<u>LATE</u> REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Croatia

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Project Title: Impact of Climate Change on the Direct Economic Costs of Coastal Hazards: A Meter-Scale Experiment in the Adriatic Basin

To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ………….	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES x	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	45 Million		
Accumulated data storage (total archive volume)[2]	[GB]	500		

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

1) Motivation and problem identification

Sea-level rise and intensifying storm surges pose escalating threats to coastal hospitality sectors, yet quantification of the impact of climate change on the direct economic costs remains limited by the too low resolution of the available climate projections. This study aims to provide a systematic assessment of storm surge-related economic damages to the hospitality sector in the Adriatic basin – with a special focus on Italy's Veneto and Emilia-Romagna regions – by leveraging high-resolution outputs from the Adriatic Sea and Coast (AdriSC) modelling suite (Fig. 1).

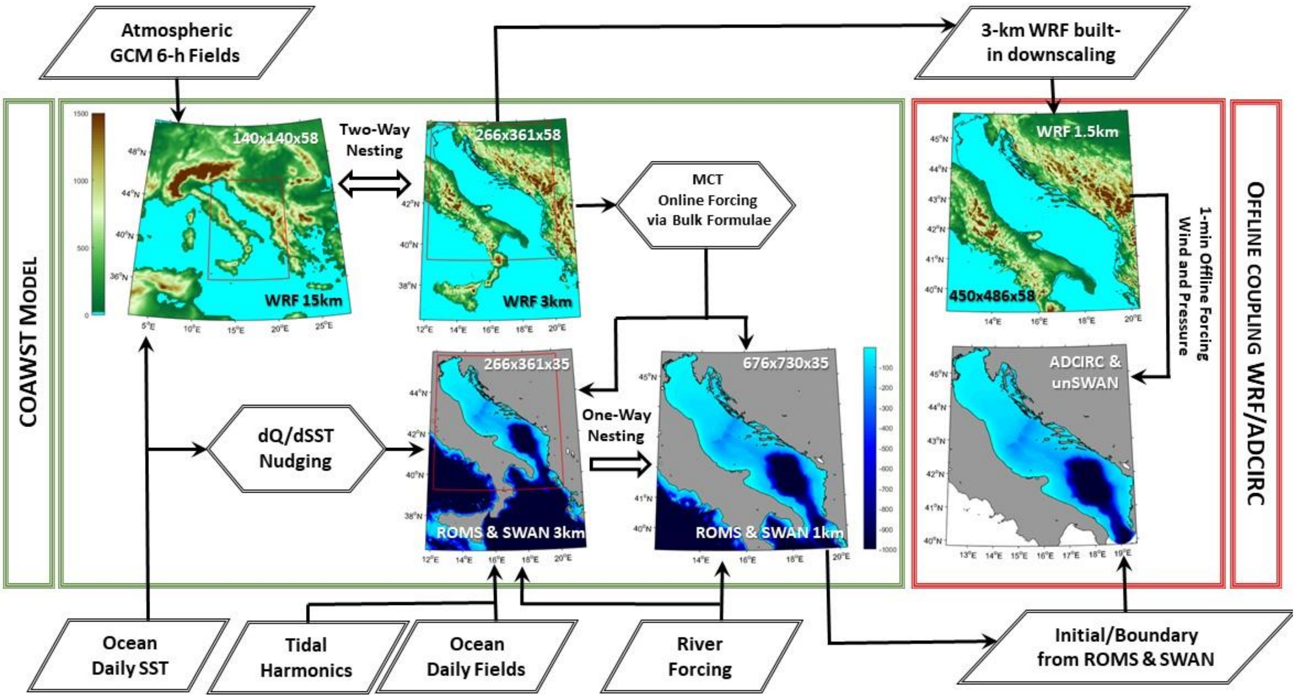


Figure 1. Modules of the AdriSC modelling suite. The basic module is based on the COAWST Model (green frame) and is run for 31-year long periods. The storm surges are run with the nearshore module consisting in the Offline Coupling WRF/ADCIRC (red frame) for a period of 2 days.

