A review of potential physical impacts on harbours in the Mediterranean Sea under climate change.

Author 1

- Agustín Sánchez-Arcilla, Professor
- (LIM/UPC) Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya (UPC), BarcelonaTech, Barcelona, Spain Tel. (+34) 93 401 78 22. agustin arcilla@upc.edu
- Centre Internacional d'Investigació dels Recursos Costaners (CIIRC), Barcelona, Spain

Author 2

- Joan Pau Sierra, Professor
- (LIM/UPC) Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya (UPC), BarcelonaTech, Barcelona, Spain
- Centre Internacional d'Investigació dels Recursos Costaners (CIIRC), Barcelona, Spain Author 3
- Sally Brown, BSc MRes PhD
- Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Southampton SO17 IBJ, UK

Author 4

- Mercè Casas-Prat, PhD, postdoctoral researcher
- Environment and Climate Change Canada, Toronto, Canada

Author 5

- Robert James Nicholls, BSc PhD
- Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Southampton SO17 IBJ, UK

Author 6

- Piero Lionello, Professor
- DiSTeBA, University of Salento, Lecce, Italy
- CMCC (EuroMediterranean Center on Climate Change), Lecce, Italy

Author 7

- Dario Conte, PhD, postdoctoral researcher
- CMCC (EuroMediterranean Center on Climate Change), Lecce, Italy

Full contact details of corresponding author

Abstract

The potential impact of climate change on port operations and infrastructures has received much less attention than the corresponding impact for beach systems. However, ports have always been vulnerable to weather extremes and climate change could enhance such occurrences at timescales comparable to the design lifetime of harbour engineering structures. The analysis in this paper starts with the main climatic variables affecting harbour engineering and exploitation. It continues with a review of the available projections for such variables first at global scale and then at a regional scale (Catalan coast in the western Mediterranean) as a study case for similar environments in the planet. The detailed assessment of impacts starts from downscaled projections for mean sea level and wave storms (wind not considered in the paper). This is followed by an analysis of the port operations and infrastructure performance that are relevant from a climate perspective. The key climatic factors here considered are relative sea level, wave storm features (height, period, direction and duration) and their combined effect, which is expected to produce the highest impacts. The paper ends with a discussion and some examples of analyses aiming at port adaptation to future climate change.

Keywords
Climate Change, Ports, Downscaling, Mediterranean, Impacts

Introduction

Climate change impacts have been considered for vulnerable systems, including coastal areas (Sánchez-Arcilla et al. 2011; Nicholls et al. 2011). Port activities, however, have received less attention in such impact analysis (Sierra et al. 2016), although harbour exploitation is clearly conditioned by climatic variables such as wind (e.g. for crane operations), waves (e.g. for agitation inside port domains), currents (e.g. for manoeuvrability or spills) or mean level (e.g. for overtopping and flooding). Port infrastructures have often been designed for present climate, including storm events with centennial return periods (Becker et al. 2012), which are likely to be affected by climate change. Port suitability under future climates (multi-decadal scale) has either not been assessed or only partially evaluated as part of the port development plans.

Future changes of average conditions and extremes will require modifying port infrastructures, if present operations are to be maintained or even expanded. The increase in mean sea level and extreme water levels (Lionello et al. 2015) or changes in wave climate (mean or extreme) will condition essential aspects of harbour operations and infrastructure. This will affect harbours in a complex manner, modifying risk levels, economic productivity and even the harbour environmental impact. This represents one of the main climatic risks in coastal zones, since ports contribute a significant percentage of economic productivity in the coastal fringe and further inland associated with transport and economic connectivity.

This paper reviews the potential impacts of climate change on ports. First, the followed methodology is described ("Methods" section). After this, the main climatic variables affecting port operation and engineering ("Climatic variables of reference" section) are analysed, presenting selected climatic projections at global scale, in terms of mean sea level and storm features ("Large-scale projections for marine variables" section). The need for downscaling meteo-oceanographic conditions to regional scales, such as required by harbour decision making, is considered ("Downscaled projections for the Mediterranean case" section) based on a challenging case such as the Catalan coast (western Mediterranean Sea), where large human pressures and sharp topo-bathymetric gradients pose special difficulties for accurate local predictions. The paper continues with an assessment of climate change impacts on harbour exploitation and safety ("Impacts on harbour exploitation and engineering" section), considering functional and resistant aspects of infrastructures and how that conditions harbour operation, maintenance and even future development. The paper ends with some conclusions ("Conclusions" section).

Methods

This paper is based on the reviewing of previous works that have studied some of the factors relevant for the impact of sea level rise and wave storms on coastal areas and how these factors may affect harbours. Based on the gathering of the sectorized knowledge generated in these previous works, all the issues related to the potential impact of climate change on ports are put together and presented in this paper.

The processes analysed are those that most affect port engineering and exploitation. As illustration, in a study carried out by the regional government of Catalonia (DPTOP 2007) reviewing the state and main problems of the 47 Catalan ports, the following processes were considered those of more concern for port engineers because they generate problems in port safety and exploitation: siltation, overtopping, agitation and breakwater stability. Therefore, this paper examines how changes in climate variables may increase (or decrease) the magnitude of such problems, to facilitate anticipatory decisions in the face of future climate.

Most of the information and data used are from previous studies carried out by the authors, although the figures shown here are original. Specific information can be found in the following publications:

- Characteristics of wave storms in the Mediterranean area: Llonello and Sanna (2005), González-Marco et al. (2008), Sánchez-Arcilla et al. (2008a, b).
- Effects of wave storms on coastal areas: Sánchez-Arcilla et al. (2008c), Casas-Prat and Sierra (2012), Sierra and Casas-Prat (2014) and Casas-Prat et al. (2016).
- Impact of SLR on coastal areas: Nicholls and Cazenave (2010), Nicholls et al. (2011), Sánchez-Arcilla et al. (2011), Brown et al. (2013), Brown and Nicholls (2015) and Hinkel et al. (2015).
- Projections of wave climate in the Mediterranean area: Lionello et al. (2008) and Casas-Prat and Sierra (2013).
- Projections of SLR in the Mediterranean area: Conte and Lionello (2013), Scarascia and Lionello (2013), Nicholls et al. (2014) and Lionello et al. (2015).
- Impacts of changes in wave storms on ports: Sierra (2015) and Sierra et al. (2015).
- Impacts of SLR on ports: Sierra et al. (2016).

Although this study focuses on the ports of the Catalan coast (NW Mediterranean) whose location is shown in Fig. 1, the analysed problems may affect ports worldwide and the obtained conclusions should be of application to other areas.

Climatic variables of reference

This study analyses the climate of the main marine variables affecting the design, construction, exploitation and maintenance of harbours, leaving out more conventional climate variables such as temperature and wind. The considered variables are (a) mean sea level (MSL) and (b) storm features (peak wind speed, significant wave height, directions and associated surges).

Mean sea level is one of the most integrative hydrodynamic climatic variables and one of the more commonly used. Port impact assessment requires reliable downscaled values since global estimates are too coarse (Scarascia and Lionello 2013) to justify harbour decisions with extensive economic implications. It also requires an accurate consideration of all relevant terms, including surges (positive or negative) and regional steric effects on mean sea level. In semi-enclosed seas, like the Mediterranean, regional air–sea interaction features and morphological factors may distort future mean sea level (Marcos and Tsimplis 2008) with respect to the neighbouring oceans (i.e. the Atlantic Ocean). Moreover, the complex topography of these restricted domains produce irregular meteorological fields (Fig. 2) which, for the Mediterranean case, reflect the convergence of Atlantic, European and African atmospheric patterns and, although linked to larger-scale climatology, generate local variability at regional scales.

Port exploitation will also be affected by storm duration, intensity and direction. For instance along the Spanish Mediterranean coast, harbour entrances are oriented towards the south (from SW to SE) since these sectors are characterized under present climatic conditions (Lionello and Sanna 2005) by waves milder than those from the east to north quadrant, where fetches are longer and waves higher (Sánchez-Arcilla et al. 2008a). Potential changes in atmospheric circulation patterns such as the northward shifts of storm tracks in Europe could favour the development of an anticyclonic pattern over the Iberian Peninsula which would result in more southern storm waves in the Spanish Mediterranean coast, associated with the clockwise meteorological sense of rotation. In addition, the relative decrease in low-pressure centre frequency will enhance the importance of see breeze, blowing also from the south. Both effects could induce more frequent southern storm waves, which have a more direct incidence on the port mouths in that area.

Harbour-scale storm features, however, require downscaling which for semi-enclosed seas like the Mediterranean entail uncertainties introduced by the gradients in topo-bathymetry illustrated by changes in shelf width, submarine canyons or the time evolution of the shallower part of the bathymetry. This will result in variations in the wave/current fields that affect harbour operation and safety. Such effects should include, for a robust assessment, the main variables related to the impact, including wave height/period and mean sea level (Sierra and Casas-Prat 2014).

