeks to find out if the downscaling methodology is reliable in the area we are interested in, so for this purpose a downscaling of the reanalysis is performed (but taken to a spatial resolution of the climate model) and compared against the values of the observatories.

A first way to represent such a check is in Figure 8, which shows the monthly averages of the amount of precipitation both observed and simulated and the monthly averages of the number of days of precipitation. It is always important to show the results by months of the year because this way we can see if the simulation follows the annual cycle of the variable, something that could be masked if we only give annual values. In the case of precipitation, it is also useful to know if we are simulating well the number of days of precipitation because correct simulations of amounts but incorrect in the number of days would indicate wrong precipitation distributions and very different daily amounts (and the extremes would be falsified).

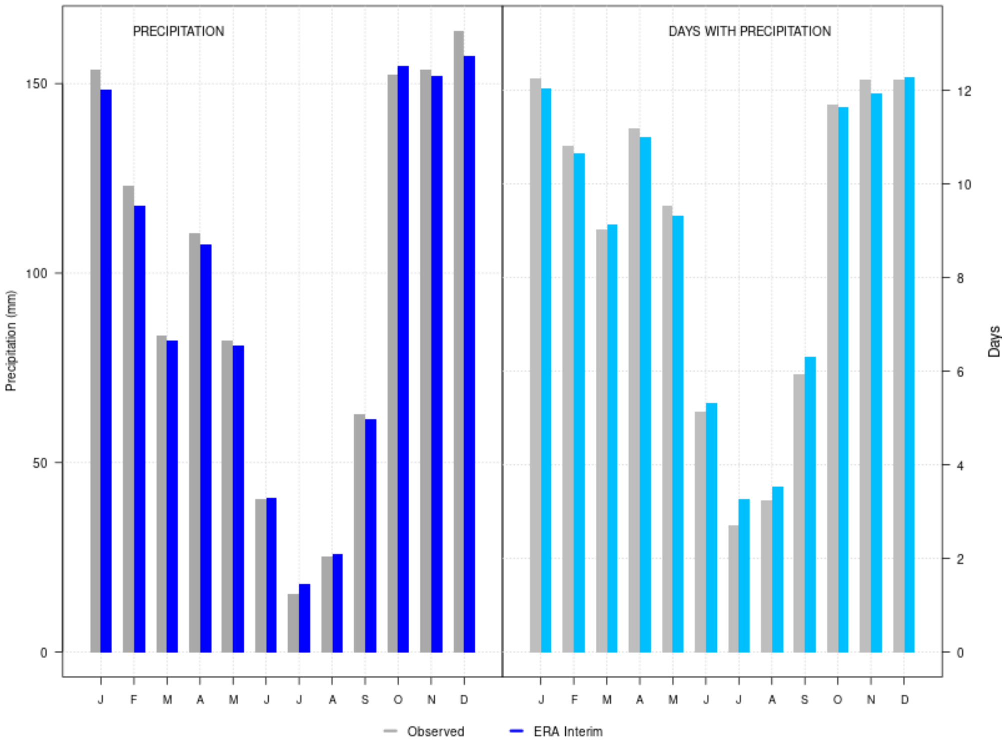


Figure 8:Verification of the downscaling methodology applied to the precipitation variable (left, amount; right, number of days) in the Aveiro port area.

The above measure of verification shows us how different the averages are, but what about the possible differences between the dispersions? Recall that to measure the error between two groups of data we must always pay attention not only to the difference between their central values (between their averages, which is the bias) but also between the dispersions of their values. One of the many possible ways of doing this is by means of the Mean Absolute Error (MAE), which we can see in Figure 9 for the precipitation verification. The figure is very interesting because it shows us both the absolute and relative MAE since the results of the precipitation variable can be shown in absolute and relative form - this is so because precipitation is a variable that can be measured in absolute form and therefore relative increments make sense, which is not the case for all meteorological variables (as for example temperature: 20°C is not 20 times more than 1°C, the concept of relative increment does not exist). Given this nature of precipitation, measuring increases in absolute or relative form is of great interest depending on what is evaluated. Thus, knowing as we do thanks to F1 that in general in Aveiro it rains very little in summer and a lot in winter, we can interpret that it makes sense that in summer the relative MAE is high and the absolute MAE is low (small absolute errors are high relative errors since it rains little) and that in winter the relative MAE is low and the absolute MAE is high (there is an error in the amounts but since these are usually large in percentage it is low).

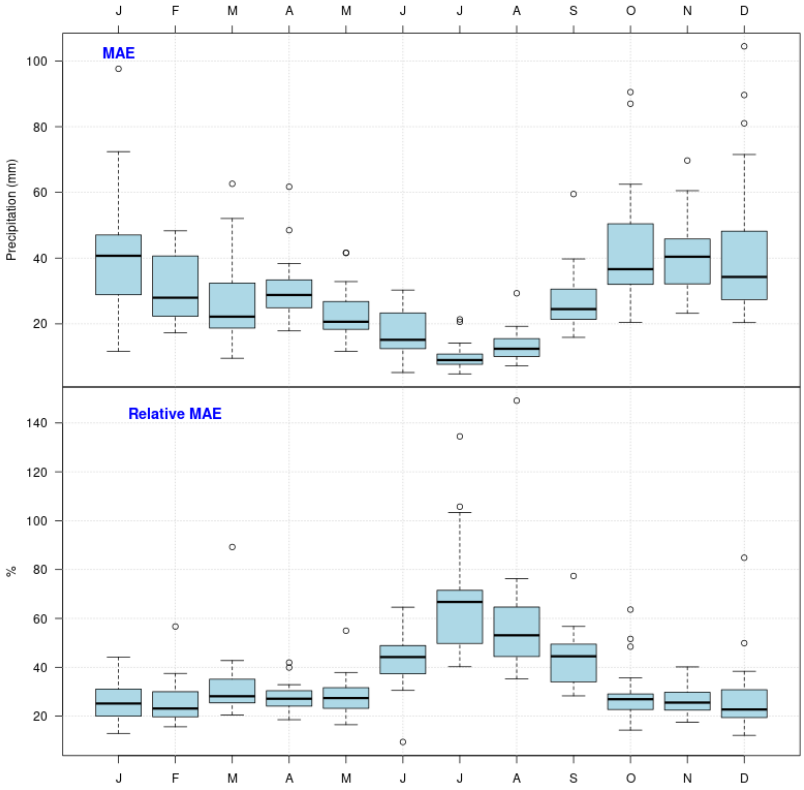


Figure 9: Verification of the downscaling methodology applied to the precipitation variable according to the monthly MAE (top, absolute; bottom, relative) in the Aveiro port area.

Another important measure of verification may be to determine whether the distributions of observed and simulated values are similar at each of the observatories. Figure 10 suggests a way to find out, using the Kolmogorov-Smirnov test, a non-parametric test (it does not presuppose a particular theoretical distribution) to determine whether two sets of data can be assumed to be from the same distribution.

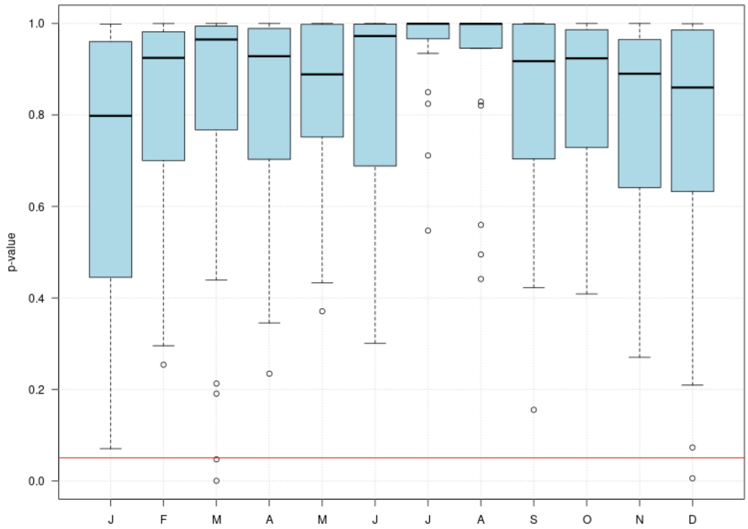


Figure 10: Verification of the downscaling methodology applied to the precipitation variable according to the monthly Kolmogorov-Smirnov test in the Aveiro port area.

Figures 11 and 12 show the future increase of the precipitation variable evaluated in absolute and relative form. The results are based on the simulation with the 10 models used in ECCLIPSE and for all available meteorological stations. From all these results, a 30-year moving average (the minimum amount of time to determine the climate of an area) has been generated for each model and from all the values obtained the median is represented as the most probable value (the 50th quantile of the distribution of values) and as a measure of the simulation error (of the dispersion of the values) the 5th and 95th percentiles of the values are taken, which corresponds to the shaded areas represented. This is a common way of representing future results (it appears repeatedly in IPCC reports) as it shows very graphically the evolution of the variable. Note that what is represented are increments, i.e., a fixed value has been taken (in this case, the period 1975-2005) and the values shown refer to the change against that value, so the value in the year 2005 (the vertical dashed line - the year when the scenarios start in the 5th Assessment Report) is 0. Showing the results by seasons of the year is not mandatory but it is useful to know if the simulations follow the annual cycle of the variable.

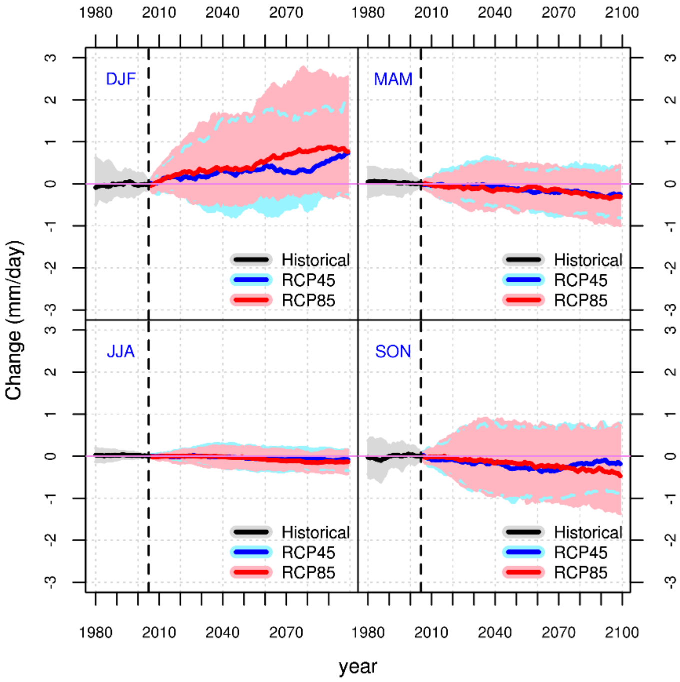


Figure 11: Future absolute increase of precipitation in the Aveiro area according to the simulation by statistical downscaling.

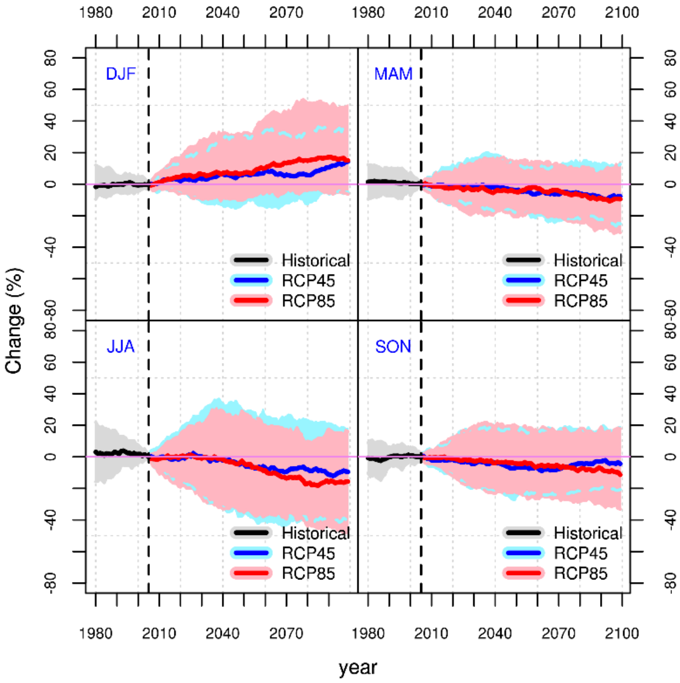


Figure 12: Future relative increase of precipitation in the Aveiro area according to the simulation by statistical downscaling.

