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Impacts on wave-driven harbour agitation due to climate change in Catalan ports

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Abstract. The objective of the present work is to analyse how changes in wave patterns due to the effect of climate change can affect harbour agitation (oscillations within the port due to wind waves). The study focuses on 13 harbours located on the Catalan coast (NW Mediterranean) using a methodology with general applicability. To obtain the patterns of agitation, a Boussinesq-type model is used, which is forced at the boundaries by present/future offshore wave conditions extracted from recently developed high-resolution wave projections in the NW Mediterranean. These wave projections were obtained with the SWAN model forced by present/future surface wind fields projected, respectively, by five different combinations of global and regional circulation models (GCMs and RCMs) for the A1B scenario. The results show a general slight reduction in the annual average agitation for most of the ports, except for the northernmost and southernmost areas of the region, where a slight increase is obtained. A seasonal analysis reveals that the tendency to decrease is accentuated in winter. However, the inter-model variability is large for both the winter and the annual analysis. Conversely, a general increase with a larger agreement among models is found during summer, which is the period with greater activity in most of the studied ports (marinas). A qualitative assessment of the factors of variability seems to indicate that the choice of GCM tends to affect the spatial pattern, whereas the choice of RCM induces a more homogeneous bias over the regional domain.

1 Introduction

Climate change has become a major focus of attention because of its potential hazards and impacts on our environment in the near future. In coastal areas, vulnerability assessments focus mainly on sea level rise (SLR), although other non-climatic drivers (e.g. socioeconomic change) that can significantly interact with climate change are often ignored, despite being essential for climate and coastal management policy development (Nicholls et al., 2008). In addition, SLR is not the only physical process of concern to coastal communities being affected by climate change. The greenhouse effect and the complex interactions of atmospheric processes may produce changes in near-surface wind and pressure patterns, potentially affecting the pattern of the wave field (e.g. Bengtsson et al., 2006; Weisse and von Storch, 2010), which is another important coastal driver. Indeed, changes in ocean wave climate have been reported in numerous studies (e.g. Aumann et al., 2008; Wang et al., 2009) suggesting that the number, intensity and location of storms will be modified (e.g. Wang et al., 2004; Leckebusch and Ulbrich, 2004; Lionello et al., 2008).

The aforementioned changes in wave conditions would affect harbour agitation in several ways. Variations in wave height would directly modify the amount of energy penetrating into harbours. Also, changes in wave period or direction would affect propagation processes such as shoaling, refraction and diffraction. Therefore they could induce changes in sediment transport patterns (potentially generating siltation) or wave penetration into harbours (Sierra and Casas-Prat, 2014), which, in turn, would affect port operability. The activities in the harbour areas are strongly dependent on wave conditions, especially in relationship with the entrance and exit of the ships in safe conditions, but also for the regular harbour operations (Rusu and Guedes Soares, 2013), including ship mooring and cargo loading/unloading.

This study aims to assess the impact on harbour agitation focusing on several harbours located on the Catalan coast (NW Mediterranean Sea). This issue was previously analysed for few Catalan ports by Casas-Prat and Sierra (2010, 2012) who raised awareness by showing a tendency of harbour agitation to increase. However, their results were based on trend analysis, which is a simple and non-computational technique that can be used to provide a preliminary assessment only because it does not consider explicitly the greenhouse scenarios and because it assumes that the obtained tendency is valid into the future. Conversely, the current study uses the high-resolution wave projections developed by Casas-Prat and Sierra (2013) that explicitly take into account the greenhouse effect. These wave projections were obtained with the SWAN model using atmospheric climate projections available from four regional circulation models (RCMs), one of them being forced by two different global circulation models (GCMs). Having different GCM–RCM combinations will also allow to inspect the inter-model variability in terms of the impact on harbour agitation. As pointed out by Casas-Prat et al. (2015) for the case of sediment transport, it is not trivial how inter-model variability translates from the wave field to the wave-driven impacts.

In this paper only variations in wave climate are taken into account, assuming that the sea level does not change. Obviously, potential changes in sea level in this area would give rise to additional variations in the agitation pattern within the harbours, but these impacts are out of the scope of this paper, which only focuses on the affectation caused by changes on wave patterns due to climate change.

The rest of the manuscript is structured as follows. In Sect. 2 the study area is described. In Sect. 3 the materials and methods are explained. In Sect. 4 the results are presented and discussed. Finally, in Sect. 5 the conclusions of this work are presented.

2 Study area

The Catalan coast, which is about 700 km long, is located in the north-western Mediterranean from latitude 40°45′ N to 42°25′ N and from longitude 0°45′ E to 3°15′ E. This area is a micro-tidal environment, with mixed tides predominantly semidiurnal and tidal ranges of about 20 cm.

Some environmental properties of the NW Mediterranean are highly conditioned by its semi-enclosed character. It features local high and low atmospheric pressure systems controlled by orographic barriers like the Pyrenees, which determine the spatial distribution of winds and, therefore, the wave field. In terms of intensity, wind climate is characterized by low to medium average winds, but some extreme synoptic events occur (Sánchez-Arcilla et al., 2008).

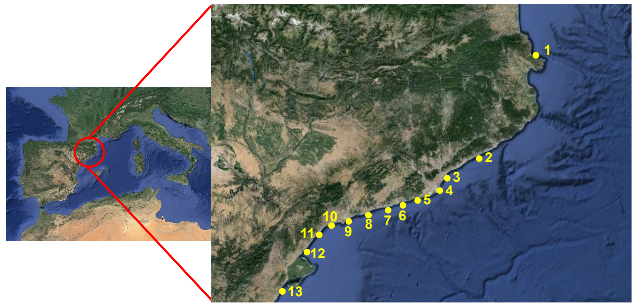

Figure 1. Location of the study area (left panel) and the studied ports (right panel). 1: Port de la Selva, 2: Arenys de Mar, 3: Port Fòrum, 4: Barcelona, 5: Garraf, 6: Vilanova i la Geltrú, 7: Segur de Calafell, 8: Torredembarra, 9: Tarragona, 10: Cambrils, 11: L'Hospitalet de l'Infant, 12: L'Ametlla de Mar, 13: Cases d'Alcanar.

The directional distribution of waves along the coast shows a predominance of NW and N wave conditions at the southern and northern sections of the coast, whereas the central part is dominated by E and S wave conditions. The largest waves come from the E or E-NE, where the largest fetches and stronger winds coincide (Sánchez-Arcilla et al., 2008).

In Catalonia, there are 47 seaports, 2 are large commercial ports (Barcelona and Tarragona), 3 small commercial (with facilities for leisure and fishing boats), 2 industrial, 18 mixed (fishing and leisure) and 22 marinas. In this paper, only 13 of them are studied due to the availability of detailed current lay-outs and bathymetries within the harbours. The location of the 13 selected ports is detailed in Fig. 1, showing that the 2 largest ports (Barcelona, num. 4, and Tarragona, num. 9) are included.