Waves are a natural “integrator” of the more variable local wind parameters and because of that wave height is often considered as preferred variable for integrated assessments of climate change effects. This, however, may result in additional uncertainties since waves can also aggregate and thus even compensate various meteorological errors, leading to erroneous conclusions. The usual approach, based on present engineering practice, starts by downscaling projections for the wave height, from which the wave period (T) and direction (Θ) are selected from a joint probability distribution function or a correlation diagram. Such an approach, excluding an actual projection of the T or Θ variables, inherently assumes that wave features (e.g. the H-T correlation) will not change with respect to present conditions (see, for example, Fig. 3, obtained from the XIOM Catalan network of meteo-oceanographic instrumentation). This hypothesis is controversial, in particular in the case of large oceans, where Hemer et al. (2013) found that the relationship between H and T is modified due to changes in swell waves. In semi-enclosed seas, due to the control of limited fetch, this swell effect becomes less important and the relationship between variables barely changes as shown by Casas-Prat and Sierra (2013). The projected changes can show opposite trends depending on regional features. For instance, in the case of Spain, there is a projected wave height increase in the North Atlantic (affecting the northern and western coasts of this country), while there does not appear to be such trend for the Mediterranean Spanish coast (Young et al. 2011; Casas-Prat and Sierra 2013). Such variability, compounded by the incertitude in projections and impact mechanisms, explain the reluctance of Harbour Authorities to act in advance with decisions that are costly (e.g. breakwater costs are in the range of 10^7 euros) and present non-negligible uncertainty.

Large-scale projections for marine variables

Projections of relative sea level rise

With climate change, temperatures are expected to increase, following the upper limit of past projections (Friedlingstein et al. 2014), and leading to a rise in global and regional mean sea levels. Determining projections of sea level rise is challenging, particularly at regional scales, as many components contribute to sea level rise and their interactions are complex (Brown et al. 2013; Church et al. 2013; Adloff et al. 2015). These components include:

(a) changes in ocean volume (thermosteric or halosteric) and dynamics;
(b) melt water from glaciers and ice caps;
(c) melt water from the large ice sheets of Greenland and Antarctica;
(d) land water storage in reservoirs.

In addition to these factors, subsidence has to be considered to assess the resulting relative sea level rise.

Thermosteric changes to ocean volume are slow to emerge from increases in global mean surface temperature, so there is a time lag (lasting decades to centuries) before their full effects will be observed, known as the commitment to sea level rise (Wigley and Raper 1993). The ice melt contribution may be larger than previous projections, and the effect of groundwater pumping and land water storage, although considered minor, is receiving increased attention (Church et al. 2013). Subsidence varies with latitude (land levels even rising with respect to sea levels due to isostatic rebounds) and with local geology. In the Mediterranean coasts, subsidence, as in many other coastal areas, becomes important for deltaic or river mouth areas. For the studied coast of Spain, this would have implications mainly for the Ebro delta and secondarily for the Llobregat delta, affecting two harbours (one at each area).

Twenty-first century sea level rise projections from Church et al. (2013) are based on 21 climate models, combined with other data and resulting in a range of projections due to scientific/model uncertainties. These include the range of possible emission scenarios called Representative Concentration Pathways (RCP) and project a likely range of global mean sea level rise between 0.26 and 0.82 m (or up to 0.98 m) by 2081–2100, both with respect to the 1986–2005 interval. Thermosteric change represents 30-55 % of this rise, with glaciers contributing 15-35 % (Church et al. 2013). Due to the commitment to sea level rise, large differences between scenarios are not seen until after mid-century. Higher rises are considered possible (up to 2m per century), although with a lower probability (Nicholls et al. 2014).

Large-scale meteo-oceanographic processes also affect variability, for example, in storm surges or temperature-related seasonal variations so marked in the Mediterranean (e.g. Jorda et al. 2012). Negative mean sea levels (negative surges, Conte and Lionello 2013) should also be considered in this area since they can change under future climatic conditions and affect harbour operations by for instance by hindering the access of larger ships.

Projections of storm tracks

The general trend in the Mediterranean (Lionello et al. 2008) shows a relative decrease in wave energy projections that, however, combined with the expected increase in mean sea level rise can still generate higher waves within harbours due to the effects of shoaling and diffraction.

Climate change may modify cyclonic activity or alter cyclonic paths in areas of sharp temperature differences. Nevertheless, projections (IPCC 2013) do not achieve high confidence on long-term trends of cyclonic activity, though some models project a likely regional (tropical) increase in their intensity. There are indications that the total number of mid-latitude storms will decrease and a medium confidence that the storm track will shift pole-ward particularly in the southern hemisphere. However, in spite of the deep uncertainties at regional scales (in predicting positions or intensities), the case of semi-enclosed seas will continue, leading to local intense low-pressure centres generation (Romero and Emanuel 2013) due to the land–water–air differences in temperature.

Even with less low–pressure centres, any increase in their strength combined with a higher MSL will produce more frequent extreme water levels (Conte and Lionello 2013). As an illustration, CHRR et al. (2005) analysed the greatest hazardous areas from a coastal perspective, which is where cyclones tend to make landfall. They found the greatest hazards occurring in central and north-east America, south-east Africa (Madagascar) and east and south-east Asia. These places are likely to experience increased extreme water levels over the coming decades, even if climate change starts to be mitigated (commitment to sea level rise). This imposes serious adaptation needs for port infrastructures and large population centres in many rapidly growing Asian locations.

Downscaled projections for the Mediterranean case

Reduction in port vulnerability to climate change requires decisions based on local (hard to achieve) or at least regional projections. Because of the scarcity of regional projections, many decision makers still rely on information obtained from global models with low spatial–temporal resolution (Becker et al. 2013).

Engineers and planners demand better regional sea level and wave climate projections, which can be modelled and downscaled from global circulation models (GCM) directly (e.g. Wang and Swail 2006) or using atmospheric climate projections from regional circulation models (RCMs), obtained through downscaling of GCMs as done, for example, in Conte and Lionello (2013). Nevertheless, the ultimate wave projections at a regional scale suffer from a cascade of uncertainties: in climate and greenhouse gas scenarios, in atmospheric–ocean (circulation) modelling and in wave modelling.

To properly assess local to regional climate change, it is necessary to consider several GCM–RCM realizations to cover as much of the uncertainty range as possible, with recent literature recommending ensembles of more than 20 elements (Déqué and Somot 2010) and excluding outliers until there is enough evidence or knowledge to explain that “unexpected” behaviour (Donat et al. 2010). Furthermore, it is far from clear which model is the “best” because model skill usually depends on analysed output variables and season, and a better simulation of the observed climate does not prove which climate response is more reliable (Déqué and Somot 2010).

These limitations of present analyses become more acute for restricted sea domains where boundary conditions and sharp gradients may easily degrade the quality of projections. This can be illustrated by the case of the Mediterranean Sea wind and wave fields, where regionalised projections based on IPCC AR5 scenarios (IPCC 2013) and CMIP5 results are currently under way (see, for example, Fig. 2). Most existing projections, however, are based on CMIP3 models (IPCC 2007), with a limited number of scenarios, as illustrated in Lionello et al. (2008), where the Mediterranean wave field was obtained with one combination of GCM–RCM and two SRES scenarios, one pessimistic (A2) and one optimistic (B2), with resolution of 50 km and 6 h. It was found that the mean significant wave height (*Hs*) over a large fraction of the Mediterranean Sea is lower for the A2 scenario than for the present climate during all seasons except in summer for two areas, those between Greece and North Africa and between Spain and Algeria, where *Hs* becomes significantly higher. These changes are similar, though smaller and less significant, in the B2 scenario, except during winter in the north-western Mediterranean, where the B2 mean *Hs* field is higher than in the present situation. Extreme *Hs* values are found to be smaller in both future scenarios except in the central Mediterranean during summer for the A2 scenario.

Alternative analyses (Casas-Prat and Sierra 2013) have projected future regional wave climate for the NW Mediterranean for the A1B scenario using 5 combinations of GCM and RCM at higher spatial (25 km) and time (3 h) resolutions. It was found a general decrease in the median *Hs* in most of the domain. However, at high latitudes near the Gulf of Genoa, there is a local rise of the median *Hs*. Summer waves show marked differences compared to winter, with a median *Hs* rising in the south part of the domain. These results are consistent with those of Lionello et al. (2008) for scenario B2. In general and for both studied seasons, maximum projected *Hs* changes are around ±10 % for mean conditions (median *Hs*) versus ±20 % for extreme climate. Results also show changes in the seasonal distribution of directional frequencies, with implications for harbour and coastal engineering.

Mediterranean mean sea level rise (Tsimplis et al. 2008; Adloff et al. 2015) has been projected (twenty-first century) using an Atmosphere-Ocean Regional Climate Models coupled over the Mediterranean basin and forced by river run-off and influxes from the Atlantic Ocean and the Black Sea. Changes in temperature and salinity under the A2 emission scenario were used to compute steric sea level changes in the region, which showed significant spatial variability with a maximum steric sea level rise of 25 cm by 2100. The mean is around 13 cm with lower values in the eastern Mediterranean and higher values at the western Mediterranean (Tsimplis et al. 2008). Further, it is clear that even at basin scale the contribution of mass addition ultimately caused by melting of ice caps remains the main source of uncertainty (Scarascia and Lionello 2013).