5.2.1.2 *Temperature*

As we have done with precipitation, let us first look at some possible results of the maximum temperature and minimum temperature verification studies in the Aveiro port area.

Figure 13 shows us the differences between the observed and simulated monthly averages of both variables.

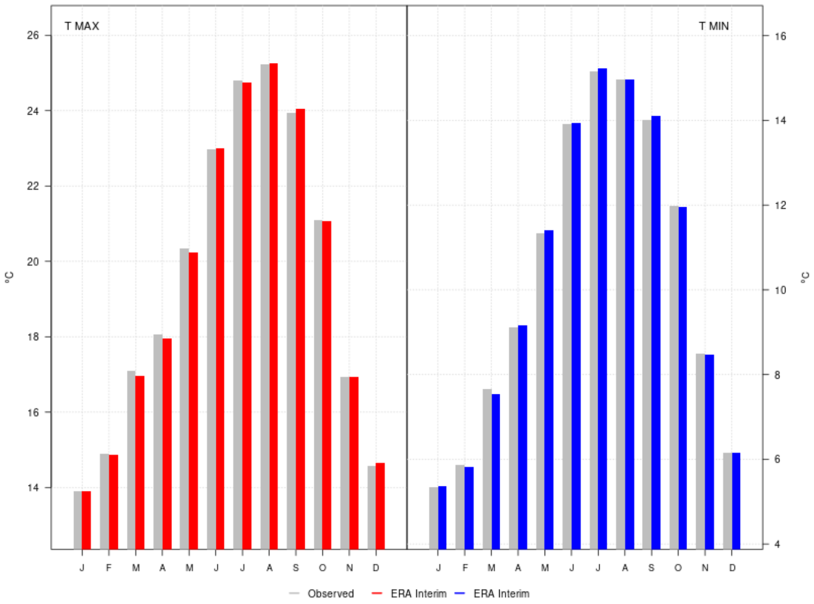


Figure 13: Verification of the downscaling methodology applied to temperature variables (left, maximum; right, minimum) in the Aveiro port area.

Figure 14 shows us, for each month of the year and for each variable, both the bias (the difference between averages - it would correspond to the difference between the values shown in Figure 13) and the MAE of both variables.

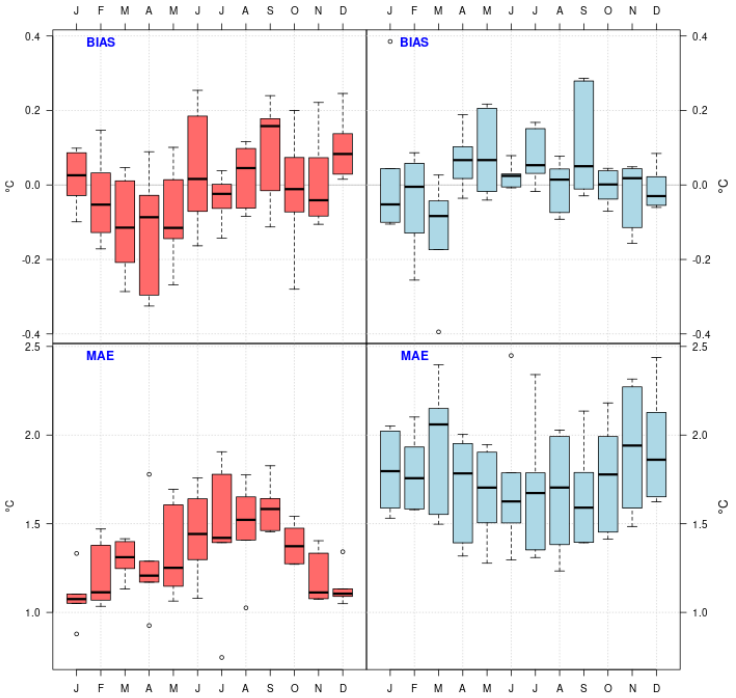


Figure 14: Verification of the downscaling methodology applied to the temperature variables (left, maximum; right, minimum) in the Aveiro port area showing bias (top) and MAE (bottom).

Figures 15 and 16 show the future increase of the maximum and minimum temperature variables. Again, the results are based on the simulation with the 10 models used in ECCLIPSE and for all available meteorological stations. Again, what is represented are increments, i.e., a fixed value has been taken (in this case, the period 1975-2005) and the values shown refer to the change against that value, so the value in the year 2005 (the vertical dashed line - the year in which the scenarios start in the 5th Assessment Report) is 0. Showing the results by seasons of the year is not mandatory but it is useful to know if the simulations follow the annual cycle of the variable.

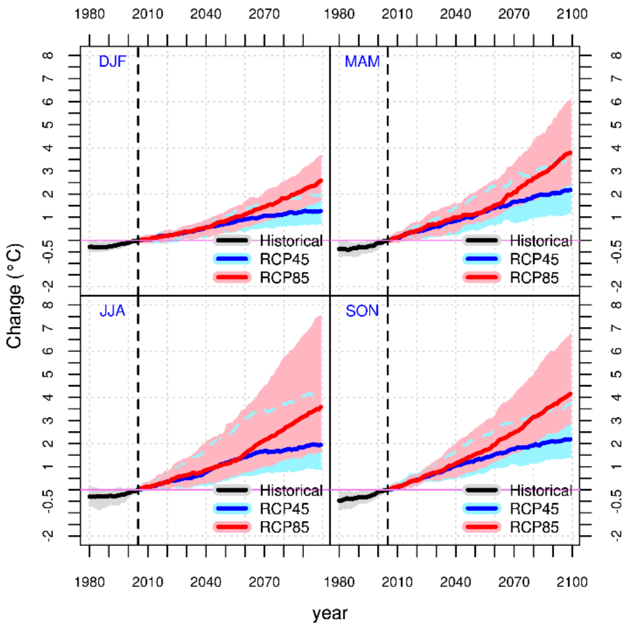


Figure 15: Future increase of the maximum temperature in the Aveiro area according to the simulation by statistical downscaling.

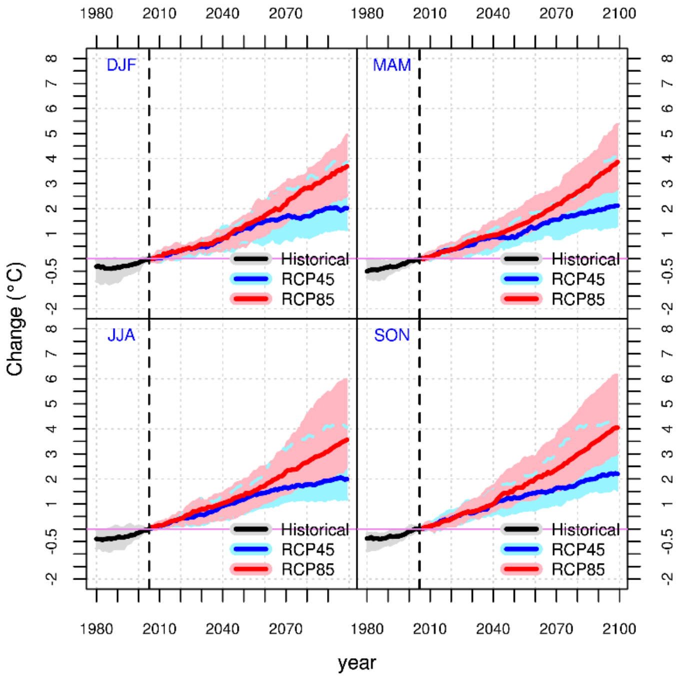


Figure 16: Future increase of the minimum temperature in the Aveiro area according to the simulation by statistical downscaling.

5.2.2 Port of Bordeaux

5.2.2.1 Precipitation

In this case we are going to see a possible way of presenting validation results, that is, we are going to evaluate how good are the climate models we are using in the project area, or rather the downscaling of such models. We are assuming a previous verification study that has determined that the downscaling method is good enough to continue using it, and now we see how the models behave simulating the past, which is precisely the simulation called Historical. Figure 17 shows, for each month of the year (again we try to verify that the annual cycle is followed), the behaviour of each model under downscaling in the observatories of the area versus the observed values in that area.

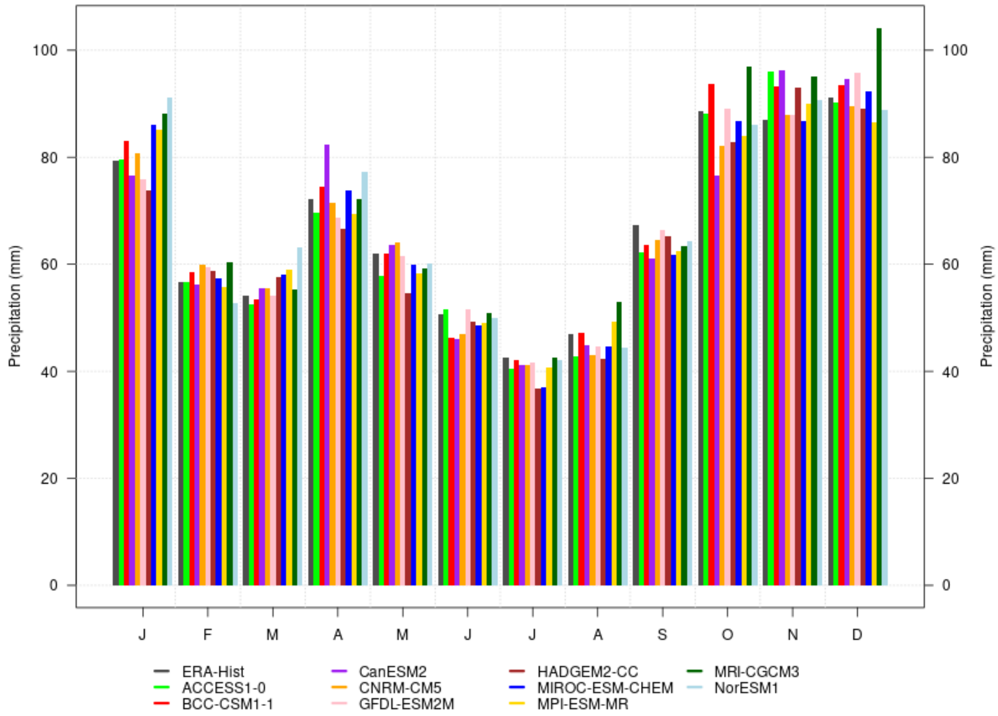


Figure 17: Validation of every climate model under the downscaling methodology applied to the precipitation variable in the port of Bordeaux area.

One way to validate that the dispersion of climate models corresponds to that expected (observed in the past) is, as shown in Figure 18, by calculating the difference between deviations. Attention, here we cannot use the MAE (or other similar measures, such as the RMSE) because the MAE is calculated based on residuals (predicted minus observed) and a climate model does not aim to simulate a day but a climate (a very long period of days) so that the validation statistics have to be calculated for long periods, such as the deviation of the data from the common period.

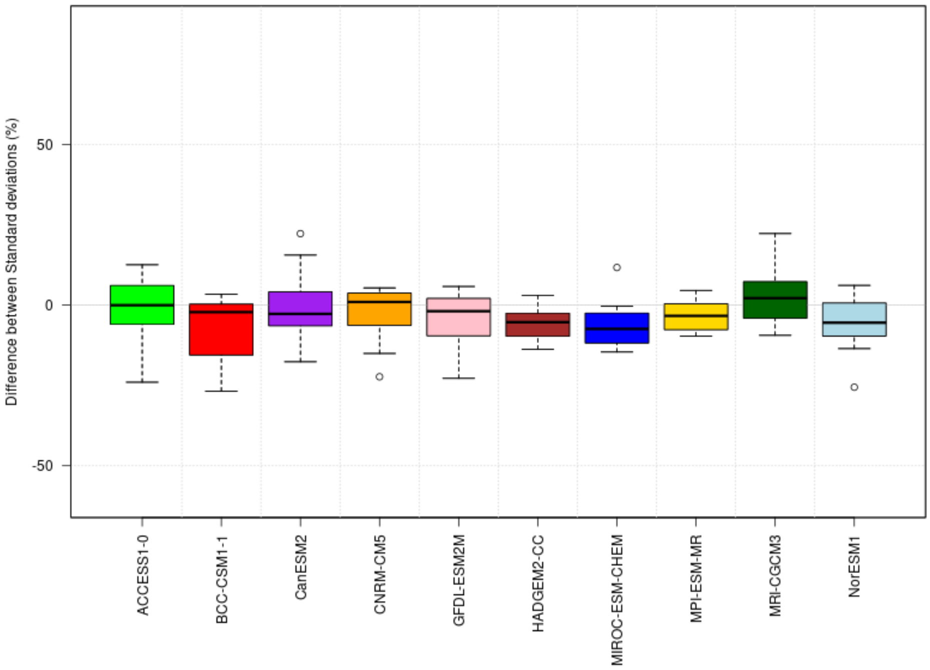


Figure 18: Validation of every climate model under the downscaling methodology applied to the differences between standard deviations of the precipitation variable in the port of Bordeaux area.

