Study of atmospheric forcing influence on harbour water renewal

Yaiza Samper, Manuel Espino, Maria Liste, Marc Mestres, Jose Alsina and Agustin Sánchez-Arcilla

Abstract

In this paper, we use observations and numerical simulations to investigate the effect of meteorological parameters such as wind and atmospheric pressure on harbours water exchanges. Knowing these water exchanges is of vital importance to care for maintain and improve the environmental health of the harbour water and its surrounding areas. In this case, the modelled hydrodynamic information is obtained from the SAMOA forecasting system, which is a high-resolution numerical model for the prediction of ocean variables at coastal and harbour scales. Firstly, this article validates the results of the SAMOA prediction system in the ports of Huelva, Gijón and Cartagena (mesotidal estuary and mesotidal and microtidal artificial lagoons, respectively) by a qualitative analysis of the time series of modelled data and observations, as well as by statistical analyses and correlations between model results and measurements. Secondly, based on the analysis of observations, it proposes the numerical study of different hydrodynamic events characterized by high renewal times. The examined data include information on wind, atmospheric pressure, sea level and current parameters. The first part of the analysis, based on observations, indicates that days with higher renewal times coincide with water inflow events, wind and increases in atmospheric pressure. In the second part, after analysing six of these events based on model results, it is observed that during these episodes, water inflow currents are generated and, in some cases a negative difference in level between the inside and outside of the harbour is produced. These last results suggest the possibility that this difference in level may be generated by atmospheric pressure variations, because the volume of water in the harbour is lower than the open sea, the harbour descends faster and a gap, a difference in level, is produced, which means that water enters towards the interior of the harbour.

1. Introduction

Coastal zones are important for human activity worldwide. They are areas of important production centres, human settlements and tourist destinations, and consequently areas with high population densities. The European Commission estimates that the population in European coastal regions is around 194 million people, 38% of the total population [1]. In addition, the increase in global maritime traffic has also contributed to accentuate the activity in coastal regions. In 2019, the total gross weight of cargo handled in European Union harbours was estimated at almost 4.1 billion tonnes, with the Spanish harbours contributing 497 million tonnes(2018) of the total [2].

Coastal cities and port activity both have a strong influence on water quality and renovation inside harbours and surrounding areas, contributing to the deterioration of coastal ecosystems, loss of biodiversity and destruction of habitats. At the same time, water circulation in coastal areas is affected by climatic events that can be extreme, such as storms and strong winds [3], which influences the port-external water exchanges and water renovation. In order to preserve the environmental health of coastal zones and improve their protection, it is important to establish and use long-term environmental management tools. The European legislation is the main guideline for developing these tools and to comply with international standards [4]. Understanding and being able to predict the physical behaviour of coastal and harbour zones is a key tool to mitigate and reduce anthropogenic impacts resulting from the exploitation of these areas.

According to the survey carried out in 26 European harbours in the framework of the PEARL project (port environmental information 2006-2008), the main environmental interests in European harbours are those related to the monitoring of currents, tides and waves, which is helpful in ensuring the safety of navigation, predicting the dispersion of pollution, identifying sources of pollution, etc. The survey also reveals the importance of water quality, meteorological parameters, sedimentation and turbidity processes [4]. In order to respond to these needs and assess the actual state and dynamics of the seas, as well as to obtain forecasts at different spatial and temporal scales, significant progress has been made in recent years in the implementation of operational ocean forecasting systems [5].

The Copernicus Marine Environmental Monitoring Service (CMEMS) reflects significant advance in operational oceanography. This service provides regular and systematic information of the physical state of the global ocean and European seas [6]. All CMEMS-derived products depend on *in situ* and satellite observations, which are used to develop new products and validate models [7]. The SAMOA (Meteorological and Oceanographic Support System of the Port Authority) forecast systems are CMEMS downstream services, being the coastal models nested into the regional CMEMS Iberia Biscay Irish forecast solution (CMEMS IBI) [8]. One of the main goals of SAMOA is to provide series of high-resolution numerical models for the prediction of ocean-meteorological variables and forecasting inside of harbours, with coastal and harbour scales.

High resolution forecasting models in harbour domains support the activity carried out within them, for example, as a guide for the handling of large vessels; to anticipate harbour closure due to extreme events; to propose improvements in operations and safety; as a source of information for the design of contingency plans in case of spills; to propose environmental management plans; to comply with current legislation related with water quality, etc. The availability and development of new forecasting systems with different domains and scales, has made it possible to use the models in a wide range of areas. The most frequent areas of application are those related to the simulation of accidental spills [9]; the physical impacts of storms and climate change [10]–[12]; the study of dominating harbours hydrodynamics [13], [14]; and the effects of port activity on nearby urban areas [15].

These current forecasting systems make it possible to study currents in different situations and under different environmental conditions. It is a useful tool to, on the one hand, analyse port hydrodynamics in strong wind conditions, without wind, during storms or under static atmospheric conditions; and on the other hand, to analyse the influence of external currents on the internal domain and to estimate how this affects the renewal capacity and, therefore, the quality of the water. This information can be used to develop plans to minimise the risk of future accidents.

The water quality of a harbour and its ecological status are mainly determined by its capacity for renewal and mixing. In addition, in case of internal discharges, turbulent mixing contributes to the decomposition of the discharged substances and thus it the impact on the external region is reduced. The renewal capacity of water in semi-enclosed domains (like ports) is mainly conditioned by the exchange with the outer domain, but also by the internal circulation within the harbour [13]. This water exchange can be influenced by severals meteo-oceanographic, geometric and geographic conditions [16]. The physical characteristics of the harbours and the region are static and invariable, but the weather conditions are constantly changing and play an important role in the circulation. Therefore, accurate model predictions of water inflow and outflow under different meteorological conditions are desired for water quality monitoring. Reliable and verified information on meteo-oceanographic dynamics can improve residence time estimation and improve environmental management systems.

The aim of the paper is to analyse the influence of atmospheric forcings on water renewal rates in harbour domains. Specifically, to examine the effect of weather conditions on water inflows and outflows in ports based on observations and modelled data. In other words, to relate the variability of the renewal time of each harbour to meteorological weather, in particular wind and atmospheric pressure.

This article is organised as follows: first, after this brief contextualisation, the "Materials and methods" section describes the study areas that are the focus of this work and the measurement campaigns. Then, the SAMOA forecasting system and the validation methodology are presented. The "Results" section is organised in two parts: the first based on observations and the second based on model results. In the first part, it describes the meteorology and hydrodynamics of each port during the measurement campaigns and highlights events of interest with high renewal times. In the second part, a selection of these events is presented in 2D images from the SAMOA forecasting model. Fourthly, the "Discussion" chapter provides an analysis of the results obtained and presents different meteorological scenarios that may justify the renewal times observed above. Finally, the paper concludes with some suggestions and proposals for future studies.

2. Materials and Methods

This section describes the procedure followed to derive water quality information from observational data and numerical simulations. First, for a correct interpretation of the data, the ports and the field campaigns are described Then, the SAMOA forecasting model is explained. To finish, the validation of the model is presented.

2.1. Study Area

This work focuses on the ports of Huelva, Gijón and Cartagena (southwest, north and southeast of the Iberian Peninsula) (see Figure 1). These harbours are located in different seas and have different physical characteristics. A study area has been delimited in each port (where the ADCP was located). Table 1 shows the main geometrical characteristics of these domains.

