Next-generation (sub-)kilometre-scale climate modelling for extreme storm-surge hazard projections

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Abstract

Due to on-going global warming, extreme storm-surges are expected to threaten a greater number of coastal communities worldwide. However, global and regional climate simulations of extreme events are still not accurate enough to respond to the growing needs of the local decision makers to prepare for these rising hazards. Here, we present a new methodology using (sub-)kilometre-scale coupled atmosphere-ocean-wave models and demonstrate the feasibility to provide meter-scale assessments of the impact of climate change on storm-surge hazards. As a proof of concept, we show that sea-level variations and distributions can be derived at the climate scale in the Adriatic Sea small lagoons and bays. Following these preliminary results, we expect that the newly developed methodology could lead to more targeted mitigation strategies of the local storm-surge hazards in regions of the world particularly vulnerable to sea-level rise and atmospherically driven extreme events.

Main

In this era of accelerated temperature rise, the climate research community still faces two main challenges. The first is the need to convince the global and local decision makers that human-driven global warming will have a strong societal impact on the sectors of energy, food, agriculture, health, urbanisation, environment and could lead to important financial and economic burdens[1]. The second is the critical importance to provide to the same decision makers more accurate climate projections of the entire Earth system, for them to better mitigate the societal impact of future extreme events[2] (e.g., droughts, storms, sea-level rise, etc.).

Importantly, due to projected mean sea-level rise[3] and intensification of atmospheric storms (e.g., hurricanes and tropical cyclones[4]) under climate warming, low-lying populated coastlines are expected to be more and more exposed to coastal hazards, especially extreme storm-surges. Consequently, local decision makers should start working on mitigation plans in order to build new infrastructures at minimal possible cost[5]. However, extreme sea-level hazard assessments are highly influenced by local processes shaped by both mesoscale atmospheric processes (e.g., occurrences, durations and intensities of the storms) and local geomorphology of the coastal areas (e.g., coastal and harbour resonances, topographic shoaling), while global and regional climate models are often too coarse to properly represent both extreme storms and endangered coastlines[6].

However, in the coupled atmosphere-ocean modelling community, the accuracy of the models, and thus of the climate projections, has been closely following different breakthroughs in computational science. This includes availability of more powerful numerical resources, better storage facilities, more efficient programming languages, etc. Historically (Fig. 1), the first coupled atmosphere-ocean global circulation models (AO-GCMs) were created in the 1980s to derive – for 100-year long periods with resolutions of about 500 km – the temperature trends resulting from the global increase of the greenhouse gases[7]. Nowadays the GCM resolutions can reach up to 25–50 km[8] and ensembles of models are run to better quantify the uncertainty of the climate projections. Further, in the 2000s-2010s, coupled atmosphere-ocean regional climate models (AO-RCMs) using dynamical downscaling of the GCM results were implemented with higher resolutions and better physics[9]. They aimed at studying the regional processes and providing vulnerability, impact, and adaptation assessments with about 10 km of accuracy. Additionally, in the 2000s, as the climate community gained better knowledge of the impact of climate change, the need for kilometre-scale climate models[10] better suited to characterise extreme events (with higher resolution and less physical parametrizations) also emerged. But, due to their extreme computational costs, these models were only developed in the atmosphere for simulations (1) ranging from few days during extreme events to 31-year periods, and (2) using the Pseudo-Global Warming (PGW) method for future climate projections. This is only in the 2020s that the PGW method was extended to the ocean[11] and implemented in the first coupled atmosphere-ocean kilometre-scale climate model. Additionally, in order to provide storm-surge hazard projections, the kilometre-scale climate results were further downscaled to a sub-kilometre-scale ocean model representing the complex meter-scale geomorphology of the coastal areas (e.g., harbours, bays, etc.). This next-generation approach to climate modelling was first implemented and tested in the semi-enclosed Adriatic basin[11,12,13] (Mediterranean Sea), where the orographically-shaped bora and sirocco winds better represented at kilometre-scales are driving storm surges in lagoons, bays and harbours only seen at (sub-)kilometre scales.

Practically, the so-called Adriatic Sea and Coast (AdriSC) climate modelling suite[14] is composed of two different modules. The general circulation module couples an atmospheric model at up to 3 km resolution with an ocean model at up to 1 km resolution. The extreme event module further downscales the general circulation results to 1.5 km in the atmosphere and to an unstructured mesh at up to 10 m resolution along the coasts with a coupled ocean-wave barotropic model. In this study, the general circulation module has been used in two 31-year long simulations: (1) a climate evaluation run for the 1987–2017 period (hereafter referred as the baseline conditions) and (2) a climate projection run following the high-emission greenhouse gas scenario (Representative Concentration Pathway 8.5; RCP 8.5) for the far-future 2070–2100 period (hereafter referred as the RCP 8.5 conditions). In addition, the nearshore module is only run for 1.5-day long simulations for an ensemble of moderate to extreme sea-level events extracted from both the evaluation and climate projection runs of the general circulation module. Further details on model setup, model and method verification and performed analyses are provided in the Methods section and as supplementary material.