Figures 19 and 20 show the future increase of the precipitation in absolute and relative values. Again, the results are based on the simulation with the 10 models used in ECCLIPSE and for all available meteorological stations. Again, what is represented are increments, i.e., a fixed value has been taken (in this case, the period 1975-2005) and the values shown refer to the change against that value, so the value in the year 2005 (the vertical dashed line - the year in which the scenarios start in the 5th Assessment Report) is 0. And again, showing the results by seasons of the year is not mandatory but it is useful to know if the simulations follow the annual cycle of the variable.

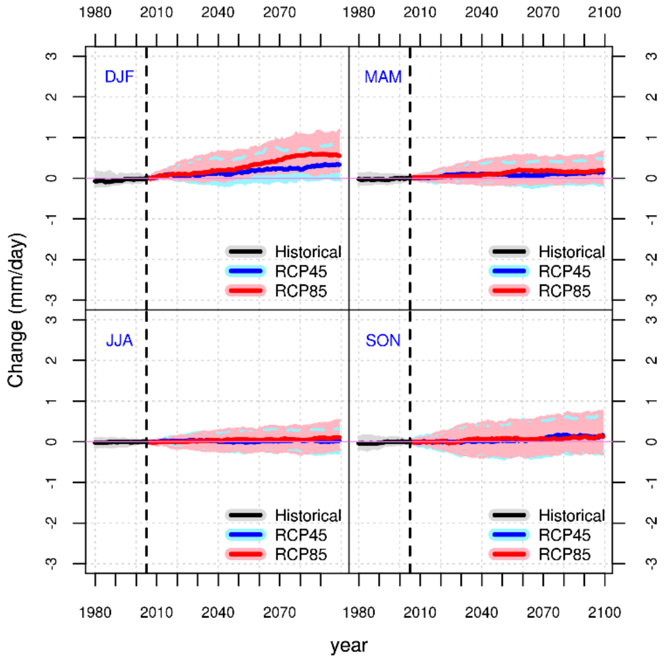


Figure 19: Future absolute increase of the precipitation in the port of Bordeaux area according to the simulation by statistical downscaling.

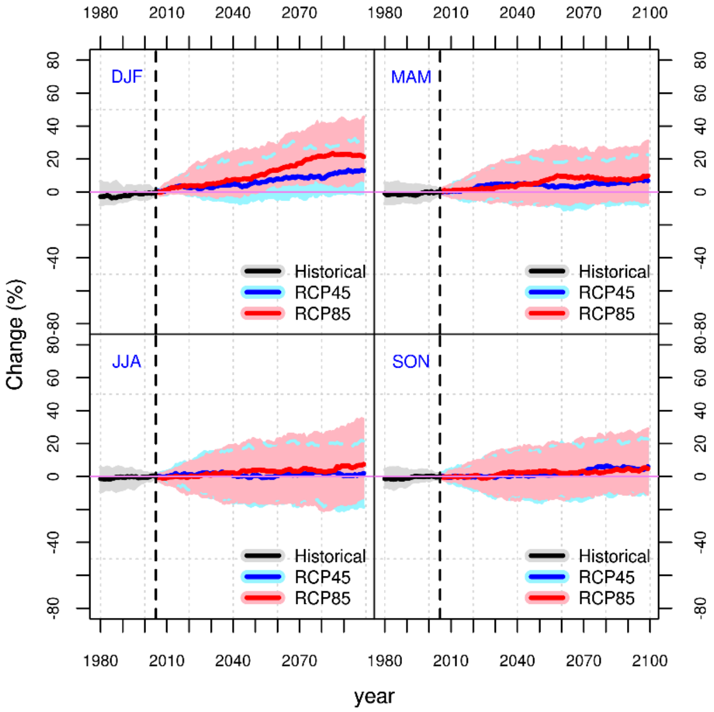


Figure 20: Future relative increase of the precipitation in the port of Bordeaux area according to the simulation by statistical downscaling.

5.2.2.2 Temperature

Figures 21 and 22 show the future increase of the maximum and minimum temperature variables for the area of the port of Bordeaux. Again, the results are based on the simulation with the 10 models used in ECCLIPSE and for all available meteorological stations. Again, what is represented are increments, i.e., a fixed value has been taken (in this case, the period 1975-2005) and the values shown refer to the change against that value, so the value in the year 2005 (the vertical dashed line - the year in which the scenarios start in the 5th Assessment Report) is 0. Showing the results by seasons of the year is not mandatory but it is useful to know if the simulations follow the annual cycle of the variable.

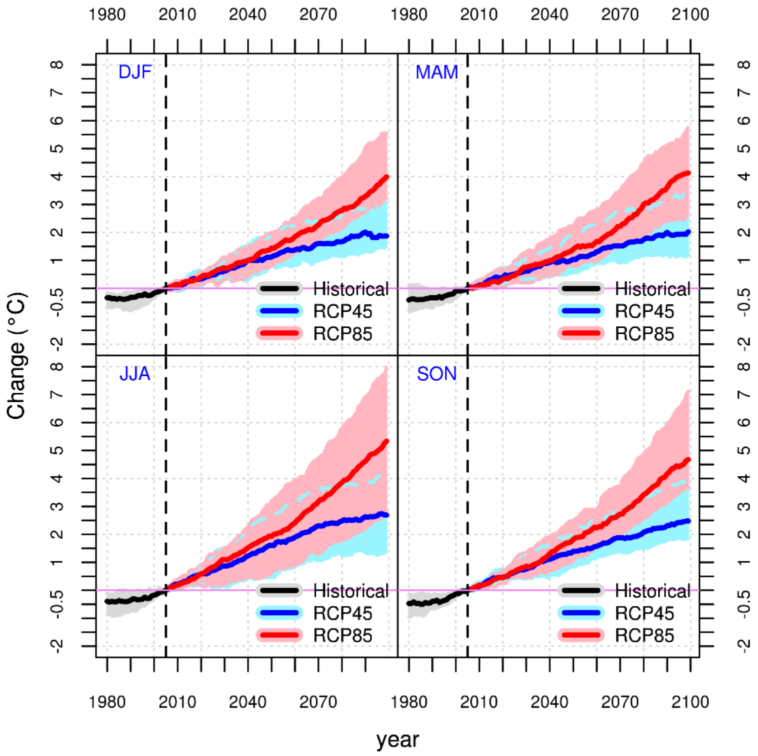


Figure 21: Future increase of the maximum temperature in the port of Bordeaux area according to the simulation by statistical downscaling.

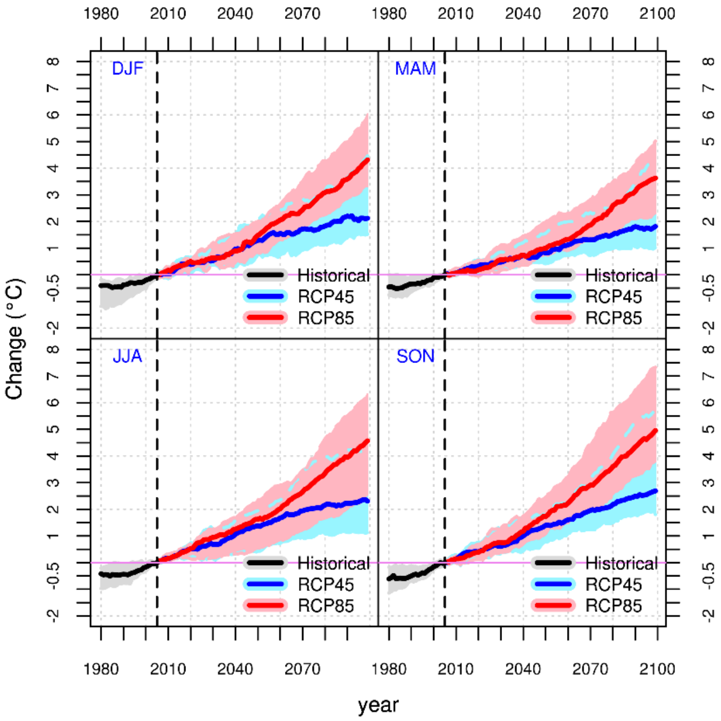


Figure 22: Future increase of the minimum temperature in the port of Bordeaux area according to the simulation by statistical downscaling.

5.2.3 Port of Valencia

5.2.3.1 Precipitation

Figures 23 and 24 show the future increase of the precipitation in absolute and relative values for the area of the port of Valencia. Again, the results are based on the simulation with the 10 models used in ECCLIPSE and for all available meteorological stations. Again, what is represented are increments, i.e., a fixed value has been taken (in this case, the period 1975-2005) and the values shown refer to the change against that value, so the value in the year 2005 (the vertical dashed line - the year in which the scenarios start in the 5th Assessment Report) is 0. And again, showing the results by seasons of the year is not mandatory but it is useful to know if the simulations follow the annual cycle of the variable.

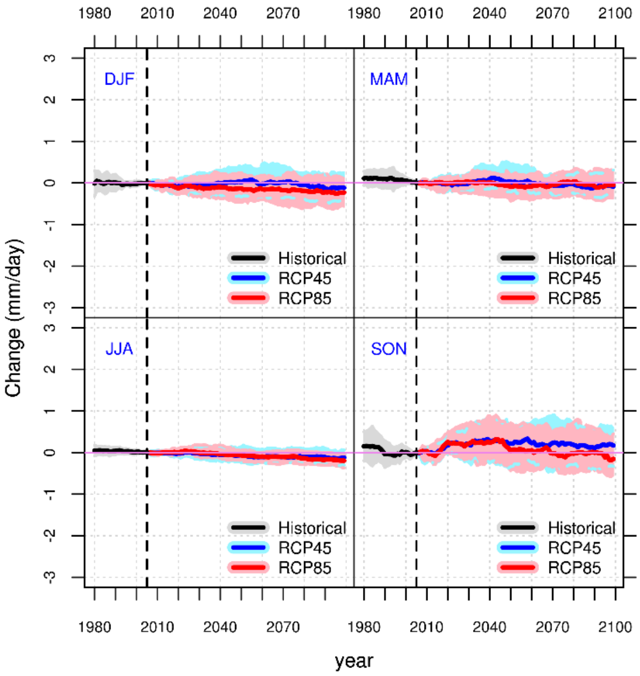


Figure 23: Future absolute increase of the precipitation in the port of Valencia according to the simulation by statistical downscaling.

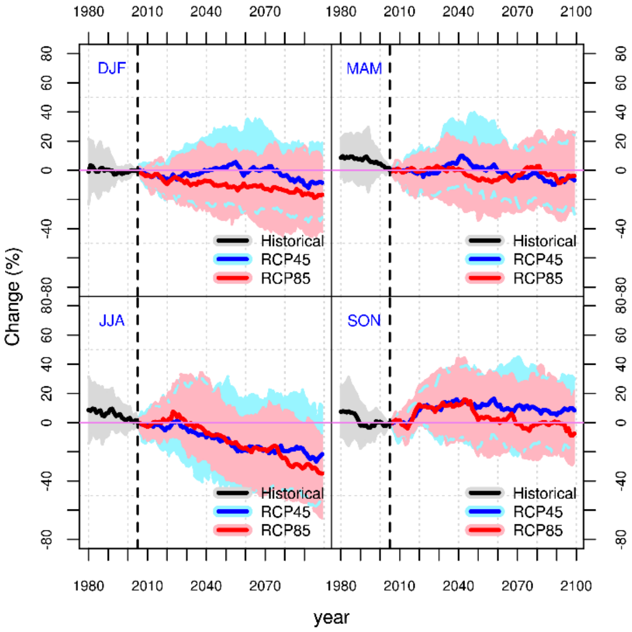


Figure 24: Future relative increase of the precipitation in the port of Valencia according to the simulation by statistical downscaling.