In the AdriSC basic module (Figure 1, green frame), the kilometre-scale coastal circulation over the Adriatic-Ionian basin is derived using the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modelling system (Warner et al., 2010). Hourly results are produced at resolutions up to 3-km for the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) in the atmosphere and 1-km for the Region Ocean Modeling System (ROMS; Shchepetkin & McWilliams, 2009). Two 31-year long climate simulations have already been performed with the AdriSC climate component. An evaluation run for the 1987-2017 period was fully evaluated against a comprehensive atmospheric and oceanic observational and remote sensing dataset (Denamiel et al., 2021; Pranić et al., 2021). The climate projection run under RCP8.5 climate warming scenario for the far-future 2070-2100 period was performed following the pseudo-global warming (PGW) method developed first in the atmosphere (Schär et al., 1996) and recently extended to the ocean (Denamiel et al., 2020a). The AdriSC climate model already provided valuable insights of the impact of climate change on long-term Adriatic Sea dynamics including the dense water formation (Denamiel et al., 2025) and the atmosphere-ocean trends and variability (Tojčić et al., 2024). The AdriSC nearshore module (Figure 1, red frame) further downscales the results of the AdriSC basic module and is based on the offline coupling between the WRF model at 1.5 km resolution and the Advanced CIRCulation model (ADCIRC-SWAN; Luettich et al., 1991) originally at up to 10 m resolution along the Adriatic coasts. Following the PGW method, the nearshore module has been used in short-term simulations in order to derive the impact of climate change on (1) extreme waves (Denamiel et al., 2020a), (2) extreme bora winds (Denamiel et al., 2020b) and (3) meteotsunamis (Denamiel et al., 2022b).

In this study, the old mesh of the nearshore module will be replaced with a new mesh designed to account for the non-linear interactions between buildings and storm-surges during extreme events.

2) Previous Storm-Surge Numerical Modelling Efforts

The evaluation of the AdriSC 1-km detrended sea-level results during the 1987–2017 period, have already been performed by using 11 long-term hourly sea-level measurements. First, some statistics such as Root Mean Square Error (RMSE), correlation, and differences between 95th, 99th, 99.9th percentiles, maximum values and ranges are presented in Table 1 to assess the AdriSC model basic skills. Second, and most importantly for this study, the comparison between observations and AdriSC model results is done for the distributions of the sea-levels above the 95th, 99th, 99.9th percentiles (Fig. 2). The basic statistical analysis shows that correlation between observations and model are equal or above 0.80 for all the stations (except 0.798 at Ploče) and RMSE is below 15 cm (except 15.5 cm at Venice). Further differences between the percentiles derived from observations and model are always below 10 cm and are on average around 5 cm. However, differences in maximum value can reach up to 26 cm in Venice.

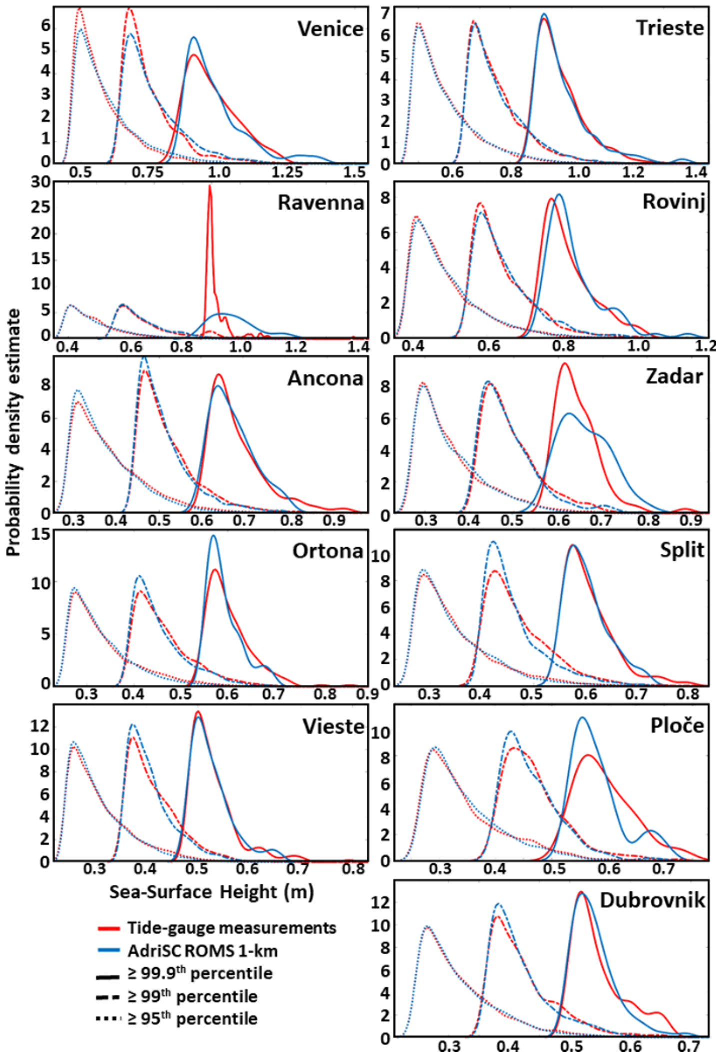
Table 1. Statistics of the comparison between the AdriSC ROMS 1-km detrended sea level model results and the tide-gauge observations during the 1987-2017 period. RMSE and %tile stand for Root Mean Square Error and percentile respectively.

