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Integrating multidisciplinary instruments for assessing coastal vulnerability to erosion and sea level rise: lessons and challenges from the Adriatic Sea, Italy.

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Abstract

The evolution of coastal and transitional environments depends upon the interplay of human activities and natural drivers, two factors that are strongly connected and many times conflicting. The urge for efficient tools for characterising and predicting the behaviour of such systems is nowadays particularly pressing, especially under the effects of a changing climate, and requires a deeper understanding of the connections among different drivers and different scales. To this aim, the present paper reviews the results of a set of interdisciplinary and coordinated experiences carried out in the Adriatic Sea (north-eastern Mediterranean region), discussing state-of-the art methods for coastal dynamics assessment and monitoring, and suggests strategies towards a more efficient coastal management.

Coupled with detailed geomorphological information, the methodologies currently available for evaluating the different components of relative sea level rise facilitate a first identification of the flooding hazard in coastal areas, providing a fundamental element for the prioritization and identification of the sustainability of possible interventions and policies. In addition, hydro- and morpho-dynamic models are achieving significant advances in terms of spatial resolution and physical insight, also in a climatological context, improving the description of the interactions between meteo-oceanographic processes at the regional scale to coastal dynamics at the local scale.

We point out that a coordinated use of the described tools should be promptly promoted in the design of survey and monitoring activities as well as in the exploitation of already collected data. Moreover, expected benefits from this strategy include the production of services and infrastructures for coastal protection with a focus on short-term forecast and rapid response, enabling the implementation of an event-oriented sampling strategy.

Keywords: Monitoring; Multi-Scale Modelling; Climate Change; Coastal Vulnerability

1. Introduction

Due to the growing awareness of the potential threats acting on coastal regions (climate change, geological processes, sea level rise, alteration of sediment supply regime) combined with the strong anthropic pressure (e.g. urbanization, tourism) on the littoral regions, the themes related to coastal morphological vulnerability and adaptability have progressively obtained increasing emphasis in the planning and management policies. In the wake of the relevance achieved by planning processes such as Integrated Coastal Zone Management (ICZM) and Maritime Spatial Planning (MSP), the last decade has envisaged in Europe a progressive enhancement of EU funding made available for interdisciplinary approaches to coastal topics. Examples are represented by single projects (e.g. EUROSION, CONSCIENCE, OURCOAST), guiding acts and declarations of intent (e.g. the Bologna Charter signed in Bruxelles in 2012), and tender projects. All these efforts have paved the way for innovative approaches and results that can directly respond to societal needs in the sector of coastal vulnerability to erosion and sea level rise, favouring the collaboration among National and International research and administration institutions.

One of the most striking difficulties when dealing with coastal morphological vulnerability, especially in a climate change perspective, is to harmonize information pertaining to different disciplines and coming from different sources into the description of physical processes occurring at different time and spatial scales (Church et al., 2013). In fact, even a careful assessment of coastal vulnerability only rarely takes into account the information retrieved from detailed process-based hydrodynamic analysis (Palmer et al., 2011). This is also the case of reference tools such as DIVA (Dynamic Interactive Vulnerability Assessment, see Hinkel and Klein, 2009; Hinkel et al., 2014), in which natural and socio-economic factors such as sea level rise, coastal topography and population are accounted for without an explicit description of coastal hydro-morphodynamics. Although recent activities endeavour to bridge this gap by channeling the information provided by hydro-morphodynamic models towards management practices (e.g. the iCOASST Project recently carried out in the UK, see Nicholls et al., 2015), this approach is not firmly established yet.

The Mediterranean basin has been identified as a climate change "hot spot", namely a region where the impacts of this process are expected to be stronger compared to other places in the world (Santoro et al., 2013; Giorgi and Lionello, 2008). The exposure of human activities to this condition is increased by the microtidal regime (mean tide around 35 cm) of the basin, which allowed to settle a large portion of the coastal region. Furthermore, large and often intensively anthropised subsiding coastal plains are exposed to an increasing flooding risk, requiring dedicated planning and protection policies in the upcoming decades.

Within this area, the relevance of the Adriatic-Ionian Region has been significantly growing from the scientific and economic point of view in the last decades, and is now the subject of several EU initiatives, such as the IPA Adriatic (2007-2013) and the Italy-Croatia (2014-2020) Cross-Border-Cooperation Programmes, as well as the ADRION Programme (2014-2020). Among the many EU funded projects dealing with coastal management and innovative methodologies for coastal protection, several involved the analysis of specific cases on the Adriatic coast. As an example, Lido di Dante, a vulnerable stretch of the Emilia-Romagna coastline was elected as study site during several EU projects, among which DELOS (Lamberti et al., 2005) and CoastView (Kroon et al., 2007, Jimenez et al., 2007), eventually leading to the implementation of innovative defence solutions (see Archetti and Zanuttigh, 2010). As in a number of similar cases, these experiences highlight that success of innovation in coastal management can receive a fundamental contribution from the involvement of local Institutions and stakeholders. Alongside these projects, the north-eastern Adriatic was the first study site of the GEOSWIM programme, that aims at surveying and collecting data by snorkeling methods along rocky coasts in the Mediterranean area, for studies on rock coast geomorphology, coastal vulnerability and sea level changes (e.g. Furlani et al., 2014a).

The Adriatic-Ionian Region is also the key test area for a specifically funded research line on "Coastal Vulnerability to Erosion and Sea Level Rise" in the framework of the RITMARE Project, a multidisciplinary effort supported by the Italian Ministry of University and Research (MIUR), aiming at integrating the Italian marine community in shared research fields in the period 2012-2017. This experience provided a sound opportunity for identifying the main achievements and open issues in different aspects of coastal vulnerability assessment and adaptation, with special attention to open opportunities and challenges related to the integration of different approaches and perspectives. The goal of this paper is thus to consolidate the background for a deeper connection among the scientific community and the actors of coastal management, bridging the existing cultural and methodological gaps, with a twofold outcome. On the one hand, this should favour a more effective assessment of the physical processes governing coastal systems and allow for more reliable predictions, especially with reference to climate change scenarios. On the other hand, we expect that a progressive shift towards a shared and holistic approach to coastal science will facilitate the interactions between scientists, policy-makers and stakeholders into organic management actions.