Harbour	Surface (km2)	Mean depth (m)	Volume considered (m3)
Huelva	5.04	10.3	51.912.000
Gijón	0.95	11.4	10.801.625
Cartagena	0.95	20.3	19.314.557

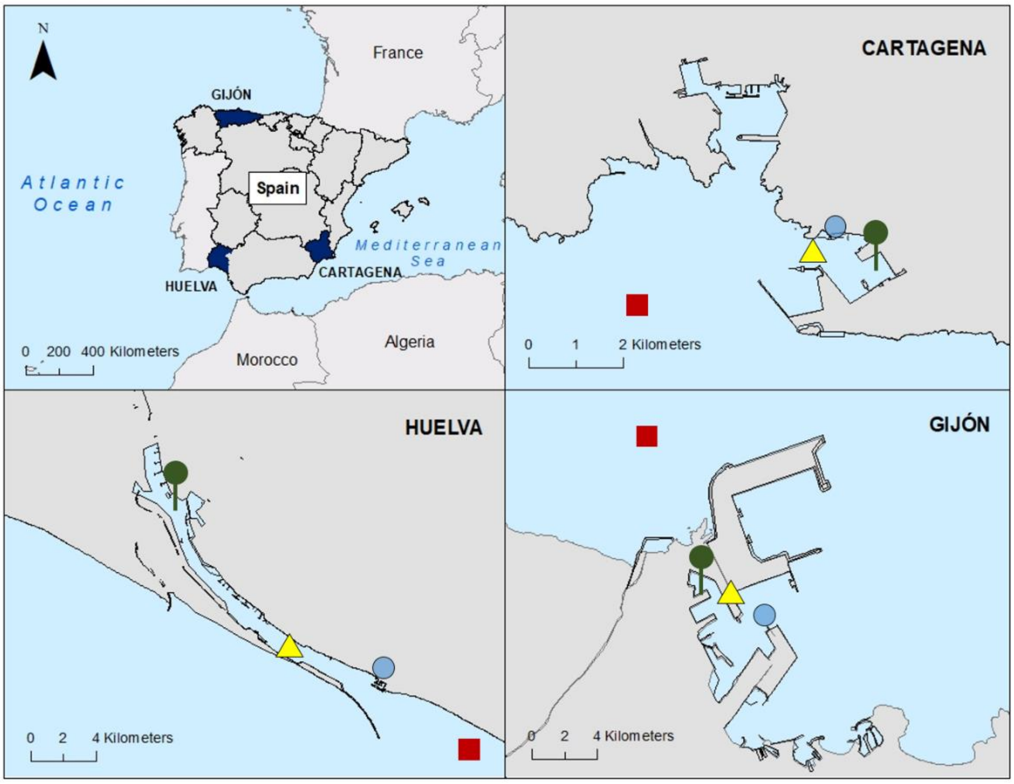

Figure 1 Location of the ports studied. The red square corresponds to the outer points discussed below; the green pin corresponds to the inner points; the yellow triangle represents the doppler locations and the blue circle indicates the meteorological stations.

Harbour	Surface (km^2)	Mean depth (m)	Volume considered (m^3)

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Table 1 Main characteristics of each study area

Huelva Harbour

The Port of Huelva is located in the Huelva estuary, in the southwest of the Iberian Peninsula. This tidal region is connected to the Atlantic Ocean and has tides of up to 3.84 m [17] which are responsible for the exchanges between the different water masses circulating within the estuary, determining the dilution capacity in the estuarine system [18]. Its location allows the port to receive daily inflows of water from both the ocean and the rivers *Tinto and Odiel*, which flow into the estuary. The port has the shape of a channel and it is 13 km long with widths of between 500 and 1000 m. Its bathymetry is between 5 and 10 metres in the inner area and reaches 20 metres in the outer area of the port (Figure 2a).

Gijón Harbour

The Port of Gijón is located in the Cantabrian Sea, in the north of the Iberian Peninsula and has tides of up to 4.62 m [19]. The port is divided into three independent areas: *Puerto del Musel*, *Puerto Deportivo* and *Marina Yates*. The area around the harbour has a complex topography, dominated mainly by the *Peñas* and *Torres* capes and the *Amosucas* shelf. These geographical features provide natural protection against storms and modify the incoming waves by diffraction and refraction [3]. The bathymetry of the inner harbour shows depths of 5 to 20 m (Figure 2b).

Cartagena Harbour

Cartagena Port is located in the Bay of Cartagena, in the southeast of the Iberian Peninsula. This bay is in the Mediterranean Sea (semi-enclosed sea), and therefore does not have significant tides (maximum tidal range 0.95 m [20]). This Port has an "open" shape, it has no defined channel and is formed by two independent basins: The Cartagena basin and the *Escombreras* basin. The maximum depth in the harbour is 25 metres and can reach 75 metres in the outermost area (Figure 2c).

2.2. Field campaigns

Observations were collected in the framework of the SAMOA project from 12th October 2020 to 8th February 2021 in Cartagena; from 14th April to 13th July 2021 in Huelva; and from 10th November 2021 to 20th January 2022 in Gijón. Time series of currents, sea level and meteorological data were measured in the three harbours.

Water currents measurements were obtained by an acoustic Doppler current metre (ADCP) in each Harbour (AWAC 1MHz model NORTEK-AS). In Huelva, the ADCP was located inside the estuary, where the port begins. Given the complex geometry and the absence of other measuring devices, this work will focus on the first 6 km of the estuary. In Gijon harbour, it was located at the mouth of the inner Musel Harbour basin and this work will focus only on this domain. In Cartagena it was located at the Escombreras basin entrance and this work will be focused on this basin.

Meteorological and sea level data were recorded by two meteorological stations with a tide gauge in each harbour. One station was located near the ADCP, while the other was outside the port. All the time series data has a sampling interval of 10 minutes.

For reading, representation and analysis of time series data (wind, level, currents and temperature) it is used Python programming language. In particular, for the graphical representation, Matplotlib and Pandas libraries are used and a 12-hour moving average for a better graphic display is generally applied.

2.3. The SAMOA operational service

SAMOA forecasts are generated using the Regional Ocean Modelling System (ROMS) [21]. These systems cover different basins at regional scales (resolution varying from 1.8 to 2.2 km) [22] and use different forcing and nesting strategies [23]. Complete information of the model and its source code are available on the ROMS website (http://myroms.org/).

The SAMOA initiative is the solution of Puertos del Estado (PdE) and the Spanish port authorities to respond to the needs of metocean information at coastal and port scale [23]. This service includes a high-resolution operational system in domains such as ports and coastal areas.

The SAMOA model application consists of two nested regular grids with a spatial resolution of ∼350 m and ∼70 m for the coastal and harbour domains, respectively. The vertical discretisation consists of 20 sigma levels in the coastal domains and 15 levels for all port domains. In this paper the results of the harbour grid for Gijón and Cartagena and of the coastal grid for Huelva have been used. It is because the Huelva harbour grid was not yet operational during the field campaign period. The characteristics of the computational domains are summarised in Table 2.