	Stations	RMSE	Correlation	95th %tile*	99th %tile*	99.9th %tile*	Maximum*	Range*
Western coast	Venice	0.155	0.872	0.035	0.056	0.098	0.264	0.167
	Ravenna	0.124	0.860	-0.022	-0.011	-0.085	-0.218	-0.388
	Ancona	0.094	0.847	-0.025	-0.034	-0.046	-0.144	-0.399
	Ortona	0.085	0.830	-0.024	-0.035	-0.041	-0.164	-0.332
	Vieste	0.080	0.834	-0.016	-0.021	-0.023	-0.133	-0.165
Eastern coast	Trieste	0.146	0.878	-0.026	-0.015	0.001	0.025	-0.091
	Rovinj	0.119	0.877	-0.030	-0.026	-0.013	0.127	-0.063
	Zadar	0.103	0.791	-0.022	-0.020	-0.031	-0.095	-0.324
	Split	0.089	0.822	-0.017	-0.018	-0.027	-0.081	-0.155
	Ploče	0.096	0.798	-0.019	-0.026	-0.021	-0.029	-0.130
	Dubrovnik	0.081	0.833	-0.006	-0.006	-0.011	0.030	-0.037

*difference between results obtained with the AdriSC ROMS 1-km model and the tide-gauge observation

The comparisons of the distributions of extreme detrended hourly sea-levels above the 95th, 99th and 99.9th percentiles, show that: (1) for most stations the AdriSC ROMS 1-km model is capable to reproduce the most extreme atmospherically-driven sea-level events, (2) some outlier values were not removed from the measurements at Ravenna station which resulted in an unrealistic distribution of the sea-levels above the 99.9th percentile, (3) the strongest difference in distributions occur at the Zadar and Ploče stations with the lowest hourly coverages (25% and 13% respectively; Table 1) for the sea-levels above the 99.9th percentile and (4) for the Trieste station with 100% of hourly coverage, the model distributions nearly perfectly fit the observational ones.

In brief, following this evaluation against 11 tide-gauge observations for the 1987-2017 period, we demonstrate that the AdriSC climate model is suitable to study storm-surges in the Adriatic Sea.



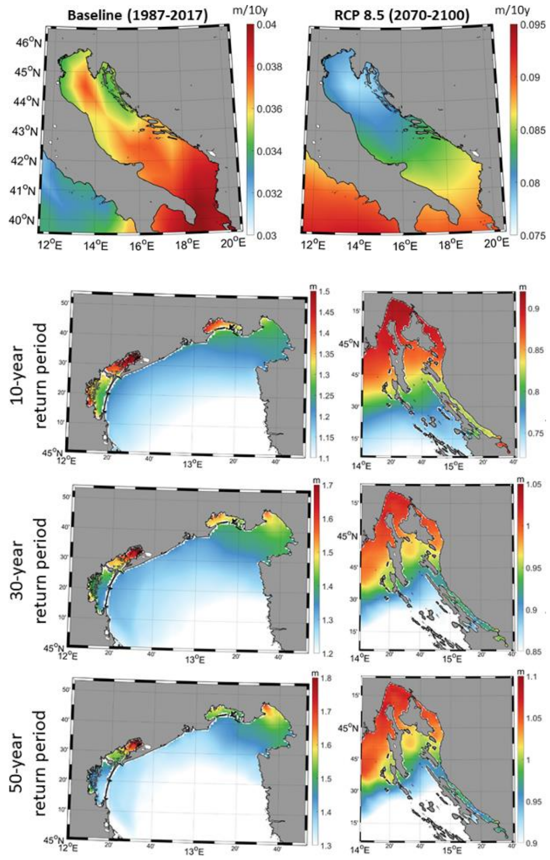
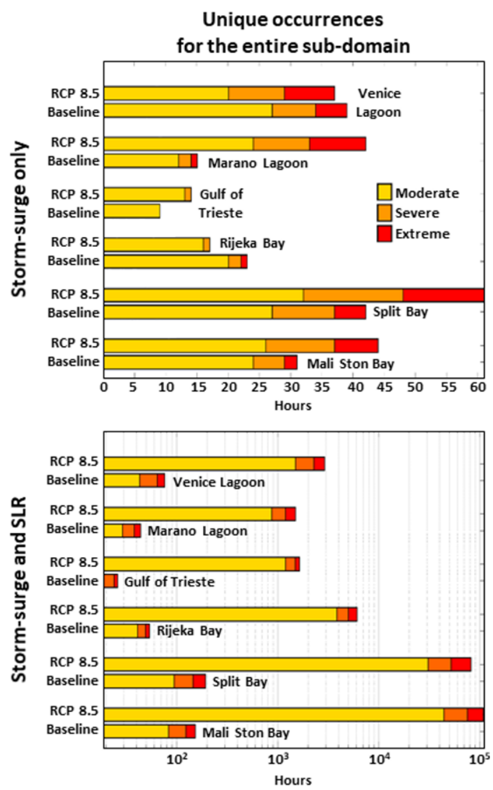