5.2.3.2 Temperature

In this case we are going to see a possible way of presenting validation results, that is, we are going to evaluate how good are the climate models we are using in the project area, or rather the downscaling of such models. Again, we are assuming a previous verification study that has determined that the downscaling method is good enough to continue using it, and now we see how the models behave simulating the past, which is precisely the simulation called Historical. Figures 25 and 26 show, for each month of the year (again we try to verify that the annual cycle is followed), the behaviour of each model under downscaling in the observatories of the area versus the observed values in that area for the maximum and the minimum temperature.

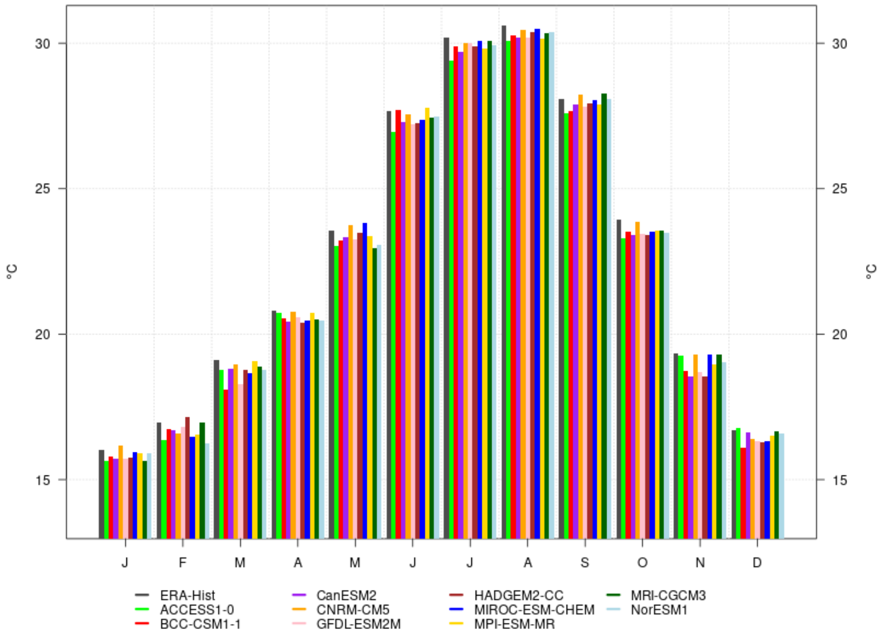


Figure 25: Validation of every climate model under the downscaling methodology applied to the maximum temperature variable in the port of Valencia area.

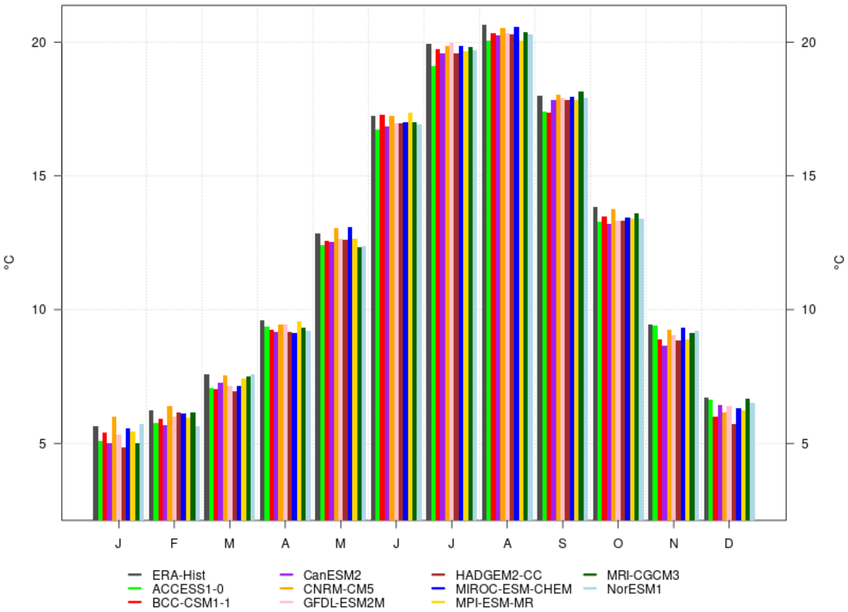


Figure 26: Validation of every climate model under the downscaling methodology applied to the minimum temperature variable in the port of Valencia area.

One way to validate that the dispersion of climate models corresponds to that expected (observed in the past) is, as shown in Figures 27 and 28, by calculating the difference between deviations. Please remember again that here in the validation we cannot use the MAE (or other similar measures, such as the RMSE) because the MAE is calculated based on residuals (predicted minus observed) and a climate model does not aim to simulate a day but a climate (a very long period of days) so that the validation statistics have to be calculated for long periods, such as the deviation of the data from the common period.

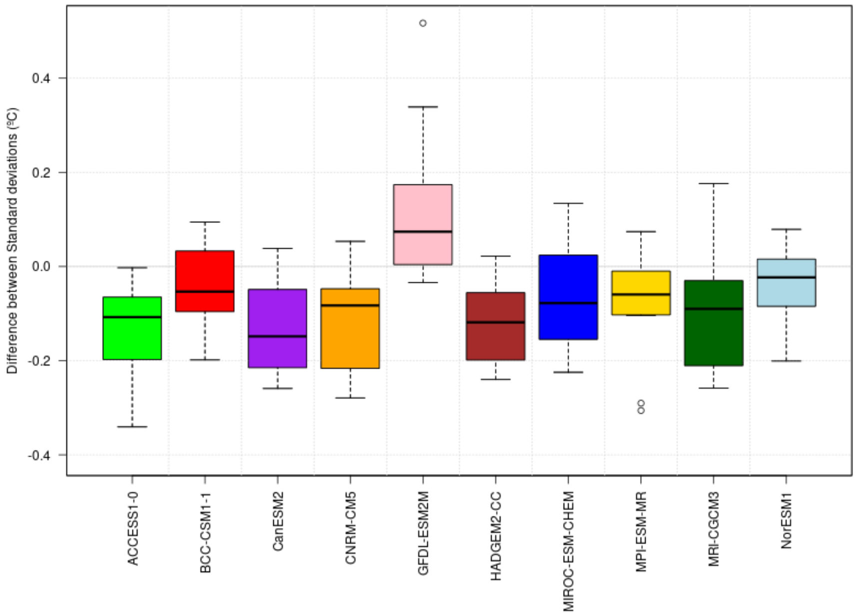


Figure 27: Validation of every climate model under the downscaling methodology applied to the differences between standard deviations of the maximum temperature variable in the port of Valencia area.

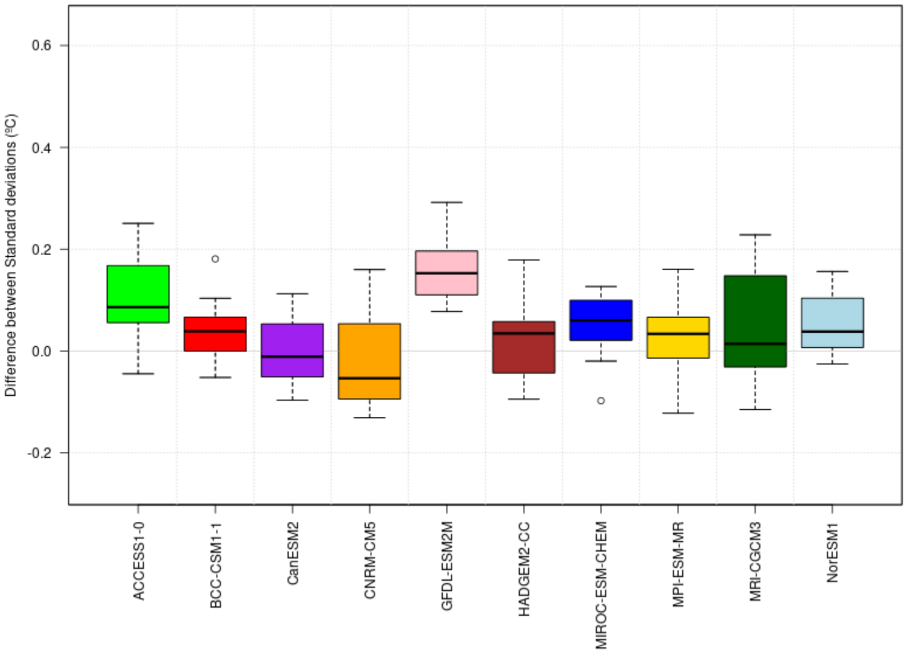


Figure 28: Validation of every climate model under the downscaling methodology applied to the differences between standard deviations of the minimum temperature variable in the port of Valencia area.

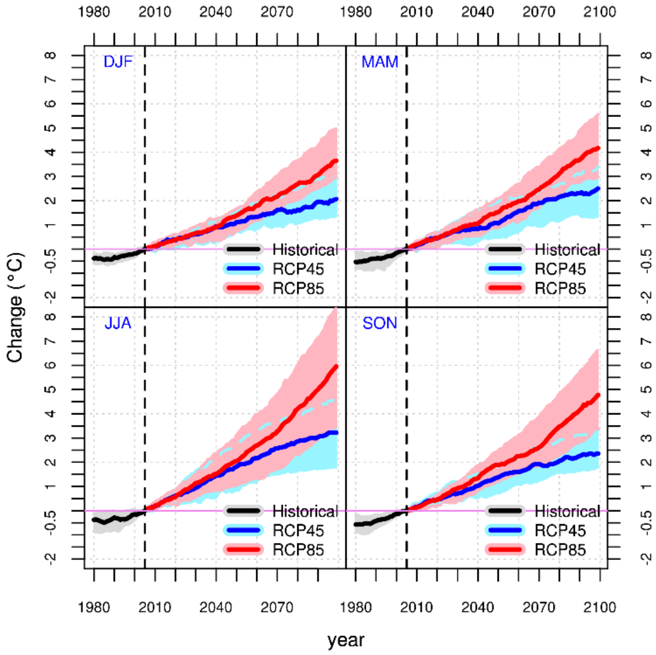


Figure 29: Future increase of the maximum temperature in the port of Valencia area according to the simulation by statistical downscaling.

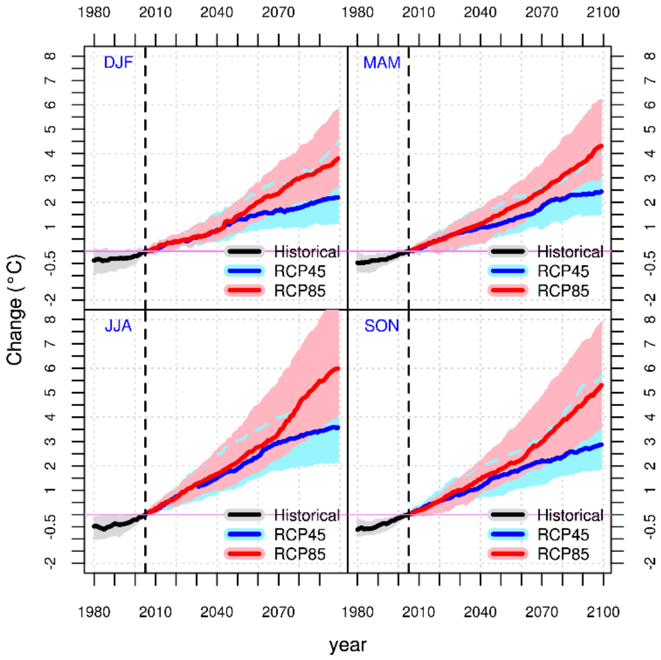


Figure 30: Future increase of the minimum temperature in the port of Valencia area according to the simulation by statistical downscaling.

Figures 29 and 30 show the future increase of the maximum and minimum temperature variables for the area of the port of Valencia. Again, the results are based on the simulation with the 10 models used in ECCLIPSE and for all available meteorological stations. And again, what is represented are increments, i.e., a fixed value has been taken (in this case, the period 1975-2005) and the values shown refer to the change against that value, so the value in the year 2005 is 0.