2. Materials and Methods: Tools for estimating coastal vulnerability to erosion and flooding

2.1 Geographical framework

The Adriatic Sea (Fig. 1) is a semi-enclosed epicontinental basin of the northeastern Mediterranean, elongated along the NW-SE direction and encompassed by the Apennines to the West, by the Alps to the North and by the Dinarides to the East. The particular basin topography and the dominance of northeasterly and southeasterly winds give rise to a wave climate characterized by the combination of generative and swell sea states, occasionally coexisting and both potentially capable of strong impacts on coastal morphology (Cavaleri et al., 1989; Archetti et al., 2016).

The geological setting of the northern and central Adriatic coast is the result of the progressive submersion of a wide portion of the palaeoalluvial plain during the Pleistocene and Holocene (Lambeck et al., 2011, and references therein). Each step of the relative sea level rise is associated with the genesis and submersion of a barrier lagoon system, whose fine sand deposits act as potential sand reservoirs for coastal nourishment (Correggiari et al., 2013).

The relatively energetic wave climate, the predominant presence of low-lying alluvial coasts and the long-lasting sediment deficit, combined with the strong anthropic pressure along the coast especially along the western side of the basin (Nelson, 1970; Torresan et al., 2012), concur in increasing the importance of a sound framework for long-term coastal planning in this region.

2.2 Estimating relative sea level rise

When tackling the field of coastal vulnerability to erosion and sea level rise, it is relevant to estimate the sea level rise projections expected over a decadal to centennial time frame.

With reference to the northern Adriatic Sea, an early assessment of the role of relative sea level rise in conditioning coastal flooding was provided by Bondesan et al. (1995). Subsequent studies by Antonioli et al. (2002) and Antonioli and Leoni (2007) extended the assessment of coastal flooding hazard, as a combination of relative sea level rise and vertical tectonic movements, throughout several sites spanning the whole Italian coasts. A further effort by Lambeck et al. (2011), based on existing datasets and newly acquired data, allowed to provide sea level rise projections for the year 2100 in 33 Italian coastal plains by adding the isostatic and tectonic contributions to the IPCC (Church et al., 2013) and Rahmstorf (2007) estimates.

In the wake of that work, during the first phase of the RITMARE Project, flooding maps were obtained using the eustatic (and steric) component as in the 8.5 IPCC 2013 scenario projections (Church et al., 2013, 700 ppm CO2 atmospheric content), and estimates by Ramshtorf (2007). Flooding scenarios for 2100, explicitly accounting for the different contributions from the expected isostatic, tectonic and eustatic-steric rates of sea level rise in coastal areas of the Adriatic Sea from Trieste to Ravenna, and in Taranto (Ionian Sea), Oristano and Cagliari gulfs (Tyrrhenian Sea), were presented in studies by Antonioli et al. (2017) and Marsico et al., 2017. Isostatic rates were derived from Lambeck et al. (2011), long-term tectonic rates were retrieved from bibliographic data referred to the Last Interglacial Period, namely the Marine Isotope Stage 5.5 elevation (approximately 125 ka BP, Ferranti et al., 2006; Antonioli et al., 2009). In particular, for the northern Adriatic region, long-term vertical tectonic movements data were mutuated from Ferranti et al. (2006) and Antonioli et al. (2009, 2015), referring to last Interglacial deposits from dozens of cores drilled along the coast between Ravenna and Trieste (Fig. 1, adapted from Lambeck et al., 2011). The estimates provided by those works have been superimposed to DTMs (Digital Terrain Models), with a definition depending on the data available from local or regional administrations, with a resolution up to 1x1 m^2 where Lidar surveys were available.

2.3 Technologies for estimating cliff erosion and retreat rates: the Apulian test case

In order to calculate the erosion and retreat rates on 2100 on the Apulian carbonate cliffs, lowering rates on limestone coasts were evaluated by using a micro erosion meter (MEM) and a traversing micro erosion meter (TMEM) built by one of the authors (Stefano Furlani) following High and Hanna (1970) and Trudgill et al. (1981). The instruments were equipped with three iron shaped supports adhering to three titanium nails (two semi-spherical and one flat-shaped) that have been previously fixed into the rock and constitute a micro erosion meter station. The exact relocation of the fixed studs was derived from the configuration called the Kelvin clamp principle (High and Hanna, 1970; Trudgill et al., 1981). The MEM used in this project was equipped with a dial gauge with a resolution of 0.01 mm and was capable of collecting one measurement for each station. The TMEM was equipped with a Mitutoyo dial gauge with 0.001 mm resolution (maximum error ±0.003 mm) and capable to collect up to hundreds of measurements for each station, as suggested by Furlani et al., (2009, 2014b).

At the end of November 2016, 11 stations were set up in four sites (Peschici, Polignano A Mare, Porto Badisco, Castro) on the eastern coast of Apulia, from Gargano to Castro (Fig. 1). The first cycle of measurements was carried out in May 2017. MEM data will be collected at least until November 2019, in order to discuss a three year-long dataset, as suggested by Stephenson et al. (2012) and Furlani and Cucchi (2013).

The occurrence of erosional forms due to abrasion and mechanical actions related to high wave energy processes at the cliff toe has been assessed in the same sites used to evaluate the micro erosion rates. For an evaluation of the mechanical erosion values due to high-energy waves, several kilometres of coasts (Peschici, Polignano A Mare, Porto Badisco, Fig. 1) were surveyed with an UAV (Unmanned Aerial Vehicle) Phantom 4 Pro equipped with a HD 20 Mpx camera. Flights have been performed following the shorelines at different altitudes ranging between 20 m and 60 m. The collected pictures underwent a photogrammetric processing based on Agisoft Photoscan, to retrieve clouds of points with a resolution up to 10 cm, used to reconstruct the DEM (Digital Elevation Model) of the surveyed area. Applying a filter for vegetal coverage on the DEM it was possible to obtain the DTM (Digital Terrain Model), that represents the base for the extraction of orthophotos with resolution ranging between 2 cm/pixel and 5 cm/pixel. Results will be evaluated studying the movement of the blocks in the sea near the cliff and by comparing the two precise DTMs repeated over a 12-month interval.