The downscaled projection of storm surges should be added to the steric variations and even the changes in set-up due to wind generated waves, as shown in Fig. 4 using a seven member model ensemble of regional climate simulations under the A1B scenario. These results compare two 30-year periods: 1971–2000 (reference interval) and 2021–2050 (future interval). The maximum water level “indicator” is defined as the 5-year return period maximum water level that can be reached under a storm, combining storm surges, wave effects and steric sea level variations. The figure shows the per cent variations of the indicator calculated as the difference between the two periods normalized with the reference period. Positive and negative values (panel a) indicate statistically significant increases and decreases in mean water level. The other three panels (b–d) show the same results but now considering an increase in sea level due to mass addition into the Mediterranean basin. These mass additions amount to 15, 30 and 45 cm representing the effect of melting ice caps and mountain glaciers. For the Adriatic basin and southern Mediterranean coast, there is a limited decrease, while there is an increase along the Greek coast, southern Sicily and the north-western Spanish Mediterranean coast, analysed as case study in this paper. It is also apparent how the contribution of mass by melting ice dominates over the other terms.

The regional projections of mean sea level also reflect the uncertainties in future dynamical oceanography (circulation) and the vertical (local) motion of land levels: isostatic uplift (e.g. in the Baltic coast) or subsidence (e.g. in deltaic sedimentary deposits, such as Mediterranean or south-east Asia deltas) (Peltier 2004; Ericson et al. 2006). Dynamic oceanography associated with episodic events may introduce several centimetres (up to more than 5 cm in the Mediterranean) of mean sea level variation (Adloff et al. 2015) although there is no predicted seasonal bias in the obtained sea level rise, indicating that the seasonal cycles will remain unaffected. The resulting relative (sea referred to land) levels also reflect more local anthropogenic impacts that can add a few millimetres to centimetres per year (Nicholls et al. 2014). This combination of factors must be considered for the assessment of harbour operability, where also the local settling of heavy infrastructure (e.g. breakwaters) may play a role in areas with soft soils.

Impacts on harbour exploitation and engineering

Impacts of sea level rise

In spite of uncertainty for MSL projections and, particularly its upper end this century (e.g. Rahmstorf 2007; Church et al. 2013), there have been many assessments for coastal areas (e.g. Nicholls and Cazenave 2010; Sánchez-Arcilla et al. 2011). Most of these studies have focused on beach impacts such as flooding or erosion, and only few of them have addressed climate change effects on seaports and their operations (Sierra et al. 2016).

The main direct impacts of MSL on ports come from overtopping and flooding through the effect of storm events for an increased mean sea level. In addition, sea level rise will change water depths and, as a consequence, it will indirectly modify wave propagation patterns, potentially affecting breakwater stability and scouring, harbour siltation and agitation. One of the earliest impacts will be that of flooding and overtopping for which there are a number of predictive formulations depending on breakwater cross section (Pullen et al. 2007). Using the more suited empirical methods for Mediterranean harbours, the impact of sea level rise has been analysed for 43 ports along the Catalan coast (NE Spain, Fig. 5). The analysis uses three scenarios besides the present situation (scenario 0). Average and high-end projections for MSL have been derived from RCP 4.5 and RCP 8.5 in IPCC AR5 (Church et al. 2013), plus a plausible although unlikely global rise of 1.8–2.0 m as representative of high-end conditions (Jevrejeva et al. 2009). These values correspond to the upper tail of the probabilistic distribution for the mean sea level value (1.8 m corresponds to the 95 % quantile associated with RCP 8.5 projections by 2100). These values could also become more likely in the event of accelerated ice sheet dynamics and rapid rate of ice melt from Greenland and Antarctica. For the RCP 4.5 scenario, representing a middle range domain for impact assessments, the central value of MSL rise by 2100 is 0.53 m, while for the RCP 8.5 scenario, representing a more unfavourable domain for impact assessments, the upper bound of MSL rise by 2100 is 0.98 m. Both SLR values represent the increase by 2100 with respect to 1986–2005. Moreover, AR5 projections (Church et al. 2013) indicate that sea level rise in the Mediterranean may be slightly lower than the global average or show a certain time lag.

Based on these considerations and assuming a Mediterranean MSL rise 10 % lower than the global average and considering that there are no MSL variations along the studied area due to its limited extension, the scenarios considered here for the year 2100 are:

- Scenario 0: Base conditions (present situation, reference period 1986–2005)
- Scenario 1: RCP 4.5 (Base conditions + 0.47 m)
- Scenario 2: RCP 8.5 (Base conditions + 0.88 m)
- Scenario 3: High-end scenario (Base conditions + 1.80 m)

To assess overtopping risks (in terms of vulnerability since we shall not deal explicitly with the hazards or probabilities of occurrence) under different sea level rise scenarios, it is essential to define "acceptable" discharges (volumetric flux rates over the structure) for each port considered. Acceptable discharges depend on the activities carried out behind the structure; for instance for isolated breakwaters, without flood sensitive assets and no moored ships in the lee side, the allowable discharge is larger than for breakwaters with docks or berthed boats (Burchart and Hughes 2003). Defining tolerable discharges based on the values suggested in Pullen et al. (2007) and considering wave storm return periods of 1, 5 and 50 years (representing mean weather conditions, relatively strong storms and exceptional storms), it is possible to analyse vulnerability to overtopping, in this case for the studied ports along the

Catalan coast. The wave height distribution under storms has been obtained from 4 wave buoys deployed along this coast.

Five vulnerability classes (very low, low, medium, high or very high) have been defined as a function of discharge exceedances following Sierra et al. (2016) and representing common risk levels in harbour operation. These five classes are the ones commonly employed for present engineering calculations (Pullen et al. 2007), and they are shown in risk maps (Fig. 5), corresponding to storm conditions with return period of 5 years and for MSL according to the four sea level rise scenarios considered. Even a moderate increase in MSL affects vulnerability (in level and number of ports affected), and, from here, any acceleration of sea level rise will increase port risk levels in the Mediterranean and worldwide.

Another potential consequence of sea level rise in ports comes from decreased clearance under bridges, causing disturbances to navigation particularly for ports located in rivers and estuaries in micro-tidal areas, where there is not the flexibility associated with high tidal ranges. MSL variations can also affect port operations, including berthing and cargo loading/unloading, due to the reduction in dock freeboards. They can also flood docks and infrastructures (railways, roads), affecting and potentially interrupting port accesses and operations. This can be illustrated by the port land areas established in deltas or other low-lying coastal tracts, such as is the case of Barcelona harbour. On the contrary, although sea level rise could change siltation rates (increasing or decreasing the amount of sediment deposited in the port), it will entail a positive impact due to the increase in the available port draft with the associated benefits for navigation.

Finally, sea level rise entails changes in water depth and therefore in the bathymetry for the port and surrounding areas. This will modify wave propagation patterns, generating changes in processes like shoaling, refraction and diffraction and giving rise to different nearshore wave fields. Although *shoaling* and refraction may have opposite (and, thus, compensating effects) on wave height, the increase in water depth could result in waves breaking closer to the coast and therefore higher maximum heights. This can affect breakwater stability and scouring, siltation and agitation, in a way that is difficult to assess because directional changes will be specific for each individual case. In some instances, wave heights can increase (reducing breakwater stability, enhancing scouring, siltation and agitation) and in others can decrease, with opposite and positive impacts. Changes in wave direction can also enhance/reduce agitation and siltation, requiring the specifics of each case for a meaningful assessment. Table 1 summarizes the potential impacts associated with sea level rise and their sign (worsening or improvement of port conditions).

Impacts of future wave storms

The effect of sea level rise via enhanced wave impacts may be compounded by changes in storm features as reported in the literature (e.g. Weisse and von Storch 2010; Sánchez-Arcilla et al. 2011). Climatic changes in ocean waves are detectable in terms of intensity and duration (e.g. Hemer et al. 2013) although with a large uncertainty associated with wave storm projections (Church et al. 2013). These changes may generate impacts on coastal erosion (e.g. Casas-Prat et al. 2016), harbour structures (Sierra and Casas-Prat 2014) and harbour agitation (Casas-Prat and Sierra 2012; Sierra et al. 2015).

Ports under climate change will have to minimize inactivity and decreases in operational performance caused by adverse (or different with respect to present design conditions) climate factors such as wind and wave patterns near or inside the harbour. Changes in wave conditions can affect harbour wave agitation (short wave oscillations without including long waves) depending on storm parameters (height, period and direction) and on harbour geometry (plan shape, bathymetry and reflectivity of structures). As a result, variability in harbour agitation patterns under climate change will be specific for each port.

Wave fields inside harbour domains cannot be calculated with compact formulations, and the use of detailed numerical models, requiring a large amount of case specific information, is required. This can be illustrated by the projected harbour agitation inside 13 harbours in the Catalan coast (see Sierra et al. 2015 for more details). The analysis was based on a model for wave propagation (Boussinesq type) which is able to reproduce reflection, diffraction and long waves inside the harbour. Such model is forced by propagated offshore wave projections that were obtained by using 5 combinations of RCM–GCMs and the A1B scenario from AR4 since the corresponding multi-model downscaled projections from AR5 were not yet available. A sample illustration of this analysis appears in Fig. 6, showing the projected yearly average wave field (present and future) inside one of the studied harbours (L'Ametlla de Mar) located at the southern sector of the Catalan coast. This figure also shows the changes between future and present conditions, where a slight increase in yearly wave intensity is observed in most of the port layout. For several other ports, the general trend was decreasing agitation but with a large uncertainty.

