Each pilot watersheds: meteo-hydrological-ocean modelling upgraded with a focus on interactions in the coastal areas

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1 INTRODUCTION

The STREAM project deals with territorial challenges connected to flooding in the different Adriatic regions.

Areas of potentially significant risk of flooding and/or erosion can have very different characteristics, therefore requiring different modelling systems. The STREAM pilot sites involved in the modelling and forecasting activities greatly differ for morphological characteristics, potential flood and erosion hazards and vulnerabilities.

The Apulia Pilots have been grouped according to the following flood types:

- coastal flood: **Peschici and Manfredonia towns (Apulia Region, Italy).**
- fluvial flood: **Ofanto watersheds (Apulia Region, Italy);**
- coastal erosion: **Lecce and Torchiarolo wetlands (Apulia Region, Italy).**

The Apulia region is one of the Italian regions with the largest coastal extension (~985 km). The three main categories of the coastal morphology are: (i) rocky coasts (about 31%), such as in the Gargano area; (ii) cliffs called "*falesie*" (about 22%) which are very steep escarpment due to the strong and continuative erosive action of the sea on the rocky coast with sheer walls; (iii) sandy coasts (about 29%), located in some spots over the entire region, with largest extension in southern part of Apulia (e.g. in Gulf of Taranto).

Coastal modelling for the Apulia region in STREAM project is mainly focused on the following pilots:

1) **Peschici-Manfredonia Pilot**. Here, the coastal ocean and the inland waters (rivers, mainly small and intermittent) interact one each other causing surge and inundation events. The Peschici area is mainly characterized by high and rocky coast, while the Manfredonia zone extending for about 20km is mainly sandy. A vulnerable area is represented by Siponto (Fig. 1), due to the presence of forest and wetland area at the interface with the ocean. This pilot area was strongly impacted by the meteo-marine extreme events, occurred on 6th September 2014 in Apulia region, causing coastal flooding and inundation (Fig. X1) mainly driven by the two rivers of Ulso and Chianara (having a hydrographic extension of about 11 and 30 km^2 respectively).
2) **Lecce-Torchiarolo Pilot**. The coastline length of Lecce town is about 21 km. It consists both in natural (beach, dunes and marshes behind the dunes) and human-impacted (man-made settlements, roads and artificial channels) features. Strong surges cause in several areas the flooding from sea into the marshland areas. The coast of Torchiarolo is characterized by the presence of a continuous beach, with a width ranging from a few meters to a few tens of meters. Cliff coasts are also present in several hotspots with height ranging between 8m and

13m. Both beaches and cliffs are affected by coastal erosion. Example of dunes in strong erosion are highlighted in Fig. 2.

3) **The Ofanto River Pilot**. Ofanto is one of the most important river and watersheed in Southern Italy. The basin (Fig. 3) extends for about 3'060 km^2, affecting the territory of three Italian regions (Campania, Basilicata and Puglia), with an average altitude of about 425 m above the mean sea level. The length of the main branch is about 180 km, making it the second longest river in Southern Italy. The hydraulic regime is torrential, characterized by prolonged periods of lean, which are associated with short but intense flood events, especially in Autumn - Winter time. The mean annual discharge at the outlet is around 15 m^{3}s^{-1}; minimum monthly climatology is 2.27 m^{3}s^{-1} in August and reaches its monthly peak, 35 m^{3}s^{-1}, on January. The inundation events in the Ofanto river-shelf-coastal area is mainly caused by the interaction of three factors: extreme inland river discharges, obstructions in riverbed due to sediment deposition and sea level extremes from ocean.

Fig. 1: Siponto in Peschici-Manfredonia Pilot. Sandy coast, marshland and forest of Siponto (left panel). Coastal flooding and inundation during the meteo-marine extreme events, occurred on 6th September 2014 (right panel)

Fig. 2: Lecce-Torchiarolo Pilot: example of dunes in strong erosion

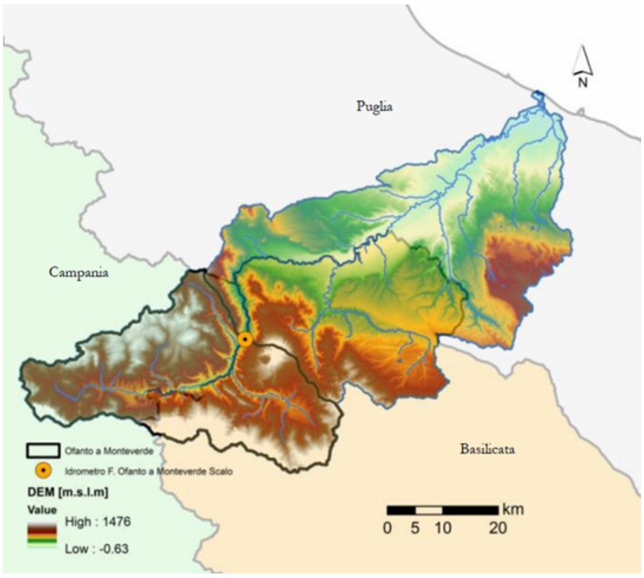

Fig. 3: Ofanto Pilot: hydrografic basin and Digital Terrain Model (DTM)

2 THE MODELS

Here we describe the different deterministic models we have adopted for the modelling chain, starting from the subregional scale (i.e. entire Adriatic Sea with ocean, wave and atmospheric models) up to the very nearshore scale of the Pilots (i.e. Apulia pilot with wave, sea level, hydrological and flooding models).

2.1 Circulation Model: SHYFEM

The circulation modelling system is based on the SHYFEM model, which is a 3-D finite element hydrodynamic model (Umgiesser et al., 2004) solving the Navier–Stokes equations by applying hydrostatic and Boussinesq approximations. The unstructured grid is Arakawa B with triangular meshes (Bellafiore and Umgiesser, 2010; Ferrarin et al., 2013), which provides an accurate description of irregular coastal boundaries. The scalars are computed at grid nodes, whereas velocity vectors are calculated at the centre of each element. Vertically a z layer discretization is applied and most variables are computed in the centre of each layer, whereas stress terms and vertical velocities are solved at the layer interfaces (Bellafiore and Umgiesser, 2010). The peculiarity of unstructured meshes is the ability of representing several scales in a seamless fashion, reaching higher resolution where necessary.

The model uses a semi-implicit algorithm for integration over time, which has the advantage of being unconditionally stable with respect to gravity waves, bottom friction and Coriolis terms, and allows transport variables to be solved explicitly. The Coriolis term and pressure gradient in the momentum equation, and the divergence terms in the continuity equation are treated semi-implicitly. Bottom friction and vertical eddy viscosity are treated fully implicitly for stability reasons, while the remaining terms (advective and horizontal diffusion terms in the momentum equation) are treated explicitly.

The model has been already applied to simulate hydrodynamics of several systems in many regions of world, proving its quality and accuracy. Exploiting the variable mesh approach, the model has been successfully applied to several scales, from the open sea (e.g. Mediterranean Sea, Black Sea, Gulf of Mexico) to the coastal seas and estuaries (e.g. coastal areas of Adriatic Ionian and Western Mediterranean Seas in Italy, Kotor Bay in Montenegro, Danube Delta in Romania) to open-sea islands (e.g. Malta) to the fjords (e.g. Roskilde, Denmark, Oslo) to the lagoons (e.g. Venice, Menor in Spain, Nador in Morocco, Dalyan in Turkey, Curonian in Lithuania, Tam Giang in Vietnam) to the ports (e.g. Apulian ports in Italy) to the rivers (e.g. Po river in Italy, Savannah river in Georgia, US) to the lakes (e.g. Geneva in Switzerland, Garda in Italy).

The modelling approach is based on the downscaling of CMEMS Marine products released at the regional scale of Mediterranean Sea. The current Med-CMEMS implementation is based on NEMO (Nucleus for European Modelling of the Ocean, Madec (2008)) finite-difference code with a horizontal resolution of 1/24 of a degree (4–5 km approximately) and 141 unevenly spaced vertical levels. The system is provided by a data assimilation system based on the 3D-VAR scheme developed by Dobricic and Pinardi (2008).

2.2 Wave Model: WW3

The wave modelling system is based on WAVEWATCH III™, a community wave modeling framework that includes the latest scientific advancements in the field of wind-wave modeling and dynamics.

The core of the framework consists of the WAVEWATCH III third- generation wave model, developed at the US National Centers for Environmental Prediction (NOAA/NCEP) in the spirit of the WAM model (Komen et al., 1994).

WAVEWATCH III, hereafter WW3 solves the random phase spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of this equation is that properties of medium (water depth and current) as well as the wave field itself vary on time and space scales that are much larger than the variation scales of a single wave. The model includes options for shallow-water (surf zone) applications, as well as wetting and drying of grid points. Propagation of a wave spectrum can be solved using regular (rectilinear or curvilinear) and unstructured (triangular) grids, individually or combined into multi-grid mosaics.

Source terms for physical processes include parameterizations for wave growth due to the actions of wind, exact and parametrized forms accounting for nonlinear resonant wave-wave interactions, scattering due to wave-bottom interactions, triad interactions, and dissipation due to whitecapping, bottom friction, surf-breaking, and interactions with mud and ice. The model includes several alleviation methods for the Garden Sprinkler Effect, and computes other transformation processes such as the effects of surface currents to wind and wave fields, and sub-grid blocking due to unresolved islands.

Wave energy spectra are discretized using a constant directional increment (covering all directions), and a spatially varying wavenumber grid. First-, second- and third-order accurate numerical schemes are available to describe wave propagation. Source terms are integrated in time using a dynamically adjusted time stepping algorithm, which concentrates computational efforts in conditions with rapid spectral changes.

The model is used worldwide by several institutions to simulate waves of several systems in many regions of the world, from global to coastal scale.

The modelling approach is based on the downscaling of CMEMS Marine products released at the regional scale of Mediterranean Sea. The current Med_Waves-CMEMS (Korres et al., 2021) implementation is based on WAM Cycle 4.6.2 with proper tuning and maximum spectral steepness limitation and it has been developed as a nested sequence of two computational grids (coarse and fine) to ensure that swell propagating from the North Atlantic (NA) towards the strait of Gibraltar is correctly entering the Mediterranean Sea (MED). The coarse grid covers the North Atlantic Ocean from 75°W to 10°E and from 70°N to 10° S in 1/6° resolution while the nested fine grid covers the Mediterranean Sea from 18.125°W to 36.2917°E and from 30.1875°N to 45.9792°N with a 1/24° (~4.6km) resolution. The Med-Waves modelling system resolves the prognostic part of the wave spectrum with 24 directional and 32 logarithmically distributed frequency bins and the model solutions are corrected by an optimal interpolation data assimilation scheme of along track satellite significant wave height observations. The system provides a Mediterranean wave analysis and 10 days Mediterranean wave forecasts updated twice a day.