2.4 Modelling tools for basin-scale hydrodynamics and metocean analysis

Together with the estimates of relative sea level rise, some key quantities characterising meteo-oceanographic processes are crucial for the evaluation of coastal vulnerability to erosion and its evolution over time. The importance of setting up appropriate numerical modelling chains has been progressively more recognised in the last decade under the impulse of increasing computational power availability, improved routines for model coupling (Warner et al., 2010, Villaret et al., 2013) and advanced parameterisations for the description of physical processes. Severe weather episodes impact the coastal environment through flooding and erosion with potential damage to the ecosystems, the private property, and the historical heritage. Global Climate Models (GCM) are used to assess possible changes in future extreme events but suffer from their coarse horizontal resolution (50-200 km), limiting their ability to properly describe small-scale signals especially in the presence of complex orography, coastlines and land surface heterogeneity. Therefore, in order to study regional processes and provide climate information at the scale of interest for impact studies, the information conveyed by GCM is dynamically downscaled by Regional Climate Models (RCM) taking initial and boundary conditions from the GCMs in which they are nested. The use of RCMs has become a quite common practice since they represent a valuable tool to study regional processes and interface with end-users community. Furthermore, efficient downscaling protocols have been developed (e.g. Giorgi and Gutowski, 2015) to minimize known errors, although many uncertainties still underlie the production of regional climate change projections. Within this framework, two main research lines have been emerging, namely the development of coupled regional Earth system models and the transition to very high-resolution, up to convection-permitting, models (Giorgi and Gutowski, 2015). The latter can be best attained by a multiple-nesting procedure, with progressively increasing resolution, which avoids the “resolution jump” identified as a source of errors in the downscaling procedure (Antic et al., 2004). The term “high-resolution modelling” can have different interpretations in the different disciplines involved in a study: for instance, 1 km horizontal resolution may be considered coarse for hydrological studies, especially in coastal and transitional systems, while it pushes the boundary of feasibility for the meteorological operational activities. For meteorological research applications, model resolution represents a critical parameter, especially when dealing with severe weather events (e.g. strong winds and heavy precipitations) and in areas characterized by complex orography (Davolio et al., 2015a; Davolio et al., 2015b).

Resolution is a primary issue also when atmospheric fields are used as a forcing for oceanographic applications, allowing or preventing an appropriate description of some primary meteo-oceanographic processes (Signell et al., 2005; Bellafiore et al., 2012). While improved nesting techniques and suitable parameterizations allow to increase the resolution and physical insight of atmospheric and oceanographic models, model coupling permits a full exploitation of these advances, providing a full description of the feedbacks between atmosphere, waves, ocean currents and sediment dynamics (Warner et al., 2010; Renault et al., 2012, Carniel et al., 2016). To this purpose, due to its peculiar morphology and its role as a cold engine for Mediterranean thermohaline circulation, the Adriatic Sea has recently been used as a test site for some innovative applications of coupled models for the description of severe events. With reference to an exceptional cold spell that took place in winter 2012 (Mihanovic et al., 2013) and the subsequent dense water production, Ličer et al. (2016) coupled ALADIN and POM models for exploring air-sea interactions during the event. For the same case study, Ricchi et al. (2016) and Carniel et al. (2016) relied on the COAWST modelling system (Warner et al., 2010) for investigating the impact of coupling in the description of the process and their implications for dense water dynamics and off-shelf fluxes.

2.5 Sub-mesoscale hydrodynamics and morphodynamics for coastal applications: monitoring and modelling

Notwithstanding the importance of obtaining a reliable estimate of shoreline change for evaluating the variability of coastal morphology, such observations are usually not carried out following any specific standards or shared good practices. Generally speaking, surveys can exhibit strong variability in terms of methods and frequency (Archetti, 2009). As an example, Emilia Romagna Regional Administration (Northern Italy) prescribes one general bathymetric survey of the regional coast every five years and a low-altitude flight to monitor the shoreline position at most once a year. Although acceptable for capturing major long-term morphodynamic processes, this frequency does not allow the retrieval of important information at shorter time scales, such as the seasonal morphological variability or the response to single storm events, thus adding some uncertainty also in the interpretation of the long-term evolution trends (Baart et al., 2009; Baart et al., 2016). In recent years, a support towards a high-frequency monitoring of shoreline changes was provided by the analysis of video images, with early examples from Turner and Anderson (2007) and Kroon et al. (2007). The most common application in image processing for coastline management is the detection and comparison of subsequent shoreline positions based on time-average (*timex*) images. Compared to the less frequent, traditional ground-based surveys (that are nevertheless necessary for the system calibration), a daily monitoring allowed by video observations permits a low-cost identification of the different time scales components of coastal evolution (Kroon et al., 2007, Uunk et al., 2010).

Besides the detection and monitoring of morphological metrics, efficient coastal planning and risk mitigation requires accurate predictions of nearshore hydrodynamic processes governing flooding, sediment transport, coastal morphology evolution and interactions with structures (Samaras et al., 2016; Gaeta et al., 2016). At present, the choice of the specific tool to be adopted strongly depends on the time and space scales of the study, but efforts aiming at a general strategy unifying the possible approaches have recently been pursued with encouraging results (van Maanen et al., 2016).

Accordingly with the features and scales of the selected modelling instrument, the wave climate should be characterised at a sufficiently high resolution, which can be achieved in the very nearshore by means of multi-model (Bonaldo et al., 2015) or multi-nesting (Gaeta et al., 2016) approaches. The majority of the modelling requirements at this scale of interest are covered by third-generation spectral wave models (see for instance SWAN, Booij et al., 1999; and WaveWatch III, Tolman and Group, 2014), simulating phase-averaged sea state spectral density dynamics within the domain by describing energy injection and dissipation, non-linear energy transfer, and wave propagation and transformation. In the need for a higher level of detail for the representation of the propagation of highly nonlinear waves within the breaker zone and/or in the presence of structures one may also resort to phase-resolving models (e.g. Beltrami et al., 2001). At the cost of significantly heavier computational requirements, these formulations are able to fully reproduce specific aspects of wave propagation and transformation, capturing processes outside the inherent limitations of phase-averaging wave models such as diffraction and harbour agitation. Karambas and Samaras (2014) show how phase-resolving models can be used for the evaluation of coastal protection works, testing an advanced nonlinear wave, sediment transport and bed morphology evolution model based on the higher-order Boussinesq equations against observational data from a beach nourishment intervention.