3 Material and methods

3.1 Wave data

As mentioned in the Introduction, the high spatial (0.125°) and temporal (3 h) resolution wave projections developed by Casas-Prat and Sierra (2013) have been used in this study to evaluate the impact on harbour agitation. They were obtained with the SWAN wave model (Booij et al., 1999) forced by winds generated with five combinations of global (GCMs) and regional circulation models (RCMs) considering the A1B scenario of the 4th Assessment Report from IPCC (2007). The wave data sets (and their corresponding simulations) will be named as in Casas-Prat and Sierra (2013), with acronyms relative to the combination of RCM and GCM used for their obtaining: HIR_E (RCM: HIRHAM5, GCM: ECHAM5), RAC_E

(RCM: RACMO2, GCM: ECHAM5), REM_E (RCM: REMO, GCM: ECHAM5), RCA_E (RCM: RCA3, GCM: ECHAM5) and RCA_H (RCM: RCA3, GCM: HadCM3Q3). These atmospheric projections were developed and provided by, respectively, DMI (Danmarks Meteorologiske Institut, Denmark), KNMI (Koninklijk Nederlands Meteorologisch Instituut, the Netherlands), MPI (Max-Planck-Institut für Meteorologie, Germany) and SMHI (Sveriges Meteorologiska och Hydrologiska Institut, Sweden), the latter providing the last two sets of atmospheric data. For each RCM-GCM combination, two 30-year time slices were used to simulate the wave climate: 1971–2000 for the "present" and 2071–2100 for the "future". Please refer to Casas-Prat and Sierra (2013) for further details.

The aforementioned wave projections at the cell grid closest to each harbour provide therefore the offshore wave conditions for the current study. In the following subsection (Sect. 3.2) it is described how these wave patterns are propagated towards the inside of the selected harbours.

3.2 Methodology

Boussinesq-type (BT) models have been widely used for simulating both wind-wave and long-wave propagation (e.g. Madsen et al., 1997; Bingham, 2000; Nadaoka and Raveenthiran, 2002). As pointed out by Rusu and Guedes Soares (2011), in the harbour areas the higher-resolution phase resolving models, based either on the mild slope equation or on the Boussinesq equations can give a realistic picture on the wave penetration inside the harbour areas and on some specific processes such as the harbour oscillations.

In this paper, we utilize a BT model to simulate the wave propagation within the harbours, as used in previous works (González-Marco et al., 2008; Casas-Prat and Sierra, 2010, 2012). There are a number of BT equations with different performances. The model employed here is based on the equations of Abbott et al. (1978), which are weakly nonlinear, and is capable of reproducing the following processes: shoaling, refraction, diffraction, reflection (which is essential when dealing with propagation within harbours), bottom friction and non-linear interactions. Recently, Filippini et al. (2015) made an analysis of nonlinear wave transformation using different types of BT models. According to this study, models based on Abbott equations perform well for $k\,h$ up to 1 (k is the wave number and h the water depth) and for greater values they start to slightly underpredict the phase velocity and also underpredict the shoaling coefficient (i.e. the wave height).

We use a model configuration that was validated with wave records obtained from 3 wave sensors deployed during a 1-year campaign in 2012 in the Port Fòrum (#3 in Fig. 1). The simulated significant wave height (H_s) inside that harbour showed a root mean absolute error between 20 and 30 %, which is reasonably good taking into account the low average of H_s at these inner points (between 0.10 and 0.22 m).

In this study almost all the ports are located at limited depths (between 6 and 12 m in the outer limit), so most of the times the model performs the simulation within the best range of applicability ($k\,h < 1$). In the case of three ports (Barcelona, Tarragona and Port de la Selva) the range of water depths is greater (up to 20 to 25 m), so for short periods the model is applied out of is best range of applicability and, as a consequence, the results are less reliable. However, the aim of the paper is focused in analyzing the difference between future and present conditions rather than in the obtaining of very accurate values of significant wave heights. In addition the simulations with the BT model are performed in similar conditions for present and future conditions, so even though the model is applied outside of its range of applicability, this does not introduce any bias in the results. Therefore, for comparative purposes as carried out in the paper, the obtained results can be considered acceptable.

The offshore wave conditions affecting each harbour are given by the wave projections described in the previous subsection (Sect. 3.1) at the closest grid point. Instead of directly propagating the whole 30-year wave time series, a wave regime characterization is previously performed in order to limit the number of simulations to be carried out. The data are grouped in eight 45° directional sectors (N, NE, E, SE, S, SW, W and NW) and five ranges of significant wave height H_s (0–1, 1–2, 2–3, 3–4, >4; in m). As explained below, each combination of wave height–wave direction entails 10 simulations (5 models $\times$ 2 time-spans), so the number of such combinations must be reduced as much as possible. This forces to find a balance between accuracy and affordable amount of model runs and for this reason we have to use these large (45°) sectors, although narrower sectors would be preferable.

After the grouping of the data, the frequency of occurrence of each group of H_s and direction is computed. Additionally, representative wave parameters are assigned to each group. For every H_s and direction, the central value of each bin is considered, with the exception of the largest group, for which a representative value of 5 m is used. The representative wave period is obtained through Eq. (1):

$$T_p = a H_s^b, \tag{1}$$

where T_p is the peak period and a, b are two coefficients fitted to each wave projection data set. This type of relationship between T_p and H_s is that recommended by the Spanish Harbour Authority (e.g. Puertos del Estado, 2013). The wave parameters thus obtained are representative of the deep/intermediate water conditions at the corresponding node location. To propagate these wave conditions to the boundaries of the aforementioned Boussinesq-model domain, the linear theory is employed. This simple approach introduces a certain error and, therefore, a limitation in the analysis, but it has been followed due to the lack of detailed bathymetries outside several harbours that prevented the application of another numerical model (e.g. SWAN) to all the

Table 1. Frequencies of occurrence for the used wave height intervals and wave direction sectors in front of the Barcelona port. Present conditions for model RCA_E.

H_s (m)	E (%)	SE (%)	S (%)	SW (%)
0–1	30.3272	19.6797	16.1446	11.3741
1–2	3.4974	0.7164	1.5057	1.8445
2–3	0.4380	0.0376	0.3091	0.1038
3–4	0.0799	0.0137	0.0297	0.0023
>4	0.0605	0.0068	0.0103	0.0000

studied ports. Hence, for the sake of using a homogeneous approach for all the ports we decided to use linear theory instead of a numerical model (as would be desirable).

Applying the linear theory is particularly critical when there are diffraction effects (due to the presence of geographical accidents) or when the parameter ε ($\varepsilon = a/h$, where a is the wave amplitude) is large and the small-amplitude hypothesis is no longer valid. In the cases studied here the wave propagation is performed in open coasts, so there is no diffraction due to the presence of obstacles. With respect to the parameter ε, greater wave heights (which entail greater non-linearity) are those with a lower frequency of occurrence and therefore are those contributing with a lower weight (sometimes negligible or even null, as it is shown as an example in Table 1) to the H_s within the harbour. Moreover, the scope of the paper (the analysis of several ports within a regional scope) is focused in analyzing the difference between future and present conditions based on the changes in the distribution of wave directional frequency, so the use of linear theory does not introduce any bias in the results for comparative purposes. For all these reasons, we consider that using linear theory for propagating waves from deep water towards outside the port, although reduces the accuracy of the results, is applicable for the purposes of the paper.

Note that only those wave groups with a wave direction capable to enter the port are propagated and used afterwards. These directions are listed in Table 2 for each port.