Finally, the local application of the (sub-)kilometre-scale methodology to the Adriatic Sea is only used as a proof of concept and all the presented approaches and results can be easily replicated at any location in the world where extreme sea-level hazard assessments fully depend on the accurate representation of the complex geomorphology of the coastal areas.

Added value of kilometre-scale sea-level climate modelling

We first present the spatial variations of the detrended 1-km sea-level maximum and skewness results (Figs. 2 and 3) for the baseline conditions (top panels) and the climate adjustments defined as the difference between RCP 8.5 and baseline conditions (bottom panels). Additional alongshore results are presented in supplementary material (Fig. S4).

To demonstrate the added value of kilometre-scale climate modelling, special attention is given to three different areas with complex geomorphology: (1) the northern Adriatic including the Venice and Marano lagoons as well as the Gulf of Trieste, (2) the Kvarner Bay where hurricane-strength easterly bora winds are blowing over a complex network of islands and (3) the region of the Dalmatian Islands including the Split and Mali Ston bays.

In the shallow northern part of the Adriatic Sea, the baseline maximum results (Fig. 2) perfectly capture the well-known increase in sea-level extremes (above 1.7 m in the Veneta Lagoon). These events are driven by non-linear interactions between tides, atmospheric surges, wave setup and basin fundamental seiches[15] which can only be simulated with high-resolution limited-area atmosphere-ocean models[16]. In particular, the AdriSC model reproduces sea-level increases (1) of up to 30 cm between the western and eastern regions of the Venice Lagoon, (2) of 10–15 cm within the Marano Lagoon and (3) of 15–20 cm in the northernmost part of the Gulf of Trieste. The associated baseline skewness (Fig. 3), reaching a maximum of 0.1 in the Veneta Lagoon and being quasi-null in the Gulf of Trieste, is the smallest of the entire Adriatic basin. This is due to the predominance of tides which have the highest amplitudes[17] in this region of the Adriatic and thus account for a large part of the sea-level distributions. Further, the skewness remains positive due to the impact of the southerly sirocco winds which produce the most extreme storm-surges in the northern Adriatic[18]. However, as the Gulf of Trieste is also influenced by the easterly bora winds decreasing the coastal sea-levels, the skewness becomes quasi-null there. Additionally, the variation of skewness within the Venice Lagoon reflects the high sensitivity of sea-level distributions to the local forcing and thus the importance to downscale climate models to the kilometre-scale for storm-surge assessments. Concerning the climate adjustments, for the maximum sea-levels an increase of 10–15 cm is projected within the western Venice and Marano lagoons and the Gulf of Trieste, while in general a decrease of 5–10 cm is seen within the northern Adriatic shelf except along the Po River plume (Fig. 2). Further, in the Veneta Lagoon, the maximum sea-levels are expected to largely decrease by 15–20 cm. These features, only be seen at the kilometre-scale, reveal a probable shift in the wind directions producing the most extreme sea-levels under extreme warming. The associated skewness (Fig. 3) is expected to overall uniformly increase by 25–30% under RCP 8.5 conditions and the sea-level distributions will tend to have more pronounced right tails. Consequently, the extreme sea-level events will tend to be more intense under RCP 8.5 conditions, despite the decrease of maximum sea-levels at certain locations.

In the Kvarner region, the baseline maximum detrended sea-levels can reach up to 1.1 m in the Rijeka Bay (Fig. 2), but do not seem to be strongly influenced by the complex network of islands. The associated positive skewness (Fig. 3) is quite large (0.25–0.30 in the north to 0.50 in the south) due to the combined influence of severe offshore bora winds[19] and an amphidromic point[17] modulating the lowest semidiurnal tidal components in the middle Adriatic. Further, climate change is expected (1) to lower in the north and increase in the south the maximum sea-levels by up to 10–15 cm and (2) to increase the skewness and thus the occurrence of the extreme sea-levels by up to 30%.

Consequently, this region seems more affected by the general changes within the basin – i.e., maximum sea-level and skewness increase in the middle Adriatic – than by the orographically-shaped local processes.

However, the Dalmatian Islands region perfectly illustrates the importance of capturing the complex coastal geomorphology in climate models. Indeed, the baseline maximum sea-levels reaching up to 0.75 m within the small bays and along the islands of the domain (Fig. 2), are clearly driven by the local seiches and topographic amplification of the incoming offshore long ocean-waves[20]. As for the Kvarner Bay, the associated skewness (Fig. 3), still influenced by the geomorphology of the region, is largely driven by the modulation of the tidal amplitudes in the Adriatic Sea. Further, extreme warming in this region is projected to have the strongest impact on extreme sea-levels in the whole Adriatic basin: maximum sea-levels are expected to increase by up to 15–20 cm over the entire Split Bay and by up to 10–15 cm in the Mali Ston Bay, with an increase of 20% in skewness and thus in the number of extreme events.