Adapting to climate change starts from an assessment of present conditions and is followed by a sequential set of interventions. By way of illustration, Fig. 7 shows how to reduce harbour agitation due to a change in wave direction (as projected to happen in the NW Mediterranean) by modifying the port layout. The analysed port (Marina de Palamós) is located on the northern Catalan coast, and the simplest solutions would be the extension of the main breakwater or the construction of a new secondary breakwater (Sierra 2015), both of them reducing (as schematized in the figure) wave agitation (height) inside the harbour. Based on this and other analyses, we expect seasonal and regional variations in the projected changes in harbour wave conditions due to port geometry and storm features. For the NW Mediterranean, there is a decreasing agitation trend in winter and an increase during the summer season. These results are relevant for management and engineering since the increase in agitation in summer will coincide with a higher port occupancy (around 97 %) in most of the facilities (marinas), hindering the use of boats as living quarters and their manoeuvrability (Sierra et al. 2015).

When subject to climate change, many existing ports will be faced with increasing risk levels due to functional or structural failure or impairment unless physical, economical, institutional or legislative adaptation occurs. The situation will aggravate for existing ports, not conveniently maintained or upgraded since the actual risk level will also be larger than that calculated at the project time, even in the absence of climate change (due, for example, to breakwater section weakening or scouring).

The more commonly suggested lines of intervention (Becker et al. 2013) are based on updating infrastructures, increasing their crest level (without any additional upgrading) or relocating (activities, terminals or even the complete harbour). Hard solutions (based on concrete or stones) will require a continuous updating at decadal scales since the rate of sea level rise will keep on growing worldwide and with an acceleration near the end of the selected projection horizon (by 2100). Soft solutions will also demand maintenance (e.g. dredging or artificial nourishment for morphodynamic impact mitigation) but with a different sequence in time, depending on the type of measure and the rate of impact.

Changes in storminess may also affect port environmental management and impacts. The barrier effect of ports on sediment transport results in erosion (requiring impact mitigation) and/or siltation (requiring dredging). Both entail expensive mitigation and maintenance depending on the amount of projected climate change at local (regional) scale and harbour and coastal geometry. Impact assessment includes a variety of processes and scales under present conditions (see, for example, Sánchez-Arcilla et al. 2008b), and becomes more uncertain for future scenarios where it is also required to project the expected sediment availability. Assuming an unlimited supply of sediment, previous studies have shown (e.g. Sierra and Casas-Prat 2014) that siltation is particularly sensitive to changes in wave height followed by changes in wave direction. For regions where no major changes in wave height are expected, the barrier effect will be mainly associated with modified wave propagation directions.

Scouring by removal of granular bed material at the seaward toe of maritime structures is another process that can be affected by storminess. The resulting erosion will depend on the wave height and period in front of the structure, the breakwater slope and depth at the slope toe. Greater structural slopes at shallower depths will experience larger scouring resulting in partial damage or, in some cases, complete failure of a structure (Burchart and Hughes 2003).

Changes in storminess may also affect structural stability. In the case of rubble mound breakwaters, the design is based on the calculation of the main armour unit weight, which is proportional to the cube of the significant wave height at the structure toe. This means that small increases in wave height (due to larger water depths in front or to increases in wave energy) will generate a nonlinear augment in the necessary weight of breakwater units. In the case of vertical structures, any increase in wave height will produce greater stresses on the breakwater, decreasing its safety coefficients for sliding and overturning. Table 1 also includes the potential impacts associated with changes in wave height or direction and their sign (worsening or improvement of port conditions).

Impacts of other climatic factors

Besides sea level rise and wave climate, there are several additional climatic (physical) factors that can have an impact on port engineering and exploitation. Any climate modification of wind velocities and directions may affect structural safety and functionality (via enhanced overtopping) and many port operations (e.g. loading/unloading, ship berthing or crane operations) that can only be performed under certain thresholds. The expected increase in temperatures will also affect in a regionally different manner MSL and the occurrence of impulsive storm development (Sánchez-Arcilla et al. 2008b). Larger storm surges and set-up will result in higher MSL (González-Marco et al. 2008) in front of the structures, affecting their performance.

Impulsive storms, such as medicanes (Romero and Emanuel 2013) in the Mediterranean, will result in higher than usual MSL occurring (according to available projections) with a lower level of yearly average wave energy. Such explosive cyclo-genesis leads to extreme precipitation that could cause localized flooding and changes in sedimentation patterns that will increase dredging requirements (Becker et al. 2012). These heavy rains can also interrupt land transport and, as a consequence, disturb cargo arrival to or evacuation from the port. Finally, extreme rains may increase river discharges, jeopardizing the facilities of many ports located in estuaries, that could be flooded and, thus, more vulnerable to other climatic factors. This may imply a different management strategy for ports and in general for any assets in the coastal zone, balancing the advantages and disadvantages of a management based on average trends versus a management considering risk levels and, thus, extremes (Hinkel et al. 2015).

All these elements will affect ports worldwide in a complex pattern that will favour certain connecting routes and hamper some of the present flow lines. Coastal typology, tidal range and the presence of ice illustrate the wide range of regional variability to be expected. For instance, the decreasing volume of ice in the Arctic may allow free passage from the Pacific to the Atlantic and affect the relative weight of certain ports in world trade. This, together with the already described effects of climate change on harbour exploitation, may force revisiting harbour infrastructure and operation criteria worldwide.

Conclusions

Climate change effects on coastal zones have been considered extensively, but the impact on sea ports has received comparatively much less attention, though it is the economic activity of harbours that often justifies the presence of coastal cities and the corresponding local beach demand. This is due to the concentration of population near coastal cities and the projected growth of coastal inhabitants that is expected to exceed that of other areas in the planet.

The main marine climatic (physical) variables for projecting impacts are mean sea level, storm surges and wave storminess. Mean sea level is the addition of a number of contributors that have global (e.g. increases in temperature) or regional/local (e.g. subsidence) scopes. It is also affected by dynamic ocean processes such as circulation or wave fields in the area. Wave features are the main "pressure" for the resistant/functional performance of port structures since they condition port operations and safety levels.

Introducing climatic projections in port engineering and management requires at least regional analyses, since it is otherwise difficult to justify costly infrastructure decisions based on global values with unspecified information at local scales. The difficulty for downscaling gets worse for semi-enclosed seas, like the Mediterranean, with sharp gradients and tough to quantify boundary conditions. This case has been selected for illustrating the analysis of climate change impacts, covering functional/resistant/environmental aspects. Their efficient mitigation requires a structured set of interventions that should be made up of a combination of hard and soft solutions, so that the port evolution with climate change can become sustainable, avoiding short-term decisions that may limit longer-term solutions under future scenarios.

This paper has shown the main potential impacts on ports associated with climate change. Considering climate projections of physical variables, these impacts can be assessed leading to engineering applications that are important for future management of ports and their infrastructure. This has been illustrated by the assessment of overtopping risks and discharges for a set of Mediterranean ports, computation of wave agitation inside harbours under various climate scenarios, indication of specific measures for mitigating the effects of likely changes of wave directions and overall impact assessment including multiple processes and scales. Such an approach requires starting from robust downscaled climatic projections and proposing efficient combinations of interventions that are suitable and remain "attractive" also under future conditions (e.g. in a future with limited energy available). Such a combined consideration of short to long timescales should allow a more realistic assessment of impacts and facilitate the introduction of climate projections into port operations and decisions.

Acknowledgments

The work described in this publication was funded by the European Union Framework Programme through the grant to the budget of the Collaborative Project RISES-AM-, Contract ENV-2013-two-stage-603396. It has also benefitted from the data in PLAN-WAVE project (CTM2013-45141-R, co-financed by FEDER funds).

References

Adloff F, Somot S, Sevault F, Jorda G, Aznar R, Déqué M, Herrmann M, Marcos M, Dubois C, Padorno E, Alvarez-Fanjul E, Gomis D (2015) Mediterranean Sea response to climate change in an ensemble of 21st century scenarios, Clim Dyn, doi:10.1007/s00382-015-2507-3

Becker A, Inoue S, Fischer M, Schwegler B (2012) Climate change impacts on international seaports: knowledge, perceptions, and planning, efforts among port administrations. Clim Change, 110:5-29. doi:10.1007/s10584-011-0043-7

Becker AH, Acciaro M, Asariotis R, Cabrera E, Cretegny L, Crist P, Esteban M, Mather A, Messner S, Naruse S, Ng AKY, Rahmstorf S, Savonis M, Song D-W, Stenek V and Velegrakis AF (2013) A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. Clim Change 120:683-995. doi:10.1007/s10584-013-0843-z

Brown S, Nicholls RJ (2015) Subsidence and human influences in mega deltas: the case of the Ganges-Brahmaputra-Meghna. Science of The Total Environment 527-528:362-374. doi: 10.1016/j.scitotenv.2015.04.124

Brown S, Nicholls RJ, Lowe JA, Hinkel J (2013) Spatial variations of sea-level rise and impacts: an application of DIVA. Climatic Change. doi:10.1007/s10584-013-0925-y

Burchart HF, Hughes SA (2003) Coastal Engineering Manual. Part VI, Chapter V: Fundaments of design. Department of the Army, U.S. Army Corps of Engineers, Washington DC, 316p.