In summary, the following methodological steps are carried out to evaluate the impact on harbour agitation:

- for each port, selection is made of the n wave directions capable to enter the port (see Table 2);
- for each selected direction, a computation is made of the wave periods associated to the five representative wave heights $H_s = [0.5, 1.5, 2.5, 3.5$ and $5]$ m under present and future conditions, for each model data set (five models);
- wave propagation is carried out using linear theory of the 25 n wave classes (5 wave heights $\times\, n$ directions $\times$ 5 models) for present and future conditions from the closest wave grid point (of the wave fields described in Sect. 3.1) to the outer limit of the Boussinesq-model domain. Note that the range of H_s and wave directions are always the same but Tp may be different for present and future and for each model;
- a simulation of the propagation is made of each 50 n (5 waves heights $\times\, n$ directions $\times$ 2 time spans – present and future – $\times$ 5 models) wave class within the harbour using the Boussinesq-model, obtaining the associated H_s;
- a computation is made of the annual H_s within the harbour (at each grid point) for present and future conditions (and for each model) by multiplying the H_s obtained in each simulation by its frequency of occurrence and adding the values of all wave classes. The same for winter and summer periods to obtain seasonal averages;
- a computation is made of the annual/seasonal spatial averaged H_s (spatial average of values at all grid points within the harbour) for each port, model and time span;
- a computation of the ensemble of the annual/seasonal H_s and that of the spatial averaged H_s (averaging over the 5 model simulations) for each port and time span.

Table 2. Wave directions affecting the different ports.

#	Port	Directions of incidence
1	Port de la Selva	N
2	Arenys de Mar	E, SE, S, SW
3	Port Fòrum	E, SE, S
4	Barcelona	E, SE, S, SW
5	Garraf	E, SE, S, SW
6	Vilanova i la Geltrú	E, SE, S, SW
7	Segur de Calafell	E, SE, S, SW
8	Torredembarra	E, SE, S, SW
9	Tarragona	E, SE, S, SW
10	Cambrils	SE, S
11	Hospitalet de l'Infant	E, SE, S
12	L'Ametlla de Mar	E, SE
13	Cases d'Alcanar	E, SE, S

4 Results and discussion

This section presents and discusses the results obtained, separating the annual and seasonal analysis, respectively, in Sects. 4.1 and 4.2. Due to the huge amount of simulations carried out the results are presented in an integrated way, focusing on the change in the spatial averaged H_s inside the harbour.

4.1 Annual analysis

Following the methodology described in Sect. 3.2, the future variation of the H_s inside each harbour is obtained. Fig-

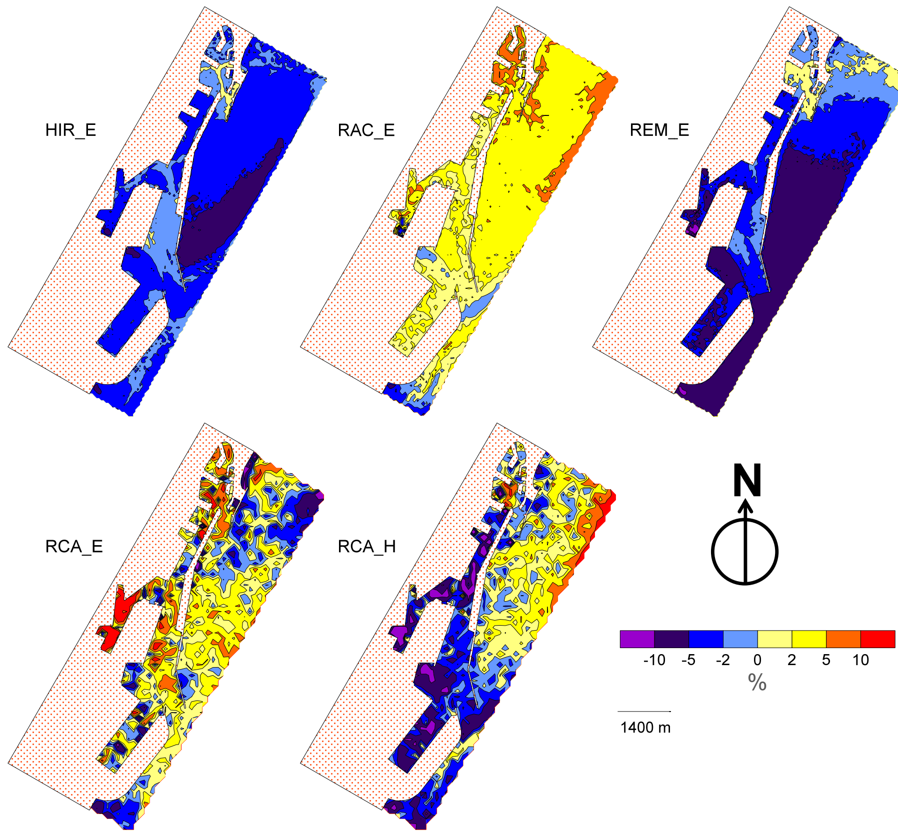

Figure 2. Projected change (future minus present in %) of H_s at Barcelona Port for the five models.

ure 2 shows, as an example, the results of Barcelona port (#4 in Fig. 1), the largest harbour and the main commercial port of this region. The port has two accesses since a second mouth was opened to facilitate the entry and exit of small crafts and cruises. This second entry, however, enables the rise of H_s in this port area, as observed in most of the models (although with different intensities). Considering the spatial average inside the whole port, there are only 2 models that project a future increase in H_s (RAC_E and RCA_H) with a mean ratio of less than 3 % but with local variations up to 10 % (RAC_E). On the contrary, spatial averaged decreases up to 5 % are obtained for the remaining models. These results highlight the large inter-model variability in terms of the harbour agitation, which was expected taking into account the variability already present in the forcing wave climate projections (Sect. 3.1), as pointed out by Casas-Prat and Sierra (2013).

Like Barcelona, the large inter-model variability is also observed in the rest of the ports, as it is shown in Fig. 3. Table 3 illustrates the results in terms of the spatial averaged H_s for each model and the corresponding ensemble (i.e. the average of the projected changes associated to the five RCM-GCM combinations). Except in the most northern and southern harbours (ports #1, 11, 12 and 13), there is a general tendency of H_s to decrease. RAC_E is the model which projects more cases of positive trend (8 out of 13 ports); on the contrary, RCA_H projects the largest number of cases with a negative trend (11 out of 13 ports) and also the largest decrease (−13 % for Vilanova i la Geltrú).

The ensemble, shown in Table 3, varies from −3.8 to 7.1 %. However, given the aforementioned inter-model variability, the ensemble value should be used with caution because it might not be representative and cancel out different patterns of change. For instance, from the 13 ports analysed, in only five cases do the five models give the same trend sign. To better illustrate the deviation of each RCM–GCM projection from the ensemble value, in Fig. 4 the corresponding anomalies for each port are plotted. We can highlight the consistent positive anomaly associated to RAC_E, whereas REM_E and RCA_H anomalies are mostly negative. It is interesting to note that the spatial patterns projected for the latter two models are remarkably different despite having the same trend sign. In the cases where REM_E presents a negative anomaly inside the port, it is usually related to a negative anomaly outside the port, in other words, H_s inside the port is reduced because the forcing H_s is reduced. In contrast, when RCA_H projects a negative anomaly inside the harbour, it is not necessarily also projected outside, especially next to the main breakwater. That means that RCA_H projects an increase of H_s associated to a certain directional sector (E,