Once the data selected and analysed for each process under investigation, the same methodology used to determine the baseline parameters should be applied to the future projections.

5.3 Climate Change Projections – Extreme Events

As mentioned previously, frequency of occurrence of events above threshold limits are crucial to evaluate the impacts of climate changes on ports operation and navigability. Considering the threshold as limits makes the values of extremes less important for the analysis (e.g., ports that close their operation with Hs above 5 meters would not have their operations further impacted for extreme events with Hs above 8 meters). However, the same rationale does not apply when the effects of climate change are being evaluated for the Port´s infrastructure. In that case, understanding and predicting extreme events are crucial for the design of structures. Furthermore, structures are often designed for long periods of operation making even more important the correct prediction of extreme events.

6 Climate Change Hazard

6.1 Baselines vs Climate Change Projections

In section 4 the baseline characterization has been presented, here a set of examples comparing the results obtained from the historical/present and climate projection data is presented taking in consideration the main issues affecting coastal ports.

6.1.1 Navigation and Ports Operation

Waves:

As an example, the impacts of waves on port's operability 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. 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/).

As discussed earlier the impacts of waves on ports operability can be evaluated by analysing the significant wave height (parameter usually used to define operational thresholds), therefore looking at its distribution is important. As shown in Figure 31 and Figure 32, 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 33 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 8).

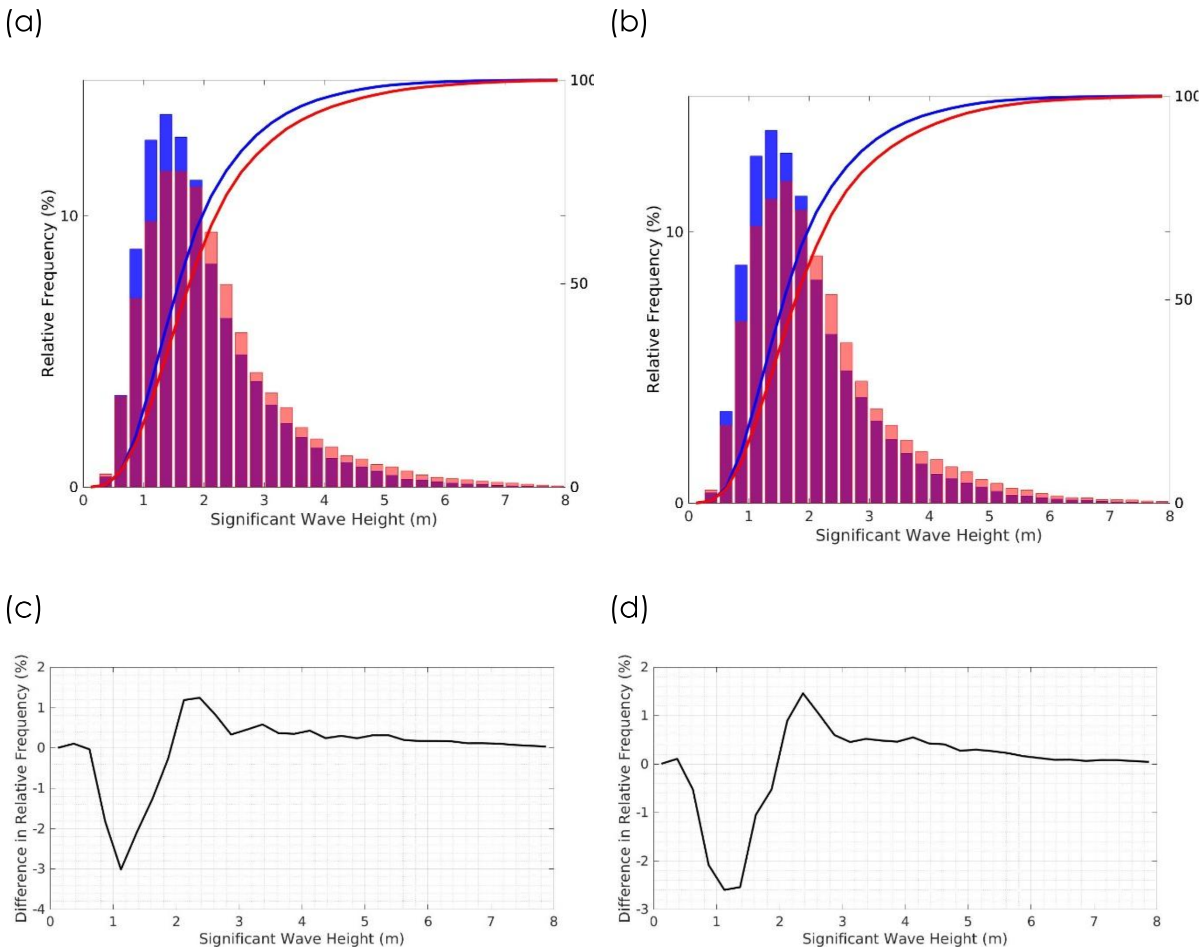
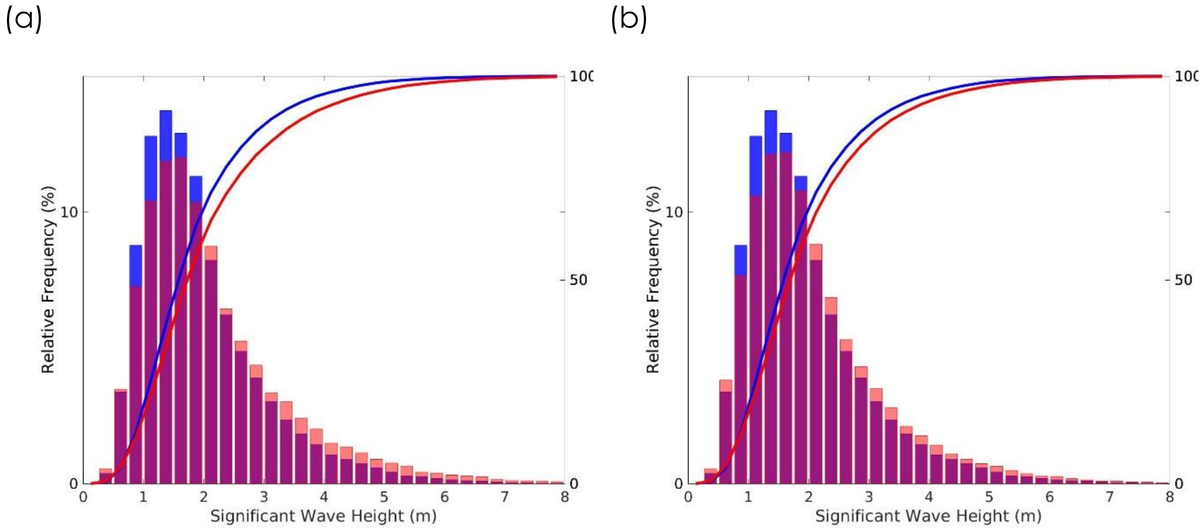


Figure 31: Frequency of occurrence of significant wave height for the present (blue) and mid-century (2040-2060) climate projections (red). (a) RCP 4.5 (b) difference in relative frequency present and RCP4.5), (c) RCP8.5 and (d) difference in relative frequency (present and RCP8.5)



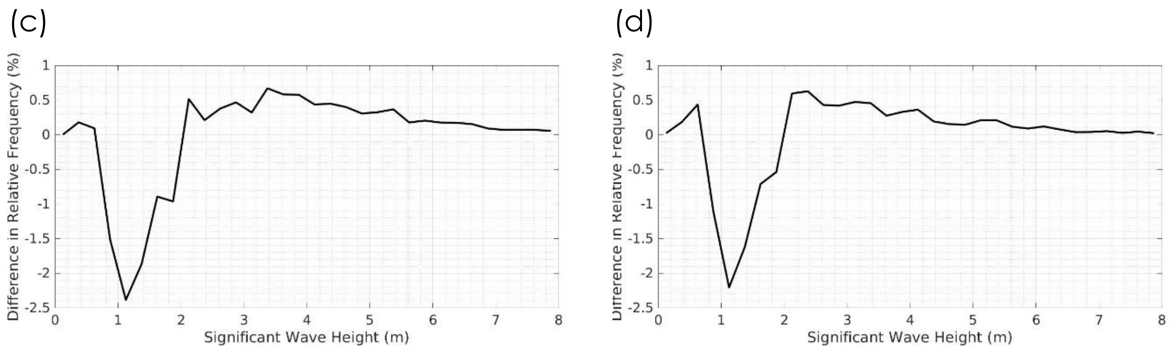


Figure 32: Frequency of occurrence of significant wave height for the present (blue) and end-century (2040-2060) climate projections (red). (a) RCP 4.5 (b) difference in relative frequency (present and RCP4.5), (c) RCP8.5 and (d) difference in relative frequency (present and RCP8.5).

Table 8: 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

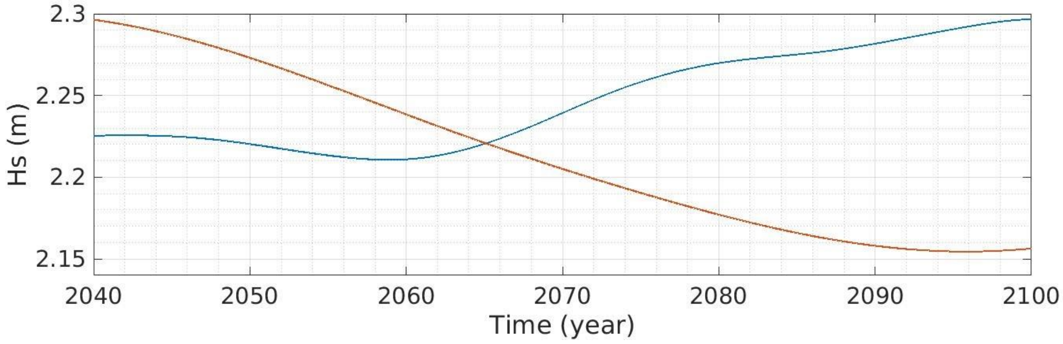


Figure 33: Significant wave height tendencies for the climate projections RCP 4.5 (blue) and RCP 8.5 (red).

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 9 and Figure 34). For all simulations the mean duration of events (Hs above 4 meters) is similar in the order of 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 9: Mean and quantiles calculated for the duration of events and interval between events.

	Present	RCP 4.5 Mid	RCP 8.5 Mid	RCP 4.5 End	RCP 8.5 End
Event (days)					
Occurrence	312	485	507	478	440
Mean	1.15	1.2141	1.195	1.304	1.14
50%	0.875	0.916	0.875	0.916	0.833
75%	1.542	1.667	1.582	1.75	1.583
95%	3	3.417	3.375	4.042	3.167
Interval (days)					
Mean	22.18	13.8	13.17	13.84	14.88
50%	5.78	3.46	3.17	3.17	3.21
75%	17.54	10.71	11.33	11.88	12.21
95%	151.4	58.62	45.5	55.08	57.96

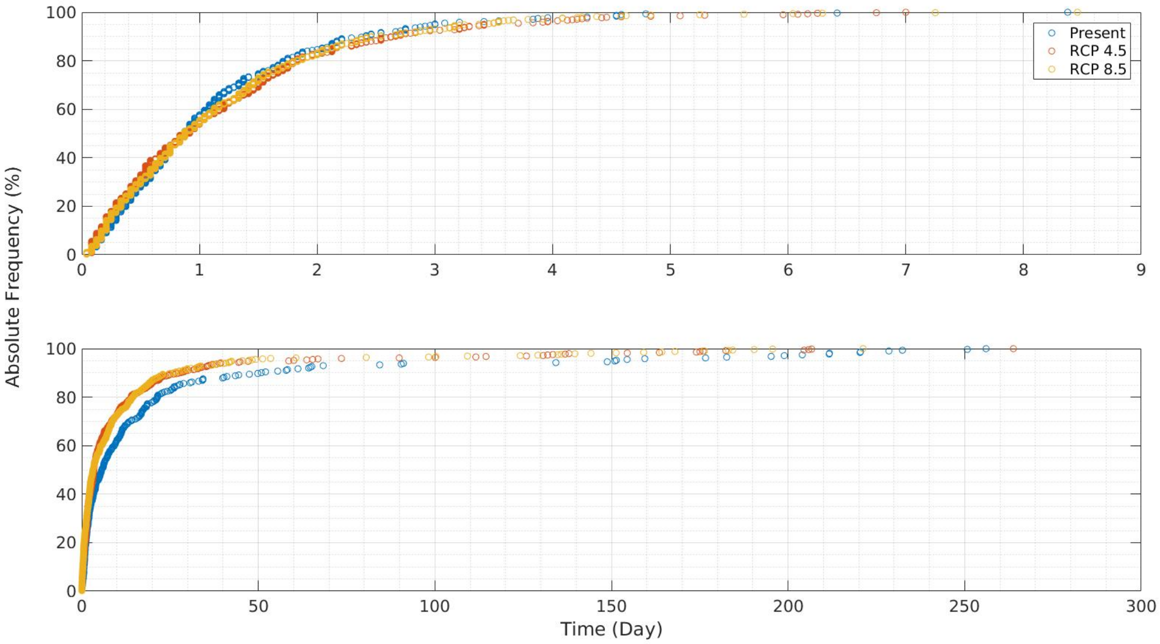


Figure 34: Duration (top panel) and interval (bottom panel) of events with Hs above 4 meters for the coastal region of Aveiro. Present (blue), mid-century climate projections RCP 4.5 (red) and RCP 8.5 (yellow).