Figure 2. Left panels: Comparison of the tide-gauge observation and the AdriSC ROMS 1-km model distributions of extreme detrended hourly sea-levels above the 95th, 99th and 99.9th percentiles at 11 stations along the Adriatic Sea for the 1987-2017 period. Right top panels: Spatial distribution of the Sea-Level Rise (SLR) trends over the entire Adriatic Sea derived from the 1° resolution IPCC-AR5 2015 data for the Historical 1987-2017 and RCP 8.5 2070-2100 periods. Right bottom panels: Spatial distributions of the 10-, 30- and 50- year return periods in the different Adriatic sub-domains derived from the detrended SSH baseline conditions for the 1987-2017 period.

To account for sea-level rise (SLR) which is not included in the long-term simulations carried out with the AdriSC general circulation module, the IPCC-AR5 2015 RCP 8.5 results – at 1° resolution obtained from an ensemble of 12 global models – have been interpolated/extrapolated in space and time to the AdriSC ROMS 1-km grid. As can be seen with the sea-level trends presented in Figure 2 (top right panels), the global models of the IPCC-AR5 ensemble are able to capture some spatial variations within the Adriatic Sea. First, for both 1987-2017 (baseline) and 2070-2100 (RCP 8.5) periods, the southern Adriatic sea-levels are rising about 1.3 time faster than in the northern Adriatic. Second, the accelerated SLR in the far future is smoothed compared to the baseline conditions. It is just regularly decreasing from the southern (0.04 m and 0.09 m per decade for the baseline and RCP 8.5 conditions respectively) to the northern part (0.034 m and 0.08 m per decade for the baseline and RCP 8.5 conditions respectively) of the Adriatic Sea while in the baseline conditions more variations are captured in the northern Adriatic in particular SLR reaches up to 0.038 m per decade in the middle northern shelf. Further, we consider 3 categories of extreme storm-surges: (1) moderate for sea-levels between the 10-year and 30-year return periods, (2) severe for sea-levels between the 30-year and 50-year return periods and (3) extreme for sea-levels above the 50-year return period. The spatial variations of these return periods are presented in Figure 2 (bottom right panels) for 2 different areas of the Adriatic Sea. It can be seen that the differences between the 10-year and 50-year return periods are only of the order of 10 cm in the Venice Lagoon and the Rijeka Bay. This means that, given all the cumulated uncertainties of climate modelling, it is better to consider all moderate, severe and extreme events while assessing the coastal hazards in the Adriatic Sea.