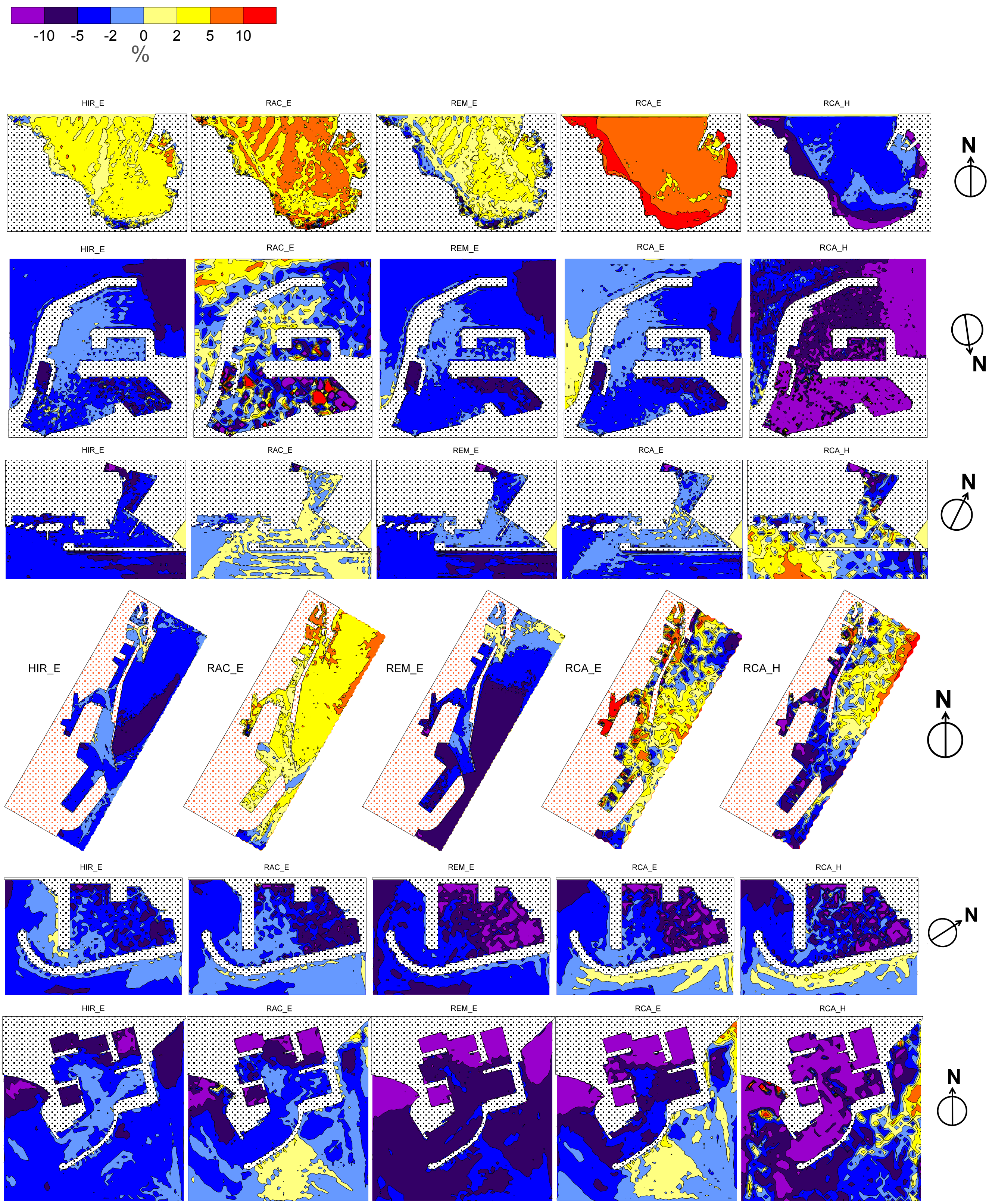

Figure 3. Projected change (future minus present in %) of H_S at the studied ports. Panels from left to right: results for HIR_E, RAC_E, REM_E, RCA_E and RCA_H models. Panels from top to bottom: Port de la Selva, Arenys de Mar, Port Fòrum, Barcelona, Garraf and Vilanova i la Geltrú.

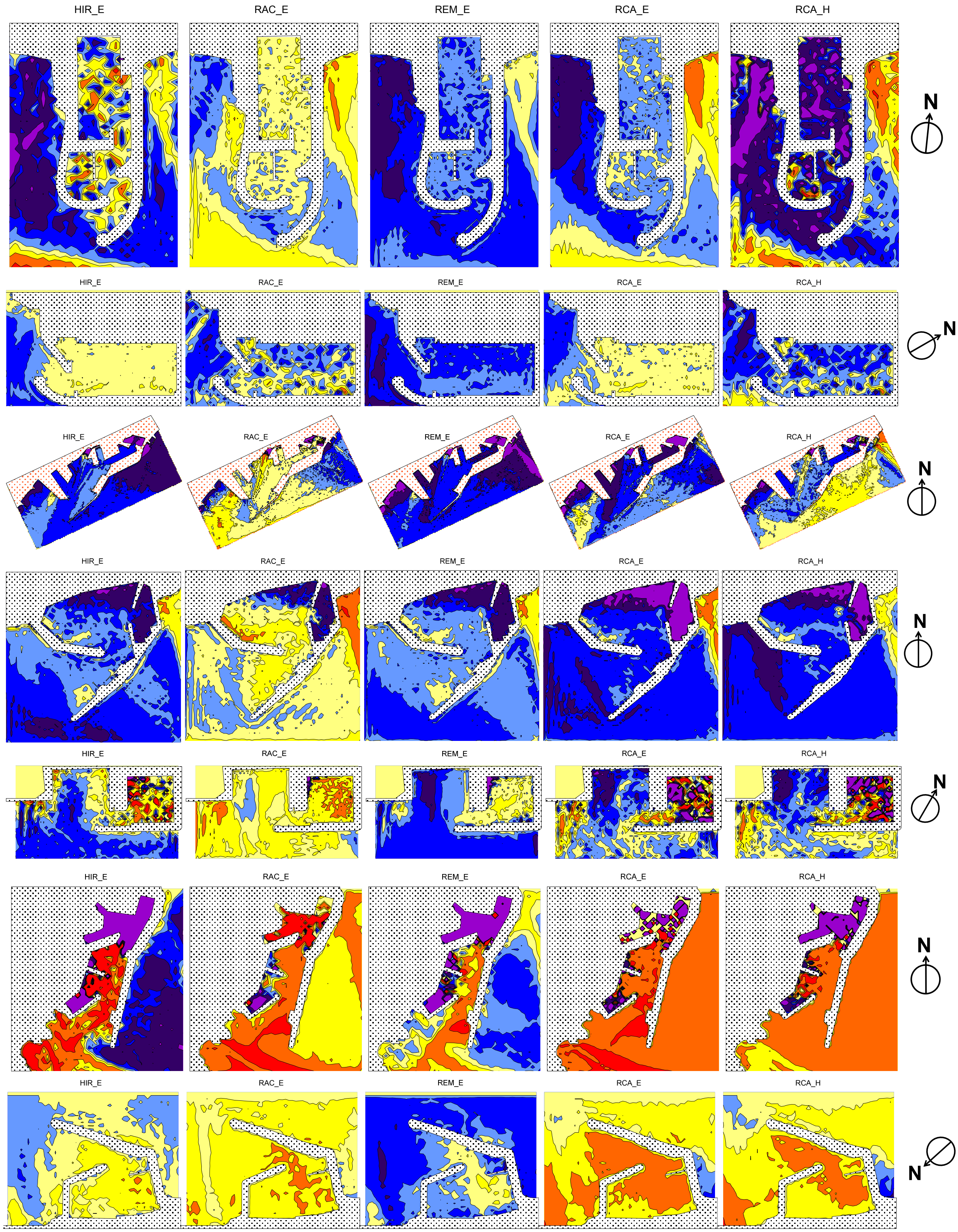

Figure 3. Projected change (future minus present in %) of H_S at the studied ports. Panels from left to right: results for HIR_E, RAC_E, REM_E, RCA_E and RCA_H models. Panels from top to bottom: Segur de Calafell, Torredembarra, Tarragona, Cambrils, L'Hospitalet de l'Infant, L'Ametlla de Mar and Cases d'Alcanar.