2.3 The atmospheric model: WRF

The Numerical Weather Prediction (NWP) model adopted in the project is the numerical Weather Research and Forecasting Model WRF (Skamarock et al., 2019) in 4.2.1 version. This version is characterized by significant improvements compared to previous ones (https://github.com/wrf-model/WRF/releases/tag/v4.2.1).

The WRF development is due to a collaborative partnership, started in the second half of the 1990s, among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration, the U.S. Air Force, the Naval Research Laboratory, the University of Oklahoma and the Federal Aviation Administration (FAA). It represents a flexible atmospheric simulation system, which allows to operate on very diverse spatial scales, from a few hundred meters to thousands of kilometers. It is completely compressible and not hydrostatic (with a hydrostatic option in run-time). Specifically in the current work ARW resolver for WRF is used, through its two programs, real.exe and wrf.exe, which provide a preprocessing phase (WRF Preprocessing System; *WPS*) through the programs *geogrid*, *ungrib* and *metgrid*. The two-dimensional grid adopted in the horizontal domain discretization is provided by the Arakawa Staggered C-grid, while the time integration scheme used in the ARW resolver is the Runge-Kutta (RK) type for low frequency motions (meteorologically signifying), with an accuracy of the third order for linear equations and second order for nonlinear equations (Skamarock et al., 2019).

2.4 Wave propagation and coastal flooding model: XBEACH

XBeach is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms. It is a public-domain model that has been developed with major funding from the US Army Corps of Engineers, Rijkswaterstaat and the EU, supported by a consortium of UNESCO-IHE, Deltares (formerly WL|Delft Hydraulics), Delft University of Technology and the University of Miami.

The XBeach model can be used as stand-alone model for small-scale (project-scale) coastal applications, but will also be used within the Morphos model system, where it will be driven by boundary conditions provided by the wind, wave and surge models and its main output to be transferred back will be the time-varying bathymetry and possibly discharges over breached barrier island sections.

The model solves coupled 2D horizontal equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave and flow boundary conditions. Because the model takes into account the variation in wave height in time (long known to surfers) it resolves the special long wave motions created by this variation. This so-called ‘surf beat' is responsible for most of the swash waves that actually hit the dune front or overtop it. Because of this innovation the XBeach model is better able to model the development of the dune erosion profile and to predict when a dune or barrier island will start overwashing and breaching.

The model has already been validated against extensive large-scale flume data sets including short and long wave distributions, return flow, orbital velocities, concentrations and profile change during dune erosion events. An essential part is an avalanching mechanism which allows a surprisingly accurate description of the evolution of the upper profile and dune face.

2.5 The hydrological and inland flooding model: HEC-RAS

HEC-RAS allows to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling.

The HEC-RAS modeling system was developed as a part of the Hydrologic Engineering Center's "Next Generation" (NexGen) of hydrologic engineering software. The NexGen project encompasses several aspects of hydrologic engineering, including: rainfall-runoff analysis (HEC-HMS); river hydraulics (HEC-RAS); reservoir system simulation (HEC-ResSim); flood damage analysis (HEC-FDA and HEC-FIA); and real-time river forecasting for reservoir operations (CWMS). The HEC-RAS system contains the following river analysis components for: (1) one dimensional steady flow water surface profile computations; (2) one-dimensional and/or two-dimensional unsteady flow simulation; (3) Quasi unsteady or fully unsteady flow movable boundary sediment transport computations (1D and 2D); and (4) one dimensional water quality analysis.

A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the water surface profiles are computed. HEC-RAS also has an extensive spatial data integration and mapping system (HEC-RAS Mapper).

2.6 The coastal erosion model

In order to define the coastal erosion along the area located between Torchiarolo and Lecce we analysed several orthophotos taken in different time spanning from 2006 to 2019. Orthophotos have been processed in QGis environment to be homogenised in terms of geodesy. After that, we digitalized the coastline in different age to calculate the erosional rates. In addition, considering that coastal erosion could increase the effects of sea level rise due to climate change, we defined scenarios of submersion for the area between Torchiarolo and Lecce at 2050 and 2100. To assess the expected effects of relative sea-level rise for the next decades, we considered the following multidisciplinary source data: (i) sea-level-rise projections for different climatic scenarios, as reported in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, (ii) coastal topography from airborne LiDAR data, (iii) Vertical Land Movement (VLM) from the analysis of InSAR and GNSS data, and (iv) shoreline changes obtained from the analysis of orthophotos, historic maps, and satellite images. To assess the expected evolution of the coastal belt, the topographic data were corrected for VLM values, assuming that the rates of land subsidence will remain constant up to 2100. The sea-level-rise projections and expected flooded areas were estimated for the Shared Socioeconomic Pathways SSP1-2.6 and SSP5-8.5, corresponding to low and high greenhouse-gas concentrations, respectively (Scardino et al., 2022, Anzidei et al. 2021, Scardino et al., 2020).

3 MODELLING SETTINGS FOR EACH SCALE AND PILOT

3.1 The regional scale: the Med-CMEMS circulation modelling system

The CMEMS (Copernicus Marine Environment Monitoring Service) Mediterranean Near Real Time System, MedFS, provides analysis and short-term forecast of the main physical parameters in the Mediterranean Sea and it is the physical component of the Med-MFC called Med-Currents. The system is composed of a coupled hydrodynamic-wave model with data assimilation implemented over the whole Mediterranean basin and extended into the Atlantic Sea in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar. The model horizontal grid resolution is 1/24˚ (ca. 4.5 km) and has 141 unevenly spaced vertical levels. The MedFS dataset can be freely downloaded from the CMEMS catalogue (Product MEDSEA_ANALYSISFORECAST_PHY_006_013, Clementi et al., 2021). Fig. 4 shows the CMEMS MedFS domain and bathymetry.

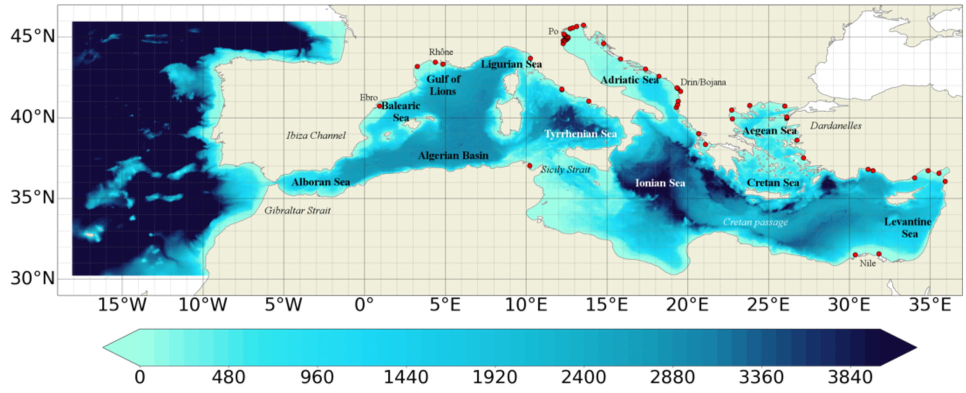

Fig. 4. CMEMS MedFS domain and bathymetry

Hydrodynamic model component (NEMO)

The MedFS oceanic equations of motion are solved by an Ocean General Circulation Model (OGCM) based on NEMO (Nucleus for European Modelling of the Ocean) version 3.6 (Madec et al., 2016). The code is developed and maintained by the NEMO-consortium. NEMO has been implemented in the Mediterranean Sea at 1/24° x 1/24° horizontal resolution and 141 unevenly spaced vertical levels (Clementi et al., 2017a) with baroclinic time step of 120 s. The model covers the whole Mediterranean Sea and also extends into the Atlantic in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar. The topography is created starting from the GEBCO 30arc-second grid (http://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_30_second_grid/), filtered (using a Shapiro filter) and manually modified in critical areas such as: islands along the Eastern Adriatic coasts, Gibraltar and Messina straits, Atlantic box edge.

NEMO model solves primitive equations using a time-splitting technique with non-linear free surface formulation and time-varying vertical z-star coordinates. The advection scheme for active tracers, temperature and salinity, is a mixed up-stream/MUSCL (more details in Oddo et al. 2009). The vertical diffusion and viscosity terms are a function of the Richardson number as parameterized by Pacanowsky and Philander (1981). The model interactively computes air-surface fluxes of momentum, mass, and heat. The bulk formulae implemented are described in Pettenuzzo et al. (2010) and are currently used in the Mediterranean operational system (Tonani et al., 2015). A detailed description of other specific features of the model implementation can be found in Oddo et al., (2009, 2014). The vertical background viscosity and diffusivity values are set to 1.2e-6 [m^2/s] and 1.0e-7 [m^2/s] respectively, while the horizontal bilaplacian eddy diffusivity and viscosity are set respectively equal to -1.2e8 [m^4/s] and -2.0e8 [m^4/s].

Tidal waves have been recently (May 2021) included in the system, so that the tidal potential is calculated across the domain for the 8 major constituents of the Mediterranean Sea: M2, S2, N2, K2, K1, O1, P1, Q1. In addition, tidal forcing is applied along the lateral boundaries in the Atlantic Ocean by means of tidal elevation estimated using FES2014 (Carrere et al., 2016) tidal model and tidal currents evaluated using TUGO (Toulouse Unstructured Grid Ocean model, ex-Mog2D, Lynch and Gray 1979).

The hydrodynamic model is nested in the Atlantic within the CMEMS Global analysis and forecast system GLO-MFC daily data set (1/12° horizontal resolution, 50 vertical levels) that is interpolated onto the Med-Currents model grid. Details on the nesting technique and major impacts on the model results are in Oddo et al., (2009). The Dardanelles Strait is also implemented as a lateral open boundary condition by using CMEMS GLO-MFC daily Analysis and Forecast product and daily climatology derived from a Marmara Sea box model (Maderich et al., 2015).

The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the 1/10° horizontal-resolution operational analysis and forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) at highest available time frequency (1 hour for the first 3 days of forecast, 3 hours for the following 3 days of forecast and 6 hours for the last 4 days of forecast and for the analysis) and the model sea surface temperature (details of the air-sea physics are in Tonani et al., 2008). The water balance is computed as Evaporation minus Precipitation and Runoff. The evaporation is derived from the latent heat flux, precipitation is provided by ECMWF as daily averages, while the runoff of the 39 rivers implemented is provided by monthly mean datasets. Objective Analyses-Sea Surface Temperature (OA-SST) fields from

CNR-ISA SST-TAC are used for the correction of surface heat fluxes with the relaxation constant of 110 $Wm^{-2}K^{-1}$ centered at midnight since the observed dataset corresponds to the foundation SST (~SST at midnight).

The scientific validation of the modelling system is provided in the Product Quality Information document (https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-MED-QUID-006-013.pdf). Fig. 5 provides as an example a tidal sea level validation in terms of model comparison with respect to tide gauges measurements for M2 and K1 tidal amplitude and phase, showing the ability of the model to accurately represent the tidal elevation.