Casas-Prat M, Sierra JP (2010) Trend analysis of wave storminess: wave direction and its impact on harbour agitation. Nat Hazard Earth Syst Sci 10:2327–2340. doi:10.5194/nhess-10-2327-2010

Casas-Prat M and Sierra JP (2012) Trend analysis of wave direction and associated impacts on the Catalan Coast. Climatic Change 115:667-691. doi:10.1007/s10584-012-0466-9

Casas-Prat M and Sierra JP (2013) Projected future wave climate in the NW Mediterranean Sea. Journal of Geophysical Research Oceans 118:3548-3568. doi:10.1002/jgrc.20233

Casas-Prat M, McInnes KL, Hemer MA, Sierra JP (2016) Future wave-driven coastal sediment transport along the Catalan Coast (NW Mediterranean). Regional Environmental Change. doi:10.1007/s10113-015-0923-x

CHRR et al. (2005) Global Cyclone Hazard Frequency and Distribution. Version 1.0. Raster digital data. Center for Hazards and Risk Research, Columbia University; Center for International Earth Science Information Network, Columbia University; International Bank for Reconstruction and Development/The World Bank; and United Nations Environment Programme Global Resource Information Database. CHRR, Columbia University, Palisades, NY

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS (2013) Sea level change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working Group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, New York NY

Conte D and Lionello P (2013) Characteristics of large positive and negative surges in the Mediterranean Sea and their attenuation in future climate scenarios. Global and Planetary Change 111:159-173. doi:10.1016/j.gloplacha.2013.09.006

Déqué M and Somot S (2010) Weighted frequency distributions express modelling uncertainties in the ENSEMBLES regional climate experiments. Climate Research 44:195-209. doi:10.3354/cr00866

Donat M, Leckebusch G, Pinto J and Ulbrich U (2010) European storminess and associated circulation weather types: Future changes deduced from a multi-model ensemble of GCM simulations. Climate Research 42:27-43. doi:10.3354/cr00853

DPTOP (2007) Pla de Ports de Catalunya. Departament de Política Territorial i Obres Públiques, Generalitat de Catalunya, Barcelona

Ericson JP, Vörösmarty CJ, Dingman SL, Ward LG and Meybeck M (2006) Effective sea-level rise and deltas: causes of change and human dimension implications. Global and Planetary Change 50:63-82. doi:10.1016/j.gloplacha.2005.07.004

Friedlingstein P, Meinshausen M, Arora V, Jones C, Anav A, Liddicoat S, Knutti R (2014) Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks. J of Climate 27:511-526. doi:10.1175/JCLI-D-12-00579.1

González-Marco D, Bolaños R, Alsina JM, Sánchez-Arcilla A (2008) Implications of nearshore processes on the significant wave height probability distribution. Journal of Hydraulic Research 46(S2):303-313. doi:10.1080/00221686.2008.9521963

Hemer MA, Fan Y, Mori N, Semedo A and Wang XL (2013) Projected change in wave climate from a multi-model ensemble. Nature Climate Change 3:471–476. doi:10.1038/nclimate1791

Hinkel J, Jaeger C, Nicholls RJ, Lowe J, Renn O, Peijun S (2015) Sea-level risk scenarios and coastal risk management. Nat Clim Change 5:188-190

IPCC 2007. Climate change 2007. The physical science basis. In: Solomon S, Qin D, Manning M (eds). Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.

IPCC 2013. Climate change 2013. The physical science basis. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds.). Contribution of working Group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535p.

Jevrejeva S, Grinsted A and Moore JC (2009) Anthropogenic forcing dominates sea level rise since 1850. Geophysical Research Letters 36, L20706. doi:10.1029/2009GL040216

Jorda G, Gomis D, Álvarez-Fanjul E and Somot S (2012) Atmospheric contribution to Mediterranean and nearby Atlantic sea level variability under different climate change scenarios. Global and Planetary Change 80-81:198-214. doi: 10.1016/j.gloplacha.2011.10.013

Lionello P and Sanna A (2005) Mediterranean wave climate variability and its links with NAO and Indian Monsoon. Clim.Dyn. 25:611-623. doi: 10.1007/s00382-005-0025-4

Lionello P, Cogo S, Galati MB and Sanna A (2008) The Mediterranean surface wave climate inferred from future scenario simulations. Global and Planetary Change 63:152-162. doi: 10.1016/j.gloplacha.2008.03.004

Lionello P, Conte D, Scarascia L, Sanchez-Arcilla A, Sierra JP, Mosso C (2015) Impacts of high-end climate change scenarios on the Mediterranean coast. Proc. AGU Joint Assembly 2015, Montreal, Canada

Marcos M and Tsimplis MN (2008) Comparison of results of AOGCMs in the Mediterranean Sea during the 21st century. Journal of Geophysical Research 113:C12028. doi:10.1029/2008JC004820

Mase H, Tsujio D, Yasuda T, Mori N (2013) Stability analysis of composite breakwater with wave-dissipating blocks considering increase in sea levels, surges and waves due to climate change. Ocean Eng 71:58–65. doi:10.1016/j.oceaneng.2012.12.037

Nicholls RJ and Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328:1517-1520. doi:10.1126/science.1185782

Nicholls RJ, Marinova N, Lowe JA, Brown S, Gusmão D, Hinkel J and Tol RSJ (2011) Sea-level rise and its possible impacts given a ‘beyond 4°C world’ in the twenty-first century. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 369(1934):161-181. doi: 10.1098/rsta.2010.0291

Nicholls RJ, Hanson SE, Lowe JA, Warrick RA, Lu X and Long AJ (2014) Sea-level scenarios for evaluating coastal impacts. Wiley Interdisciplinary Reviews WIREs. Climate Change 5, pp.129–50

Peltier WR (2004) Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) model and GRACE. Ann. Rev. Earth. Planet. Sci. 32:111-149. doi: 10.1146/annurev.earth.32.082503.144359

Pullen T, Allsop NWH, Bruce T, Kortenhaus A, Scüttrumpf H, van der Meer JW (2007) EurOtop wave overtopping of sea defences and related structures: assessment manual. Kuratorium für Forschung in Küsteningenieurwesen, Heide

Rahmstorf S (2007) Sea-level rise a semi-empirical approach to projecting future. Science 315:368-370. doi:10.1126/science.1135456

Romero R and Emanuel K (2013) Medicane risk in a changing climate. Journal of Geophysical Research, Atmospheres 118:5992-6001. doi:10.1002/jgrd.50475

Sánchez-Arcilla A, Gonzalez-Marco D, Bolaños R (2008a) A review of wave climate and prediction along the Spanish Mediterranean coast. Nat. Hazards Earth Syst. Sci. 8:1-12. doi:10.5194/nhess-8-1217-2008

Sánchez-Arcilla A, Gonzalez-Marco D, Doorn N, Kortenhaus A (2008b) Extreme values for coastal, estuarine, and riverine environments. Journal of Hydraulic Research 46(S2):183-190. doi:10.1080/00221686.2008.9521953

Sánchez-Arcilla A, Mendoza ET, Jiménez JA, Peña C, Galofré J, Novoa M (2008c). Beach erosion and storm parameters. Uncertainties for the Spanish Mediterranean. Proc 31st Int Conf on Coastal Eng, Hamburg, pp. 2352-2362

Sánchez-Arcilla A, Mösso C, Sierra JP, Mestres M, Harzallah A, Senouci M and El Rahey M (2011) Climatic drivers of potential hazards in Mediterranean coasts. Regional Environmental Change 11:617-636. doi:10.1007/s10113-010-0193-6

Scarascia L and Lionello P (2013) Global and regional factors contributing to the past and future sea level rise in the Northern Adriatic Sea , Global and Planetary Change 106:51-63. doi: 10.1016/j.gloplacha.2013.03.004

Sierra JP (2015) Study of agitation for improving the Marina of Palamós. Maritime Engineering Laboratory, Technical Report TR-LIM/AHC-15-1, Barcelona, 30p (in Catalan).

Sierra JP, Casanovas I, Mösso C, Mestres M, Sanchez-Arcilla A (2016) Vulnerability of Catalan (NW Mediterranean) ports to wave overtopping due to different scenarios of sea level rise. Regional Environmental Change. doi: 0.1007/s10113-015-0879-x

Sierra JP, Casas-Prat M (2014) Analysis of potential impacts on coastal areas due to changes in wave conditions. Climatic Change 124:861-876. doi:10.1007/s10584-014-1120-5

Sierra JP, Casas-Prat M, Virgili M, Mösso C and Sanchez-Arcilla A (2015) Impacts on wave-driven harbour agitation due to climate change in Catalan ports. Natural Hazards and Earth System Sciences 15:1695-1709. doi:10.5194/nhess-15-1695-2015

Suh K-D, Kim S-W, Kim S, Cheon S (2013) Effects of climate change on stability of caisson breakwaters in different water depths. Ocean Eng 71:103–112. doi:10.1016/j.oceaneng.2013.02.017

Takagi H, Kashihara H, Esteban M, Shibayama T (2011) Assessment of future stability of breakwaters under climate change. Coast Eng J 53:21–39. doi:10.1142/S0578563411002264

Tsimplis MN, Marcos M and Somot S (2008) 21st century Mediterranean sea level rise: Steric and atmospheric pressure contributions from a regional model. Global and Planetary Change 63:105-111.doi: 10.1016/j.gloplacha.2007.09.006

Wang X and Swail V (2006) Climate change signal and uncertainty in projections of ocean wave heights. Climate Dynamics 26:109-126. doi:10.1007/s00382-005-0080-x

Weisse R and von Storch H (2010) Marine climate and climate change. Storms, wind waves and storm surges. Springer, Praxis Publishing, Chichester, UK