Ocean currents dynamics and the modulation of sea surface over time and space are often modelled by means of formulations based on the 3D Reynolds-Averaged Navier-Stokes (RANS) equations or the 2D shallow water equations, generally accounting for a number of sources and sinks of momentum, fluid mass and tracers within the basin. Within these modelling efforts, it is rather common to find a mixed use of open source and commercial models. For example, the open source TELEMAC suite (Hervouet, 2007) and the commercial software MIKE21 (developed by ©DHI Group) have been extensively validated and used over the last years in research, operational and engineering design applications in maritime/coastal hydraulics. TELEMAC includes TOMAWAC for the modelling of waves, TELEMAC-2D for 2D-hydrodynamics and SISYPHE for sediment transport, which can be run fully coupled (namely, with bidirectional feedback and exchange of information between models) and have been applied in a series of studies over the years (Brown and Davies, 2009; Luo et al., 2013; Villaret et al., 2013 among others). MIKE21 includes the respective modules MIKE21–SW (waves), MIKE21-HD (hydrodynamics) and MIKE21-ST (sediment transport), with examples of their use that can be found (among others) in the works by Siegle et al. (2007) and Ranashinghe et al. (2010).

Worth mentioning, an alternative strategy for the description of coastal systems hydrodynamics at the small scale has been suggested by recent efforts of implementing a Large Eddy Simulation (LES) approach in harbours, closed and semi-enclosed basins (Petronio et al., 2013, Galea et al., 2014). This methodology is based on the application of a low-pass filter on the Navier-Stokes Equations and on the subsequent exact computation (within the limits of the numerical discretization) of all the flow features below the time and space scale of the filter, while the smaller and shorter features are parameterised (Burchard, 2002).

2.6 Tools for coastal vulnerability assessment

Expected changes in meteo-marine climate, combined with the effect of relative sea level rise, represent a major source of hazard for shoreline stability and coastal development. One of the main goals of the coastal vulnerability assessment is to achieve decision support tools for coastal problems, in order to face episodic inundation or long-term erosion and flooding hazard. According to Kaminsky and Genfelbaum (2000), whichever tool or procedure is adopted needs to satisfy two requirements: i) predict coastal behaviour at scales relevant for coastal zone management; ii) provide technical assistance that directly links scientific research with management and policy-making needs. A broad variety of approaches has been progressively developed in this direction, following strategies based on synthetic indices and indicators, or on dynamic representations of the ongoing processes at different possible degrees of conceptualization, possibly based on GIS tools (Ramieri et al., 2011).

The forefather of the index-based approaches is the Coastal Vulnerability Index (CVI, Gornitz et al., 1991) method, based on the combination of a set of quantitative or semi-quantitative physical and morphological variables and resulting into a single parameter characterising the system. This procedure is largely adaptable with respect to specific hazard factors, such as sea level rise (Özyurt, 2007), flooding (Balica et al., 2012) or wave storms (Mendoza and Jimènez, 2008), including socio-economic factors (Szlafsztein and Sterr, 2007) and allowing for multiple spatial (McLaughlin and Cooper, 2010) and temporal (Greco and Martino, 2016) scales. This schematisation provides immediate information and a prompt criterion for the identification of the intervention priorities, usually at the cost of little transparency on the choice of the variables and on the propagation of uncertainty from the basic assumptions to the final results. This issue is partially addressed by indicator-based methods, considering sets of independent parameters each addressing a specific aspect of coastal vulnerability, allowing for a possible second-step integration of these quantities into synthetic indices (e.g. Eurosion, 2004).

Deeper insight in the complexity of the coastal zone dynamics for the comparison of possible management strategies can be achieved by means of software-based Decision Support Systems (DSSs), whose main purpose is to convey the scientific information into a suitable framework for stakeholders and decision makers at different levels (Santoro et al., 2013). With specific reference to the impacts of sea level rise and coastal erosion, and to the implications of possible adaptation strategies, a paramount example of DSS in the EU context is given by the Dynamic Interactive Vulnerability Assessment model (DIVA, Hinkel 2005; Richards and Nicholls, 2009). This approach, developed within the DINAS-Coast project (Hinkel and Klein, 2009), considers a number of biophysical and socio-economical parameters over typical coastal segment length spanning several tens of kilometres, and has been mostly applied over national to global level.

Over a smaller spatial scale, the northern Adriatic Sea has been the test site for several applications of the DESYCO system (Torresan et al., 2010, Torresan et al., 2012; Santoro et al., 2013), combining downscaled climate change projections of key meteo-oceanic and morphological quantities with biogeophysical and socio-economic factors into a multidisciplinary coastal vulnerability assessment at the regional scale.

Although all the methods summarised above aim at fulfilling the two requirements stated by Kaminsky & Genfelbaum (2000), a degree of uncertainty remains intrinsic in some part of the process. Regardless of the methodology implemented, strengthening the characterization of the physical processes and feedbacks acting on the coastal system (Payo et al., 2016) reduces the need for more or less arbitrary assumptions.

3. Results and discussion: recent achievements and upcoming challenges

In this Section we provide an overview of recent achievements obtained in the different scientific fields involved in the RITMARE activities on coastal vulnerability to erosion and sea level rise. Besides collecting information that can be useful for a quantification of processes ongoing in the Adriatic-Ionian region (especially in the western side) or as a methodological guideline, the goal is to gather some elements for the identification of strategies and possible limitations for an integrated approach in a decision support perspective.

3.1 Sea level rise and flooding hazard along the Adriatic coasts

With reference to the Italian coasts, and in particular to the Adriatic Sea, the most comprehensive and up-to-date estimates are collected in the above mentioned works by Lambeck et al. (2011) and Antonioli et al. (2017), explicitly considering the effects of eustasy, isostasy and tectonic movements.

The IPCC scenario adopted by Antonioli et al. (2017) in their projections for 2100 provides minimum and maximum values of eustatic sea level rise at 53 and 97 cm, respectively, while for the Rahmstorf scenario 1.4 metre sea level rise is expected. Lambeck et al. (2011) provided variable isostatic rates along the Italian coasts, ranging between -0.12 and -0.64 mm/year with minima in the northern Adriatic and maxima in Sardinia. Long-term tectonic rates are ranging from -1.05 to + 1.9 mm/year and were derived from bibliographic data referred to the Last Interglacial Period, namely the Marine Isotope Stage (MIS) 5.5 (approximately 125 ka BP) elevation (Ferranti et al., 2006; Antonioli et al., 2009). For the northern Adriatic region, long-term vertical tectonic movements data were mutuated from Ferranti et al. (2006) and Antonioli et al. (2009, 2015), referring to last Interglacial deposits identified from dozens of cores collected along the coast between Ravenna and Trieste. The elevation of lagoonal fossils of the late Holocene sampled on core data, when compared with predicted sea level curve, showed high subsidence rates due to soil compaction and/or anthropogenic subsidence. Conversely, data older than 6 ka cal BP show rates similar to MIS 5.5. Different tectonic rates can thus be computed in the northern Adriatic Sea, ranging from -0.3÷0.5 mm/yr between Trieste and Caorle to -0.5÷0.7 mm/yr between Caorle and Chioggia and -0.7÷1.0