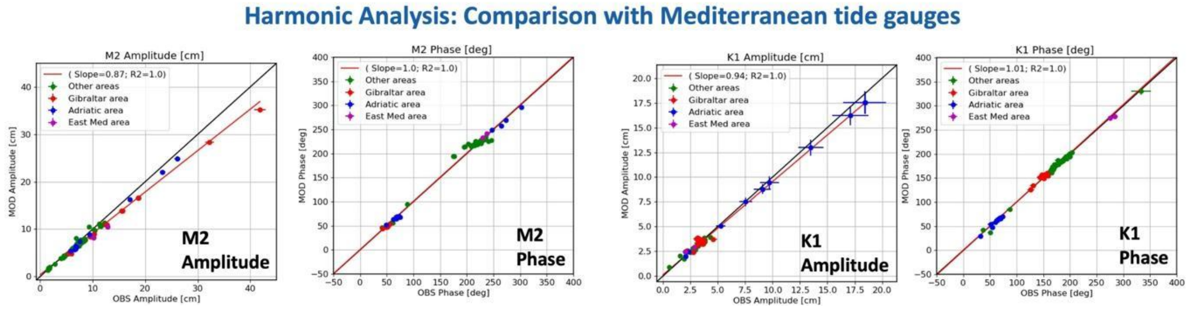

Fig. 5. Scatter plots: Model M2 and K1 tidal amplitude and phase with respect to tide gauges measurements.

Wave model component (WW3)

The wave dynamic is solved by a Mediterranean implementation of the WaveWatch-III (WW3) code version 3.14 (Tolman, 2009). WaveWatch covers the same domain and follows the same horizontal discretization of the circulation model (1/24° x 1/24°) with a time step of 240 sec. The wave model uses 24 directional bins (15° directional resolution) and 30 frequency bins (ranging between 0.05 Hz and 0.7931 Hz) to represent the wave spectral distribution.

WW3 has been forced by the same 1/10° horizontal resolution ECMWF atmospheric forcing (the same used to force the hydrodynamic model). The wind speed is then modified by considering a stability parameter depending on the air-sea temperature difference according to Tolman (2002).

The wave model takes into consideration the surface currents for wave refraction but assumes no interactions with the ocean bottom. In the present application WW3 has been implemented following WAM cycle4 model physics (Gunther et al., 1993). Wind input and dissipation terms are based on Janssen’s quasi-linear theory of wind-wave generation (Janssen, 1989, 1991). The dissipation term is based on Hasselmann (1974) whitecapping theory according to Komen et al. (1984). The non-linear wave-wave interaction is modelled using the Discrete Interaction Approximation (DIA, Hasselmann et al., 1985).

Model coupling (NEMO-WW3)

The coupling between the hydrodynamic model (NEMO) and the wave model (WW3) is achieved by an online hourly two-way coupling and consists in exchanging the following fields: NEMO sends to WW3 the air-sea temperature difference and the surface currents, while WW3 sends to NEMO the neutral drag coefficient used to evaluate the surface wind stress. More details on the model coupling and on the impact of coupled system on both wave and circulation fields can be found in Clementi et al. (2017b).

Data assimilation scheme (OceanVar)

The data assimilation system is based on a 3D variational ocean data assimilation scheme, OceanVar, developed by Dobricic and Pinardi (2008) and later upgraded by Storto et al. (2015). The background error covariance matrices vary monthly at each grid point in the discretized domain of the Mediterranean Sea. The observations that are assimilated are derived from CMEMS products: along-track sea level anomaly (a satellite product including dynamical atmospheric correction and ocean tides is chosen) and in-situ vertical temperature and salinity profiles from VOS XBTs (Voluntary Observing Ship-eXpandable Bathythermograph) and ARGO floats.

The reanalysis products: the extreme event analysis and return time for the Adriatic Sea

The Med MFC physical multiyear product is generated by a numerical system composed of a hydrodynamic model, supplied by the Nucleous for European Modelling of the Ocean (NEMO) and a variational data assimilation scheme (OceanVAR) for temperature and salinity vertical profiles and satellite Sea Level Anomaly along track data. It contains a reanalysis dataset and an interim dataset which covers the period after the reanalysis until 1 month before present. The model horizontal grid resolution is 1/24˚ (ca. 4-5 km) and the unevenly spaced vertical levels are 141.

MEDSEA_MULTIYEAR_WAV_006_012 is the multi-year wave product of the Mediterranean Sea Waves forecasting system (Med-WAV). It contains a Reanalysis dataset and an Interim dataset covering the period after the reanalysis until 1 month before present. The Reanalysis dataset is a multi-year wave reanalysis starting from January 1993, composed by hourly wave parameters at 1/24° horizontal resolution, covering the Mediterranean Sea and extending up to 18.125W into the Atlantic Ocean. The Med-WAV modelling system is based on wave model WAM 4.6.2 and has been developed as a nested sequence of two computational grids (coarse and fine) to ensure that swell propagating from the North Atlantic (NA) towards the strait of Gibraltar is correctly entering the Mediterranean Sea. The coarse grid covers the North Atlantic Ocean from 75°W to 10°E and from 70° N to 10° S in 1/6° resolution while the nested fine grid covers the Mediterranean Sea from 18.125° W to 36.2917° E and from 30.1875° N to 45.9792° N with a 1/24° resolution. The modelling system resolves the prognostic part of the wave spectrum with 24 directional and 32 logarithmically distributed frequency bins. The wave system also includes an optimal interpolation assimilation scheme assimilating significant wave height along track satellite observations available through CMS and it is forced with daily averaged currents from Med-Physics and with 1-h, 0.25° horizontal-resolution ERA5 reanalysis 10m-above-sea-surface winds from ECMWF.

The sea level and wave extremes are investigated for the model nodes closest to the coastline adopting the Goda (2010) method and fitting with Weibull and Gumbel distributions. The maps of sea level and significant wave height for the return period of 10, 25 and 50 years are shown in Fig. 6.

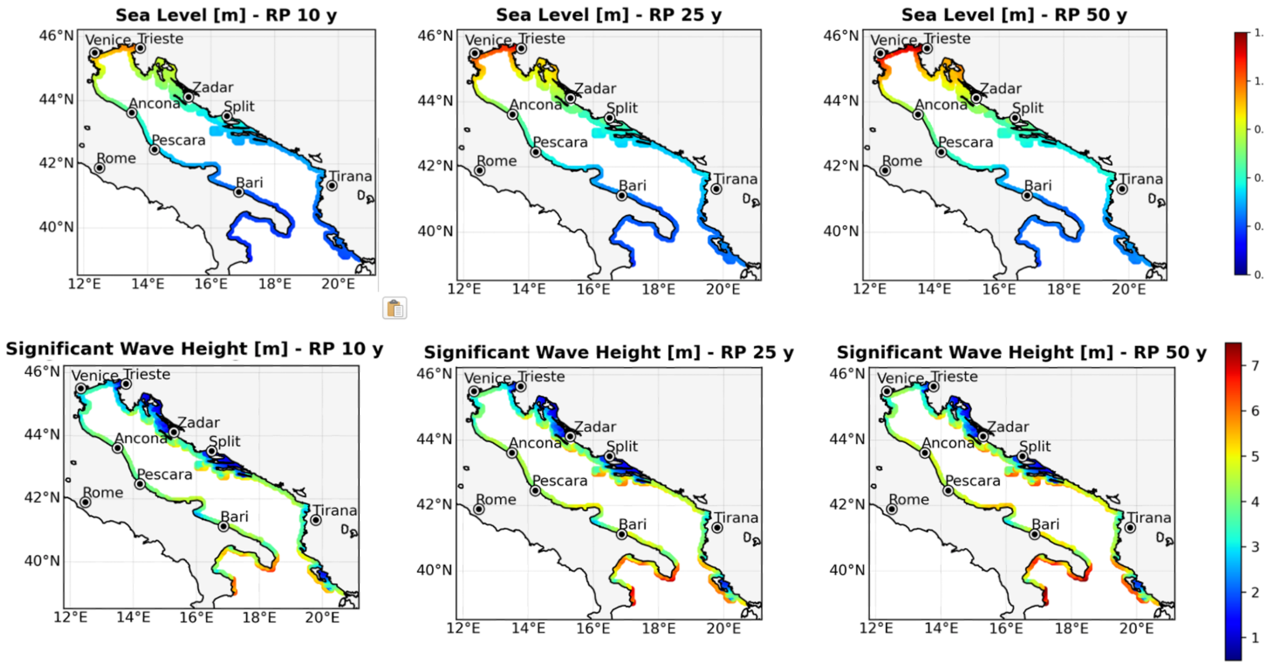

Fig. 6: Maps of sea level and significant wave height of The Adriatic Sea for the return period of 10, 25 and 50 years at the model nodes closest to the coastline

3.2 The subregional and coastal scale: from Adriatic Sea to Apulia coastal waters

3.1.1 Ocean component

The area covered by the ocean model is the Adriatic Sea from 12 to 21°E and 39 to 45.8°N with a horizontal unstructured-grid resolution ranging from 2.5km in open sea to 300m at overall coasts. The configuration is named AdriFs. Fig. 7 shows the geographical domain, the bathymetry and the overlapped grid. In Fig. 8 some enlarged views of the grid in four different coastal hotspots are reported.