Harbour	Domain	Extension (km)	Dimension (cells)
Huelva	Coastal	106 x 70.5	303 x 202
	Harbour	26 x 24.3	372 x 347
Gijón	Coastal	77.9 x 40	223 x 115
	Harbour	15.5 x 9.9	222 x 142
Cartagena	Coastal	55.4 x 39	159 x 112
	Harbour	17.26 x 8.13	177x132

Table 2 characteristics of the computational domains

To provide sufficiently detailed bathymetry, the SAMOA model uses a combination of global (GEBCO - https://www.gebco.net/) and local data sources (provided by the port authorities). Figure 2 shows the location and extension of the coastal (red box) and harbour (yellow box) domains in all the ports studied with the corresponding bathymetry in contour plots ranging from yellow to blue (from shallowest to deepest). The SAMOA models are nested into the daily regional forecasts delivered by CMEMS- IBI [5]. At the sea surface, the SAMOA models are forced by high frequency (hourly) wind stress, joint with atmospheric pressure, fluxes of water (evaporation minus precipitation) and surface heat derived from the Spanish Meteorological Agency forecast (AEMET) (based on the AEMET HARMIONE model 2.5 km application nested into the ECMWF IFS forecast). CMEMS - IBI provides hourly data for water currents and sea level and are applied as open boundary conditions (OBC). Moreover, it also provides daily values of temperature and salinity in the water column. Where freshwater discharges may be relevant, the river discharge is taken into account considering climatological data and a constant salinity of 18 PSU. A detailed description of the SAMOA operational system can be found at [22] and [23].

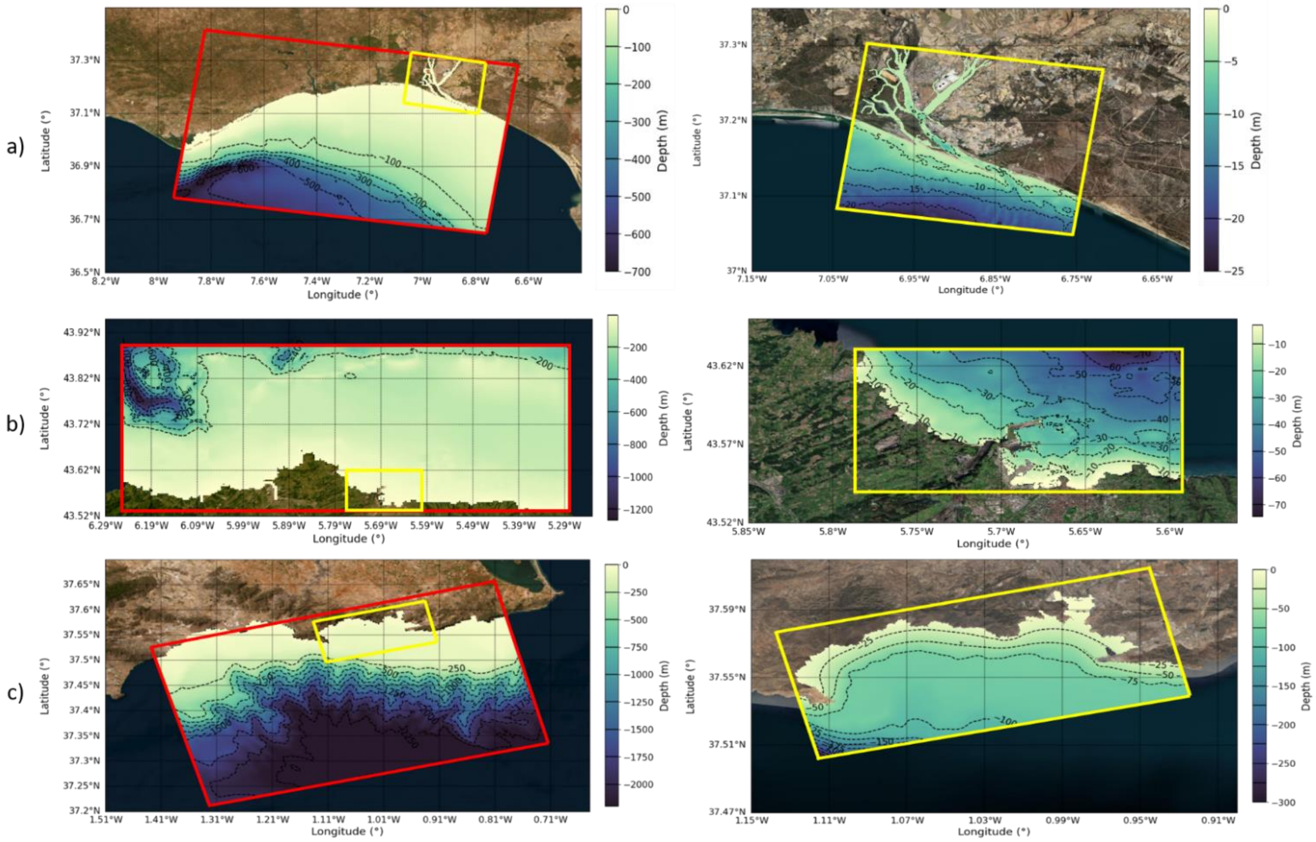

Figure 2 Location and extension of the coastal (red box) and harbour (yellow box) domains in Huelva (a), Gijón (b) and Cartagena (c). The bathymetry of each domain is also shown (yellow corresponds to shallower and dark blue to deeper areas).

2.4. Validation

To validate the forecasting system, the set of observations obtained during the campaigns and the results provided by the model are used. These modelled results correspond to the mean of the grid four points closest to the observation point in each case. For the present study, model results for atmospheric pressure, meteorological tide and currents have been used, therefore, the qualitative and quantitative validation of these variables has been carried out. For this validation, the data number presented in table 3 has been used, which corresponds to one hourly data during the whole duration of the campaigns.

Table 3 Number of data (observations and model results) used for the validation of the variables analysed.

Variable	**Number of data for the validation**		
	Huelva	**Gijón**	**Cartagena**
Atmospheric pressure	1729	224	452
Meteorological tide	1793	1463	2752
Currents through the mouth	2161	1729	2752

The validation process is carried out in two phases: an initial plotting of time series at hourly intervals; and a second analysis by calculating different basic statistics such as BIAS, RMSE and correlations (R and values of the correlation line).

Qualitative analysis of the atmospheric pressure, meteorological tidal and currents time series (an example is presented in Figure 3), shows the SAMOA model results are in accordance with the observations in all the three harbours.

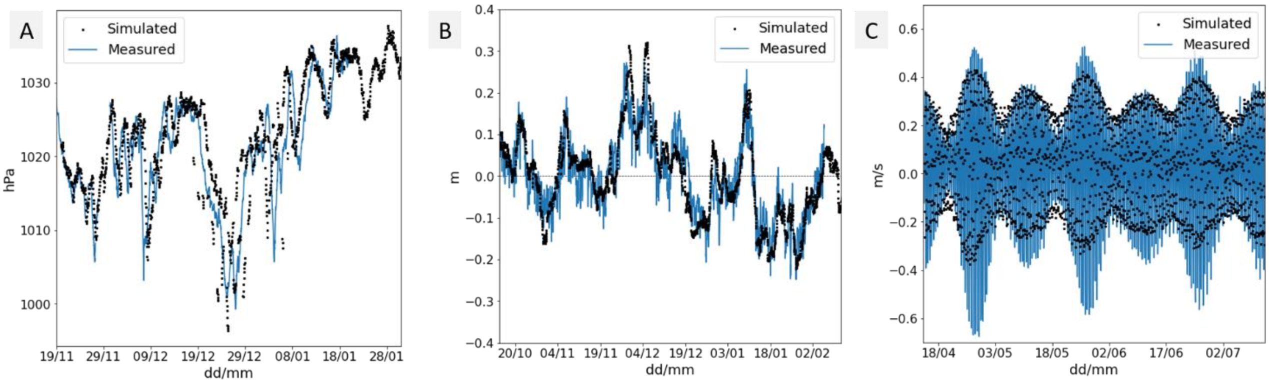

Figure 3 Time series of atmospheric pressure in Gijón (A), meteorological tide in Cartagena (B) and currents through the mouth in Huelva (C). The observations correspond with the blue lines and forecasted by SAMOA are the black dots.