mm/yr between Chioggia and Cesenatico. The sum of the different contributions led to an estimate of the relative sea level rise in 2100 ranging between 1.38 and 1.43 m according to the Rahmstorf model, associated with the potential flooding of a 5451.7-km^2 region, as well as a retreat of the coastline up to 61.3 km (Fig. 2). In the southern areas of the Adriatic Sea, Lambeck et al. (2011) estimated combined isostatic and tectonic vertical displacement expected for 2100 as -0.038 m and -0.040 m in Lesina and Manfredonia respectively, yielding a relative sea level rise up to 1.44 m in the worst case scenario envisaged by Rahmstorf (2007) or Horton et al. (2014). Concerning the eastern coast of the Adriatic Sea (Slovenia, Croatia, Montenegro, Albania), information on relative sea level rise suffer from large uncertainties in the estimate of the tectonic component, due the lack of the MIS 5.5 marker.

Present methodologies thus allow an accurate evaluation of the different components of the vertical land movement leading to relative sea level rise in coastal areas. Besides providing an indication on the vulnerability to flooding, this can be a crucial element in the definition of a coastal sediment budget, concurring to the identification of the priority and feasibility of different protection strategies (Blum and Roberts, 2009).

3.2 Integrating Models and Measurements for Coastal Vulnerability Assessment

The capabilities and advances in the descriptive and predictive potentials of the numerical models presented in the previous sections have been recently strongly benefiting from the outcomes of the RITMARE Project. Indeed, on the one hand the efforts dedicated to the study of some strategic key areas of the Project allowed to rely on a good wealth of high-quality geomorphological and hydrodynamic data for several sites along the Italian coasts, and the Adriatic-Ionian region in particular. On the other hand, the development, improvement and testing of specific numerical models was accomplished as an explicit requirement of some tasks of the Project.

Samaras et al. (2016) presented a detailed comparison of the TELEMAC and MIKE21 suites in the representation of nearshore hydrodynamics and proposed a multiparametric scenario-based approach for the rapid assessment of wave conditions in coastal zones, all applied to study areas located in Southern Italy (i.e. Brindisi – Torre Guaceto and Bari, Fig. 1). That work was based on the consideration that some specific activities in coastal planning, vulnerability/risk assessment and coastal protection design, may not always require a full integration of atmosphere, ocean and coastal models. This is the case in which either only parts of local hydrodynamics information are required, or the modelling analysis is focused on the study of frequent/extreme condition scenarios (Reikard, 2009; Stockdon et al., 2012; Burcharth et al. ,2014).

Beyond the achievements obtained in the improvements and evaluation of single, stand-alone numerical models, the Adriatic Sea has been used as a study area for several coastal applications of model coupling. The first high-resolution experience carried out at the sub-basin scale (0.5 km horizontal grid step in the northern Adriatic) led to the assessment of the effect of wave-current interactions for ocean dynamics descriptions in a shallow, semi-enclosed sea (Benetazzo et al., 2013) and their impacts on tracer advection and sediment resuspension and transport (Sclavo et al., 2013). The use of different coupling configurations among atmosphere, waves, and ocean currents models within the COAWST modelling system allowed to quantify the implications of explicitly describing the air-sea interface quantities (an example can be found in Fig. 3) and their interactions for the evaluation of heat and momentum fluxes (Ricchi et al., 2016). This improved information can also positively impact the description of deep sea dynamics, with strong benefits for the study of the continental margin dynamics influencing thermohaline circulation (Carniel et al., 2016; Bonaldo et al., 2018) and, more generally, a consistent energy budget for climate studies. Worth pointing out, the more consistent physical description provided by model coupling does not necessarily always imply a clear improvement in model performances. Indeed, present models have mostly been calibrated with reference to uncoupled configurations, in which atmosphere-wave-currents interactions were parameterized with a considerable degree of conceptualization: thus, the benefits provided by these achievements will progressively be disclosed as new dedicated calibrations are carried out with reference to coupled configurations.

In the perspective of a more integrated and interdisciplinary approach to the assessment of the physical drivers of coastal vulnerability to erosion and flooding, significant results have been obtained by linking models referring to different systems, scales and process insight or degree of abstraction into more or less complex modelling chains. The cooperation between the Italian oceanographic and atmospheric research communities provides a number of successful examples. The Kassandra forecasting system (Ferrarin et al., 2013) is an operational modelling tool for the prediction of storm surges in the northern Adriatic Sea, for which high-resolution (1.25 km) meteorological fields from MOLOCH forecasts (Davolio et al., 2015b) are provided to the hydrodynamic (SHYFEM) and wave (WWMII) models. Other operational forecasts of waves and currents in the Adriatic Sea are provided by a coupled wave-current implementation of COAWST with a nested domain discretization modulating the horizontal resolution between 2 km in the south and 0.5 km in the northern sub-basin (Russo et al., 2013).

Over longer time scales, climatological atmospheric fields provided at 14 km horizontal resolution by COSMO-CLM (Bucchignani et al., 2013 – online in 2011) were used as a forcing for a 30-years long SWAN simulation (Benetazzo et al., 2012), allowing an assessment of the possible wave climate modifications to be expected in the Adriatic in a climate change scenario. This kind of information has a broad range of applications. With reference to the same modelling run, Barbariol et al. (2013) explored the implications of such modifications for wave energy productivity in the Adriatic Sea. Bonaldo et al. (2015) added a further link to the modelling chain by using DHI LITPACK, which provides a simplified description of hydro-morphodynamics within the active beach, for estimating the possible consequences of wave climate modifications in terms of coastal sediment transport on a small stretch of the northern Adriatic coastline. Benefiting from this experience and from the new estimates on relative sea level rise fostered by RITMARE (Antonioli et al., 2017), it is now possible to extend the approach to the Adriatic-Ionian region and other tracts of the Italian coast, providing the description of present and expected meteo-marine climate in a climate change scenario together with a robust physically-based support to coastal intervention and adaptation planning. Indeed, a new version of COSMO-CLM has recently been developed and implemented over Italy, pushing the horizontal resolution down to 8 km (Bucchignani et al., 2015) and exhibiting an unprecedented capability of capturing the peculiar patterns and the directional structure of wind events (Fig.4) in the Adriatic basin (Bellafiore et al., 2012; Bonaldo et al., 2017). This significantly improves the potential for a satisfactory assessment of wave climate and coastal sediment transport in this region, particularly due to the semi-enclosed geometry of the basin, by which a small change in the orientation of winds can lead to strong implications for coastal dynamics (Soomere et al., 2015).