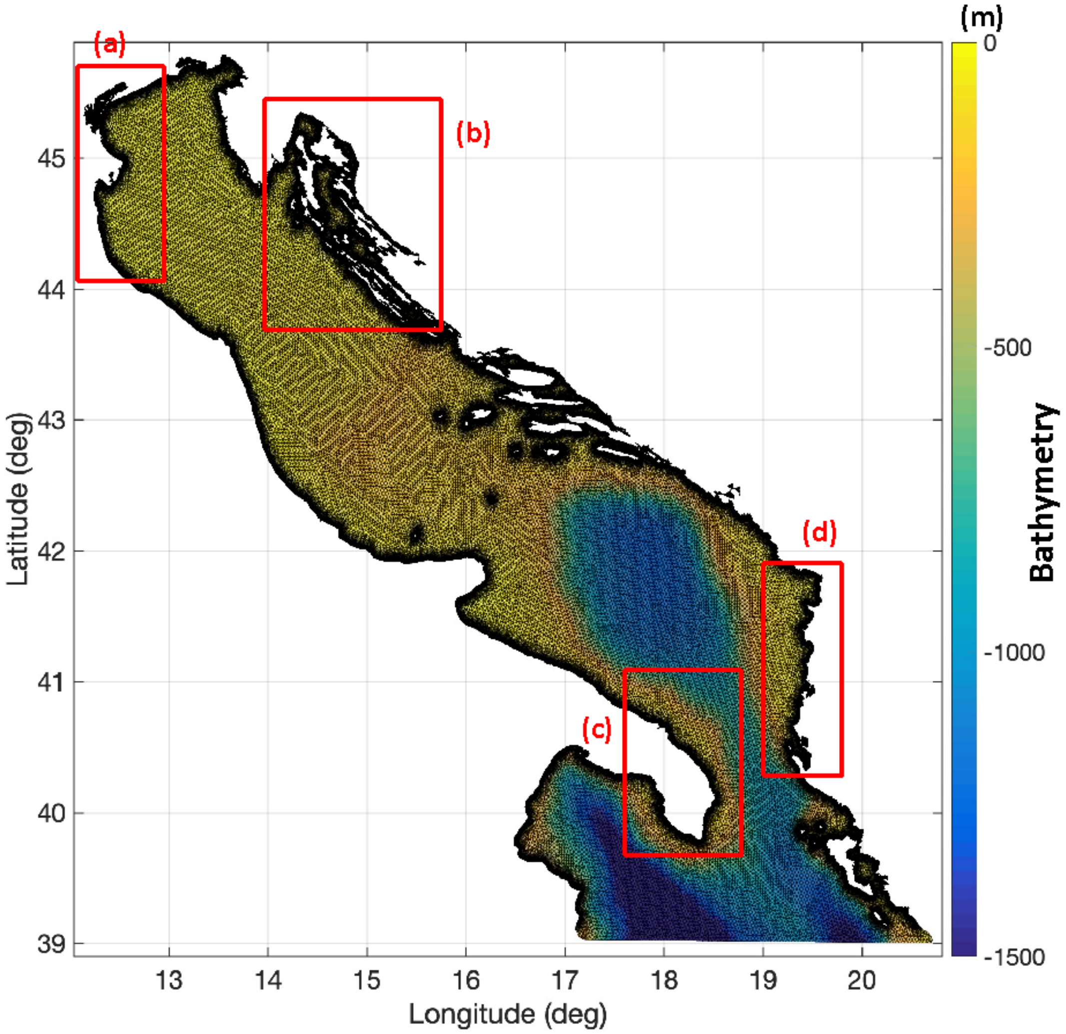

Fig. 7: Geographical domain, bathymetry and grid of high-resolution coastal model AdriFs for Adriatic Sea

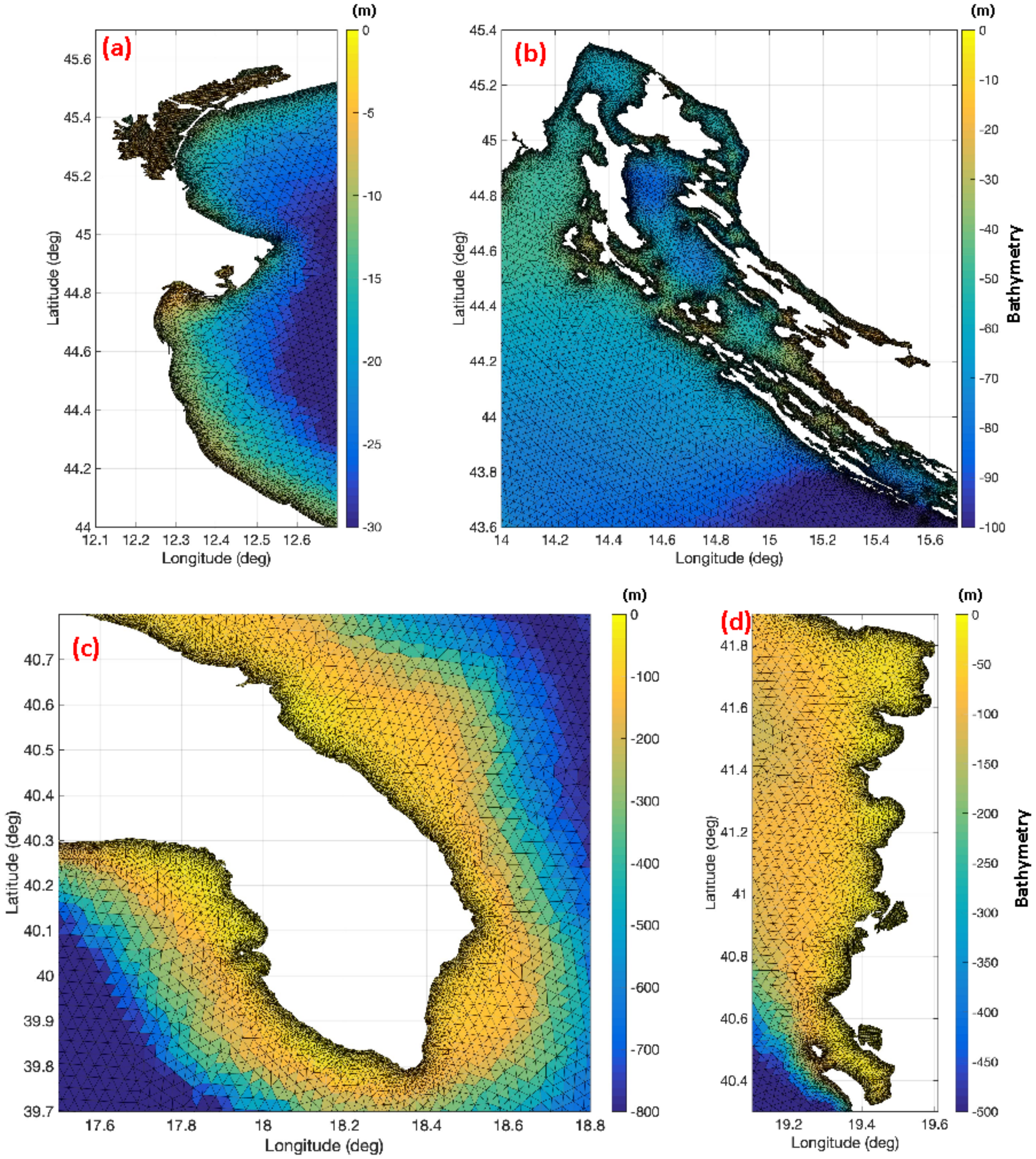

Fig. 8: Enlarged views (bathymetry and grid) in coastal zones of high resolution coastal modelling for Adriatic Sea

The bathymetric data used is EMODNET (https://www.emodnet-bathymetry.eu/) product at resolution of 1/16 x 1/16 arc-minutes (circa 110 x 110 meter) resolution. The vertical discretization is based on z-layers approach with 99 levels. The layer thickness is 1m from surface to 20m, then we have 2m of thickness up to 90 meters, then the vertical spacing is progressively (stepwise) increased down to the bottom with a maximum layer thickness of 200 m. This is appropriate for solving the field both in coastal and open-sea areas (Federico et al., 2017).

The modelling systems are three-dimensionally downscaled from Med-CMEMS both in terms or initialization and open boundaries. Clamped type open boundary conditions were employed at the boundary for sea level and inflow active tracers. Total velocities were nudged at the open boundaries and zero gradient boundary conditions were used for outflow active tracers.

The basic surface boundary conditions are:

- For temperature, the air-sea heat flux is parameterized by bulk formulas described in Pettenuzzo et al. (2010), computing Net Long wave radiation (Bignami et al., 1995), Sensible heat (Kondo, 1975), Latent heat (Kondo, 1975), Evaporation (Kondo, 1975), Short Wave Solar Radiation (Reed , 1977), Solar Penetration (Jerlov, 1975).
- For momentum, surface stress is computed with the wind drag coefficient according to Hellermann and Rosenstein (1983).

For the atmospheric fields, well-consolidated analysis products from ECMWF (~10km resolution and 6h frequency) are adopted as forcing. The atmospheric fields are corrected by land-contaminated points following Kara et al. (2007) and horizontally interpolated at each ocean grid node by means of Cressman’s interpolation technique (Cressman, 1959). The atmospheric variables used for the parametrization are 2 m air temperature (T2M), 2 m dew point temperature (D2M), total cloud cover (TCC), mean sea level atmospheric pressure (MSL), and meridional and zonal 10 m wind components (U10M and V10M) and total precipitation (TP).

The release of 62 Adriatic and Ionian rivers in total, 53 flowing into the Adriatic Sea and 9 into the Ionian Sea, has been implemented into model domain (for the dataset refers to Verri et al., 2018). Rivers inputs are treated as clamped boundary condition imposing the discharge, salinity and temperature. Due to a lack of available observations, river inflow surface salinity is fixed to a constant value of 15psu at the river boundaries, except 17 psu for the Po river. These constant salinity values are the result of sensitivity tests performed on the basis of salinity profiles measured at river mouths (Simoncelli et al. 2011) and at the center of the basin (Oddo et al. 2005). Water temperature at the river adapts to the environmental inner value inside the basin (zero-gradient boundary conditions). For all rivers except Po river, monthly climatologies of discharge are imposed. The monthly discharges have been interpolated on daily basis according to the Killworth (1996) procedure. The Po river discharge consists of daily averages based on observations recorded at Pontelagoscuro station with 30minute frequency (around 40km usptream of the delta mouths). The Po river discharge is unequally subdivided between the nine grid points representing the nine branches of the delta (Po di Goro, Po di Gnocca, Po di Tolle, Po di Bastimento, Po di Scirocco, Po di Bonifazi, Po di Dritta, Po di Tramontana, Po di Maistra) according to percentages in Provini et al. (1992).

About the main numerical settings, in the transport and diffusion equation for scalars we use an average gradient of upwind node scheme for horizontal advection and a TVD (total variation diminishing) scheme for the vertical advection. Horizontal advection of momentum is discretized by an upwind scheme and horizontal eddy viscosity is computed by the Smagorinsky's formulation. For the computation of the vertical viscosities and diffusivities, a k–ε turbulence scheme is used, adapted from the GOTM (General Ocean Turbulence Model) model described in Burchard et al. (1999). The bottom drag coefficient is computed using a logarithmic formulation via bottom roughness length, set homogeneous over the whole system to a value of 0.01 m (Ferrarin et al. 2017).

Thanks to this high resolution at overall coastal scale, the model outputs of the Adriatic Sea system will be also exploited by the Pilots for which specific numerical modeling is not provided in the project.

Coastal modelling for the Apulia region in the STREAM project is mainly focused on the following pilots of Peschici-Manfredonia, Ofanto and Lecce-Torchiarolo. Due to the continuity between the three Pilots and between the hydrodynamic features (e.g. the southward-oriented coastal current Western Adriatic Coastal circulation), we have adopted a seamless modelling approach for the entire Adriatic coastal waters of Apulia. The modelling system was named SOAP (Southern Adriatic Apulia forecasting system). The area covered by the model designed for the Apulia Pilot scale is the Southern Adriatic Sea from 14.6 to 19.9°E and 39.8 to 43.5°N with a horizontal resolution ranging from 2.0km in open sea to 30m at overall Apulian coasts. Fig. 9a shows the whole geographical domain, the bathymetry and the overlapped grid, with enlarged views of the grid (Fig. 3b and c) including the three Pilots. Also for this case, the model used is SHYFEM and the main modelling setting are similar to the ones descried in section 2.2.