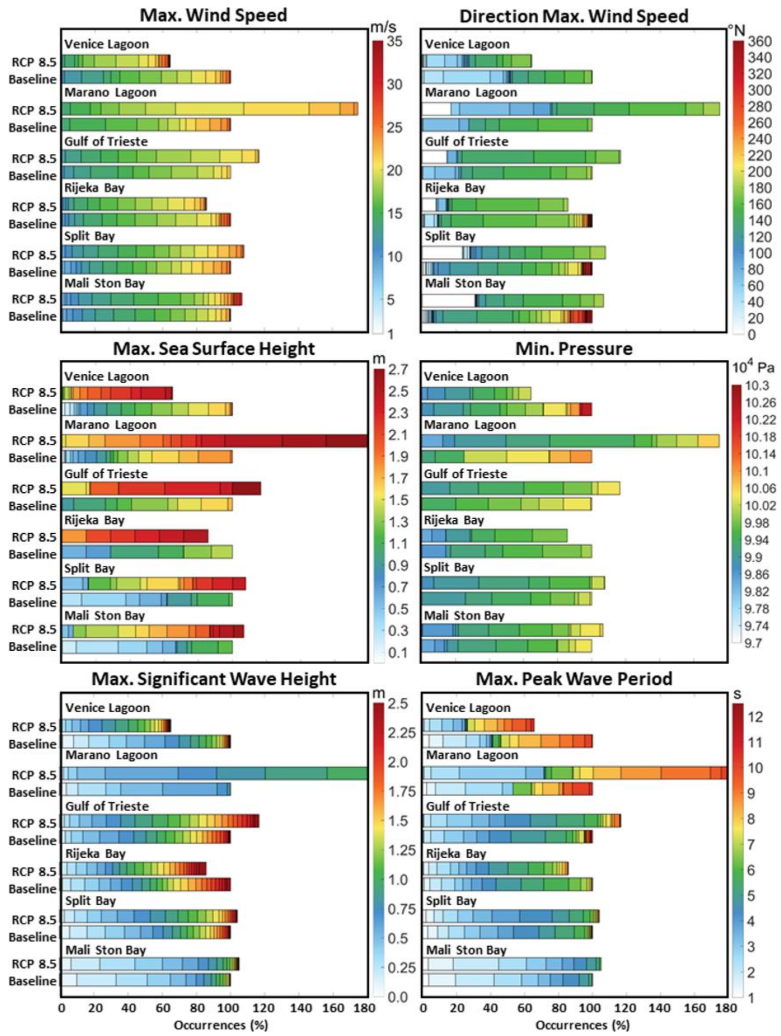


Figure 3. Left panels: Storm-surge hazard assessments in 6 Adriatic Sea sub-domains (i.e., Venice Lagoon, Marano Lagoon, Gulf of Trieste, Rijeka Bay, Split Bay and Mali Ston Bay) for three categories: moderate, severe and extreme conditions. Right panels: Distributions of the (sub-)kilometre-scale maximum (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.

Then, classical engineering methods have been used to project the impact of climate change on the duration and frequency of moderate, severe and extreme events (Fig. 3, left panels). 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. 3, 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. 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. 3, bottom left panel). 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.

Finally, in order to quantify the storm-surge hazards, the AdriSC nearshore module has been run for the ensemble of unique days extracted from the storm-surge only analysis (i.e., **38 for the 1987-2017 period and 37 for the 2070-2100 period**; Fig. 3, right panels). SLR was also added 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. 3).

However, these results have not yet been published as reviewers found that the ADCIRC/SWAN mesh used in the nearshore module was not accurate enough (coarse resolution, coarse topo-bathymetry, no proper inundation) to assess the impact of climate change on storm-surges along the Adriatic coastlines.

3) Proposed Work

The proposed work thus aims at bridging this gap. First, a new mesh has been generated using a new Digital Terrain Model composed of:
- topographic and bathymetric data at 2 m resolution within the Venice Lagoon (https://figshare.com/articles/dataset/Bathymetry_of_Lagoon_of_Venice_2002/1293558?file=2288070 and http://cigno.ve.ismar.cnr.it/layers/geonode%3Alag02_okart_export)
- topographic data at 10 m resolution along the Italian coast (https://tinitaly.pi.ingv.it/)
- topographic data along the Croatian, Montenegrin and Albanian coastlines extracted from the EURODEM 2023 at 2 arc seconds (https://www.mapsforeurope.org/datasets/euro-dem)
- bathymetric data at 1/16°arc minute extracted from EMODNET for depth greater than 10 m (https://emodnet.ec.europa.eu/en/bathymetry)
- bathymetric data from the old AdriSC DTM between 0 and 10 m depth (Denamiel et al., 2019)

In addition, the building shape and height along the Croatian and Italy's Veneto and Emilia-Romagna coastlines have been extracted from:
- POI data purchased only for the Italian side
- the Eubucco Dataset (https://docs.eubucco.com/data/)
- the overture Dataset (https://overturemaps.org/download/)
- the Google API Places on the Italian side only
- public and available data used on the Croatian side, cross-checked with Meta (https://dataforgood.facebook.com/dfg/tools/places) and OpenStreetMap (https://download.geofabrik.de/) datasets which also include heights
- on the Italian side, the methodology derived by Milojevic-Dupont et al. (2020) was used to predict buildings without height

The new mesh was generated with the new DTM and the shape of the buildings included as barriers with at least 5 m resolution. In areas where the density of the buildings was too high and would have required to have resolutions below 1 m, the buildings have been grouped into neighbourhoods as illustrated for the City of Venice (Fig. 4).