Furthermore, considering the fact that sediment discharge from rivers and natural streams is one of the strongest drivers (as the main sediment source) for the evolution of coastal morphology, processes in the upstream watersheds should not be neglected. Monitoring the alterations in sediment discharge at the estuaries may, of course, allow for a detailed study of the past and present evolution, but lacks the identification of the drivers behind these alterations within the watersheds and thus the prediction of their future impact on the connected coasts. Accordingly, research attempts on the integrated modelling of watershed-coast systems seem to be gaining traction in the last few years. For instance, Ashton et al. (2013) set up a modelling framework for the long-term evolution of an imaginary watershed-coast system. Samaras and Koutitas (2014a) described the dynamics of such a system in northern Greece by coupling a watershed model with a shoreline evolution model, based on an integrated approach previously proposed by the same authors (Samaras and Koutitas, 2012). Moreover, such attempts could also include climatic pressures as forcings for the various terrestrial/coastal processes and investigate their concurrent effect in both fields, offering a significant advantage to the study of coastal morphology evolution under a changing climate (see Samaras and Koutitas, 2014b; Duong et al., 2016).

The technique based on the use of videocameras for coastal processes monitoring, proposed by Holman and Stanley (2007) and widely used at low costs in recent years (Archetti and Zanuttigh, 2010; Archetti et al., 2016), highlighted the potential of a cost-effective method for monitoring wave climate and beach morphodynamics in sandy coasts. A modular deployment allows to cover long coast stretches, permitting to follow the main features of the shoreline evolution of a coastal sediment cell, defined as "a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks" (Inman, 2005). Also, the integration of wave and current measurements introduces the possibility of calibrating, besides small-scale hydrodynamic and morphodynamic models, empirical parameterisations for a running estimate of the morphodynamic effect of a storm with known characteristics (Bonaldo et al., 2014). An application of shoreline monitoring aimed at understanding the response of a beach to single storms was presented by Archetti et al. (2016). On the study area, located in Jesolo beach (northern Adriatic Sea), a video monitoring station and an acoustic wave and current profiler were installed in spring 2013, respectively recording images and hydrodynamic data. Variations in the shoreline were quantified in combination with available nearshore wave conditions, making it possible to define a parametric, site-specific relationship between the shoreline displacement and the wave features, following the sketch in Fig. 5. The implementation of numerical models solving RANS equations and including filtration law through low crested coastal structures, as presented in Archetti and Gaeta (2012), represents another suitable approach in the estimation of effects induced by defence measures on run-up and inundation dynamics.

It is worth noting that the procedure proposed by Archetti et al. (2016) is based on a few simple formulae that require only a few wave parameters, easily retrievable from any operational wave forecasting model (e.g. Samaras et al., 2016). Therefore, this represents a clear example of how simple tools can be developed for providing synthetic information of key quantities for coastal defence (e.g. the expected shoreline retreat in response to a predicted storm event) and support decision making about preemptive protection measures if an intense storm event is forecast.

Further opportunities in the joint use of continuous morphological and hydrodynamic survey tools can also come from recent procedures relying on acoustic backscatter information for estimating sediment transport in -or at the edge of- the surf zone (Guerrero et al., 2012; Guerrero et al., 2014). This approach can be particularly effective if the available instrumentation is sufficient for surveying a whole transect and capturing the cross-shore variability of hydrodynamics and sediment transport (Ribas et al., 2012).

3.3 Coastal erosion in the Adriatic Sea: from data management to decision support.

Due to the socio-economic relevance of the Adriatic coasts and to the crucial importance of sandy deposits as a resource for coastal nourishment in the Adriatic Sea, specific tools have been developed for an appropriate data management enabling engineers and authorities to have an up-to-date overview of the system in the aftermath of several nourishment and protection interventions. To this aim, examples of joint actions between academic and administrative Institutions can be drawn from recent activities in this area.

Emilia Romagna Region and CNR-ISMAR designed a tool (in_Sand, see Correggiari et al., 2016) to provide management with a regional control of the various interventions and to predict scenarios in the preparation of executive plans. Under the aegis of the RITMARE Project, a geodatabase for the environmental monitoring of the sand resource (env_Sand, see Grande et al., 2015) has been conceived and created by CNR-ISMAR and ISPRA (the Governmental Institution for Environmental Protection), fostering the harmonisation and interpretation of environmental data belonging to different sectors, such as water column, sediment, and biota.

The practical approach for data cataloguing and elaboration now adopted by some of the Adriatic regions is based on sediment budget computation as a core information, and is managed by means of subsequent evolutions and modifications of the "Littoral Cells Management System" (*Sistema Gestionale delle Celle Litoranee*, SICELL) developed by the Emilia-Romagna Region, Italy (Regione Emilia-Romagna, 2011). This system is an information tool developed in 2010 within the COASTANCE EU Project, providing key morphological quantities gathered from different sources and grouped following a spatial subdivision into littoral cells. A subsequent adaptation, developed in collaboration with the Veneto Region in the framework of the RITMARE Project (Fontolan et al., 2015), includes a classification based on the lost sediment volume and the necessary amount for a minimum equilibrium survival at a given time scale. In addition, it includes a vulnerability assessment based on a specific procedure (see Fontolan et al., 2011 and references therein) that accounts for several coastal parameters describing the physical characteristics of the coastal area, its evolution, and the human activities impacting the geomorphological setting. The new version of SICELL also includes an alternative classification of the potential sedimentary sinks, as the river mouths and tidal inlets, in the perspective of re-using the sediments within adjacent cells when dredging or maintenance interventions for navigation are needed.

More recent results concerning the application of SICELL integrated with an operational database permit to obtain a rational organization of the coastal data and a practical subdivision of the coastal cells in term of sedimentary budget (Fig. 6), thus focusing on the erosional hot spots and on the possible conflicts with the urban planning and tourism management.