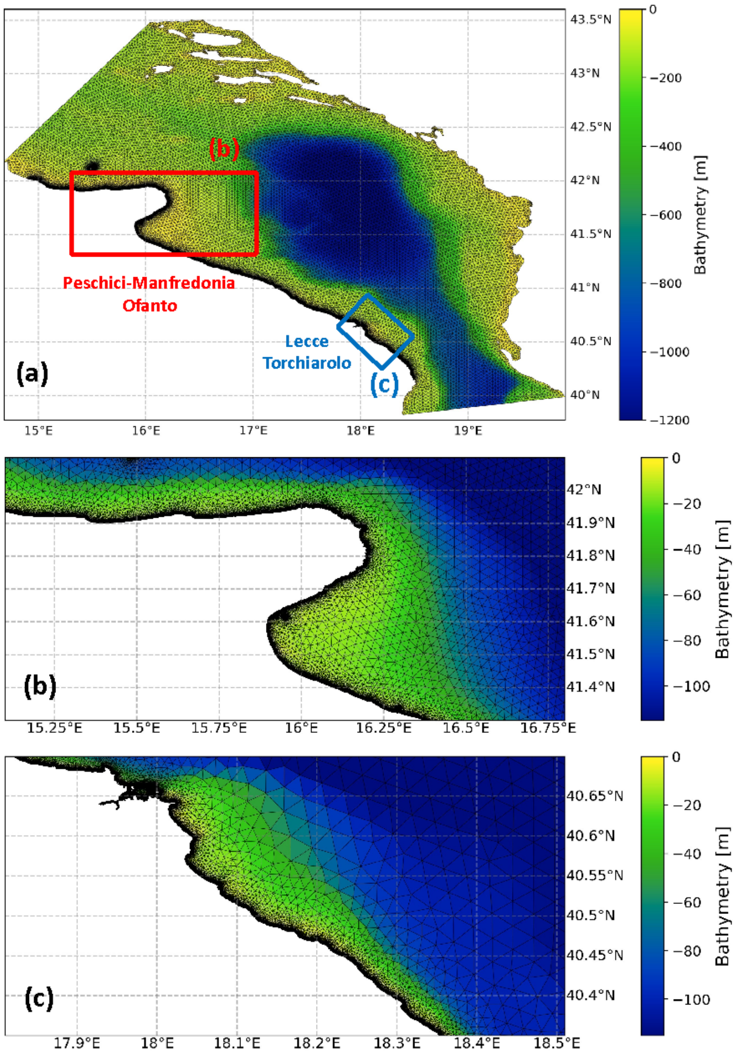

Fig. 9: Geographical domain, bathymetry and grid of very high-resolution coastal model SOAP for Apulia Pilots

3.1.2 Wave component

The wave modelling component runs over the same unstructured grids (one for the entire Adriatic Sea, as in Fig. 9, and one for the Apulia Pilot as in Fig. 10) of the ocean component, as described in

§3.1.1. The modelling systems are downscaled from Med-Waves-CMEMS in term of open boundaries. The scalar fields from Med-Waves-CMEMS (significant wave surface height, peak wave period and mean direction) are treated at the boundary nodes of the nested system through the Yamaguchi, 1984 approximation, to rebuild local wave spectra.

Both model configurations are initialized using the fetch limited approach: the local JONSWAP spectrum is calculated using the local wind speed and direction, using the spatial grid size as fetch.

Meridional and zonal 10 m wind components (U10M and V10M) of well-consolidated atmospheric products from ECMWF (6.5 km resolution and 3h frequency) are adopted as forcing. The atmospheric fields are corrected by land-contaminated points following Kara et al. (2007) and horizontally interpolated at each ocean grid node by means of linear interpolation.

The modelling configurations has been implemented following WAM Cycle4 model physics (Günther et al. 1992). The propagation scheme used is a third order scheme (Ultimate Quickest) with "Garden Sprinkler Effect" alleviation method of spatial averaging. Wind input and dissipation are based on Ardhuin et al., 2010, in which the wind input parametrization is adapted from Janssen's quasi-linear theory of wind-wave generation (Janssen, 1991, Chalikov and Belevich, 1993), following adjustments performed by Bidlot et al. 2005 and Bidlot 2008. Nonlinear wave-wave interaction have been modelled using the Discrete Interaction Approximation (DIA) (Hasselmann et al. 1986, Hasselmann et al. 1985).

The model system includes shallow water physics for coastal processes. Nonlinear triad interactions are modelled using the LTA model of Eldeberky (1996). Depth-induced breaking has been implemented using the approach of Battjes and Janssen (1978).

3.1.2 Atmospheric component

Here the main settings, grid, configuration of the atmospheric model for Adriatic and Southern Adriatic areas based on WRF. In the framework of the STREAM Project, simulations at high (WRF-2km) and very high (WRF-566m) resolution (~ 1700m and 566m respectively) have been conducted with WRF forced by the Integrated Forecasting System (IFS; Hortal, 2002) analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF; https://www.ecmwf.int/) over the period 01/01/2019-05/01/2019. The validation has been carried out on a domain that includes the Apulia Region, which, during the period under consideration, was characterized by intense advective precipitation (https://www.wetterzentrale.de/).

Starting from the IFS analyses, through a single step downscaling the WRF-2km configuration (~1700m; d01) is obtained, while through a double nesting (two-way) a resolution of about 566 meters is achieved (WRF-566m; d02), taking the boundary conditions by the parent domain d01 (Fig. 10).

Fig. 10. The two nested WRF domains d01 and d02.

The modelling configuration of these simulations is shown in Table 1.

Table 1. Modelling Configuration	**WRF-2km / WRF-566m**
Model	WRF
Forcing	IFS (ECMWF) 0,075°
Grid	Lat-Lon regular (Lambert)
Horizontal Resolution	~1700m/566m
Horizontal Discretization	Arakawa-C Grid
Timestep	12 s / 3 s
Vertical Coordinates	Sigma-pressure (60 vertical levels)
Temporal Integration Scheme	3rd order scheme Runge-Kutta
Spatial Integration Scheme	6th order centered difference

Table 1. WRF model configuration at 566m (WRF-566m), 2km (WRF-2km) and 6km horizontal resolution (WRF-6km).

3.3 The Pilot of Peschici-Manfredonia and the Ofanto river

The flooding along the coasts of the Gulf of Manfredonia was modelled in the XBeach environment, a numerical model able to reconstruct wave propagation, coastal sedimentary transport and sea floor variations, considering: the mean sea level, wind stress, and water level (McCall et al., 2014; Roelvink and Costas, 2019). Simulations have been performed in hydrostatic solution (wave resolving mode) using Nonlinear Shallow Water (NLSW) equations aimed to define run-up and overwash also in the back dune areas.

Modelling have been realized considering the event of 10–13 November 2019, which was particularly intense and caused critical effects on the northern Adriatic, and for storms with a return period of 10yr, 25yr and 50yr. Analyses have been conducted in three specific domains (Fig. 11):

1) The area between Manfredonia and Margherita di Savoia;

2) The area of Peschici;

3) The Ofanto river mouth.

To assess the effects of the storm events, the spectral wave parameters were inserted in the boundary conditions of XBeach grid domains for bathymetry and topography. Bathymetry domain has been constructed using regular grids with different cell resolution, starting from 500x20m in the offshore (obtained by nautical charts issued by Istituto Idrografico Militare) and reaching 10x10m along the coastal area (obtained by data owned by Dipartimento di Scienze della Terra e Geoambientali dell'Università di Bari surveyed through Multi Beam Echo Sounder surveys) (Fig. 12). Topographical domain has been defined interpolating 2x2m Digital Surface Modell (DSM), provided by Ministero dell'Ambiente and obtained by airborne Light Detection and Ranging (LiDAR) survey, and 1x1m Terrestrial Laser Scanner data surveyed by personnel of Dipartimento di Scienze della Terra e Geoambientali dell'Università di Bari. Modelling outputs are provided in NetCDF format, reporting values for wave heights, sea level and flow with interval of 1 hour. Flooding areas have been defined, evaluating the combined effect of storm surge and wave setup, from the coastline in the three considered domains (Fig. 13). The sea level and significant wave height data extracted from the extreme event analysis at different Return Time RT (Fig. 6) have been used to force the flooding model at RT=10 years (Fig. 14), RT=25years (Fig. 15) and RT=50years (Fig. 16)

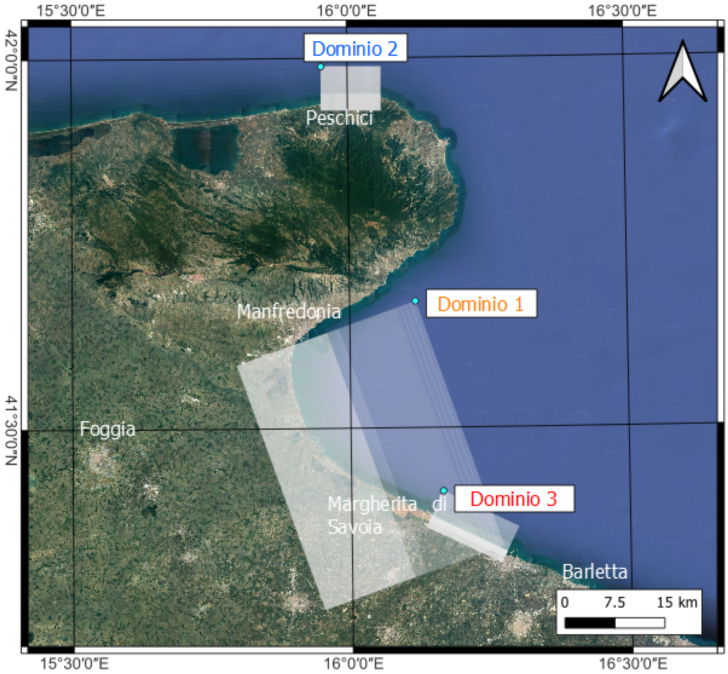

Fig. 11. Considered domains for XBeach analyses.