Wigley TML and Raper SCB (1993) Future changes in global mean temperature and sea level. In: R.A. Warrick, E.M. Barrow and T.M.L. Wigley (Eds.) Climate and sea level change: observation, projections and implications. Cambridge University Press, Cambridge, UK:111-113

Young IR, Zieger S and Babanin AV (2011) Global Trends in Wind Speed and Wave Height. Science 332(6028):451-455. doi:10.1126/science.1197219

Process	Climatic variable						Previous studies
	Wave height		Wave direction		SLR		
	Sign	Impact	Sign	Impact	Sign	Impact	
Dock flooding	↑	-	N	-	↑	W	
	↓	-	S	-			
Basin agitation	↑	W	N	I	↑	W	Casas-Prat and Sierra (2010, 2012) Sierra et al. (2015)
	↓	I	S	W			
Port siltation	↑	W	N	I	↑	I	Sierra and Casas-Prat (2014)
	↓	I	S	W			
Breakwater stability	↑	W	N	U	↑	U	Takagi et al. (2011) Mase et al. (2013) Suh et al. (2013)
	↓	I	S	U			
Breakwater overtopping	↑	W	N	U	↑	U	Sierra and Casas-Prat (2014) Sierra et al. (2016)
	↓	I	S	U			
Breakwater scouring	↑	W	N	U	↑	U	Sierra and Casas-Prat (2014)
	↓	I	S	U			

Table 1: Port processes affected by climatic change, climatic variables, trend of the impact according to the sign of the variable and previous studies. ↑ indicates increase and ↓ decrease in the climatic variable; N denotes turning northwards and S southwards; W means worsening and I improvement with respect to present conditions; U denotes unpredictable (i.e. the trend cannot be previously predicted and depends on the specific port features).

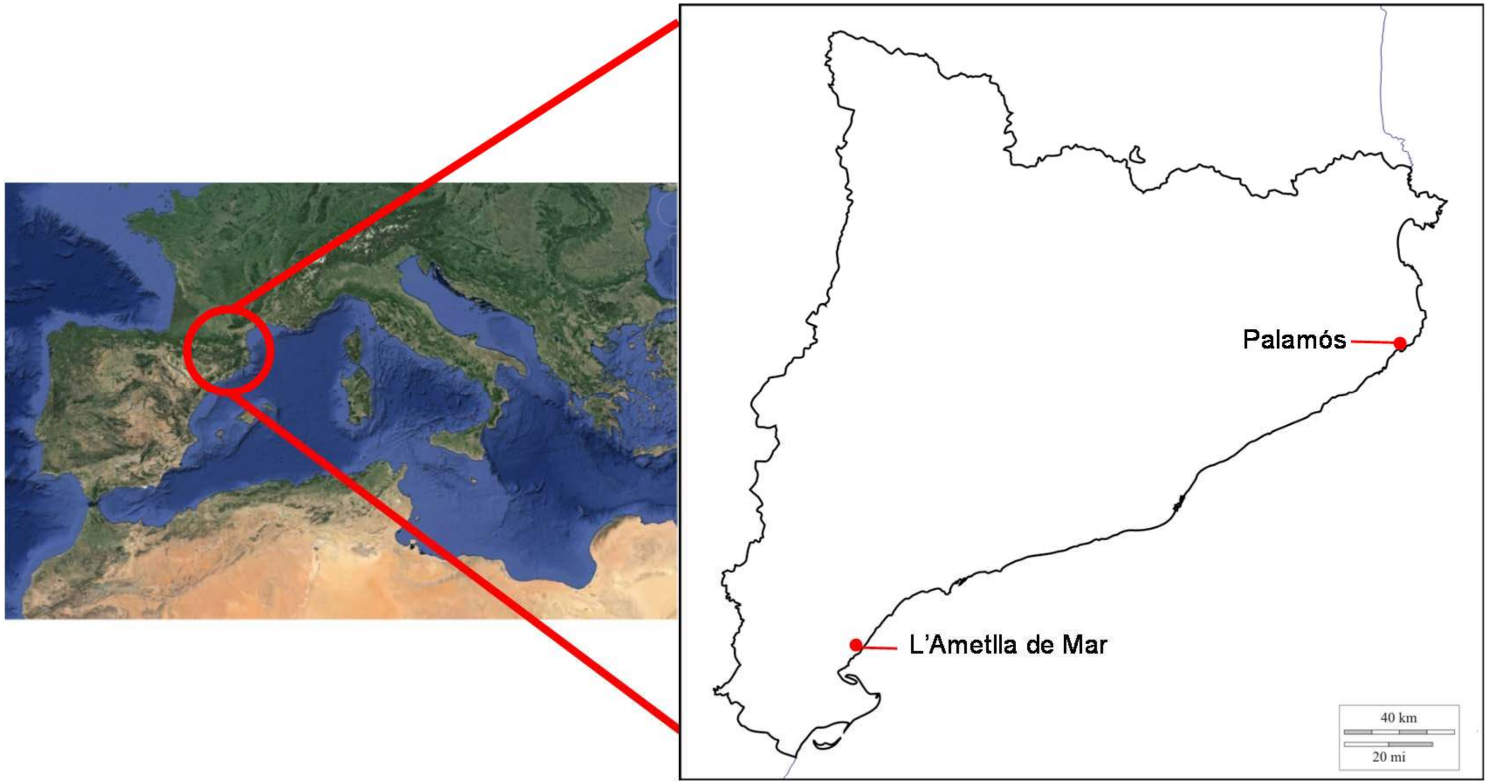

Fig 1 Location of the study area in the NW Mediterranean. The location of two analysed ports is also shown.

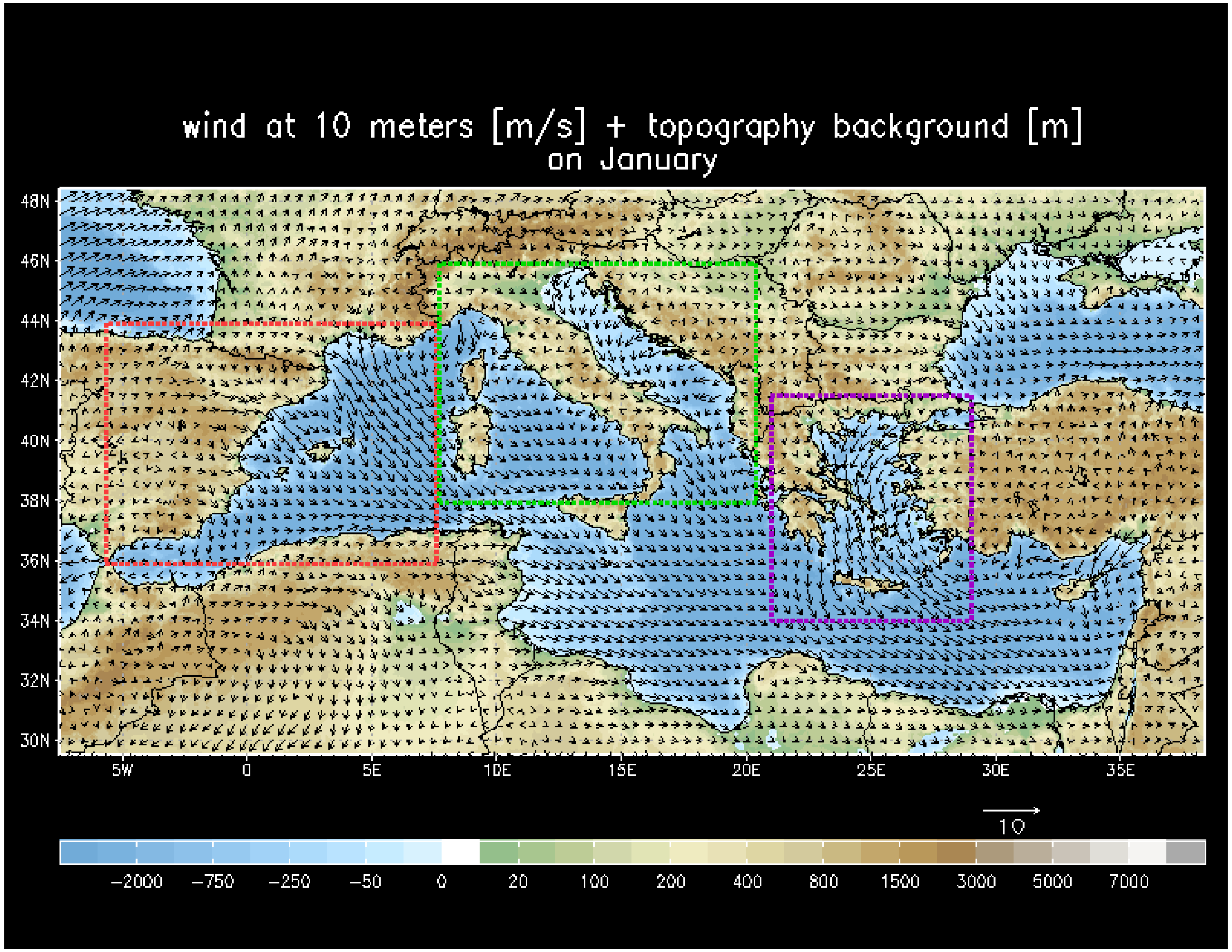

Fig 2 Simulated meteorological field over the Mediterranean, reflecting how the topography (in particular the mountain ranges) affects the European and African wind patterns. Because of this complexity, present-day forecasting and future scenario projection are subject to higher uncertainties than for the case of more regular and larger domains. The *boxes* indicate subdomains where downscaling is performed.