Currents:

For coastal ports located inside estuaries with significant tidal prism, currents at its entrance can create hazardous conditions posing risk to navigation. Port of Aveiro is an example where current velocities are the main metocean process affecting its operability. With the projected increase in mean sea level the tidal prism at Ria the Aveiro is likely to follow the same trend. As a result, an increase in the velocities at the entrance are expected to reduce the periods of operation (current velocities below 1 m/s).

Since mean sea level is not characterized as an event-like process the analysis differ from what is presented above. Instead of searching for intensity and frequency of occurrence of events, high-resolution hydrodynamic simulations were performed to evaluate the impact of the discreate increase in mean sea level. The results are interpreted in terms of duration of currents with intensities below operational limits.

Figure 35, Figure 36, Figure 37, Figure 38 show the results of the impact of mean sea level change in the tidal currents along the channels of Ria the Aveiro for spring and neap tides, respectively. As expected, as the tidal prism increases with the mean sea level resulting in a significant reduction in operational windows especially during large tidal amplitudes.

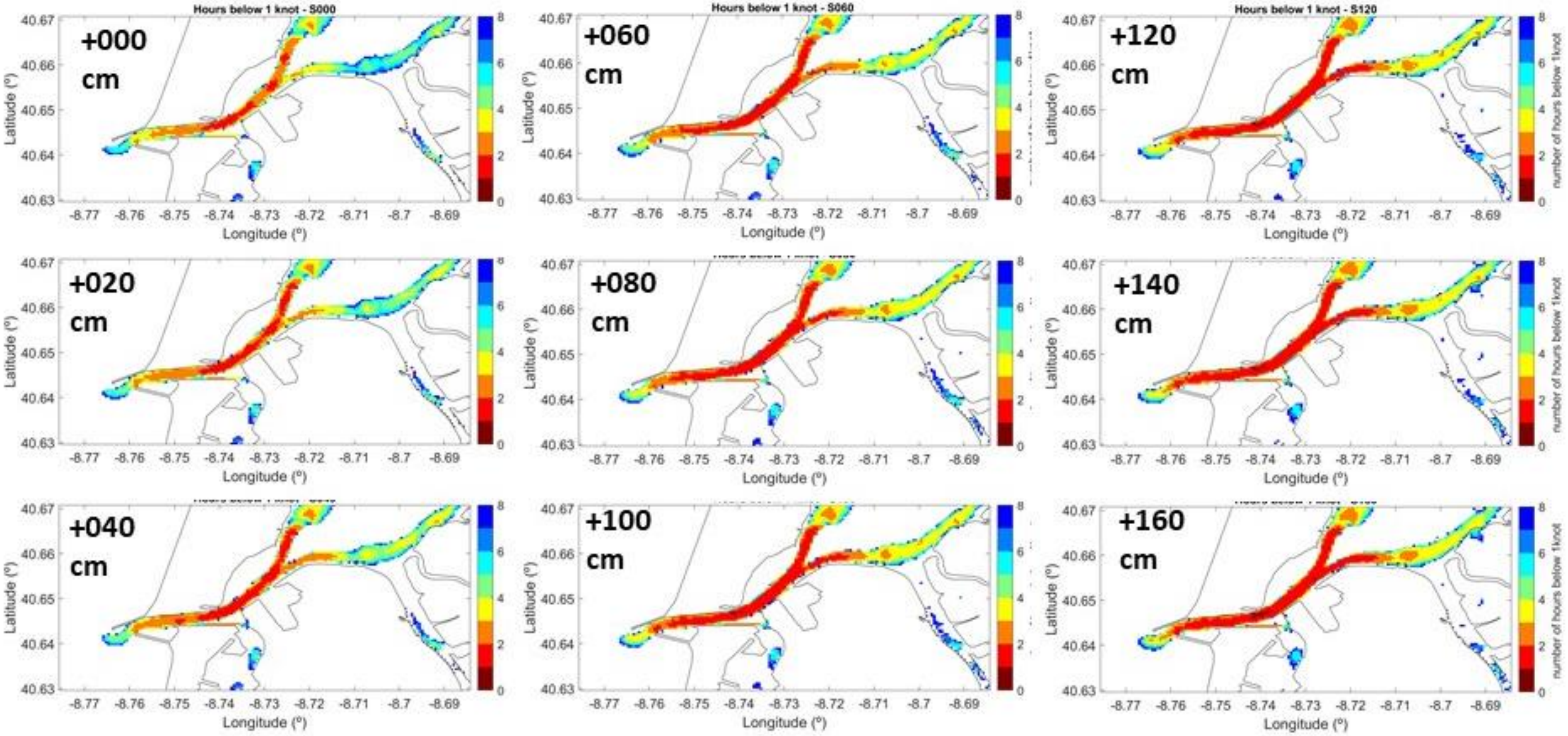
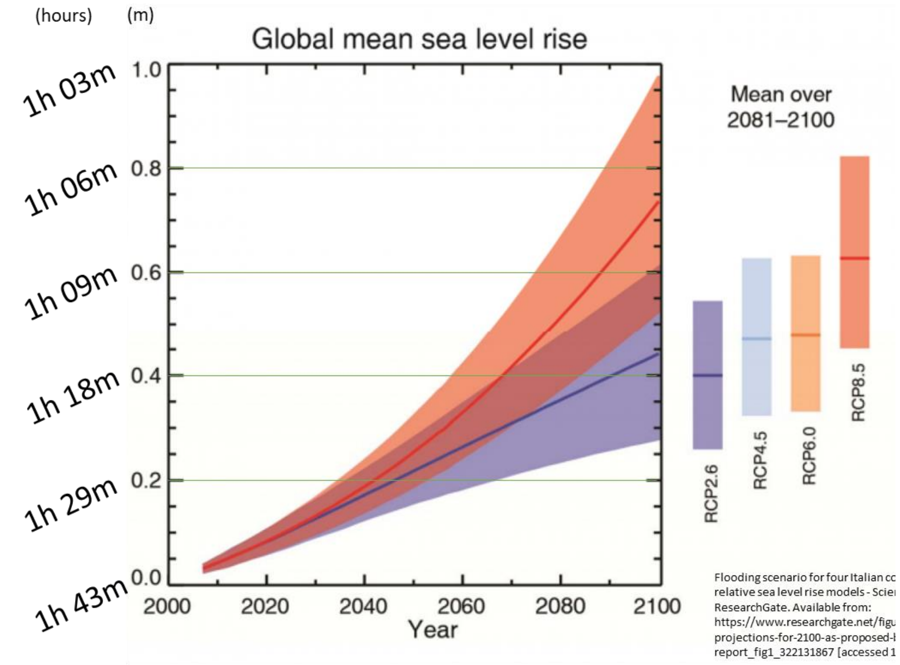


Figure 35: Number of hours with currents below threshold (1 knot) for spring tide.

Spring Tide		
+cm	Point1 [h/day]	
000	1h 43m	
020	1h 29m (-14%)	
040	1h 18m (-24%)	
060	1h 09m (-33%)	
080	1h 06m (-36%)	
100	1h 03m (-39%)	
120	1h 01m (-41%)	
140	1h 00m (-42%)	
160	0h 59m (-43%)	



Flooding scenario for four Italian cc
relative sea level rise models - Scie
ResearchGate. Available from:
https://www.researchgate.net/figu
projections-for-2100-as-proposed-
report_fig1_322131867 [accessed 1

Figure 36: Operational downtime due to tidal currents. Summary of the results presented in Figure 35.

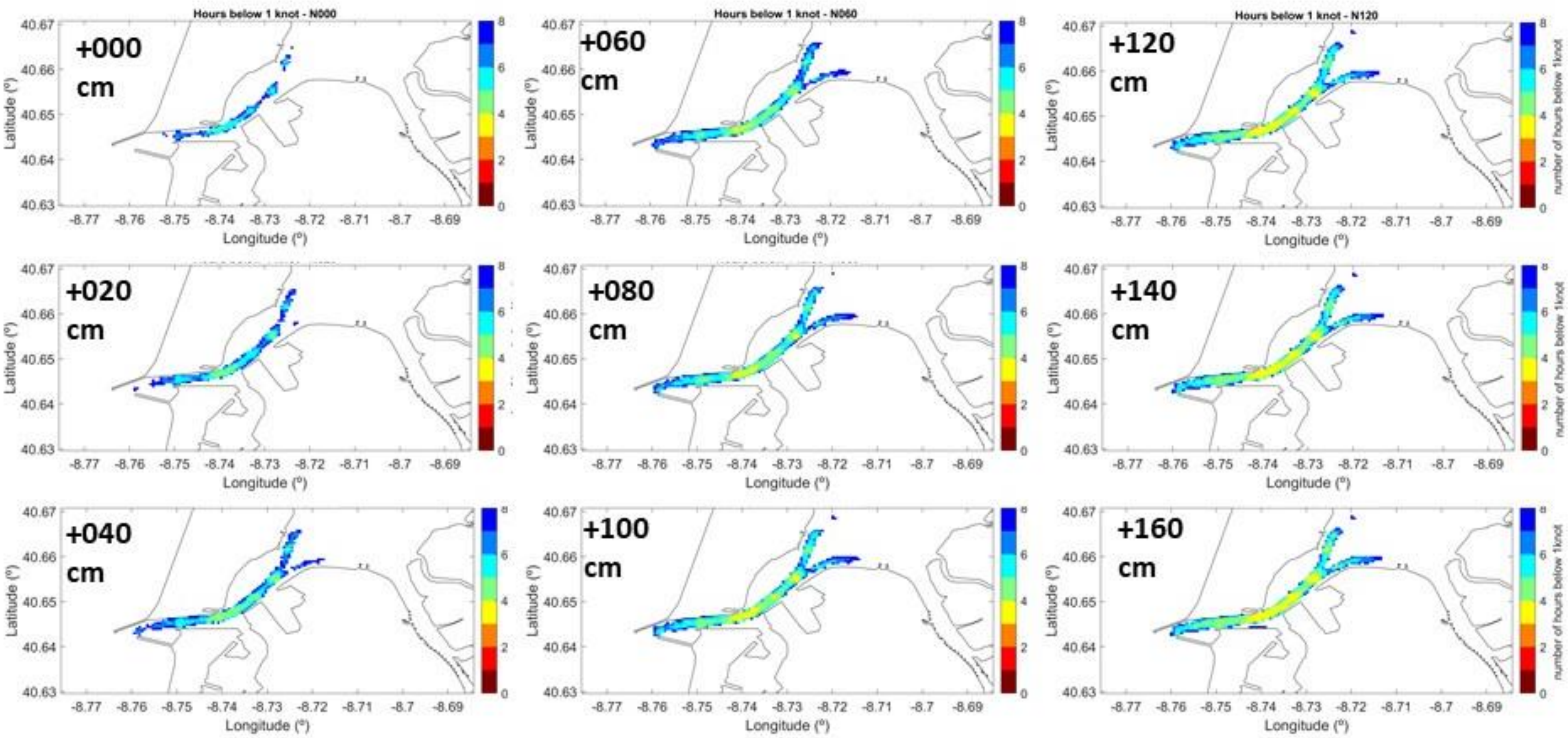


Figure 37: Number of hours with currents below threshold (1 knot) for neap tide.