The statistical analysis (presented in Table 4) confirms the fit of the model for the observations, with correlations of 0.89, 0.57 and 0.76 for Huelva; 0.99, 0.76, and 0.29 for Gijón; and 0.99, 0.88 and 0.34 for Cartagena respectively. Geometric complexity of each domain and tides intensities can have a significant influence on measurement and predictions.

Table 4 Model validation metrics for simulated atmospheric pressure, meteorological tide and currents through the mouth compared with observation from campaigns data.

Variable	Statistical	Huelva	Gijón	Cartagena
Atmospheric pressure	**RMSD**	0.891 hPa	0.998 hPa	0.999 hPa
	R	0.8907	0.9978	0.9985
Meteorological tide	**RMSD**	0.09 m	0.09 m	0.05 m
	R	0.57	0.76	0.88
Currents through the mouth	**RMSD**	0.1560 m/s	0.0618 m/s	0.0670 m/s
	R	0.7595	0.2946	0.3413

3. Results

The methodology used to calculate the renewal time follows the techniques described in [16], which assumes that water exchanges take place only at the mouth of the port, ignoring the permeability of the dikes and overtopping. In this study, to estimate the renewal time in the ports of Huelva, Gijón and Cartagena, the second method presented in the mentioned article is used. That is, based on the measurements of currents at the mouth and the dimensions of each study area, the inflow and outflow of water are calculated and the renewal time (TR). TR obtained was daily-averaged currents. In the three harbours analysed, the time series of renewal time shows days with some high values (Figure 4a, 5a and 6a).

shows the renewal times information obtained from the current measurements at the mouth of each port. Average values of 27, 21 and 25 days are observed for the ports of Huelva, Gijón and Cartagena respectively. These values correspond to 28%, 27% and 25% of the total series in each case. In order to understand the origin of these results, wind and atmospheric pressure variations (from campaign data), together with currents and sea level (from observations and model results) are studied.

Table 5 Comparative summary of the renewal times calculated from the inflow and outflow currents recorded during the measurement campaigns.

	Mean TR	**Days above average (%)**
HUELVA	27 days	28
GIJÓN	21 days	27
CARTAGENA	25 days	25

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3.1 Metocean field data

The renewal time series (Figure 4a, 5a and 6a), show data gaps on some days. These data gaps correspond to days during which there are no outflows of water, that is, the outflow is almost zero for the whole day. High renewal times therefore indicate that there is more water coming in than going out. Figure 4a, 5a and 6a show the harbour mouth current intensity (positive values means inflow and are in red).

To identify the possible reason for these high inflows, wind during these events are analysed. It is observed that some of these TR (Renewal time) peaks coincide with wind episodes (vertical purple shades areas in Figure 4a, 5a and 6a) that favour water inflow (these favourable directions are highlighted by a grey horizontal band). However, others coincide with positive gradients in atmospheric pressure (vertical green shades areas in Figure 4a, 5a and 6a). In other words, some TR peaks (defined as peaks as above-average values) seem to be related to wind events favourable to water inflow and others to increases in atmospheric pressure.

In the case of the Port of Huelva, observing the time series in Figure 4, there are 25 days with TR above the average. These high TRs seem to be related, on some occasions, to winds that favour the entry of water; and on others, to increases in atmospheric pressure. In this figure, one event of each type (wind with a purple band and atmospheric pressure with a green band) has been selected for later model analysis.

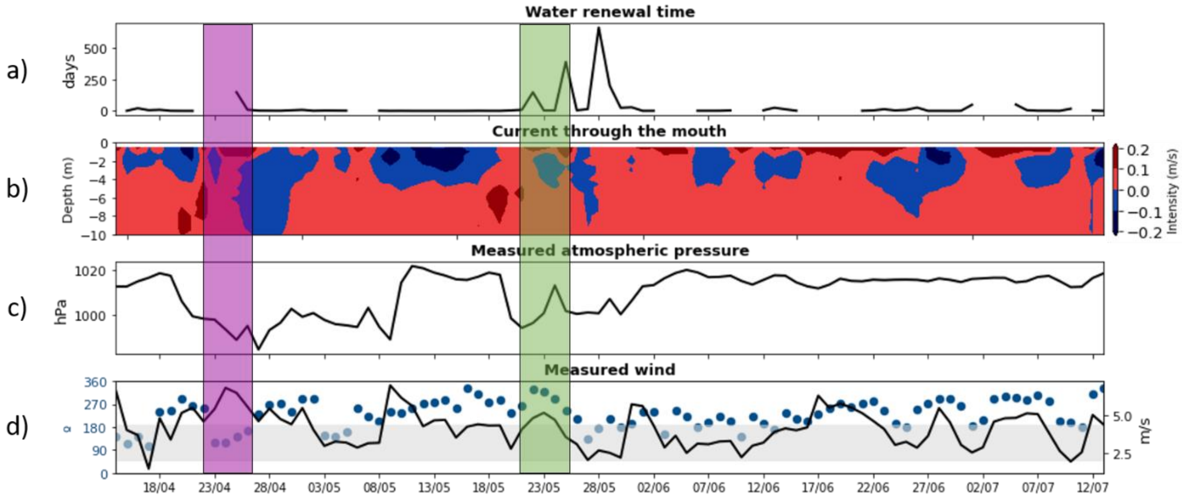

Figure 4. From top to bottom, water renewal time (a), currents at the mouth (b), measured atmospheric pressure (c), and measured wind (d) (the grey shaded area highlights the direction that allows water inflow) in Huelva's harbour. The boxes show two examples of high renewal time episodes: the purple one, related to an episode of wind favourable to water inflow; and the green one, linked to an increase in atmospheric pressure.

In the Port of Gijón, 23 days are observed with renewal times (or data gaps implying an outflow close to 0 m3/s) above average. During some of these events, the wind favours the entry of water into the port and during others, the atmospheric pressure increases (in the Figure 5 the wind event is highlighted with a purple band and one atmospheric pressure related event with a green band). In the following section, two of these events will be analysed on the basis of the results provided by the model.

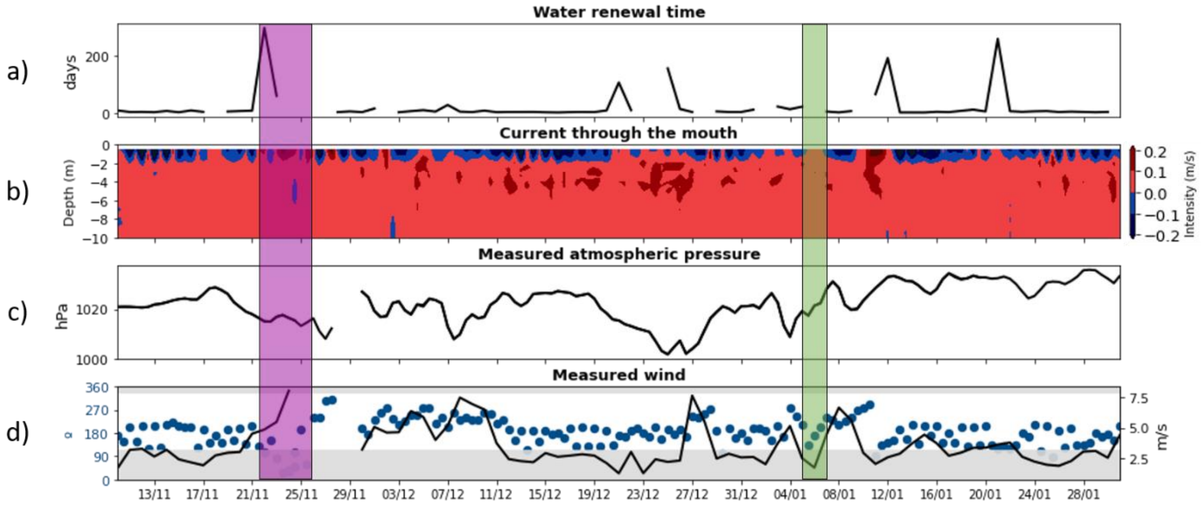

Figure 5 From top to bottom, water renewal time (a), currents at the mouth (b), measured atmospheric pressure (c), and measured wind (d) (the grey shaded area highlights the direction that allows water inflow) in Gijón's harbour. The boxes show two examples of high renewal time episodes: the purple one, related to an episode of wind favourable to water inflow; and the green one, linked to an increase in atmospheric pressure.