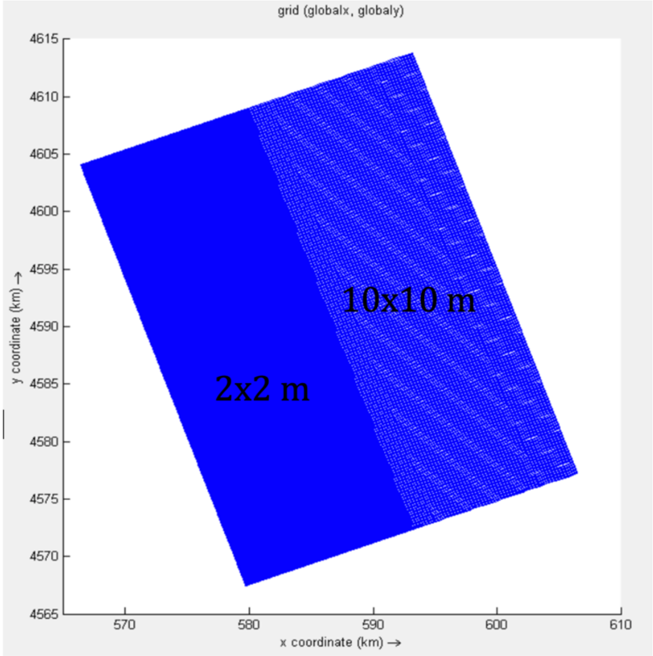

Fig. 12. Bathymetry grid domain constructed for XBeach

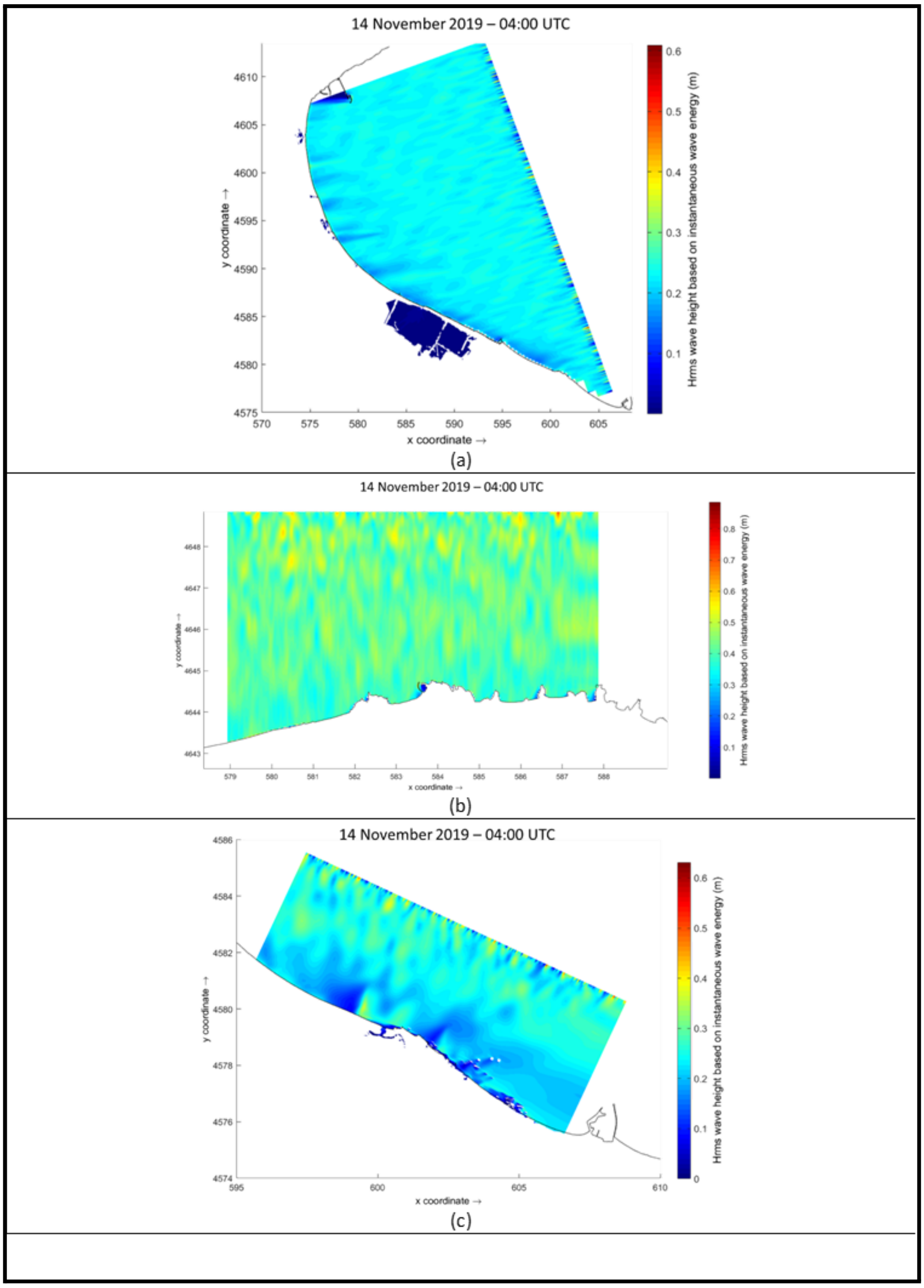

Fig. 13. Flooding scenarios for: a) Peschici, b) Manfredonia, c) Ofanto

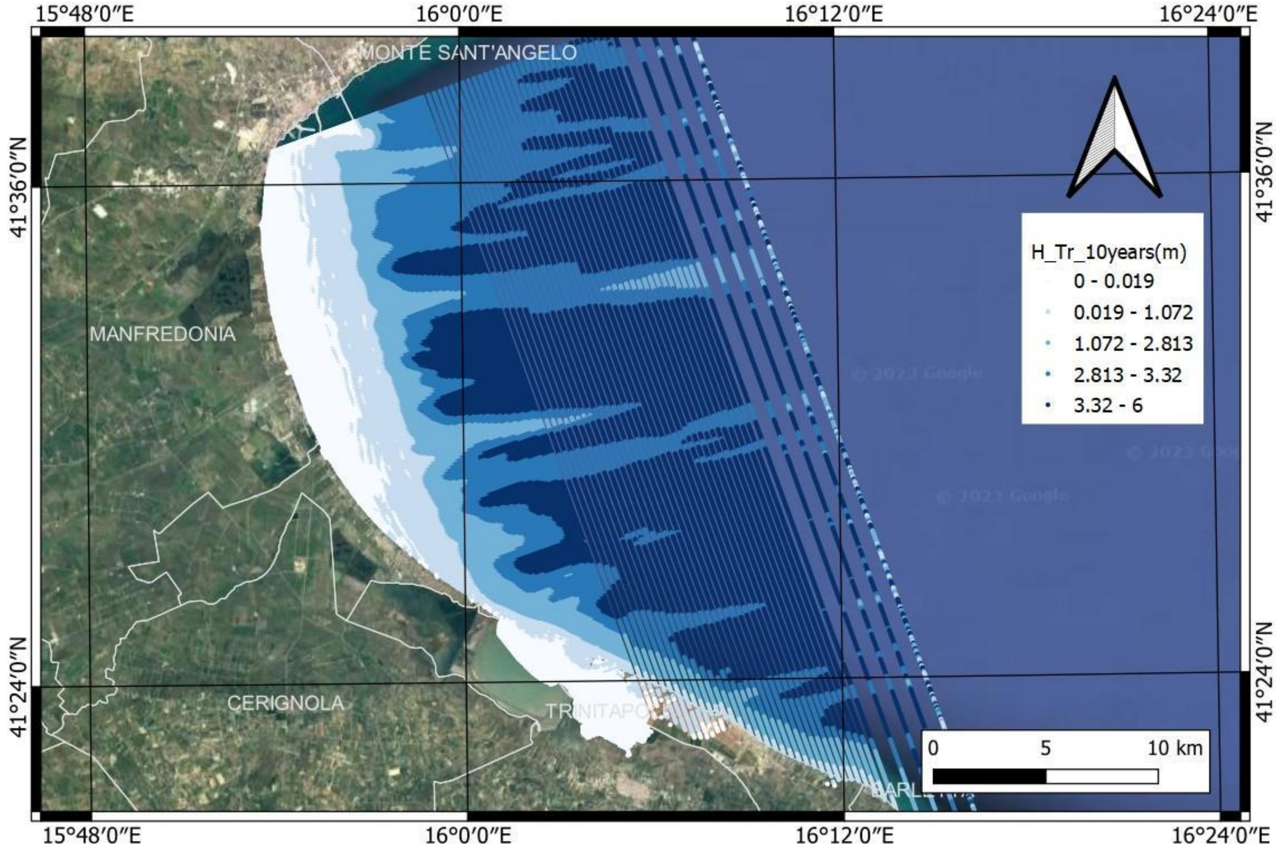

Fig. 14. Flooding scenario for 10y return period

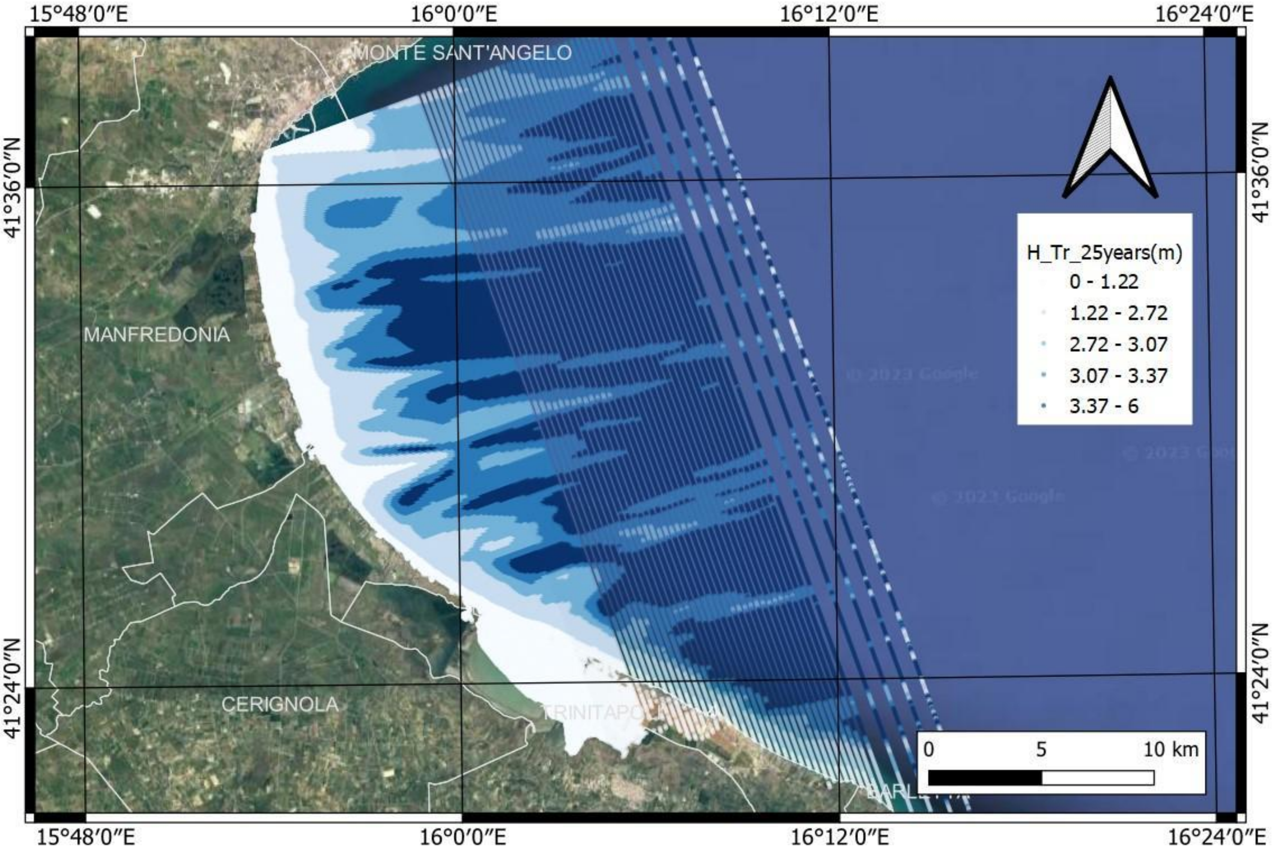

Fig. 15. Flooding scenario for 25y return period

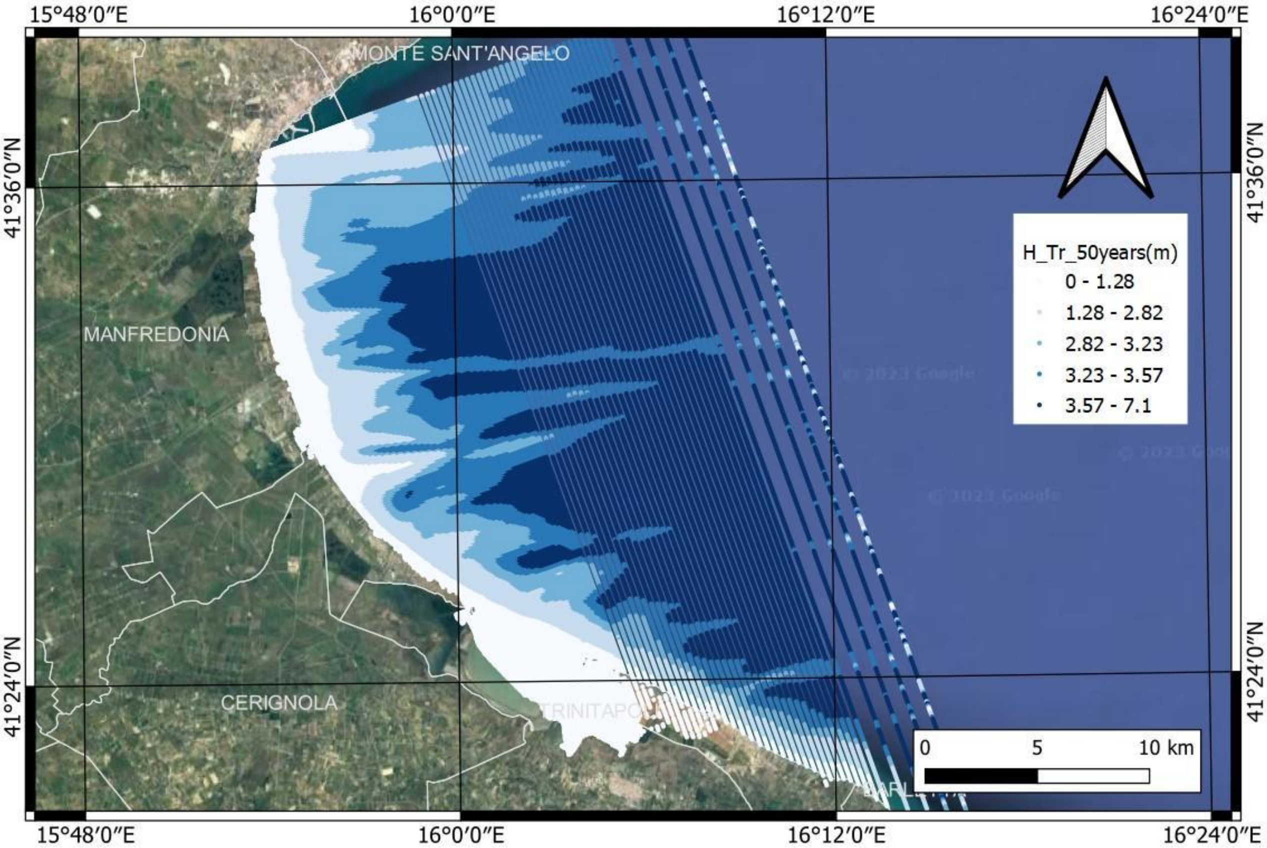

Fig. 16. Flooding scenario for 50y return period

For the definition of flooding area along the coast of Ofanto river mouth we considered the combined effect, during the storm event of 10–13 November 2019, of river and marine inundation. With this aim, we defined the watershed through a GIS analysis of the Digital Terrain Model DTM (Grid 2x2). We considered the pluviometric data provided by Civil Protection of Regione Puglia to define the flooding scenario (Fig. 17). In order to combine inland and marine contribution to final flooding we considering for the modelling of Ofanto river mouth, a sea level increased according to results obtained from XBeach analyses described in the previous sector.

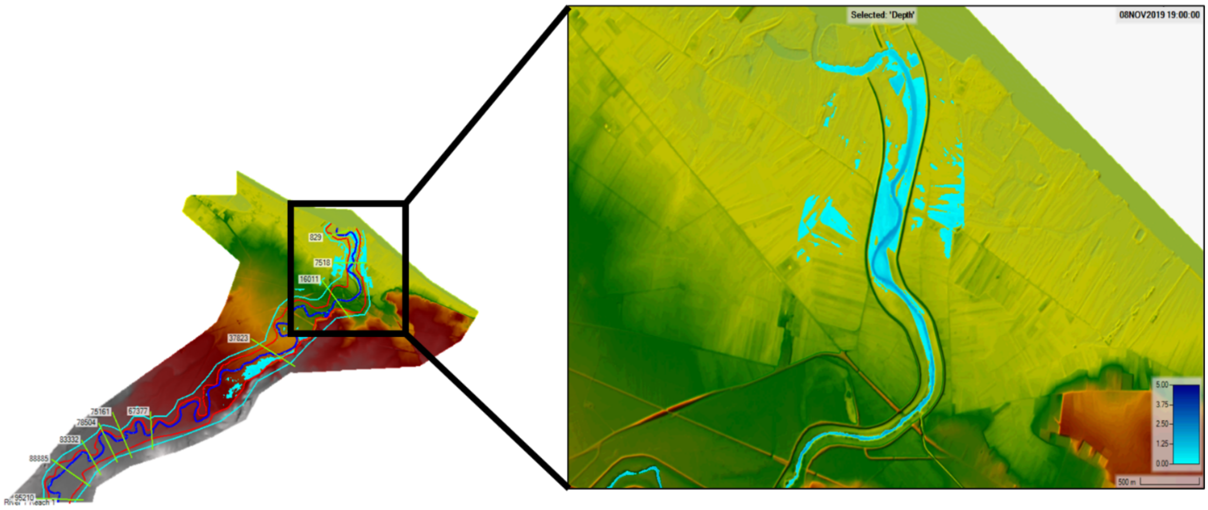

Fig. 17. Ofanto river inland inundation in HEC RAS

3.4 The Pilot of Lecce-Torchiarolo

Coastal erosional rates have been estimated through the analysis in GIS environment of ortophotos, provided by Regione Puglia, taken in 2006 and 2019. Coastlines have been digitalized with the aim to highlight difference in the considered period (Fig. 18).

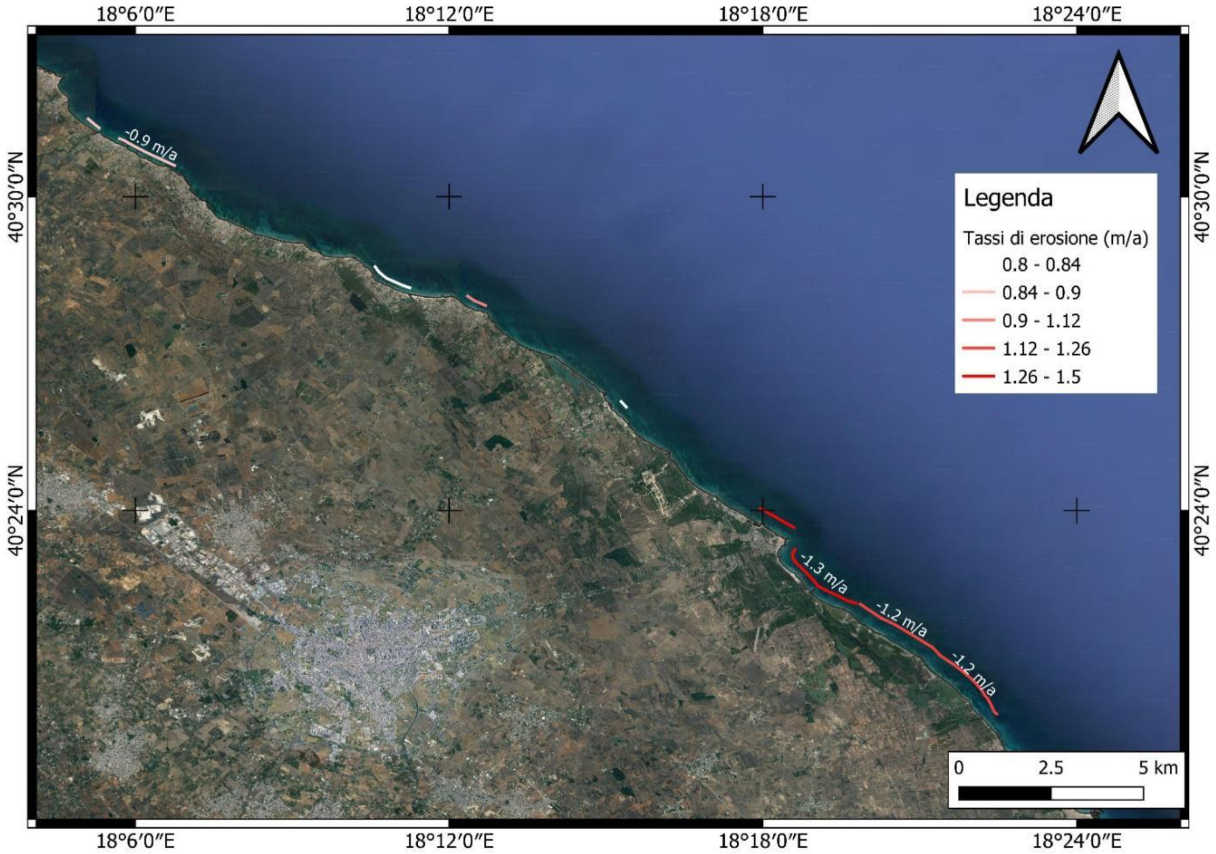

Fig. 18 – Erosional rates estimated for the coastal area between Torchiarolo and Lecce

The permanent flooding due to sea-level rise was determined following the method shown in Scardino et al., 2020. This analysis was based on the combined effects caused by vertical components of RSLR and horizontal components of shoreline changes. Regional-scale projections of long-term vertical SLR were obtained from the IPCC AR6 projections, downscaled