Neap Tide		
+cm	Point1 [h/day]	
000	5h 00m	
020	4h 30m (-11%)	
040	4h 10m (-18%)	
060	3h 54m (-23%)	
080	3h 41m (-27%)	
100	3h 30m (-31%)	
120	3h 23m (-33%)	
140	3h 16m (-36%)	
160	3h 12m (-37%)	

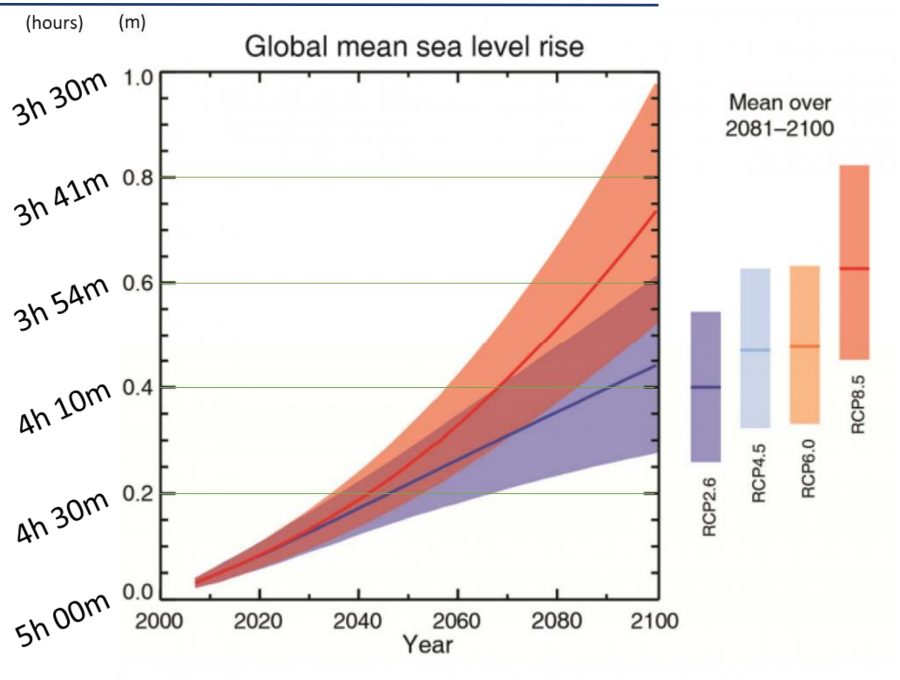


Figure 38: Operational downtime due to tidal currents. Summary of the results presented in Figure 37.

6.1.2 Port´s Infrastructure

In section 5.3 the importance of extreme analysis to infrastructure design has been highlighted. As an example, the comparison between extreme analysis applied to water level is presented, taking in considerations the present (ERA5 reanalysis) and future projections obtain from the Deltares Global Tide and Surge Model (GTSM) forced with the regional climate model (HIRHAM5) from the Danish Meteorological Institute (DMI). Figure 39 shows the projected of extreme sea level return periods (likelihood of occurrence) using a Peak Over Threshold analysis for present and future projections. The results indicate that for both future projections extreme water levels are expected to increase.

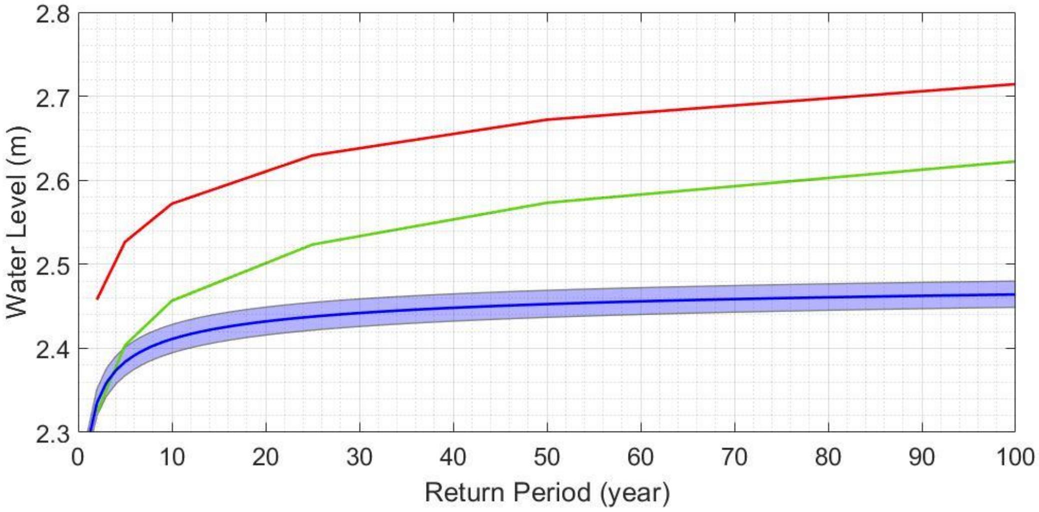


Figure 39: Extreme Sea level analysis applied to blue line (present), red line end of the century (RCP 4.5) and green line mid-century (RCP 8.5).

7 CONCLUSIONS

Ports are crucial components of the supply chain and are constantly under pressure of the increasing demand and challenges. One of the key challenges is to cope with the effects of climate change. To improve the understanding and quantification of impacts that changes in climate have in ports a strategy to identify problems, causes and consequences is needed as well as a methodology to compare baseline conditions with future projections. In this report a step approach to climate change impact evaluation was presented using the three ports of the SUDOE space as pilot test for the methodology.

By applying the developed methodology problems, causes and consequences were addressed by identifying assets and activities likely to be impacted by metocean processes; determined the relevant metocean processes; gather the relevant information on each process to create the baseline conditions and future scenarios; compare and quantify the amount of change expected and their respective impact on the identified asset/activity.

To guide the reader through the step approach presented, examples using the assets and meteocean related problems identified for the Ports of Aveiro, Bordeaux and Valencia have been used. Results show that by using coherent datasets (for both baseline and future projections) valuable information regarding future changes can be extracted such as changes in operation windows due to changes in wave clime or higher mean sea level. The results presented in this report were used with the intent to exemplify the methodology, a full analysis using for each port using the proposed approach is the subject of the next project deliverable.

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8 ANNEXES

8.1 THE IPCC

The efforts to coordinate all matters related to climate change are the responsibility of the Intergovernmental Panel on Climate Change (IPCC), the United Nations intergovernmental body responsible for producing reports covering "scientific, technical and socio-economic information relevant to understanding the scientific basis for the risk of human-induced climate change, its potential impacts and options for adaptation and mitigation." These reports contribute to the work of the United Nations Framework Convention on Climate Change (UNFCCC), the main international treaty on climate change. Its objective is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system".

The IPCC is an internationally accepted authority on climate change and produces reports that have the agreement of leading climate scientists and the consensus of participating governments. It periodically publishes reports that gather all the advances and studies developed by the scientific community and multisectoral experts on Climate Change. The reports corresponding to the IPCC Sixth Assessment Report are currently being evaluated and are expected to be published shortly. Previously, the findings of the IPCC Fifth Assessment Report were presented at the end of 2014, right now the last of the Assessment Reports fully finished.

Parallel to the IPCC, the Coupled Model Intercomparison Project (CMIP) is a collaborative framework designed to improve understanding of climate change. It was created in 1995 by the Working Group on Coupled Modelling (WGCM) of the World Climate Research Program (WCRP). The WGCM has led to a better understanding of past, present and future climate change and variability in a multi-model framework, and also defines protocols for experimentation, forcings and common results. It is developed in phases to foster the improvement of climate models, but also to support national and international climate change assessments. Throughout the different phases of this project, improvements have been made to the quality of climate models up to the current ESMs. Likewise, new emission scenarios have been defined in each of the phases, adjusting to the new adaptation and mitigation needs in the face of climate change.

8.2 THE 5th ASSESSMENT REPORT

In 2014, the IPCC presented conclusions on Climate Change drawn from a large set of simulations of different climate models (https://www.ipcc.ch/report/ar5/syr/). In order to be able to perform forward-looking simulations of all these models, a set of possible future scenarios were generated in the framework of that Assessment Report under which the climate scenario simulations were performed. Already in 2000, the

IPCC defined future climate change scenarios (https://www.ipcc.ch/site/assets/uploads/2018/03/sres-en.pdf) as follows

> Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation.

For this 5th Assessment Report, the defined scenarios to be used were the so-called Representative Concentration Pathways (RCPs).

8.2.1 THE REPRESENTATIVE CONCENTRATION PATHWAYS (RCP)

Future Climate Scenarios are usually associated in Climate Change studies with emissions scenarios as plausible descriptions of how future changes will be in a wide range of variables: socioeconomic, technological, energy, land use, greenhouse gas (GHG) emissions, and air pollutants. To fulfill this function, sets of emission scenarios were developed, such as IS92 or SRES (those associated with the fourth IPCC report). However, the need for scenarios with more detailed information has arisen in the scientific community. In response to this need, the IPCC proposed the definition of new scenarios. In this case, the proposal is for the scientific community to define these scenarios through the joint collaboration of the heads of the different centers that generate Climate Models and the heads of the Integrated Assessment Modelling centers. The idea of bringing them together lies in the fact that the latter provide additional information on socioeconomic aspects that complement the information generated by the models.

The new future scenarios to be used, those associated with the fifth IPCC report, have been named Representative Concentration Pathways (RCPs) and their definition is based on the following criteria:

1) RCPs should be based on existing emission scenarios developed by different centers and collected in the literature. At the same time each RCP should, by itself, be a plausible and internally consistent description of the future,

2) should provide information on all radiative forcings needed for climate modelling (land use, GHG emissions and air pollutants).,

3) must be harmonized, i.e. the seamless transition between the historical period (the *Historical* experiment) and future periods must be ensured and,

4) should provide information up to 2100 and be available to simulate even further out.

The name of the RCPs reflects two of their main characteristics:

1. Representative: refers to the idea that an RCP represents a set of existing emissions scenarios. In other words, the RCP must be compatible with both extreme and average scenarios.

2. Concentration Pathway: This term emphasizes that RCPs are not end products, but are the tool (input) towards the generation of emission scenarios, hence the use of concentrations instead of emissions. RCPs are understood as a sufficiently consistent set of radiative forcing components but are not a complete set of climate, socioeconomic and emission projections.

The scientific community (made up of more than 20 working groups from around the world) determined in September 2008 in Paris that the new scenarios would be RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (the name refers to the radiative forcing reached in 2100); Figure 41 represents the behaviour of these scenarios over time, expressed as radiative forcing, and Table 10 shows the features of the definition of each scenario or RCP.

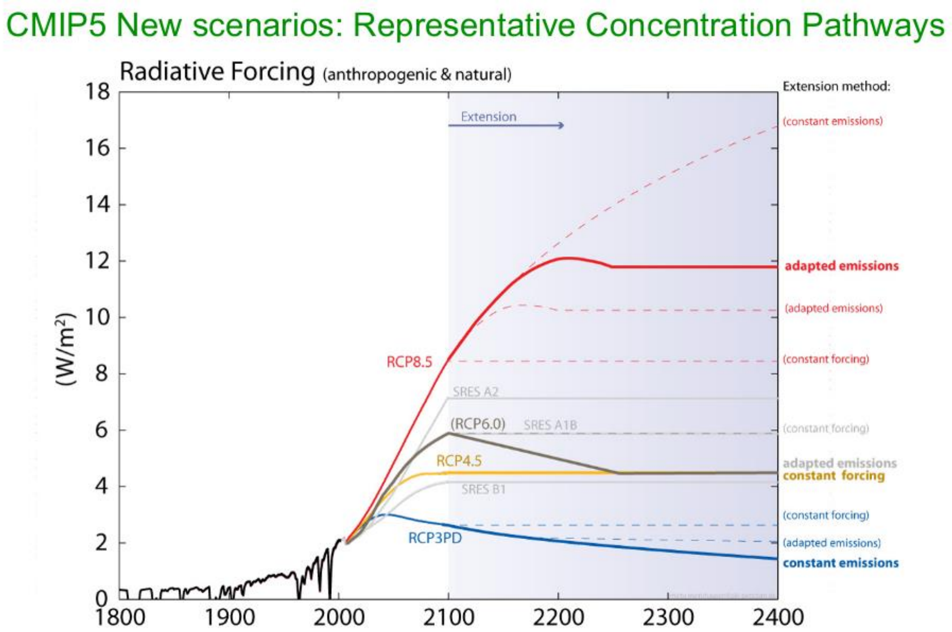

Figure 40: Radiative forcing over the 21st century associated with the different RCPs and their relationship with the IPCC 4th report scenarios (SRES). The RCP2.6 scenario appears under its original name, RCP3PD. Fuente: Meinshausen, Smith, et al. (2011).