Impact of climate change on storm-surge hazards

We now use classical engineering methods to project the impact of climate change on the duration and frequency of moderate, severe and extreme events (Fig. 4). The storm-surge hazards are derived from both the AdriSC 1-km detrended hourly sea-levels only (top panels) and with sea-level rise (SLR) added (bottom panels). The analysis is presented for 6 sub-domains – the Venice and Marano lagoons, Gulf of Trieste, Rijeka, Split and Mali Ston bays – where the impact of climate change was found to be the strongest.

For the storm-surge only, the analysis of the unique occurrences of moderate to extreme events, highlights the large spatial variability of the climate change impact under RCP 8.5 scenario (Fig. 4, top left panel). For example, the occurrences of moderate to extreme conditions are expected to decrease by 2 hours in the Venice Lagoon but to be multiplied by more than 2.5 in the Marano Lagoon located less than 90 km further in the northern Adriatic. Also, the severe and extreme conditions are expected to increase by approximately 1.5 times in the Venice Lagoon, 7 times in the Marano Lagoon, 2.5 times in the Split Bay and 3 times in the Mali Ston Bay but to decrease by 3 times in the Rijeka Bay. Further, the analysis of the occurrences of moderate to extreme events averaged over the entire sub-domains (Fig. 4, top right panel) confirms that extreme climate change conditions will increase severe and extreme events for all sub-domains – even in the Gulf of Trieste where severe events, non-existent in the baseline conditions, will occur. The exception is the Rijeka Bay, where on average only moderate events will take place. Further, under these far future conditions, areas like the Marano Lagoon and the Split and Mali Ston bays may face more extreme storm-surge conditions for which they are not prepared nowadays.

When SLR is added, the number of unique days with moderate to extreme events, including all sub-domain points, is multiplied by nearly 2 and more than 150 for the baseline and RCP 8.5 conditions, respectively. Due to this dramatic change in mean sea-level (i.e., up to 0.5 m SLR under RCP 8.5 scenario), the occurrences of the moderate events are expected to increase by 1 to 3 orders of magnitude for all the sub-domains (Fig. 4, bottom panels).

Further, severe and extreme storm-surge conditions are expected to occur in average: (1) more than 2500 hours, instead of 2–5 hours under the baseline conditions, in Split and Mali Ston bays, (2) 150 hours instead of 1.5 hours in the Rijeka Bay, and (3) between 20 and 40 hours, instead of less than 10 hours, in the Venice and Marano lagoons and in the Gulf of Trieste. Consequently, independently of the intensification of the atmospherically driven storm-surges, the Rijeka, Split and Mali Ston bays are found to be the locations the most endangered by SLR in the Adriatic Sea.

Sub-kilometre-scale coastal hazard assessments

In order to quantify the storm-surge hazards, we run the AdriSC extreme module for the ensemble of unique days extracted from the storm-surge only analysis (Fig. 4, top left panel). However, we also add SLR to the AdriSC 1-km detrended sea-levels forcing the unstructured ocean mesh for these events. Here, we present the distributions of maximum sea-levels, significant wave height, peak period, wind speed and associated direction as well as minimum pressure for all the 6 sub-domain points, under both baseline and RCP 8.5 conditions for the selected moderate to extreme daily events (Fig. 5).

As seen in previous analyses, under extreme warming, the occurrences of moderate to extreme conditions are expected to rise by 80% in the Marano Lagoon, 20% in the Gulf of Trieste and about 10% in the Split and Mali Ston bays. However, a decrease of about 15% in the Rijeka Bay and 30% in the Venice Lagoon is also simulated. These spatial variations of the storm-surge hazards can be explained by the changes in atmospheric conditions. In fact, under RCP 8.5 conditions, the intensification of the maximum wind speeds by up to 5 m/s in the Split and Mali Ston sub-domains is accompanied by a strong shift in direction (absence of westerly directions, above 180 °N) and a slight increase in the minimum pressure (about 2–3 hPa). In the Venice Lagoon the direction of the maximum winds stays similar, but the minimum pressure drops (absence of values above 990 hPa). This drop of minimum pressure is also seen in the Marano Lagoon and, to a smaller extent, in the Gulf of Trieste, and is associated with a small shift of direction (increase of north-easterly directions below 90 °N). In the Rijeka Bay, the wind speeds are decreasing (up to 3 m/s), and the associated directions are strongly shifting (absence of westerly directions above 180 °N) while the minimum pressure is slightly dropping (2–3 hPa). Consequently, a shift of the low-pressure system driving the southerly sirocco events responsible for the strongest northern Adriatic storm-surges may be expected under extreme warming. Due to this shift of the atmospheric conditions under RCP 8.5 scenario, storm-surges are expected (1) to reach up to 2.4–2.7 m in the Split and Mali Ston bays (instead of 0.9–1.1 m in the baseline conditions), (2) to increase by 20 to 40% for values above 2.5 m in the Marano Lagoon and the Gulf of Trieste and (3) to always be below 2.5 m in the Venice Lagoon. Concerning the wave hazards under extreme warming, the maximum significant wave heights are expected to be similar to the baseline conditions for all sub-domains, except the Marano Lagoon where they will rise by up to 0.5 m. The associated maximum peak periods are however expected to slightly decrease except in the Marano Lagoon.