for the Mediterranean Sea, which take into account the thermosteric and surface-mass balance contributions, the Greenland and Antarctic ice sheets, the glacier- and land-water storage, the GIA adjustment, and the inverse barometer effect. Two specific projections were used, SSP1-2.6 and SSP5-8.5, which represent low and high greenhousegas concentrations, respectively, and are thus representative of best- and worst-case projections, respectively. The assessment of horizontal components due to the sediment movements was obtained through the analysis of shoreline change rates. To predict the shoreline migration in 2050, 2100, and 2150, we incorporated the sealevel projections in the model reported by Scardino et al., 2020. This model was implemented in the MATLAB environment by considering the future shoreline position through the relationships reported by Scardino et al., 2020. The projected shoreline position was computed from the combination of vertical displacement (Δz) (due to the future RSLR) and horizontal displacement, obtained from the easterly (Δx) and northerly (Δy) movement of the shoreline. Vertical Land Movements have been estimated through the analysis of Persistent Scatter (PS) InSAR data from ESA's Sentinel-1 satellites were used (C-Band SAR sensor, with a wavelength of 5.6 cm), from both ascending and descending orbits, covering the period from September 2014 to January 2021. Sentinel-1 satellites are operated by ESA in the Terrain Observation with Progressive Scans SAR (TOPSAR) acquisition mode (VV polarization); data are freely distributed (https://sentinel.esa.int/web/sentinel/ missions/sentinel-1, accessed on 18 August 2022). Specifically, we considered 94 images along the descending orbit covering the time interval from September 2014 to January 2021 with a revisiting time of 12 days, enough to detect the land movement in the investigated area. The same procedure was considered for the ascending orbit, selecting 117 images from December 2015 to March 2018.