The results of the application to the Veneto littoral led to quite positive results, since 70% of the beaches are currently stable or accretionary (Fontolan et al., 2011; 2015). However, data on sediment budget compared to the large amount of sand used for nourishment (around 10 million cubic metres), highlighted the persistency of erosional hot spots, not completely contrasted by beach replenishment. For these cases, different strategies or integrated defence interventions need to be evaluated, in order to reduce the high costs of ongoing almost unsuccessful maintenance.

As far as the small interventions (less than 50,000 – 100,000 cubic metres) are concerned, the modified version of SICELL can collect and organize also data on the potential nearshore sedimentary sinks, as the ebb-tidal delta deposits. For these systems, the modified SICELL evaluates their present state against their equilibrium conditions based on the tidal prism and potential ebb delta volume (Fontolan et al*.,* 2007), in the perspective of sediment dredging re-use for nourishment purposes. In many cases the ebb-shoal mining practice (Cialone & Stauble, 1998) can also be used, particularly in the need of navigation maintenance interventions. This permits to operate on the shallowest areas of accumulation requiring a limited amount of dredged sand, in order to limit the effect of the re-configured topography on wave refraction patterns and avoid the formation of new erosional hot-spots. Since a large part of coastline undergoes a historical sediment deficit due to the scarce supplies from the river catchments (Bondesan et al., 1995), other type of sedimentary sinks as the delta front of the Adriatic rivers may not be sufficient to maintain the local delicate sedimentary equilibrium. In this situation, the integration of the SICELL system with similar databases considering off-shore sediment sources as potential borrow sites would provide some valid alternatives to nearshore sedimentary sink re-adjustment or removal. Also, a significant step towards an operational use of the modified SICELL system as a DSS would be given by the inclusion of the results of specific small-scale sediment transport modelling runs for the assessment of the most suitable defence design and sand replenishment duration.

The above-described approach to the management of coastal erosion and long-term coastal sediment budget is generally suitable for urban beaches and anthropised coasts. In these systems, the main aim is to contrast the sediment loss with periodic beach nourishment derived from sand reservoir, in order to preserve the back beach areas from flooding, and to maintain an appropriate space for recreational uses. In particular, in the northern Adriatic region the widespread use of beach nourishment as a strategy for coastal protection and restoration was made relatively straightforward by a good compatibility between beach sediments and sand reservoir, characterized by a common geological source. Generally speaking, a great variability of sediment types can nevertheless occur, especially in semi-natural transgressive beaches along starved shelves such as in western Sardinia, controlled by complex interactions among geological, geomorphological, oceanographic and ecological factors (Simeone and De Falco, 2012; De Falco et al., 2014; Simeone et al., 2014). As a consequence, in this case there could be little compatibility between beach sediments and reservoirs along the shelf, and a deeper evaluation of beach sediment characteristics related to reservoir is needed, with a broader evaluation of all the factors controlling coastal resilience (De Falco et al., 2014) and the complexity of the physical forcings of the coastal system.

4. Conclusions

The common focus of different research tasks on a complex geographical setting within the framework of a single Project, as has been the case in RITMARE, allowed to take stock of the state of the art of methods, technologies and procedures for coastal vulnerability assessment under different science and management points of view. This also permitted to highlight a number of opportunities for integrating different approaches into a unified multidisciplinary strategy for coastal monitoring and protection. In this direction, some suggestions can thus be drawn from the results of the recent experiences and from the evaluation of upcoming challenges and critical issues, also in the broader perspective of defining good practices for the exploitation of marine resources.

The outcomes of the monitoring activities carried out in the northern Adriatic Sea show how an integrated observational system, merging geomorphological information with the quantification of some of the key drivers of morphodynamic processes, enhances the insight into the physical processes and can provide products and services for coastal protection, such as parameterizations for emergency response to severe events. Benefiting from the creation of synergies among different observational activities, the effort of a measurement campaign can be optimised by organising multi-purpose surveys in which the available technology is fully exploited. For instance, instrumentation and post-processing algorithms presently available for multibeam bathymetric surveys allow for unprecedented degree of detail in the morphological description and the extraction of additional information content from secondary data, such as seabed composition retrieved by backscatter measurements. Together with a more accurate estimate of the sand volumes available for coastal nourishment and protection, a survey carried out by fully exploiting this potential would allow to use evidences from small-scale bedform patterns to formulate hypotheses on local hydrodynamics (Foglini et al., 2016; Bonaldo et al., 2016), whereas backscatter data can be used for habitat mapping purposes (Montereale Gavazzi et al., 2016). Although the ecological implications of coastal vulnerability to erosion and sea level rise are beyond the scope of the present work, it is worth mentioning the possible relevance of our discussion for these topics. The identification of submarine habitats, biodiversity hotspots and their connectivity structure, together with the characterisation of their possible stressing factors, requires a holistic view on the different sectors of the pelagic system, involving information from geomorphology, hydrodynamics and biogeochemistry as well as biological indicators.

From the operational point of view, as the complexity of the physical processes is disentangled and in order to further improve its understanding, the measurement and monitoring planning should particularly emphasize the identification of environment-shaping events and the rapid response to their occurrence. Such a shift from a *frequency-oriented* to an *event-oriented* sampling strategy may require some reorganization and flexibility in the monitoring activities, but the increasing availability of reliable high-resolution numerical models for meteo-oceanic prediction and early warning can significantly enhance the efficiency of this effort, provided that sound Rapid Environmental Assessment protocols are defined.

With the progress towards an explicit description of causal connections and feedbacks among different processes, emerging when the coastal system is described in an integrated framework, also the geographical context of the analysis should be compatible with the description of links and interactions at different scales. In this perspective, the subdivision of the coastal region into littoral cells can partially reduce the possibilities for a description of sediment fluxes and the underlying physical drivers. Indeed, although this widespread approach has been successfully adopted for analysis and management in a large number of cases (Cooper and Pontee, 2006; Simon et al., 2016), the behaviour of transitional and coastal systems is the response to natural and anthropogenic forcings that cannot be easily encompassed within a rigid spatial framework (Jäger et al., 2018). Worth noting, a change in the scale of the analysis allowing to generally account for large-scale transport patterns would also provide useful information for ecological assessment and the management of Marine Protected Areas (Gabriè et al., 2012; Boero, 2014).