To conclude, despite many well-funded public and private projects studying climate change in the Venice Lagoon, the preliminary results presented in this study reveal that, in the Adriatic Sea, other locations less studied by lack of funding, interest, expertise, etc., may be more endangered by the direct impact of climate warming. These areas are the Marano Lagoon where the largest marina of Italy is located, the Split Bay, the second most populated area of Croatia which heavily relies on tourism and cruises, and the Mali Ston Bay internationally known for the quality of its oysters. Scientists, engineers and local decision makers should thus shift their attention to these locations in order, for example, to better understand the impact of (1) the wave height increase on the Marano mooring complex, (2) SLR, likely to flood historical towns in the Split area and (3) the storm-surge intensification on the production of oysters in the Mali Ston Bay.

Moreover, this study is just the first step towards global storm-surge assessments, as the uncertainties linked to climate change must be properly quantified in order to provide meaningful results to the local decision makers. This is achieved by running ensembles of simulations forced by multiple global climate models under multiple warming scenarios[21]. However, the presented method running coupled atmosphere-ocean kilometre-scale models for 31-year long periods may be too prohibitive, in terms of numerical cost, to be used to create large ensembles of long-term climate simulations. As the added value of such climate approach has been proven, we now envision to produce robust sub-kilometre-scale storm-surge hazard assessments by directly downscaling extreme events from global climate model ensembles to short-term kilometre-scale and sub-kilometre simulations based on modelling suites similar to the AdriSC model. With this solution, the numerical resources, previously spent to produce long-term simulations, would be used to quantify the climate change uncertainty and consequently to properly assess the meter-scale storm-surge hazards along the worldwide coastlines, with the aim to increase the preparedness of coastal communities to the upcoming rise in sea-levels and extreme events.

Methods

Adriatic Sea and Coast (AdriSC) climate model

The Adriatic Sea and Coast (AdriSC) climate modelling suite[14] is composed of two different modules which can be used together or independently to quantify a variety of climate-related processes. The AdriSC general circulation module is designed to run long-term climate simulations. It is based a modified version of the (COAWST[22]) model and couples online the Weather Research and Forecasting (WRF[23]) model with the Regional Ocean Modeling System (ROMS[24]). In this module, (1) the two atmospheric grids at respectively 15-km and 3-km of resolution are two-way nested, while (2) the one-way nested ocean grids at 3-km and 1-km of resolution are forced by the 3-km atmospheric grid. The AdriSC extreme event module is only used to further downscaled the general circulation results for short-term simulations (1 to

3 days). It couples offline the WRF results downscaled at 1.5-km of resolution with the fully coupled unstructured ADvance CIRCulation – Simulating WAves Nearshore (ADCIRC-SWAN[25]) storm surge barotropic model at up to 10 m of resolution along the Adriatic coasts. Detailed descriptions of the modelling suite (e.g., physics setup, tidal- and river- forcing, coupling, etc.) can be found in Denamiel et al.[26] and Pranić et al.[27].

Pseudo-Global Warming (PGW) method

The main principle of the PGW method – created to downscale the sparse results of Regional Climate Models (RCMs) to kilometre-scale simulations – is that the impact of climate change can be assessed by imposing an additional climatological change to the forcing used to produce the 31-year long evaluation run. In practice, for the atmosphere[28,29], the 6-hourly ERA-Interim[30] air temperature, relative humidity and horizontal wind velocities three-dimensional and surface reanalysis results are modified by adding climatologic changes. In the ocean[11,12], for the Mediterranean Sea, the daily MEDSEA[31] ocean temperature, salinity and currents three-dimensional reanalysis results are also modified by adding climatologic changes. In this study, the PGW method[10,11] was applied to the coupled atmosphere-ocean LMDZ4-NEMOMED8 RCM model[32,33] forced by the IPSL-CM5A-MR GCM model (simulations r1i1p1) and part of the CORDEX experiment[34,35].

Climate simulations

As a proof of concept that coupled atmosphere-ocean kilometre-scale climate modelling could be achieved, two 31-year long simulations have been carried out with the AdriSC general circulation module: (1) an evaluation run for the 1987–2017 period forced by the 6-hourly ERA-Interim and the daily MEDSEA reanalysis products and fully evaluated against an extensive ocean and atmospheric dataset[26,27] and (2) a far future climate projection run for the 2070–2100 period following the Representative Concentration Pathway 8.5 (RCP 8.5) forced with the PGW method presented above. Each of these simulations required 18 months to be completed with a continuous run using 260 CPUs on the European Centre for Middle-range Forecast (ECMWF) supercomputing facilities. Additionally, the 600 TB of hourly climate data generated by the two 31-year long runs is stored on the ECMWF tape system.