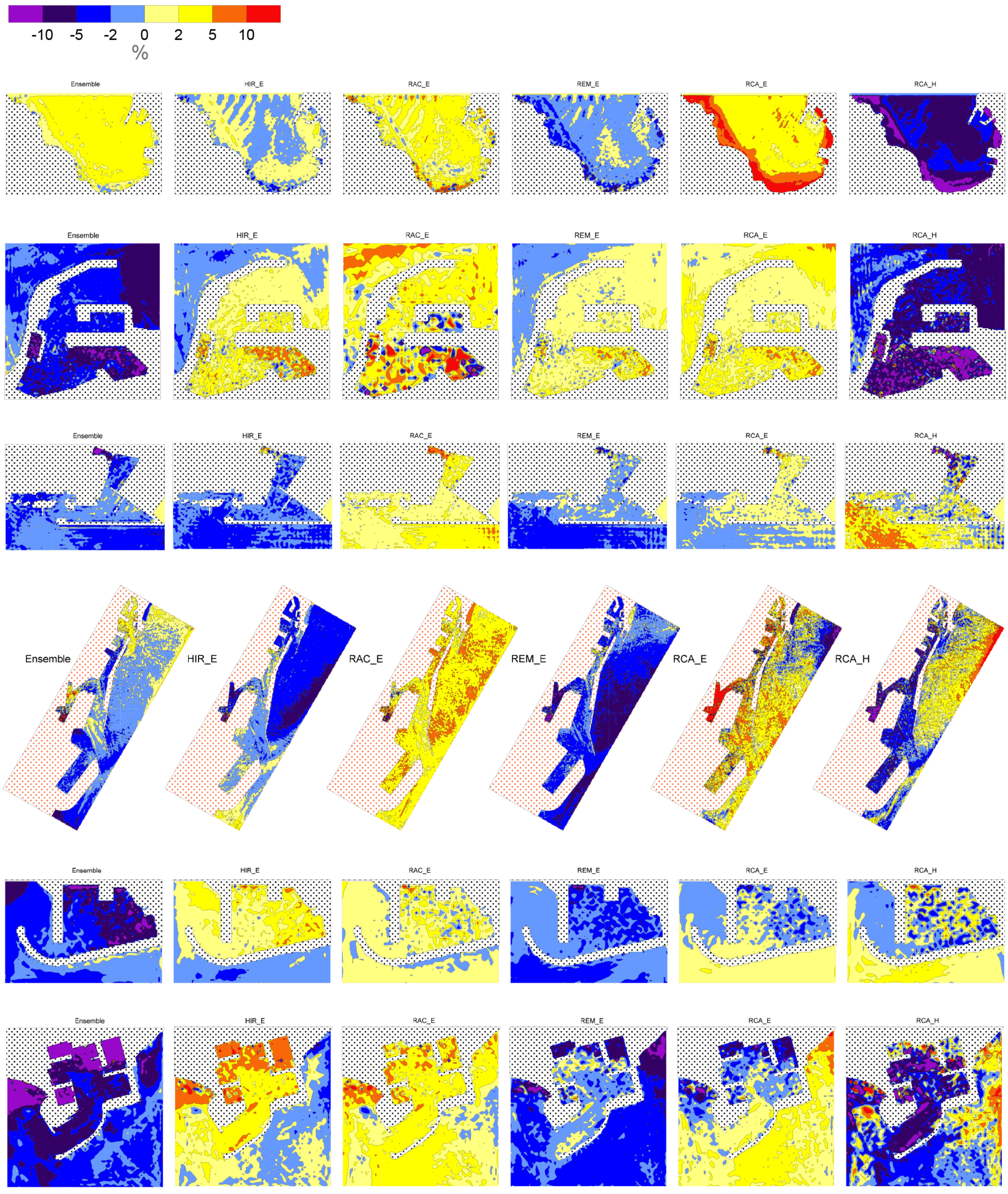

Figure 4. Projected change (future minus present in %) of H_s at the studied ports presented as an ensemble of the five models and the anomalies of each model with respect to the ensemble. Panels from left to right: results for the ensemble and anomalies for HIR_E, RAC_E, REM_E, RCA_E and RCA_H models. Panels from top to bottom: Port de la Selva, Arenys de Mar, Port Fòrum, Barcelona, Garraf and Vilanova i la Geltrú.