4 REFERENCES

- Bellafiore, D., Umgiesser, G., 2010. Hydrodynamic coastal processes in the north Adriatic investigated with a 3D finite element model, Ocean Dynam., 60, 255–273.
- Bellafiore, D., Mc Kiver, W., Ferrarin, C., Umgiesser, G., 2018. The importance of modeling nonhydrostatic processes for dense water reproduction in the southern Adriatic Sea. Ocean Model. 125, 22–28. doi:10.1016/j.ocemod.2018.03.001
- Bignami, F., S. Marullo, R. Santoleri, and M. E. Schiano, 1995: Longwave radiation budget in the mediterranean sea. J. Geophys. Res, 100 (C2), 2501–2514, doi:10.1029/94JC02496.
- Clementi, E., Pistoia, J., Delrosso, D., Mattia, G., Fratianni, C., Storto, A., Ciliberti, S., Lemieux, B., Fenu, E., Simoncelli, S., Drudi, M., Grandi, A., Padeletti, D., Di Pietro, P., Pinardi, N., (2017a). A 1/24 degree resolution Mediterranean analysis and forecast modelling system for the Copernicus Marine Environment Monitoring Service. Extended abstract to the 8th EuroGOOS Conference, Bergen.
- Clementi, E., Oddo, P., Drudi, M., Pinardi, N., Korres, G., Grandi A., (2017b). Coupling hydrodynamic and wave models: first step and sensitivity experiments in the Mediterranean Sea. Ocean Dynamics. doi: https://doi.org/10.1007/s10236-017-1087-7.

- Clementi, E., Aydogdu, A., Goglio, A. C., Pistoia, J., Escudier, R., Drudi, M., Grandi, A., Mariani, A., Lyubartsev, V., Lecci, R., Cretí, S., Coppini, G., Masina, S., & Pinardi, N. (2021). Mediterranean Sea Analysis and Forecast (CMEMS MED-Currents, EAS6 system) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/MEDSEA_ANALYSISFORECAST_PHY_006_013_EAS6
- CMEMS Copernicus Marine Services https://marine.copernicus.eu/
- Dobricic S., and N. Pinardi (2008). An oceanographic three-dimensional variational data ssimilation scheme. Ocean Modelling, 22 (3-4) 89-105.
- Ferrarin, C., Umgiesser, G., Bajo, M., De Pascalis, F., Ghezzo, M., Bellafiore, D., Mattassi, G., Scroccaro, I., 2010. Hydraulic zonation of the Lagoons of Marano and Grado, Italy. A modelling approach. Estuarine Coastal Shelf Sci. 87, 561–572. doi:10.1016/j.ecss.2010.02.012
- Ferrarin, C., Roland, A., Bajo, M., Umgiesser, G., Cucco, A., Davolio, S., Buzzi, A., Malguzzi, P., Drofa, O., 2013. Tide-surge-wave modelling and forecasting in the Mediterranean Sea with focus on the Italian coast, Ocean Model., 61, 38–48.
- Ferrarin, C., Bellafiore, D., Sannino, G., Bajo, M., Umgiesser, G., 2018. Tidal dynamics in the inter-connected Mediterranean, Marmara, Black and Azov seas. Prog. Oceanogr. 161, 102–115. doi:10.1016/j.pocean.2018.02.006
- Federico, I., Pinardi, N., Coppini, G., Oddo, P., Lecci, R., Mossa, M., 2017. Coastal ocean forecasting with an unstructured grid model in the Southern Adriatic and Northern Ionian seas, Nat. Hazards Earth Syst. Sci., 17, 45–59.
- Gunther, H., Hasselmann, H., Janssen, P.A.E.M., (1993). The WAM model cycle 4, DKRZ report n. 4.
- Hasselmann, K. (1974). On the characterization of ocean waves due to white capping, Boundary-Layer Meteorology, 6, 107-127.
- Hasselmann, S., and Hasselmann, K. (1985). Computations and parameterizations of the nonlinear energy transfer in a gravity wave spectrum. Part I: A new method for efficient computations of the exact nonlinear transfer integral, J. Phys. Ocean., 15, 1369-1377.
- Hasselmann, S., Hasselmann, K., Allender, J.H., Barnett, T.P., (1985). Computations and parameterizations of the nonlinear energy transfer in a gravity wave spectrum. Part II: Parameterizations of the nonlinear energy transfer for application in wave models, J. Phys. Ocean., 15, 1378-1391.
- Janssen, P.A.E.M. (1989). Wave induced stress and the drag of air flow over sea wave, J. Phys. Ocean., 19, 745-754.
- Janssen, P.A.E.M. (1991). Quasi-Linear theory of wind wave generation applied to wave forecasting, J. Phys. Ocean., 21, 1631-1642.
- Jerlov N.G., Optical Oceanography, page 194. Elsevier, 1968.

- Kara, B. A., Wallcraft, A. J., Hurlburt, H. E., 2007. A Correction for Land Contamination of Atmospheric Variables near Land–Sea Boundaries, J. Phys. Oceanogr., 37, 803–818.
- Killworth PD (2006) Time interpolation of forcing fields in ocean models. J Phys Oceanogr 26:136–143
- Komen, G.J., Hasselmann, S., Hasselmann, K., (1984). On the existence of a fully developed windsea spectrum, J. Phys. Ocean., 14, 1271-1285.
- Kondo, J. 1975. Air-sea bulk transfer coef- ficients in diabatic conditions. Boundary- Layer Meteorol., 9: 91-112.
- Madec, Gurvan and the NEMO team, (2016). NEMO ocean engine: version 3.6 stable. Note du Pole de modelisation, Institut Pierre-Simon Laplace N 27. ISSN No 1288-1619. https://www.nemo-ocean.eu/wp-content/uploads/NEMO_book.pdf
- Oddo P., N. Pinardi, M. Zavatarelli, 2005. "A numerical study of the interannual variability of the Adriatic Sea (2000-2002)", The Science of the Total Environment, 353, 39-56
- Oddo, P., Adani, M., Pinardi, N., Fratianni, C., Tonani, M., Pettenuzzo, D., (2009). A Nested Atlantic-Mediterranean Sea General Circulation Model for Operational Forecasting. Ocean Sci. Discuss., 6, 1093-1127.
- Oddo, P., Bonaduce, A., Pinardi, N., Guarnieri, A., (2014) Sensitivity of the Mediterranean sea level to atmospheric pressure and free surface elevation numerical formulation in NEMO. Geosci. Model Dev., 7, 3001–3015.
- Pacanowsky, R.C., and Philander S.G.H., (1981) Parameterization of vertical mixing in numerical models of tropical oceans. J Phys Oceanogr 11:1443-1451
- Pettenuzzo, D., Large, W.G., Pinardi, N., (2010) On the corrections of ERA-40 surface flux products consistent with the Mediterranean heat and water budgets and the connection between basin surface total heat flux and NAO. Journal of Geophysical Research 115, C06022, doi:10.1029/2009JC005631
- Provini A, Crosa G, Marchetti R (1992) Nutrient export from Po and Adige river basins over the last 20 years. Sci Total Environ Suppl:291–313
- Reed, R. K. 1977. On estimating insolation over the ocean. J. Phys. Oceanogr., 17: 854- 871.
- Simoncelli, S., Pinardi, N., Oddo, P., Mariano, A. J., Montanari, G., Rinaldi, A., and Deserti, M.: Coastal Rapid Environmental As- sessment in the Northern Adriatic Sea, Dynam. Atmos. Oceans, 52, 250–283, 2011.
- Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., … Huang, X. -yu. (2019). A Description of the Advanced Research WRF Model Version 4.1 (No. NCAR/TN-556+STR). doi:10.5065/1dfh-6p97
- Smagorinsky, J., 1963. General circulation experiments with the primitive equations. The basic experiment. Monthly Weather Review 91,99–152.

- Storto, A., Masina, S., Navarra, A., (2015). Evaluation of the CMCC eddy-permitting global ocean physical reanalysis system (C-GLORS, 1982-2012) and its assimilation components. Quarterly Journal of the Royal Meteorological Society, 142, 738–758, doi: 10.1002/qj.2673.
- Tolman H.L. (2009). User Manual and system documentation of WAVEWATCH III version 3.14. NOAA/NWS/NCEP/MMAB Technical Note 276, 194 pp + Appendices.
- Tolman H.L. (2002). Validation of WAVEWATCH III version 1.15 for a global domain.NOAA / NWS / NCEP / OMB Technical Note 213, 33 pp.
- Tonani, M., Balmaseda, M., Bertino, L., Blockley, E., Brassington, G., Davidson, F., Drillet, Y., Hogan, P., Kuragano, T., Lee, T., Mehra, A., Paranathara, F., Tanajura, CAS, Wang, H., (2015) Status and future of global and regional ocean prediction systems. J Operational Oceanography 8:201-220, doi:10.1080/1755876X.2015.1049892.
- Tonani, M., Pinardi, N., Dobricic, S., Pujol, I., Fratianni, C., (2008). A high-resolution free-surface model of the Mediterranean Sea. Ocean Sci., 4, 1-14.
- Umgiesser, G., Melaku Canu, D., Cucco, A., Solidoro, C., 2004. A finite element model for the Venice Lagoon. Development, set up, calibration and validation. J. Mar. Syst. 51, 123–145. doi: 101016/j.jmarsys.2004.05.009