Detrended sea-levels

As this study mainly focuses on the impact of climate change on atmospherically driven extreme sea-levels and as the ocean RCMs and reanalysis products implemented in the Mediterranean Sea do not account for global sea-level rise, the strategy of using detrended sea-levels included tides, seiches, storm-surges but not sea-level rise is adopted as follows. First, the AdriSC ROMS 1-km hourly results are extracted from the multiple files of the 31-year long simulations and merged into a single file. Then, the Theil-Sen trend estimation method[36] – insensitive to outliers and significantly more accurate than simple linear regression for skewed and heteroskedastic data – is used to detrend the merged 31-year long AdriSC ROMS 1-km hourly sea-level results. Finally, the AdriSC detrended 1-km hourly sea-levels are evaluated against 11 tide-gauges stations along the Adriatic Sea for the 1987–2017 period (supplementary material, Figs. S1-S3 and Tables S1-S2). Overall, it is found that the observed storm-surges (i.e., detrended tide-gauge data above 95th, 99th and 99.9th percentiles) are well reproduced by the AdriSC ROMS 1-km model results (Table S2 and Fig. S3).

Sea-Level Rise (SLR)

As global sea-level rise cannot be ignored in extreme sea-level hazard studies but is not taken into account in the AdriSC climate simulations, the results from the RCP 8.5 scenario of the IPCC-AR5 2015 ensemble[37]of 20 global models – provided at 1°resolution and including 10 geophysical sources that drive long-term changes in sea-levels (e.g., Antarctic dynamic ice and surface mass balance, global thermostatic anomaly, terrestrial water, glacial isostatic adjustment, etc.) – are added to the detrended AdriSC ROMS 1-km sea-levels. However, it should also be noted that only 12 models of the AR5 ensemble provide results in the Mediterranean Sea. Practically, the IPCC-AR5 2015 yearly results are interpolated in space and time to generate hourly results covering the AdriSC ROMS 1-km grid for both the 1987–2017 and the 2070–2100 periods. Decadal trends of sea-level rise derived from these interpolated results for each of the two periods are presented over the Adriatic Sea domain (Supplementary Material, Fig. S4). The results show that, despite the coarse resolution of the IPCC-AR5 2015 products, some noticeable spatial SLR variations are captured by the ensemble within the semi-enclosed Adriatic basin.

Return periods

In this study the 10-year, 30-year and 50-year return periods are extracted from the AdriSC detrended 1-km hourly sea-levels during the 1987–2017 period following the extreme value theory that derives the Generalized Extreme Value (GEV) distribution[38,39]. Practically, the hourly sea-levels are fitted to the GEV distribution at each point of the AdriSC ROMS 1-km grid. Then, from these fitted distributions it is estimated how often the extreme quantiles occur with a certain return level (in this study 10, 30 and 50 years). These spatially varying return period values (illustrated in Fig. S5 of the supplementary material) are then used to define three categories of atmospherically driven events: (1) moderate events for sea-levels between the 10-year and 30-year return periods, (2) severe events for sea-levels between the 30-year and 50-year return periods and (3) extreme events for sea-levels above the 50-year return period. It should be noted that even so-called moderate events have the potential to cause material damages and human casualties (e.g., flood, drowning, etc.).

Adriatic storm-surges

In this study, storm-surges are derived at each point of 6 different sub-domains (Venice and Marano Lagoon, Gulf of Trieste, Rijeka, Split and Mali Ston bays) selected from the spatial climate adjustment results (Fig. 1). The number of points within the 6 sub-domains for both the AdriSC ROMS 1-km grid and the AdriSC ADCIRC-SWAN unstructured mesh are presented in Supplementary Material. To obtain robust statistics, storm-surge hazard in each sub-domain is defined when at least one point of the sub-domain falls within the three categories defined by the spatially varying return periods. All sub-domain points considered, the number of unique days with moderate, severe and extreme events derived from the AdriSC ROMS 1-km detrended hourly sea-levels with the return-period method described above are: (1) 38 for the 1987–2017 period and (2) 37 for the 2070–2100 period under RCP 8.5 scenario. With SLR added to the AdriSC ROMS 1-km detrended hourly sea-levels, the number of unique days rises to: (1) 70 for the 1987–2017 period and (2) 6229 for the 2070–2100 period under RCP 8.5 scenario. To test the reliability of the method to properly select the moderate to extreme storm-surges, the events occurring only in the Venice Lagoon sub-domain are extracted from the 70 ones including SLR during the 1987–2017 period and compared to the Venice flood events selected by Lionello et al.[40] (supplementary material, Table S3). Despite missing two events probably due to a lack of synchronisation between extreme storm-surge and maximum tides in the AdriSC ROMS 1-km model and the fact that moderate events can be below the 1.4 m threshold chosen by Lionello et al.[40], the method is found to show skills in accurately extracting the most extreme sea-level events in Venice which is the only location in the Adriatic Sea where long-term flood recordings exist.