In the Cartagena harbour, 30 days with renewal times above the mean (or data gaps) have been detected. In the course of these events, wind that favours the entry of water into the port and atmospheric pressure increases happens. In the following section, two of these events will be analysed using the results provided by the model.

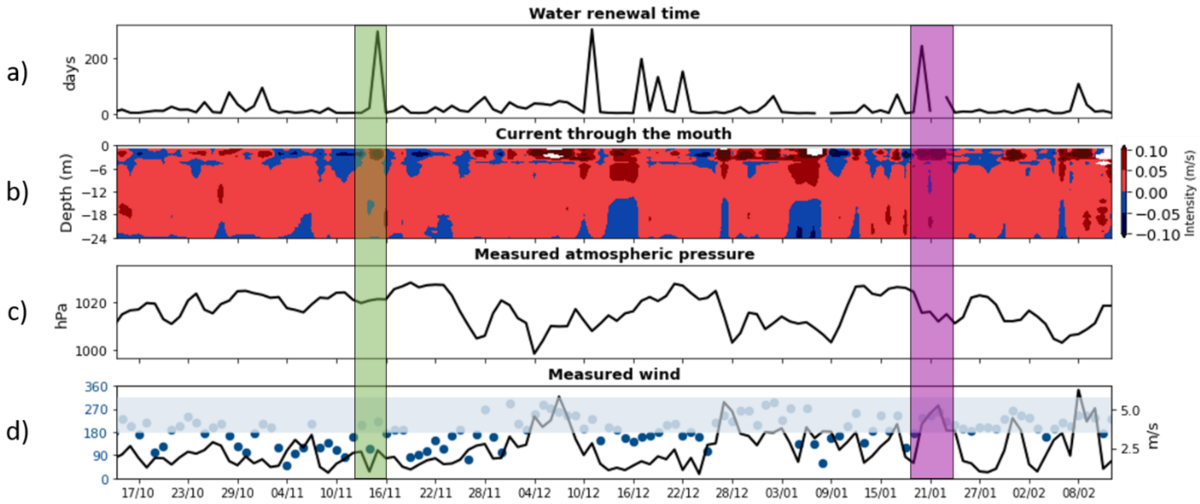

Figure 6 From top to bottom, water renewal time (a), currents at the mouth (b), measured atmospheric pressure (c), and measured wind (d) (the gray shaded area highlights the direction that allows water inflow) on Cartagena's harbour. The boxes show two examples of high renewal time episodes: the purple one, related to an episode of wind favourable to water inflow; and the green one, linked to an increase in atmospheric pressure.

Once all the days with high TR values had been identified and analysed, in Table 6**¡Error! No se encuentra el origen de la referencia.** a recount was made of the days with peaks that were apparently related to the entry of water due to a favourable wind direction; the days with peaks that seem to be related to the entry of water due to the difference in level generated by the increase in atmospheric pressure; and the days with high values that do not seem to be related to either of these two causes.

Table 6 Summary of the causes that seem to justify the increases in renovation times in the three ports analysed.

	Days with renewal time above average		
	Cause		
	Wind (%)	**Atmospheric pressure (%)**	**Unknown (%)**
HUELVA	20	32	48
GIJÓN	26	44	30
CARTAGENA	53	27	20

3.1. Model results

After analysing the observations (which correspond to a single measuring station), the model results are used to complement them and to study the currents in and around the harbour more extensively. This section examines the inflow and outflow currents and sea level variations during six of the identified events with high renewal times, two for each harbour.

The results provided by the model indicate that, during these events, water inflows into the harbour predominate, which it agrees with observations. In the following, high TR events associated, on the one hand, with wind events favourable to water inflow and, on the other hand, with episodes of increased atmospheric pressure will be analysed. Therefore, modelled results of two events will be presented for each harbour (the first related to wind and the second to atmospheric pressure).

Figure 7 shows the currents in the Port of Huelva and its coastal area according to the results provided by the model for 24/04/2021. According to the observations, during this day there was an episode of intense wind from the southeast which could favour the entry of water into the port through its mouth oriented in this same direction. The model results show inflow currents for the same day, which would justify the increase in TR.

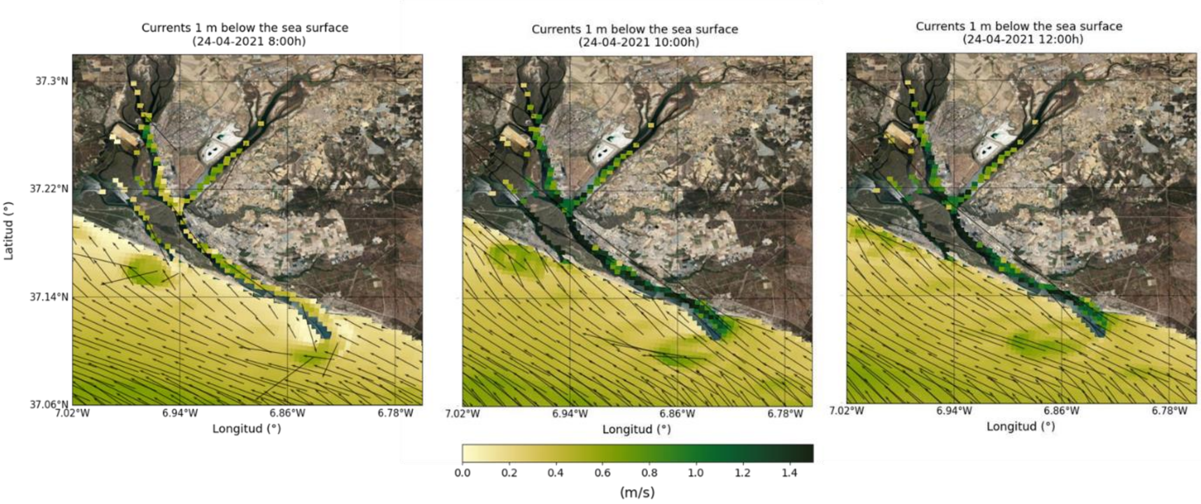

Figure 7 Intensity and direction of the sea currents in the port of Huelva during the southeast wind episode on 24/04/2021.

Figure 8 presents the sea level variation in the port of Huelva based on the results provided by the model for 22/05/2021. During the first hours of the day, the figure shows an irregular sea level variation for the area inside and outside the harbour. In the inner harbour, this variation is negative, i.e. the level inside the harbour is falling, reaching 80 cm below the mean level. However, the outer harbour area maintains a constant level without significant changes.