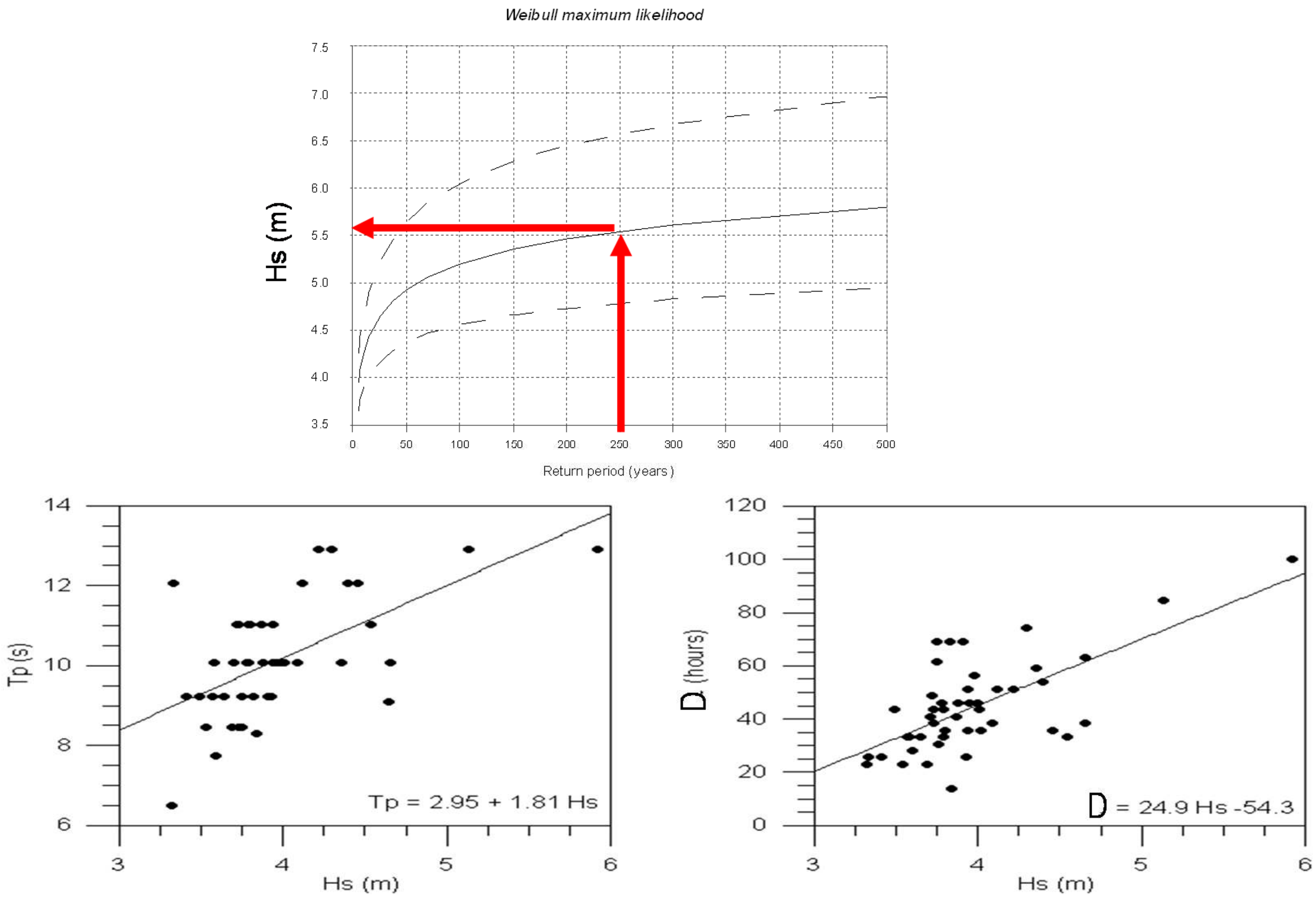

Fig 3 Illustration of the correlation between wave height (*Hs*) and wave period (*Tp*), showing how in the conventional approach only the wave height (upper panel) is assessed from a probabilistic analysis. The period (bottom left panel) and other storm parameters such as duration (D) (bottom right panel) are normally selected in a deterministic manner, with important uncertainty intervals as shown by the correlations in the panels. Data were obtained from the Catalan network of buoys (XIOM). For additional information, see Sánchez-Arcilla et al. (2008a, 2008b, 2008c) and González-Marco et al. (2008).

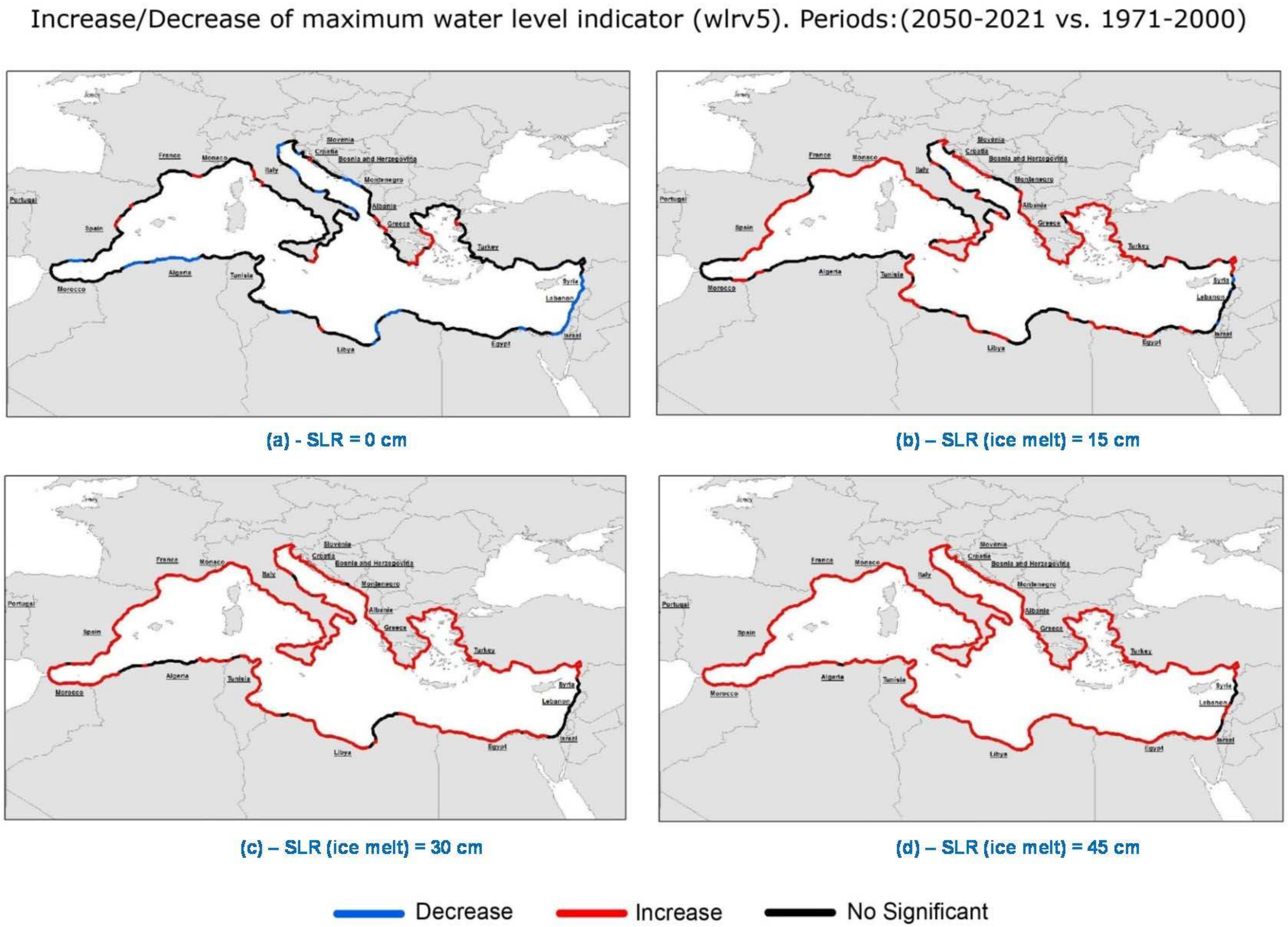

Fig 4 Maximum water level indicator (mean sea level resulting from storm surges plus wave effects plus steric effects) along the Mediterranean coast for the case of no net mass addition (panel a) and for three other scenarios of mass addition: 15 cm (b), 30 cm (c) and 45 cm (d). The colours indicate where the trend is statistically significant, showing the dominance of the climatic change signal (mass addition) and how that affects with limited increases the Greek coast, southern Sicily and the north-west Mediterranean coast. For additional information, see Lionello et al. (2015).