Coastal hazard assessments

As this study mostly focused on atmospherically driven sea-levels and as running about 6300 events would have been too costly in terms of numerical resources, the coastal hazards in the 6 sub-domains are derived with the AdriSC extreme event module, for 1.5-day long simulations, but only for the unique events selected from the detrended hourly sea-levels (i.e., 38 for the 1987–2017 period and 37 for the 2070–2100 period). However, SLR is added to the ROMS 1-km sea-level results used to force the ADCIRC-SWAN model in order to account for the non-linear interactions between waves, tides, mean sea-levels, seiches, and atmospherically driven surges. The coastal hazard assessments are then extracted from the maximum wind speed and associated direction, sea-levels, significant wave height and peak period as well as for the minimum pressure, for each sub-domain (see Supplementary Material) and for all moderate to severe storms derived for each sub-domain point in order to produce robust statistics. In this analysis, for each subdomain and each variable, the number of baseline conditions represents 100% of the occurrences in order to visualize the impact of climate change on the number of RCP 8.5 conditions. Consequently, due to the wet and dry set-up used in the ocean model, percentages of RCP 8.5 conditions might slightly vary between atmospheric and ocean results.

Data availability

The model results as well as the post-processing scripts used to produce this article can be obtained under the Open Science Framework (OSF) FAIR data repository (https://doi.org/ 10.17605/OSF.IO/2HGFM).

Code availability

The code of the COAWST model as well as the ecFlow pre-processing scripts and the input data needed to re-run he AdriSC climate model in evaluation mode for the 1987–2017 period can be obtained under the Open Science Framework (OSF) FAIR data repository (https://doi.org/10.17605/OSF.IO/ZB3CM).

Declarations

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Competing Interests

The Authors declare no Competing Financial or Non-Financial Interests.

Author Contributions

IV and CD contributed to the study conception and design. Material preparation was done by CD. Set-up of the model and simulation were performed by CD. Analysis of the results and production of the figures were performed by IV and CD. The first draft of the manuscript was written by CD and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

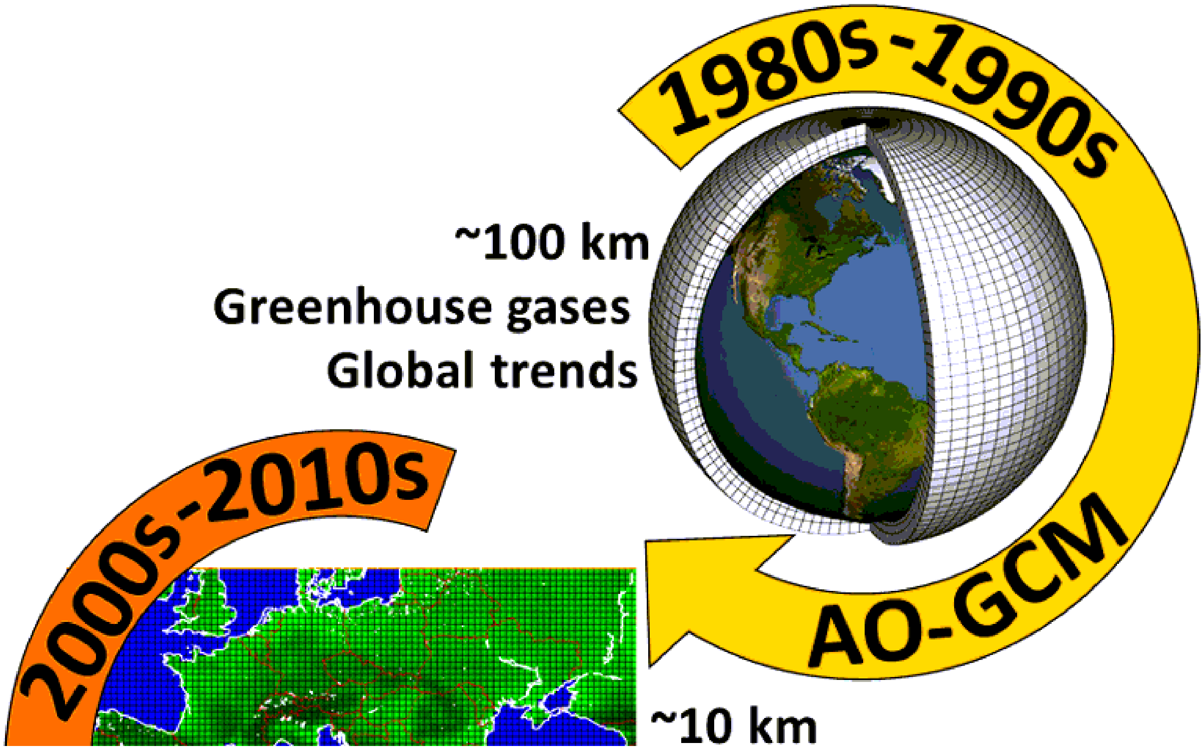

Figure 1

Historical evolution of the coupled atmosphere-ocean (AO) climate models: from the Global Circulation Models (GCMs) in the 1980s-1990s, to the Regional Circulation Models (RCMs) in the 2000s-2010s, to the recent development (2020s) of (sub-)kilometre-scale models providing extreme sea-level hazard assessments at up to 10 m resolution along the coast and within harbours.