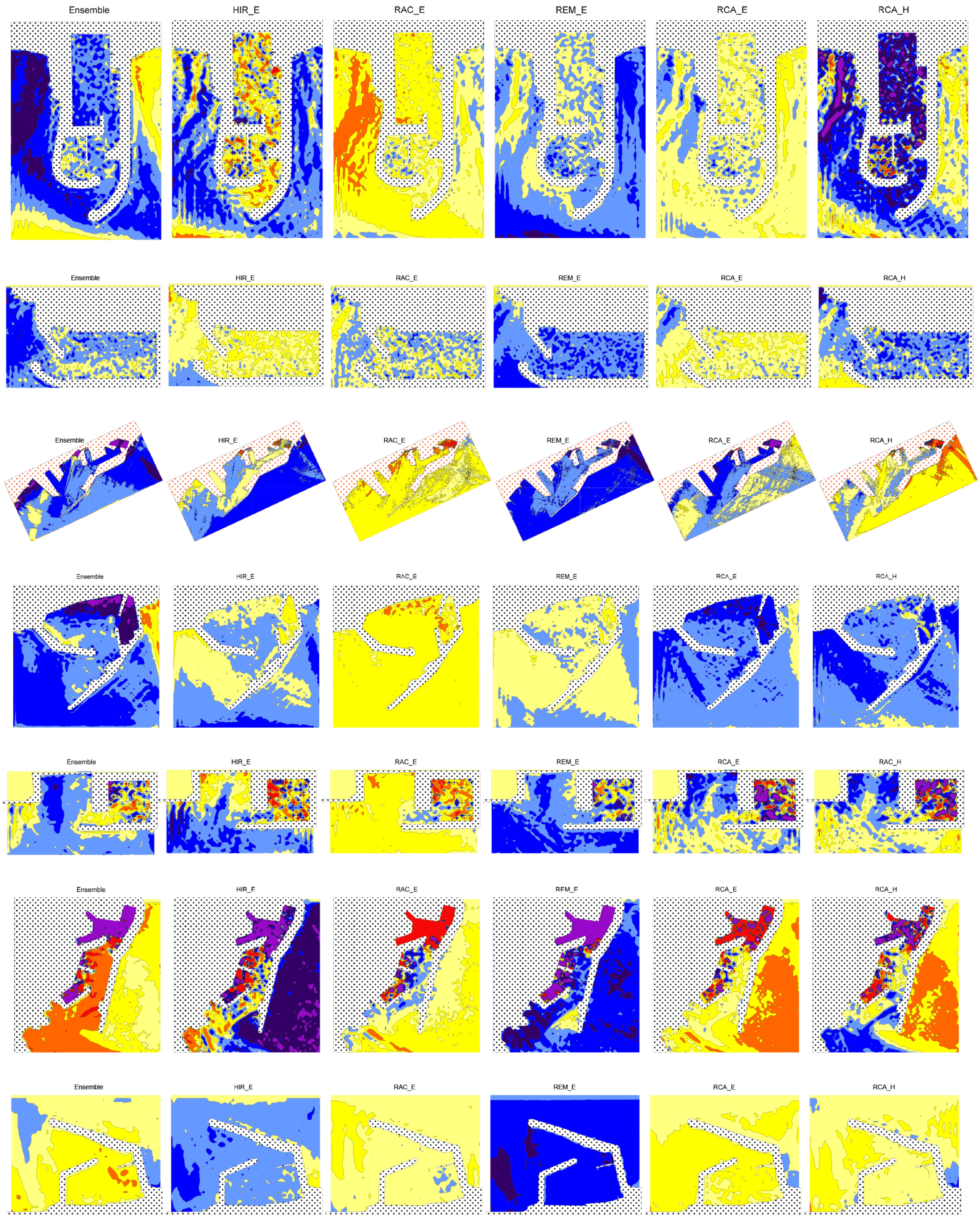

Figure 4. Projected change (future minus present in %) of H_s at the studied ports presented as an ensemble of the five models and the anomalies of each model with respect to the ensemble. Panels from left to right: results for the ensemble and anomalies for HIR_E, RAC_E, REM_E, RCA_E and RCA_H models. Panels from top to bottom: Segur de Calafell, Torredembarra, Tarragona, Cambrils, L'Hospitalet de l'Infant, L'Ametlla de Mar and Cases d'Alcanar.

Table 3. Projected change (future minus present in %) of the spatial averaged H_s at the 13 studied ports.

#	Port	Ensemble (%)	HIR_E (%)	RAC_E (%)	RCA_E (%)	REM_E (%)	RCA_H (%)
1	Port de la Selva	2.5	3.3	4.1	8.0	1.5	−4.5
2	Arenys de Mar	−4.1	−2.1	−2.0	−2.3	−2.8	−11.1
3	Port Fòrum	−1.0	−3.4	0.2	1.2	−1.8	−1.3
4	Barcelona	−1.1	−2.2	2.2	2.7	−3.4	−4.8
5	Garraf	−2.7	−2.0	−1.6	−3.5	−5.3	−1.0
6	Vilanova i la G.	−7.5	−3.6	−4.1	−8.3	−8.8	−12.9
7	Segur de Calafell	−1.5	0.5	0.8	−0.6	−1.7	−6.6
8	Torredembarra	−0.6	1.1	−0.5	0.9	−2.2	−1.8
9	Tarragona	−1.8	−2.8	1.2	−5.3	−4.4	−1.3
10	Cambrils	−3.8	−3.9	−0.4	−6.5	−3.3	−4.8
11	Hospitalet de l'I.	0.6	3.0	3.7	−2.7	1.1	−2.1
12	L'Ametlla de Mar	7.1	7.3	7.4	9.6	2.6	8.5
13	Cases d'Alcanar	3.4	2.7	4.3	5.6	−0.3	4.6

as commented later on), which does not get to significantly enter the port.

The inter-model variability in terms of the averaged H_s inside the harbour is undoubtedly a consequence of the inter-model variability in terms of the forcing wave conditions which can be in turn separated into the variability induced by the choice of RCM and GCM, respectively. Casas-Prat and Sierra (2013) pointed out that GCM contributed to a larger variability than RCM, especially for the regional directional wave distribution in the winter season. The fact is that the inter-model variability not only varies depending on the season but also on the parameter analysed (e.g. wave height, wave direction) and therefore a general estimation of the inter-model variability is not possible. Additionally, despite studying a relatively small region, there is a certain spatial variability which can partly explain the discrepancies among the ports. In fact, Casas-Prat and Sierra (2013) concluded that the northern Catalan coast would be affected by more energetic future wave conditions than the rest of the coast. Note that in this study we omit the inter-scenario variability because we only use one greenhouse gas scenario (A1B). In a more general framework, this would be an additional factor to consider.

However, the evaluation of the variability in terms of the projected changes in the H_s inside the harbour, as calculated in this study, is even a more challenging problem because it is affected by a larger amount of factors. Apart from the aforementioned inter-model and spatial variability associated to the forcing wave climate, the characteristics of the receptor can play an important role in making changes in the forcing wave climate more or less effective to increase/decrease harbour agitation. One could divide the coastal receptor factors into two main groups, those related to the coastal orientation and port shelter (which determine the effective wave directions), and the design parameters of each harbour (water depth, mouth width, harbour orientation, port layout, etc.).

Quantitatively estimating each factor of this chain of variability components is a difficult task, not only because of the several factors involved but also because their mutual interactions, which cannot be neglected in many cases. For instance, port orientation can be an important factor of variability when there are substantial changes in the frequency of forcing wave climate relative to the same direction, but not if the forcing wave climate remains unchanged for such direction.

This study qualitatively investigates the effect of those factors by means of analysing the changes in the wave conditions at different steps of the methodology. For each location we compare the rate of the change of (see Fig. 5): (a) the offshore H_s (obtained from the forcing wave climate), (b) the offshore H_s resulting from the contribution of only the effective wave directions for each port (see Table 2), (c) the spatial averaged H_s inside the harbour (representative parameter in this study of the harbour agitation). Note that here and throughout the rest of the paper, the term "offshore" is related to the wave conditions at the nearest grid cell of the forcing wave projections, described in Sect. 3.1, without necessarily implying deep water wave conditions (it could be intermediate water).

Figure 5a illustrates the change of the offshore H_s associated to each harbour, whose variability is only affected by the inter-model and spatial variability. Regarding the latter, we can see that in the northernmost location, all models produce a tendency to either increase or slightly decrease the future H_s, while in the rest of the studied domain there is a clear tendency to future H_s decrease. As it can be observed in Fig. 1, the first port (Port de la Selva) is considerably more separated from the rest and if we analysed more offshore locations between Port de la Selva (#1) and Arenys de Mar (#2) we would better appreciate the transition between those two behaviours. Note that the small existing ports between #1 and #2 have not been analysed due to the lack of detailed

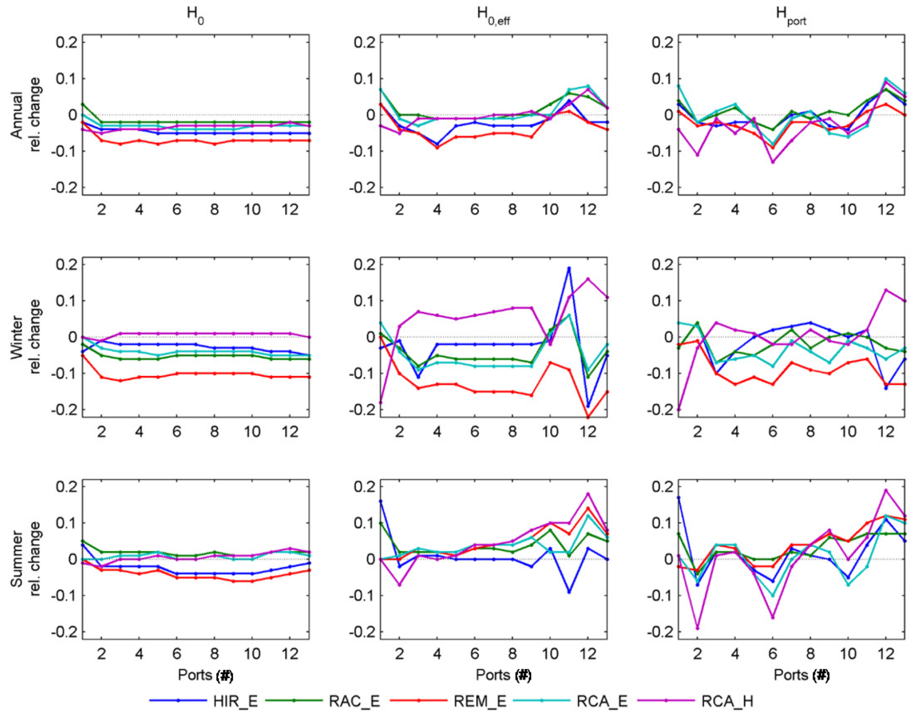

Figure 5. Projected relative changes (future minus present expressed as a decimal) for the: offshore H_S **(a, d, g)**, offshore H_S only accounting for the effective wave directions affecting each harbor **(b, e, h)** and the spatial averaged H_S inside the harbor **(c, f, i)**. From top to bottom panels: annual analysis **(a, b, c)**, winter analysis **(d, e, f)**, summer analysis **(g, h, i)**.