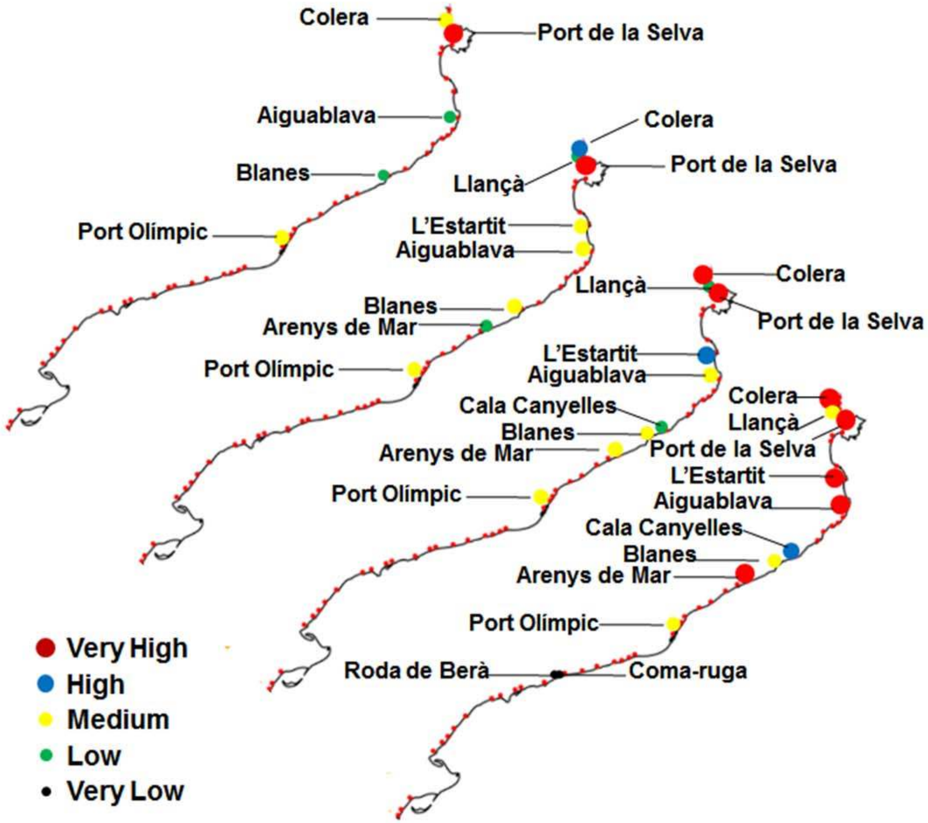

Fig 5 Overtopping risk (ratio to present level) for harbours along the Catalan coast in the NW Mediterranean (see inset) showing the cases where vulnerability increases in a statistically significant manner (low increases in green, medium in yellow, high in blue and very high in red). The assessment has been done for the 4 scenarios described in the text: upper panel corresponds to present conditions, intermediate panels to RCP 4.5 and 8.5 and lower panel to a high-end scenario of 1.80m sea level rise. For additional information, see Sierra et al. (2016).

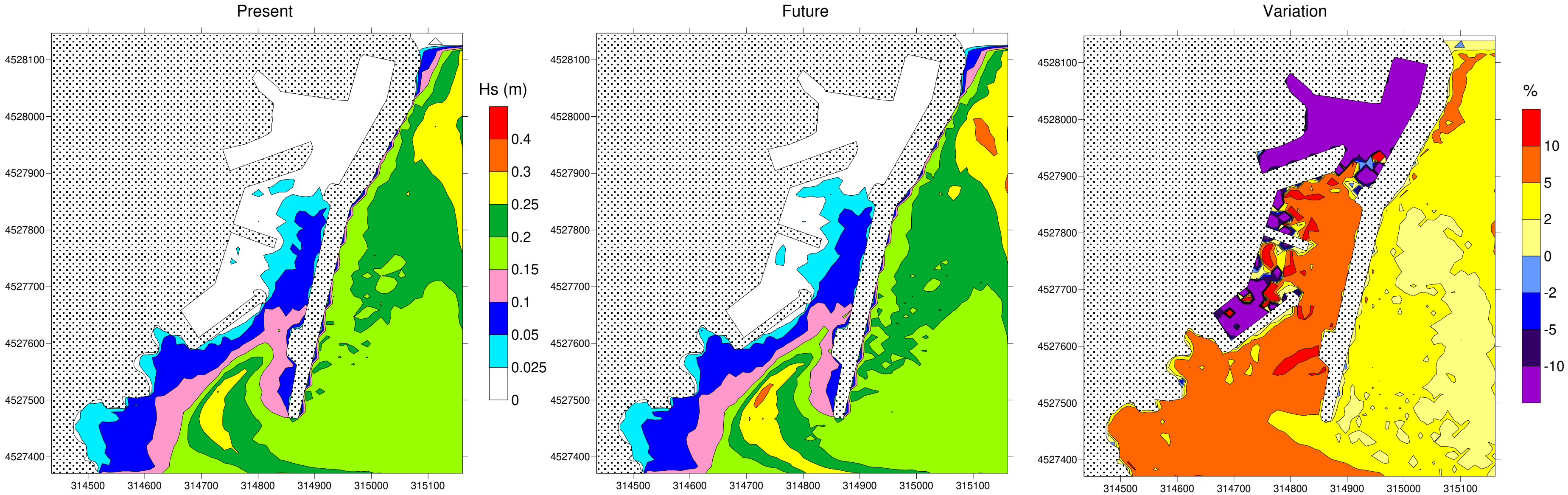

Fig 6 Annual average significant wave height *Hs* (m) in the l'Atmella de Mar port (on the southern sector of the Catalan coast) for an ensemble of five combinations of GCM–RCM models. The set of 5 models employed corresponds to A1B scenario. The figure shows significant wave height inside and around the harbour, for present conditions (*left panel*) and future conditions (*central panel*), as well as the percentage of variation of future with respect to present (*right panel*). For additional information, see Sierra et al. (2015).

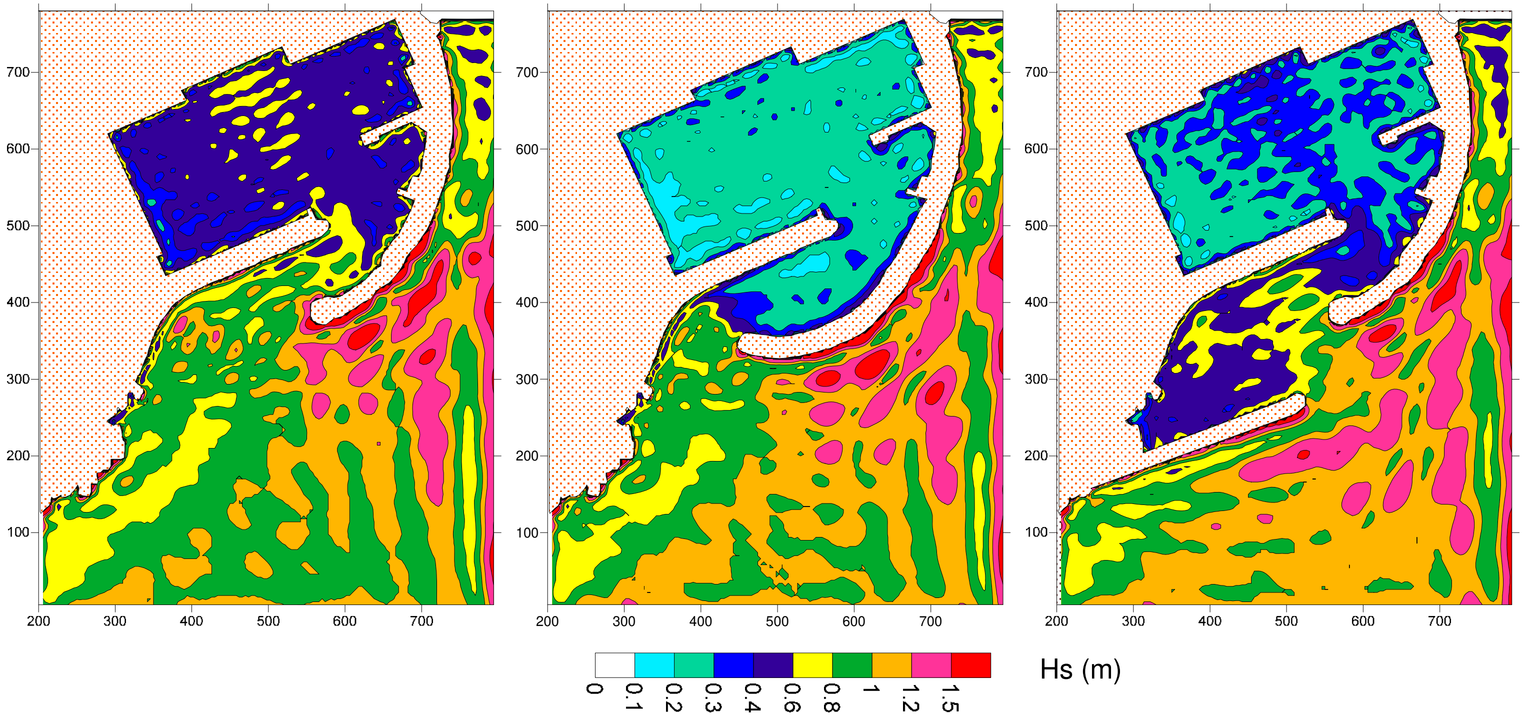

Fig 7 Significant wave height (*Hs*) inside the Marina of Palamós on the northern sector of the Catalan coast for projected waves (2100) from SSW for three different layouts: present geometry (*left*) and two solutions for adaptation to climate change, leading to a significant reduction in *Hs*. One corresponds to an extension of the main breakwater (*centre*) and the other to the construction of a new secondary breakwater (*right*). For additional information, see Sierra (2015).