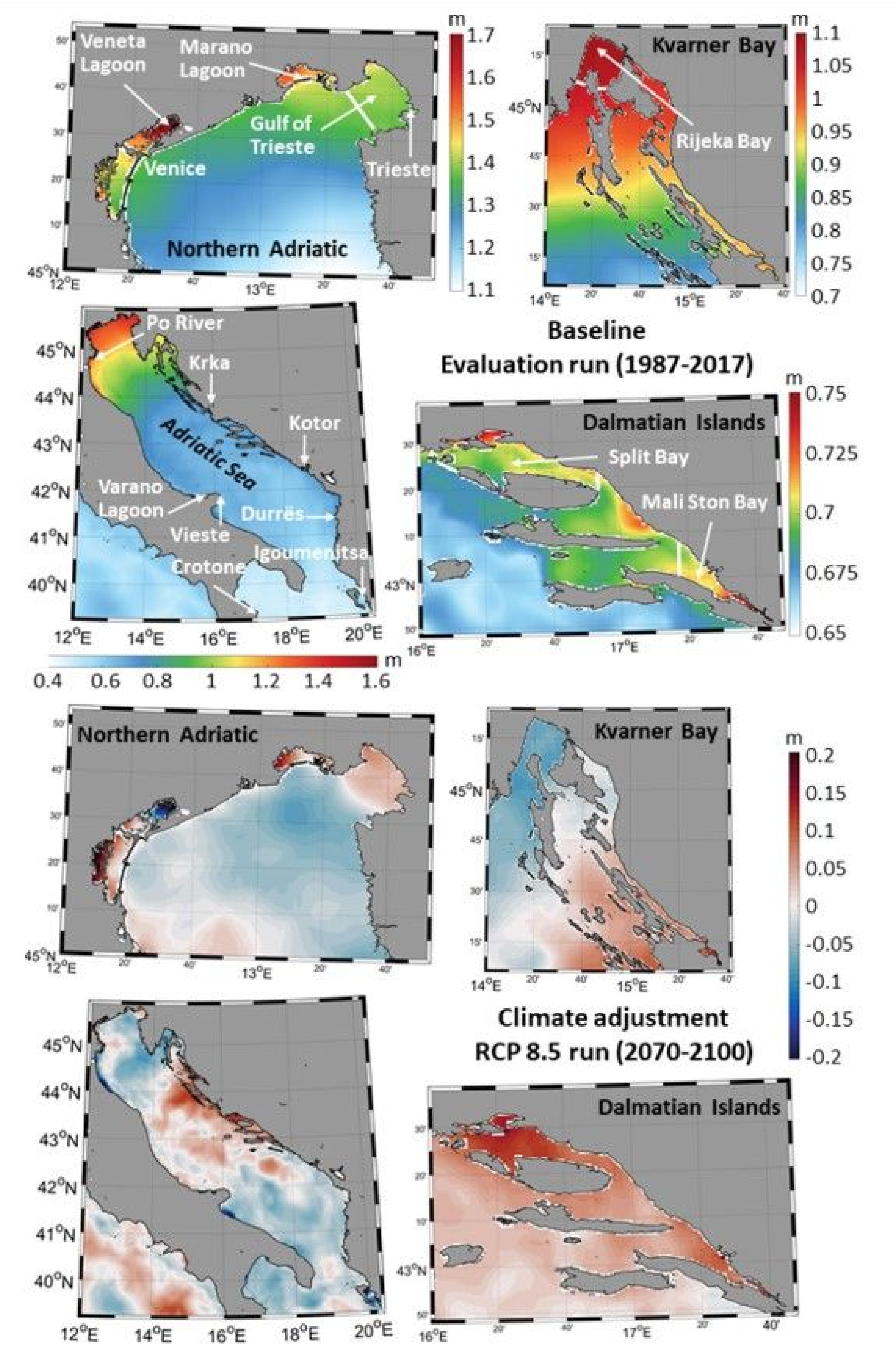

Figure 2

Detrended 1-km sea-level maximum baseline conditions for the 1987-2017 period (top panels) and RCP 8.5 climate adjustments for the 2070-2100 period (bottom panels) over the entire Adriatic Sea and the northern Adriatic, Dalmatian Island and Kvarner Bay sub-domains.