bathymetries inside these ports. Regarding the inter-model variability, one interesting feature is that the results associated to HIR_E, RAC_E, REM_E and RCA_E (same GCM but different RCM) exhibit a very similar spatial pattern although within a range of variability, i.e. the positive/negative bias associated to each model is more or less constant for all locations. In contrast, RAC_H (the only one with a different GCM) projects a different spatial pattern: the ratio of change slightly increases from north to south. In other words, the bias induced by the selection of the GCM seems not to be constant over space.

When considering only the effective range of wave directions for each location, the range of variability in the projected changes increases (Fig. 5b). This can be explained by the fact that the directional distribution of waves has a greater variability than that of the integrated H_S for all directions. It is interesting to highlight the positive change obtained for the southern locations, despite the reduction previously found when considering all directions (Fig. 5a).

Finally, Fig. 5c illustrates the actual changes of the spatial averaged H_S inside the harbour, which are those previously detailed in Table 3. Compared to Fig. 5b, the uncertainty further increases which is reasonable considering the larger amount of factors of variability involved. Firstly, the inter-model variability itself becomes larger than that of Fig. 5b, because now it does not only matter the change in the whole block of effective wave directions but also each individual variation, which can have a relevant effect on the H_S inside the harbour. For example, two models might depict different variations in the SW and E wave directions (which will have different consequences on the harbour agitation) but might have a similar variation of the whole range of E–SW directions. Such an effect cannot be easily isolated. We could see (not shown) that the changes in the harbour agitation cannot only be explained by the changes in H_S associated to the most effective wave direction only (i.e. that of the harbour mouth orientation). This is probably because of the reflection and diffraction wave processes. Secondly, each port configuration can additionally alter the final pattern of harbour agitation. No significant correlation has been found between the change ratio of the averaged H_S inside the harbour and some harbour parameters like mean water depth or harbour mouth width (not shown). However, the largest decrease of H_S at Vilanova i la Geltrú could be related to the relatively larger harbour mouth entrance, in comparison to the surrounding ports with similar forcing conditions.

We see therefore that the areas of positive changes previously highlighted when commenting Table 3, are generated by different processes. In the northernmost location, the positive change is related to an increase of the mean H_S offshore, whereas the increase considerably consistent occurring at the southern part seems to be more related to a change in the directional distribution. Indeed, changes in the wave distribution explains why the RCA_H projects decreases of

Table 4. Projected change (future minus present in %) in the spatial averaged H_s inside the port for the winter and summer seasons, respectively, in terms of the ensemble and the range of variation among the five models.

#	Port	Winter		Summer	
		Ensemble (%)	Range (%)	Ensemble (%)	Range (%)
1	Port de la Selva	−4.7	(−20.1, 4.4)	4.9	(−2.2, 17.1)
2	Arenys de Mar	−1.3	(−3.3, 4.0)	−7.7	(−19.1, −3.1)
3	Port Fòrum	−6.1	(−10.3, 3.9)	2.6	(1.3, 4.3)
4	Barcelona	−5.0	(−13.6, 1.6)	2.7	(1.5, 4.5)
5	Garraf	−3.9	(−10.6, 1.1)	−2.5	(−4.2, −0.4)
6	Vilanova i la G.	−4.4	(−12.6, 2.4)	−6.9	(−16.0, −0.3)
7	Segur Calafell	−1.1	(−7.0, 2.9)	1.5	(−1.8, 4.2)
8	Torredembarra	−2.0	(−8.7, 4.0)	2.9	(0.9, 4.5)
9	Tarragona	−3.0	(−9.5, 2.3)	4.7	(0.1, 8.4)
10	Cambrils	−1.5	(−6.6, 1.2)	−0.6	(−7.2, 5.2)
11	Hospitalet de L'I.	−1.1	(−6.4, 2.1)	4.7	(−1.9, 9.6)
12	L'Ametlla Mar	−4.7	(−14.1, 13.1)	12.2	(6.5, 18.6)
13	Cases d'Alcanar	−3.2	(−13.3, 10.1)	9.0	(4.8, 12.4)

H_s, whereas in terms of the offshore wave climate, REM_E is clearly the model most associated to negative changes (Fig. 5a and b).

4.2 Seasonal analysis

Table 4 summarizes the results obtained for the projected change of the spatial averaged H_s inside the port by means of the ensemble and the range of variation among all models. In winter there is a general tendency of H_s to decrease (more accentuated than in the annual analysis), whereas in summer, there is a majority of ports showing a positive trend. In winter there is a larger inter-model variability than in summer, for which a larger agreement among models is found. This can be illustrated with the fact that 8 ports (out of 13) have the same trend sign for all RCM–GCM combinations (whereas none have the same trend sign in winter).

As for the annual analysis, the comparison between projected changes of H_s between offshore conditions and inside the port has led to a better understanding of the variability (Fig. 5d–j). In terms of the offshore wave conditions, Fig. 5a illustrates a larger spread among models in winter (than for the annual analysis, see Fig. 5a), being the REM_E (RCA_H) the one exhibiting a larger decrease (increase). The drastic drop associated to REM_E is in agreement with the notable decrease of storms (typically occurring in winter) found by Casas-Prat et al. (2015) for this RCM–GCM combination. When only considering the effective wave directions (Fig. 5e), this range of variation becomes even larger with a general positive rate of change associated to RCA_H, in contrast to the remaining models. Actually here we can see what was less obvious in Fig. 5a and b (annual analysis) and is that the different simulations associated to different RCM but the same GCM have similar spatial patterns (with a more or less homogeneous bias over space), whereas the simulation with a different GCM (RCA_H) exhibits a different spatial pattern, which can be explained by the significant rise of waves coming from E for the HadCM3Q3 GCM (as pointed out by Casas-Prat and Sierra, 2013). In fact, the only two ports with a negative ratio (#1 and #10) are the only ports where the E direction is not considered as an effective direction due to the port shelter configuration. For example, Cap Salou blocks E waves to Cambrils (#10).

The variability associated to Fig. 5f (spatial averaged H_s inside the port) is surprisingly reduced in comparison to Fig. 5e. The reason is twofold: (i) the future increase of the offshore H_s associated to the range of effective wave directions is not reflected into the change of the H_s inside the harbour because of the port configuration (e.g. E direction predicted by RCA_H does not easily get inside most of the harbours whose mouths are typically orientated SW), (ii) the negative ratio associated to HIR_E, RAC_E, REM_E and RCA_E obtained in Fig. 5e masks an increase of the SW component for many locations (see Casas-Prat and Sierra, 2013), which is usually the most (but not the only) influent direction in terms of the agitation inside the harbour. The last two locations are an exception and exhibit a similar rate of change between Fig. 5e and f. The large increase in the spatial average obtained at Cases d'Alcanar (#13) agrees with the opposite mouth harbour orientation of this harbour (NE, instead of SW). Results at L'Ametlla (#12) are a bit surprising. Although the port is orientated towards the S, E waves manage to enter the port, as it can be derived from Fig. 3. Therefore, in this case the local port configuration seems to be relevant in determining the final change in the agitation conditions.