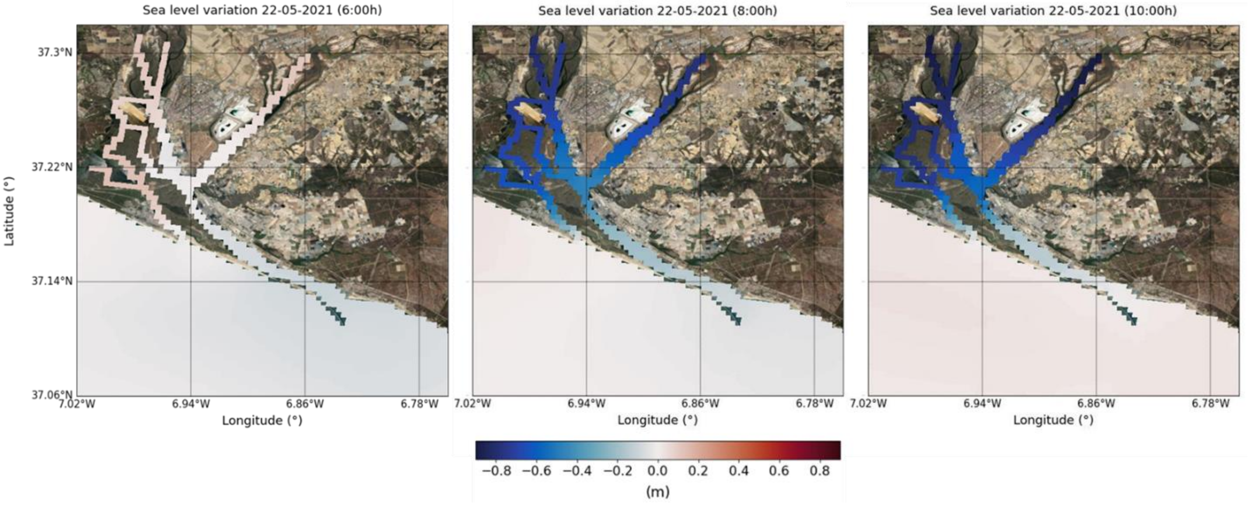

Figure 8 Variation of the sea level in the port of Huelva during the episode of increased atmospheric pressure on 22/05/2021.

Figure 9 presents the currents in the Port of Gijón and its coastal area based on the model results for 23/11/2021. According to the observations, during this day there was an episode of strong north-easterly wind which seems to have favoured the entry of water into the harbour through its mouth. The model shows inflow currents, which could justify the TR peak on this day.

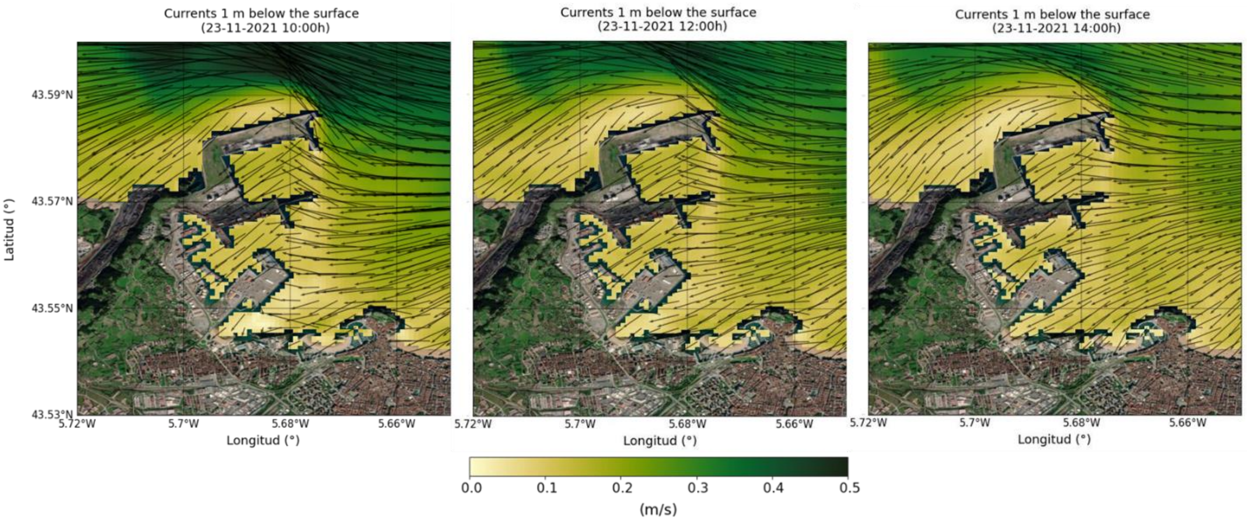

Figure 9 Intensity and direction of the sea currents in the port of Gijón during the northeast wind episode on 23/11/2021.

Figure 10 shows the sea level variation in the port of Gijón from the results provided by the model for 4/01/2022. In the figure it can be seen, that the variation in sea level is not equally distributed between the harbour area and the area outside the harbour. In the sheltered area of the harbour, this variation is negative, i.e. the level is decreasing, reaching 2 cm below the mean level. However, in the outermost area and outside the harbour, this variation is positive, reaching 2 cm above. Therefore, a difference in level of up to 4 centimetres can be observed between the inside and outside of the port.

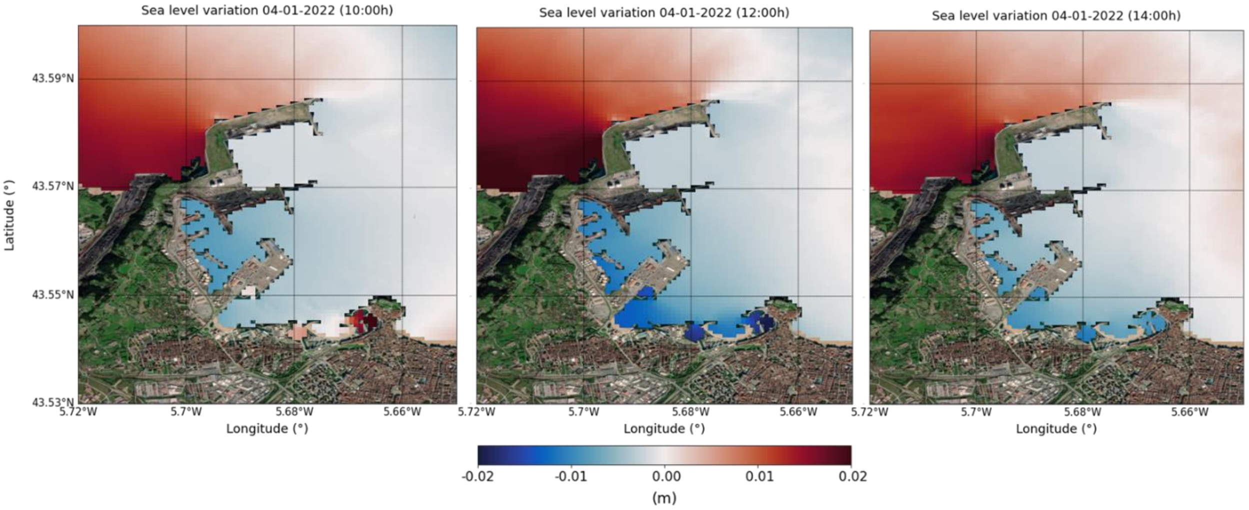

Figure 10 Variation of the sea level in the port of Gijón during the episode of increased atmospheric pressure on 4/01/2022.

Figure 11 shows the currents in the Port of Cartagena and its coastal area according to the results provided by the model for 21/01/2021. Based on the data collected by the measurement campaign, on this day there was an episode of strong westerly wind which may have favoured the entry of water into the Escombreras dock at the mouth. According to the results of the model, inflow currents were observed during that day, which would justify the increase in the TR.