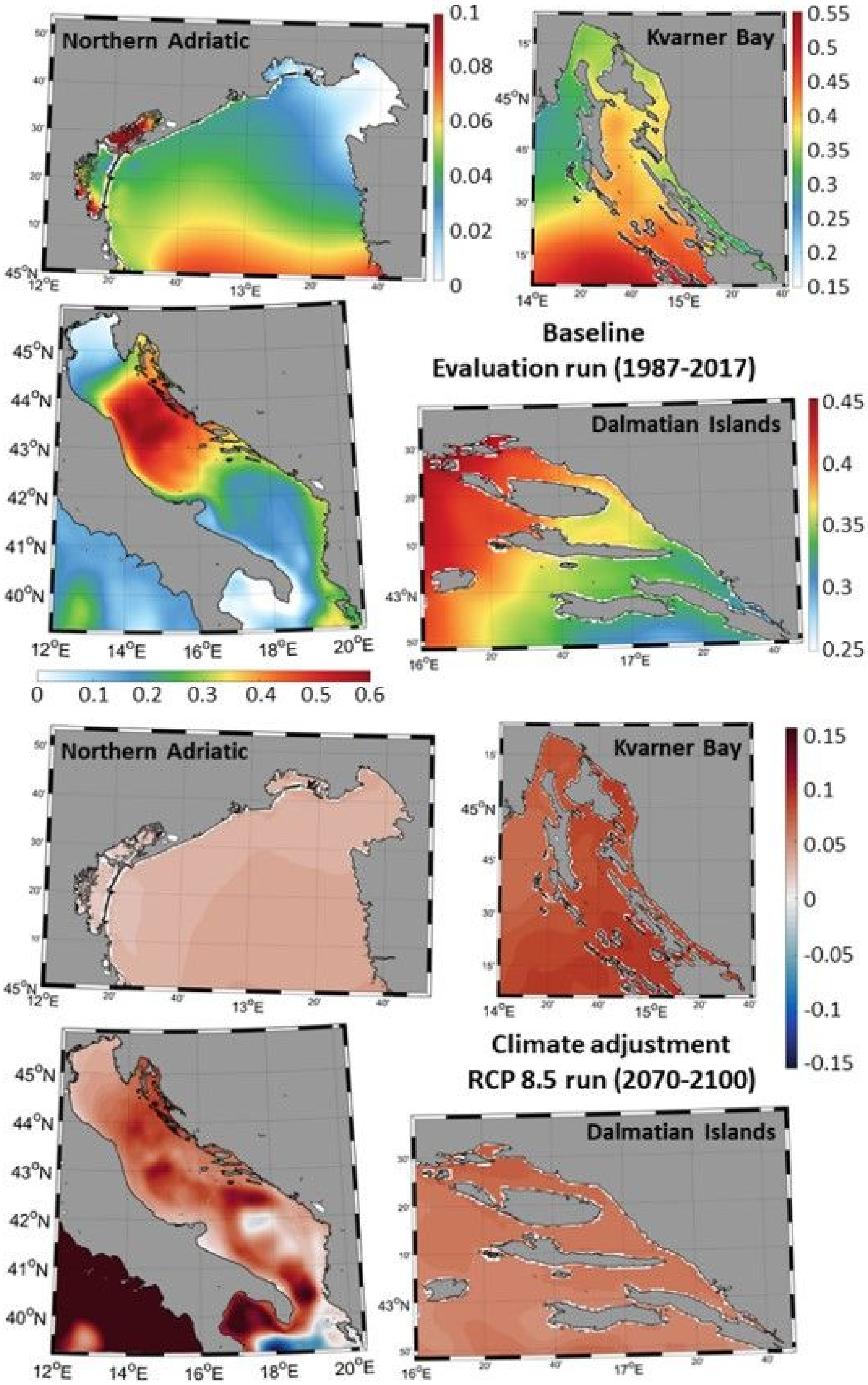

Figure 3

Detrended 1-km sea-level skewness baseline conditions for the 1987-2017 period (top panels) and RCP 8.5 climate adjustments for the 2070-2100 period (bottom panels) over the entire Adriatic Sea and the northern Adriatic, Dalmatian Islands and Kvarner Bay sub-domains.

Figure 4

Storm-surge hazard assessments in 6 Adriatic Sea sub-domains (i.e., Venice Lagoon, Marano Lagoon, Gulf of Trieste, Rijeka Bay, Split Bay and Mali Ston Bay) for three categories: moderate, severe and extreme conditions. The conditions are defined for detrended 1-km sea-level values only (top panels) and with additional estimated Sea-level Rise (SLR, bottom panels) between the 10- to 30- year return periods (moderate), between the 30- and 50- return periods (severe) and above or equal to the 50-year return period (extreme). All return periods are derived from the baseline storm conditions for the 1987-2017 period. The chosen hazard assessments integrate both events and length of the events by considering the number of hours falling to each category either as a unique occurrence (left panels) or as the average over the number of sub-domain points (right panels).

Figure 5

Distributions of the (sub-)kilometre-scale maximum (max.) wind speed and associated direction at 10 m, minimum (min.) mean sea-level atmospheric pressure, maximum sea surface height, maximum significant wave height and peak period for the baseline and RCP 8.5 moderate, severe and extreme unique daily events derived in Figure 4 storm-surge only results but including SLR.

Supplementary Files

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