In this special project, we propose to use the event-based downscaling approach described in the previous section with the **new mesh** which is composed of **69942262 elements and 35282298 nodes** (**more than 100 times bigger than the original mesh** of the AdriSC nearshore module). Given the size of the mesh and based on previous experience with the new ATOS HPC at ECMWF, the new mesh should be run with 5 to 15 Cores in order to achieve reasonable time of execution.

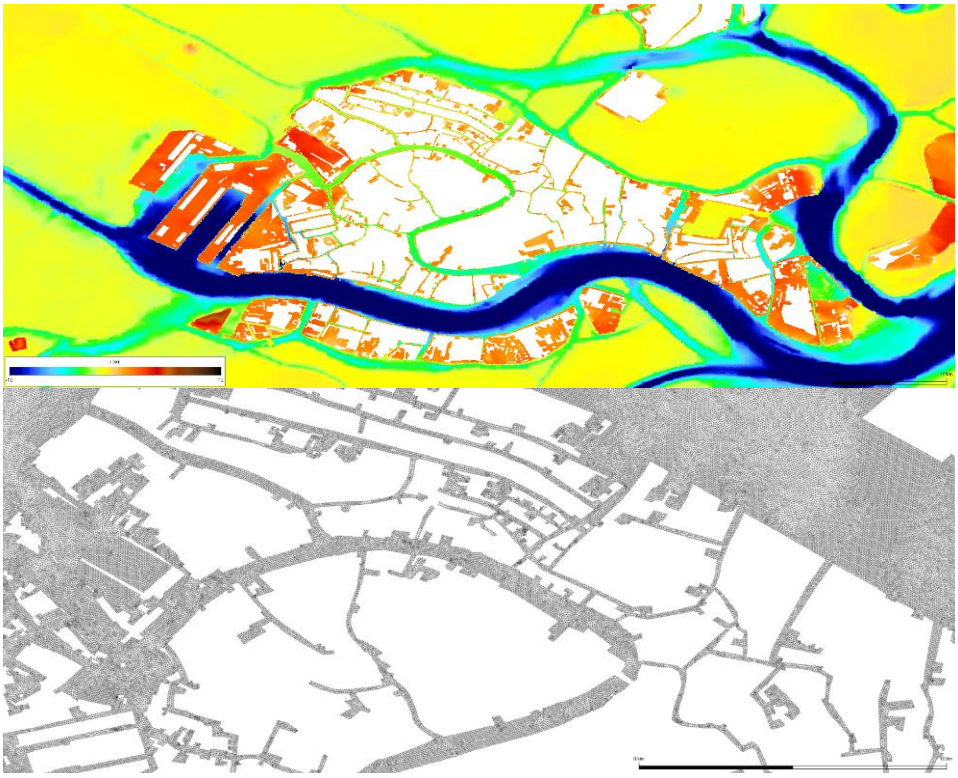


Figure 4. Zoom in the Venice lagoon (Northern Italy) used to illustrate the features of the new topo-bathymetry (top panel) and mesh (bottom panel) accounting for inundation and building impact on the storm surges.

The targeted use of the ECMWF resources is thus 45 000 000 SBUs and 500 GB of storage for year 2025.

The modelling strategy of the project consists in the following points:

<u>Test/validation of the new mesh of the AdriSC nearshore module</u>

This task will focus on optimizing the simulations and assessing the number of Cores to be used.

Computing resources needed: About **5 to 15 Cores * 1 day * 86400 s * P * 10 simulations = ~ 5 MSBUs** are planned to be used for this phase of the ECMWF special project.

<u>Event-downscaling of the historical storm-surge events with historical SLR</u>

In this task, the impact of historical extreme events on the Adriatic Sea storm-surges will be studied.

Computing resources needed: Following our first estimate, **10 Cores * 1 day * 86400 s * P * 38 simulations = ~20 MSBUs** and up to **250 GB** will be used in the framework of the ECMWF special project to fully cover these runs.

<u>Event-downscaling of the RCP 8.5 storm-surge events with median RCP 8.5 SLR</u>

In this task, the impact of future extreme events on the Adriatic Sea storm-surges will be studied.

Computing resources needed: Following our first estimate, **10 Cores * 1 day * 86400 s * P * 37 simulations = ~ 20 MSBUs** and up to **250 GB** will be used in the framework of the ECMWF special project to fully cover these runs.

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