Regarding the summer conditions, a lower variability is obtained in terms of the change of the offshore H_s (Fig. 5g) but, again, when considering only the effective wave directions the uncertainty increases. In this season this rise especially happens in the northern and southern most locations. This feature can be explained by the fact that, at these locations, the local geomorphology limits the number of effective wave directions. Therefore, the discrepancies among models become more noticeable than when a larger number of directions is analysed (maybe masking possible discrepancies). At a regional scale, Casas-Prat and Sierra (2013) concluded that the patterns of change of the directional distribution during summer were similar among all models, with an increase of E and SE wave directions along the mid-southern Catalan coast. This seems to lead to a tendency of the spatial averaged H_s inside the harbour to increase in general but especially at the southern locations, however, with a few models depicting negative values. This can be partly related with the fact that although there is a general agreement for all models at a regional scale, as expected their discrepancies become more relevant at the local scale of harbour agitation. However, such variability is still considerably lower than in winter. Regarding the inter-port variability, only two ports (#2 and #6) deviate significantly from the general positive trend. It is difficult to determine why but it might be due to local factors, like a wider harbour mouth in comparison to the surrounding ports (125 and 180 m, respectively).

5 Summary and conclusions

The main objective of this paper was to analyse how changes in wave patterns due to the effect of climate change can affect harbour agitation. We focus on 13 harbours located on the Catalan coast (NW Mediterranean), which have been selected considering data availability (in particular detailed bathymetries).

The study is based on the high-resolution wave projections developed by Casas-Prat and Sierra (2013), which were obtained with the SWAN model for five combinations of regional and global circulation models (RCMs and GCMs) considering the A1B scenario (IPCC, 2007). These projections were performed for two 30-year periods: present (1971–2000) and future (2071–2100). With the wave climate derived for each harbour and each time span, a representative set of wave parameters are propagated using linear theory from the closest SWAN node to the limit of the simulation domain used by a Boussinesq-type model. This model simulates therefore the propagation of waves within the ports for the set of representative wave parameters of each time span. Finally, the annual (or seasonal) H_s has been obtained considering the corresponding frequencies of occurrence. From the comparison of present and future H_s, the percentage of variation can be estimated for each model which serves to assess the potential changes in wave agitation.

The main limitation associated to the used methodology, which has a general applicability, is the use of linear theory to propagate the offshore wave conditions to the boundary of the Boussinesq-type model domain. It would be preferable to apply a wave numerical model to carry out this propagation (e.g. SWAN itself), but the lack of detailed bathymetries prevented from doing so. Nevertheless, taking into account the large uncertainty associated to climate change scenarios and model projections, the error introduced using linear theory is acceptable.

Considering the ensemble (making an average of the five models) for each port it results in a general slight decrease in the annual agitation in most of the ports, although in the northernmost and southernmost areas of the region, a slight increase is obtained. Such increase, in the first case seems to be caused by a general increase of H_s offshore, and, in the second case, by an increase for the effective wave directions. The seasonal analysis projects a decrease during winter more accentuated than for the annual analysis (12 out of 13 ports have a negative ensemble). In contrast, in summer, the pattern of change is mostly positive (9 of the 13 ports have a positive ensemble) which can be associated to an increase of waves coming from SE direction in the mid-southern area, and an increase of N waves in the northern area. Note that although summer is associated with low energetic H_s conditions, it is the period with greater activity in most of the studied ports (marinas).

The ensemble has to be used with caution though, given the large inter-model variability in the results, which is complex itself given the interaction between the changes in the forcing wave height and forcing wave direction. In addition, inter-model variability is not the only factor involved in the H_s inside the harbour. Although the area of study is a small region, there is a certain spatial variability (e.g. the northern Catalan coast projects more energetic future offshore wave conditions compared to the rest). Also, the characteristics of the receptor further affect the variability by means of the coastal configuration, port shelter and specific port layout (harbour mouth, depth, etc.). In turn, these factors are not necessarily independent one from each other and can lead to further interactions. For example, the effect of the port orientation in making certain forcing wave conditions more or less capable to affect the agitation inside the port depends on the changes of the most effective wave directions.

Given the aforementioned complexity of factors, it is therefore very difficult to quantify each source of uncertainty. However, this paper has qualitatively evaluated the contribution of each variability factor by means of comparing the changes in the offshore conditions and H_s inside the port.

For the offshore wave conditions, an interesting conclusion is derived regarding the choice of RCM and GCM. Casas-Prat and Sierra (2013) already pointed out that, especially for winter, the variability induced by GCM is larger than that induced by RCM. In this study we have got deep insight and seen that the choice of GCM contributes to modify the spatial pattern of change, whereas, the choice of RCM adds a more or less constant bias over space (given the region studied). In terms of the H_s inside the port though, such behaviour is somewhat altered by the specific configuration of each port together with the coastal orientation and port shelter. However, no significant correlation has been found between the changes in H_s inside the harbour and the typical port configuration parameters, which is reasonable taking into account the varying forcing wave conditions among ports.

In this study, the RCM–GCM combination with a different GCM is RCA_H. As opposite to the rest of simulations, for example, an increase of E waves is associated with this model during the winter season, which is typically associated to more energetic wave conditions (Casas-Prat and Sierra, 2013). However, this is not reflected in the H_s inside the port in most of the Catalan ports, whose mouths have a SW orientation.

To our knowledge, there is no clear indication of one RCM–GCM model being “the best”, and the general rule is to consider all of them to be equally feasible. Casas-Prat et al. (2015) found that HIR_E is not very suitable to properly simulate the longshore sediment transport along the Catalan coast but clearer evidence would be preferable to discard this model in terms of harbour agitation. In a more general framework, in order to simplify the results of impact on harbour agitation and towards a more effective port assessment (quay by quay for example), we could consider only a “pessimistic” and an “optimistic” model combination for each GCM, or even an ensemble for each GCM, but it is not recommended to mix projections driven by different GCM.

Ultimately, the obtained results show that potential changes in wave patterns can produce clear spatial and seasonal variations in agitation at the Catalan coast ports. Although most of the realizations entail a “positive” impact (reduction of agitation in ports, increasing their safety and operability), the possibility of “negative” impact (increase of waves within the port, reducing their safety and operability) is non-negligible. For the annual analysis, for example, most of the ports have RCM–GCM combinations showing an increase in H_s. Also, although the analysis of spatial averaged values indicate limited magnitude of the changes, a detailed analysis of their distribution within the harbours show that in certain areas the increase of wave heights may be very notable (greater than 20 %) potentially leading to serious management problems. The port community needs therefore to be aware of this potential problem. However, further studies are needed in this regard, trying to reduce the obtained uncertainty, for example, by using updated climate projections and/or a larger amount of RCM–GCM that enables a proper characterization of the inter-model variability. In this regard, based on the finding of this paper, in order to properly characterize the variability induced by RCM and GCM it is important to account for the spatial pattern or correlation, and not only to focus on the performance of each location separately. Additionally, it would be of great interest to investigate the variability induced by the greenhouse gas scenario.

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