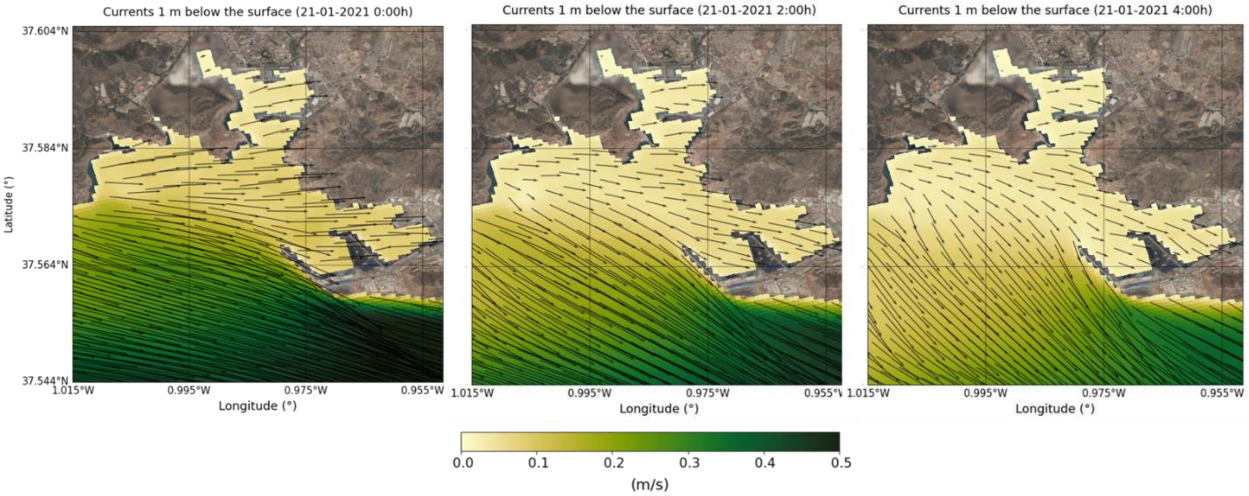

Figure 11 Intensity and direction of the sea currents in the port of Gijón during the northeast wind episode on 23/11/2021.

Figure 12 shows the results of the model of sea level variation in the port of Cartagena for the day 15/11/2020. In the figure the sea level variation shows inequalities between the inside and outside of the bay in which the port is located. In the inner zone, this variation is negative, i.e. the level is falling. On the other hand, in the outer zone, this variation is positive, reaching 2 cm above the average level. There is therefore a difference in level of about 3 cm between the inner and outer harbour.

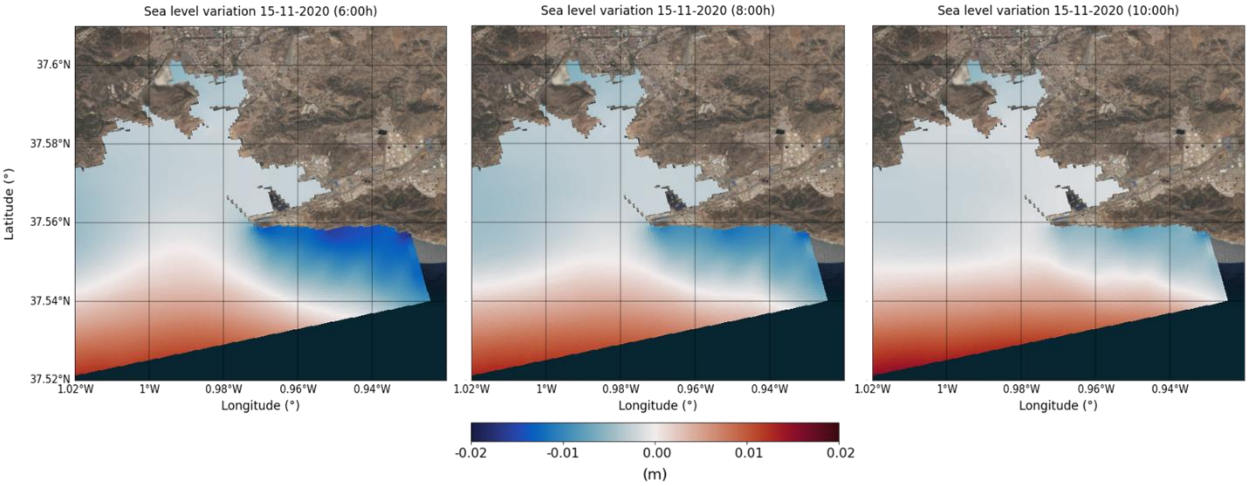

Figure 12 Variation of the sea level in the port of Cartagena during the episode of increased atmospheric pressure on 15/11/2020.

4. Discussion

Ports and their surrounding areas are environments susceptible to changes in water quality as a result of their own activity. For this reason, and in order to avoid serious or irreversible damage, it is of vital importance to control the quality of the water inside the port; to know the mechanisms that help its renewal and exchange with the outside; and to be able to predict possible damage in the event of accidents or adverse climatic situations in order to anticipate and implement the best possible management.

In confined domains, such as harbours, water quality is related to its renewal capacity. This capacity, in turn, is determined by different factors such as the size, shape, number of mouths, their orientation, the possible supply of fresh water, the meteorological conditions of the region, etc. On the one hand, these physical characteristics of the harbours and their surroundings are static and invariable, but the weather conditions are constantly changing and play a fundamental role in shaping the sea currents. On the other hand, under specific conditions, external water currents can influence the internal circulation of the harbour.

Therefore, studying the meteorology of harbour regions can be a useful tool for understanding the configuration of water currents; analysing their influence on the interior domain and estimating how they affect the renewal capacity and, therefore, the quality of the water. In this article, the wind and the atmospheric pressure variability effect on the inflow and outflow of Huelva, Gijón and Cartagena harbours has been studied from in situ observations and modelled data.

In the first part of the analysis, the estimated daily renewal time for each of the harbours was compared with the currents measured at the harbour mouth, wind and atmospheric pressure (Figure 4, 5 and 6). After this first analysis, it was observed that some of the days with high renewal time seems be related, on the one hand, to wind episodes and, on the other hand, to increases in atmospheric pressure. This coincidence is repeated throughout the time series analysed in the three harbours despite their different physical characteristics.

For the second part of the analysis, six events with high renewal times have been selected, two for each harbour, and the currents and sea level variations have been analysed using data provided by the model (from Figure 7 to 12). The analysis shows that during these wind episodes, water inflow currents are generated and during the atmospheric pressure increases events, a negative sea level gradient between the exterior and interior of the harbour is produced, indicating a lower sea level inside the harbour.

Comparing the information obtained from the analysis of the observations and the model data, it seems that the difference in level between the inner and outer harbour can be generated by the variations in atmospheric pressure (identified previously from the observations), since the volume of water in the harbour is lower than that of the open sea, the sea descends faster and a gap, a difference in level, is produced, which means that water enters the interior of the harbour. It has been observed that this difference in level is not maintained over time, but occurs when the atmospheric pressure begins to change.

Figure 13 compares the time series of the level difference (these points are identified in Figure 1) between the outer and inner harbour (data from the model) with the time series of the renewal time (observational data). In this figure it can be seen that, generally, at the times with the highest level difference, the renewal time is high. This fact could be the origin of an inflow of water when there is a gradient level inside the harbour. Consequently, this water inflow would imply an increase in the water renewal times in the harbour. Therefore, it is probable that, in situations of high atmospheric pressure, inflow currents would be generated to the port, increasing the vulnerability and the risk of water quality problems.