Table 10: Main features of the different RCPs.

RCP	Features
2.6	A peak of 3 W/m^2 is reached before 2100 and then decreases to 2.6 W/m^2
4.5	Stabilizes without exceeding the level of 4.5 W/m^2 (equivalent to about 650 ppm) in 2100.
6.0	Stabilizes without exceeding the level of 6.0 W/m^2 (equivalent to about 850 ppm) in 2100.
8.5	

	Reaches 8.5 W/m^2 (equivalent to about 1370 ppm CO2 eq.) in 2100 and levels do not stabilize until 2050.

Together with the new RCPs, CMIP5 (Climate Model Intercomparison Project 5) was formed with the aim of creating a working base where all the climate information to be used in the work related to the 5th IPCC report could be made available to the scientific community.

Due to the huge amount of information generated by the different research centers, the CMIP5 has divided the information into different levels so that all the research centers provide a minimum of common information that allows comparison between them. Thus, the first level, called "Core" and to be provided by all members, is formed by RCPs 4.5 and 8.5. The second level, called "Tier 1", contains RCPs 2.6 and 6.0 and more detailed experiments, and the last level, called "Tier 2", contains more complex experiments, such as the Extended Concentration Pathways, extensions of the RCPs up to the year 2300.

8.3 THE 6th ASSESSMENT REPORT

The CMs are continuously being renewed and improved, and a new version usually appears every 4-6 years, which is used for the corresponding IPCC Assessment Report. Currently, the most recent CMs are those of CMIP6 (Coupled Model Intercomparison Project Phase 6), from which the IPCC Sixth Assessment Report (AR6) is prepared, which are currently replacing the CMIP5 CMs used in AR5.

CMIP Phase 6 began in 2013 and a summary of the design and organization was published in 2016. In 2018, 23 Model Intercomparison Projects (MIPs) involving 33 modeling groups from 16 countries were approved and were the starting point for the development of CMIP6. The structure of CMIP6 has been expanded from CMIP5 with the creation of the so-called CMIP Diagnostic, Evaluation and Characterization of Klima (DECK), which together with a set of IPMs aim to improve the description of aspects of climate models beyond the core set of common experiments included in the DECK (https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6). This new generation of CMs is now being made available to the scientific community for use in climate research: some are already available, and others are currently being made available or completed.

If possible, using these new CMs is important, as relevant new developments have been introduced in CMIP6, related to the World Climate Research Programme (WCRP) Grand Science Challenges: Clouds, Climate Circulation and Sensitivity, Changes in the Cryosphere, Climate Extremes, Regional Sea Level Rise, Water Availability, Short-Term Climate Prediction and Biogeochemical Cycles and Climate Change.

Also new in CMIP6 is the way in which future GHG concentration scenarios are considered, now through the so-called SSP (Shared Socioeconomic Pathways), instead of the RCP (Representative Concentration Pathways) used in CMIP5. The new SSP scenarios cover a similar range as the RCPs, but fill critical gaps such as, the role of certain forcings (land use and short-lived species or air quality), the effect caused by peak and trough forcings and the consequences of limiting warming below 2 °C (Eyring et al., 2016).

Such important changes mean that studies carried out with previous CM will probably soon be considered technically obsolete, so that the scientific community will recommend the use of the projections generated by this CMIP6, and stop using previous CM if possible.

8.4 THE SHARED SOCIOECONOMIC PATHWAYS (SSP)

The SSPs are scenarios of global socioeconomic changes projected up to 2100 that describe alternative socioeconomic developments. Each of the SSPs describes a line of evolution (Figure 41):

- *SSP1: Sustainability (Taking the Green Road)*
- *SSP2: Middle of the Road*
- *SSP3: Regional Rivalry (A Rocky Road)*
- *SSP4: Inequality (A Road divided)*
- *SSP5: Fossil-fueled Development (Taking the Highway)*

Figure 41: Schematic of the new SSPs. Source: O'Neill et al., 2013

Compared to the RCPs, the top five SSPs (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are more widely spaced in terms of their expected global mean temperatures, extend to lower temperatures in 2100 and sea level rise than the RCP ensemble (Meinshausen et al., 2019). Figure 42 gives an idea of the changes in temperature for the different SSPs and allows comparison with those associated with RCPs.

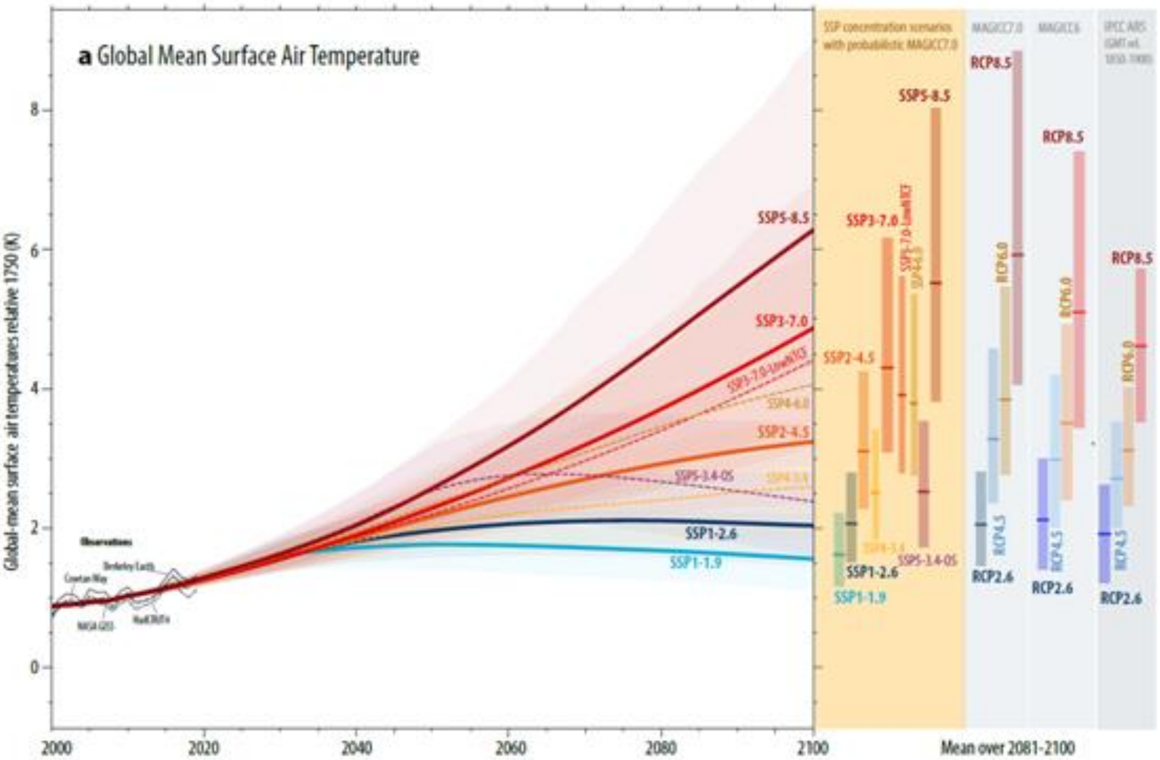

Figure 42: Comparison of illustrative projections of global mean surface temperature in the SSP and RCP scenarios. Global mean temperatures are shown relative to pre-industrial levels (1750), normalized to 0.92°C over the period 1995-2014. Time series for the period 2000-2100 are shown for the nine SSPs relative to 1750, with bold solid lines indicating the highest priority SSP scenarios and thin dashed lines indicating other so-called "level 2" scenarios. The shaded areas indicate the 5% to 95% confidence intervals for each scenario. Bar graphs illustrate the mean 2081-2100 relative to 1750 for the nine SSPs (yellow shaded area with bar graphs), and the RCP scenarios, using the same MAGICC7.0 configuration (light gray bar shaded area on the left) and an earlier MAGICC6 configuration used at the time of IPCC AR5 (light gray area on the right). Also shown is the likely range of temperature increase averages according to IPCC AR5 for that period, based on multiple lines of evidence (set of dark gray shaded bars on the right). Observational data for global mean surface temperatures, normalized over the same 1986-2005 period, are shown for Berkeley Earth (solid black), Cowtan & Way (Cowtan & Way, 2014) (long dashes), HadCRUT4 (Morice et al., 2012; Brohan et al., 2006) (small dashes), and NASA GISS (Lenssen et al., 2019) (dashes). Source: Meinshausen et al., 2019.

CMIP6 has established SSP1(2.6), SSP2(4.5), SSP3(7.0) and SSP5(8.5) as the main scenarios (from now, referred to as Tier 1). Unlike CMIP5, CMIP6 extends Tier 1 from 2 to 4 scenarios (Figure ZZ5).

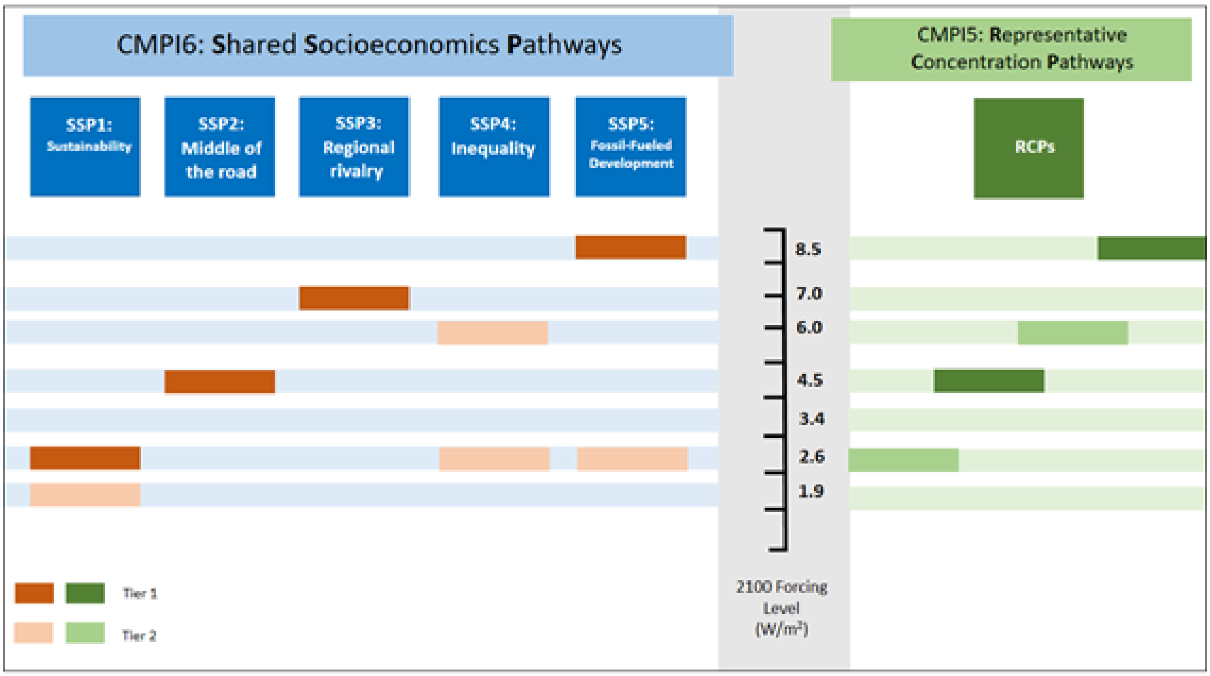

Figure 43: Comparison between the scenarios defined in CMIP6 and those defined in CMIP5. Level 1 and level 2 are defined as the scenarios to be provided on a mandatory and optional basis, respectively, by all climate models that are part of each CMIP phase. Figure based on O'Neill et al, 2016.