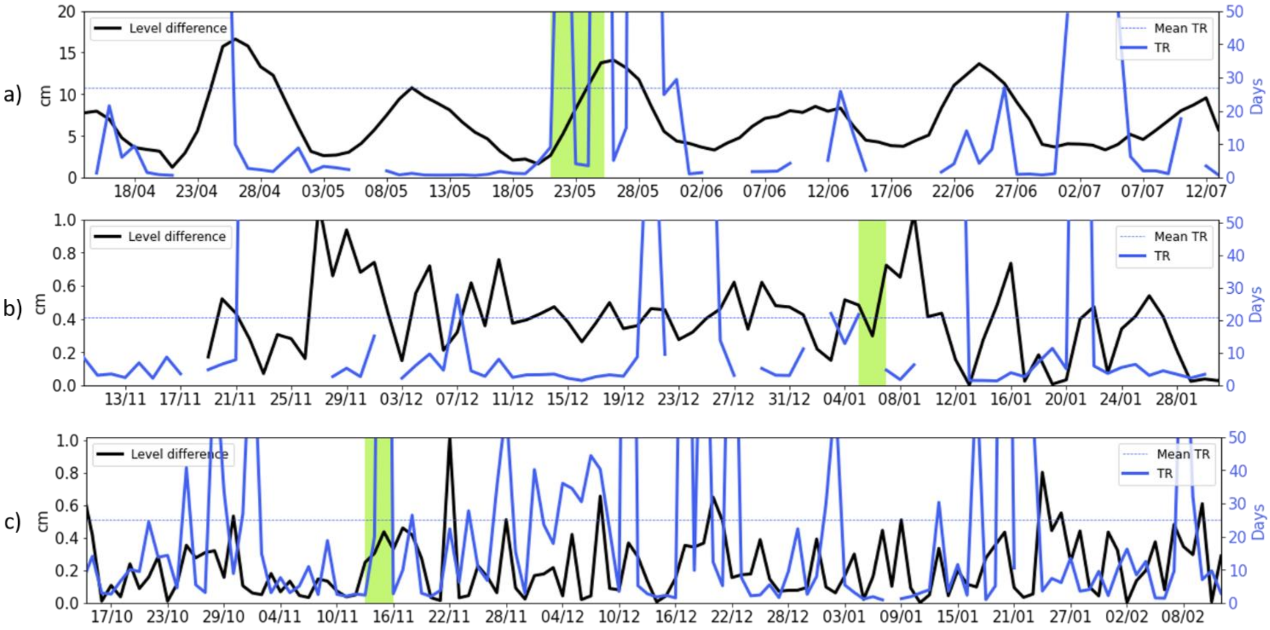

Figure 13 Difference (cm) in sea level between the interior and exterior of the harbour (black line) and renewal time (days) in Huelva (a), Gijón (b) and Cartagena (c) harbours. The green boxes highlight the events analysed by the model during which the atmospheric pressure and the renewal time increase. Note the difference of scales on centimetres axes between the different ports for better visualisation.

As shown in Table 6, in the case of the port of Huelva, the proportion of days with TR peaks due to an unknown cause is 48% of the cases. This high percentage may be due to the location of the port in an estuary, where it constantly receives water inflows that were not quantified at the time of the study. These inputs have a significant influence on harbour hydrodynamics and add complexity to the analysis. In addition, due to its channel shape, the wind would drive water inland only from a specific direction.

In the case of Gijón harbour, the main cause of the TR peaks seems to be atmospheric pressure increases (44%) and less probably wind (26%). This may be due, on the one hand, to the fact that the volume of water in this harbour is relatively small and changes in atmospheric pressure have a greater effect. On the other hand, the harbour mouth is sheltered and therefore less influenced by the wind.

Finally, in the port of Cartagena, the main cause of TR increases seems to be the wind (53% of cases). This is due to the fact that, because of its open shape, wind from many directions can blow water into it.

From the analysis it can be concluded that in the three harbours most of the TR peaks can be explained by atmospheric forcings (winds or atmospheric pressure). Therefore, it is recommended the use of meteorological stations as a tool for environmental management in harbours and the integration of this information in the hydrodynamic and water quality studies of these domains.

5. Conclusions

The main objective of this work was to study how atmospheric forcings can drive water renewal time in three Spanish ports: Huelva, Gijón and Cartagena. These three ports have different geometries and characteristics and are located in different regions of the Spanish coast. However, the results obtained from the different analyses lead to two common hypotheses for the three ports.

The renewal times are usually calculated with data from models due to the lack of observations; however, in this case, data from the measurement campaigns have been used to make these calculations. Studies based only on observations have two main disadvantages. On the one hand, the lack of spatial variability when taking data, in this case only a Doppler was available at a specific point; and, on the other hand, the time limitation of the measurement campaign, in this case, limited to a few months.

On the one hand, it is observed that during episodes of favourable wind direction at the mouth of the port, inflow currents occur and TRs increase (for example, on 24/04/2021, 23/11/2021 and 21/01/2021 in Huelva, Gijón and Cartagena respectively). On the other hand, in other occasions, days with high renewal times do not coincide with these wind events. In some of these cases, increases in atmospheric pressure are identified that seem to have caused a level gradient between the inner and outer harbour (e.g. on 25/05/2021, 4/04/2022 and 15/11/2020 in Huelva, Gijón and Cartagena respectively), generating inflows and increasing the TRs.

The diagram in **¡Error! No se encuentra el origen de la referencia.** summarises the second of the hypotheses: changes in atmospheric pressure generate a difference in level between the interior and the exterior of the port (since the volume of water in the interior is less than that of the open sea) which implies the entry of water and, consequently, an increase in the renewal time. In turn, this increase in the renewal time could lead to a worsening of the quality of the harbour water if these conditions are maintained over time.

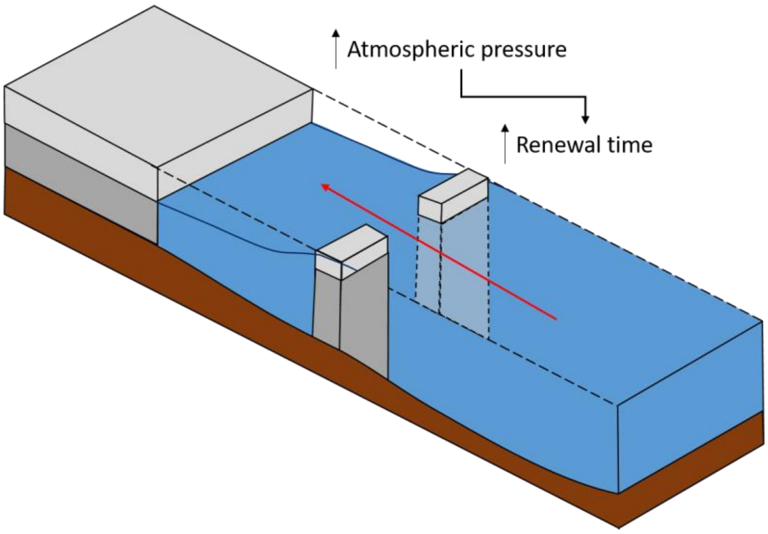

Figure 14 Profile of a harbour and its external zone with a water level difference between interior and exterior. The red arrow indicates the inflow at the mouth of the harbour. This figure explains the theory of the movement of water from the exterior to the interior as a consequence of the difference in level generated by increases in atmospheric pressure. The volume of water in the harbour is smaller and therefore the level decreases faster, which generates a difference in level with the outside and a consequent inflow of water.

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