Numerical modelling provides a variety of valuable instruments for filling the gaps in our capability of describing the physical forcings of the coastal systems and their interactions with the open sea at the mesoscale and sub-mesoscale. Indeed, numerical models allow to partially overcome the lack of adequate data availability, and to extrapolate trends from the recent past observations into future scenarios. The use of numerical models at an appropriate scale (nonetheless validated on robust observational data sets) allows to outline a unitary and comprehensive picture of the system under investigation more efficiently than purely observational approaches, in which possible dishomegeneities in the sampled quantities or in the sampling strategies can significantly hamper the comparability and interoperability of the information. Overcoming the spatial limitation of a cell-based approach, in this kind of description the environmental signals reconstructed in each site of the domain, possibly at a high resolution, are mutually correlated (or uncorrelated) following a common physical framework, encoded in the model and largely recognisable and characterisable during the post-processing phase. In particular, basin-scale hydrodynamic and sediment transport modelling can play a fundamental role in the identification of preferential sediment pathways (Carniel et al., 2016; Bonaldo et al., 2018), offshore erosional and depositional hot spots (Bonaldo et al., 2016), and meteomarine climate indications for risk assessment in present conditions as well as in climate change scenarios (Benetazzo et al., 2012).

In the broader perspective of management processes like Integrated Coastal Zone Management, modelling results, field measurements and morphodynamic monitoring techniques should be conceptually linked to the processes occurring within the upstream watersheds. This comes at the cost of further issues arising, such as the difficulties in the computation of a basin-scale sediment budget (Syvitski and Kettner, 1992) and the uncertainties related to poorly surveyed, though potentially of primary importance, sediment sources such as small mountain rivers (Milliman and Syvitski, 1992; Milliman et al., 2016). Nevertheless, flanking the coastal analysis with this additional information (see Samaras and Koutias, 2012; and Peckham et al., 2013 for some examples of suitable approaches) would provide a quantitative tool for connecting changes in coastal morphology and vulnerability to erosion and sea level rise also including pressures from the mainland and supporting decision making at a macro-regional scale.

Figure Captions

Fig. 1: Adriatic Sea geography and its position in the Mediterranean basin. Thin and thick blue contours represent isobaths spaced by 50 and 250 m respectively. Coloured diamonds and squares represent the vertical movement rates due to tectonics and isostasy, computed respectively on Holocene and MIS5 averages. Inner dots represent the isostasy contribution alone. Rates adapted from Lambeck et al., 2011

Fig. 2: Expected coastlines for 2100 in the Northern Adriatic Sea. Red and green lines depict the limits of marine ingression expected for 2100 in the Rahmstorf (2007) scenarios and the 5 m contour line

Fig. 3: Modelled Sea Surface Temperature (SST) at Acqua Alta Oceanographic Tower (top right) and Paloma Buoy (bottom right), northern Adriatic Sea, during the winter 2012 cold air outbreak under different coupling configurations (Ricchi et al., 2016). The comparison among in-situ observations (OBS), radiometer data, and results from a stand-alone ocean model (ROMS), a two-way coupled ocean-atmosphere (ROMS-WRF) simulation, and a full two-way coupling of ocean-atmosphere-wave models (ROMS-WRF-SWAN) shows the uncertainties of the radiometer data in the presence of coastal fronts and the improved estimate deriving from the use of coupled modelling approaches.

Fig. ***4*****:** Wind climate at Venice observatory (12.4265E; 45.4182N), measurements (left) and modelled climatology provided by COSMO-CLM (right), modelling framework described in Bucchignani et al. (2015) and wind dataset presented in Bonaldo et al. (2017). Bars length and colour represent the frequency and intensity of the wind blowing from different directions.

Fig. 5: Sketch of integrated monitoring and modelling approach to assess physical features of a site: (1) collection of field data (wave -a-, wind and currents -b-); implementations of 2DH (c) and 2DV (d) numerical models; method validation by means of morphological observations (e); (2) processing of data; (3) definition of site-specific parametric relationship between shoreline evolution and wave features

Fig. 6: Example of the SICELL classification applied to a coastal stretch (Isola Verde, Chioggia, Northern Adriatic Sea). Data on sediment budget (years 2001-2010) refers to the orthogonal bathymetric sections, and is reported as cubic metres per year (mc/y). The cells are classified according to the ASPE (Accretionary, Stable, Precarious, Erosional) code (modified after Fontolan et al., 2015, to refer for details)

References

Antic S, Laprise R, Denis B, de Elia R (2004) Testing the downscaling ability of a one-way nested regional climate model in regions of complex topography. Clim. Dyn. 23(5): 473-493. doi: 10.1007/s00382-004-0438-5

Antonioli F, Leoni G, Gambarelli G, Caiaffa E, Goria A (2002) *Piana di Fondi carta del rischio di inondazione per innalzamento del livello del mare, calcolo del valore della perdita* (in Italian) Workshop ENEA Fondazione ENI Enrico Mattei, Volume Abstract, RT ENEA 04.07.2002.

Antonioli F, Leoni G (2007) *Mappa Nazionale delle aree a rischio di allagamento da parte del mare. Dossier ENEA per lo studio dei cambiamenti climatici e loro effetti* (in Italian) RT ENEA, 83pp.

Antonioli F, Anzidei M, Lambeck K, Auriemma R, Gaddi D, Furlani S, Orrù P, Solinas E, Gaspari A, Karinja S, Kova V, Surace L, 2007. Sea level change in Italy during Holocene from archaeological and geomorphological data. Quat. Sci. Rev. 26(19-21):2463-2486. doi:10.1016/j.quascirev.2007.06.022

Antonioli F, Ferranti L, Fontana A, Amorosi A, Bondesan A, Braitenberg C, Dutton A, Fontolan G, Furlani S, Lambeck K, Mastronuzzi G, Monaco C, Spada G, Stocchi P (2009) Holocene relative sea-level changes and vertical movements along the Italian coastline. Quat. Int. 206(1-2):102-133. doi:10.1016/j.quaint.2008.11.008

Antonioli F, Lo Presti V, Anzidei M, Deiana G, De Sabata E, Ferranti L, Furlani S, Mastronuzzi G, Orrù P, Pagliarulo R, Rovere A, Sannino G, Sansò P, Scicchitano G, Spampinato CR, Vacchi M, Vecchio A (2015) Tidal notches in the Mediterranean Sea. Quat. Sci. Rev. 119:1-19.

Antonioli F, Anzidei M, Amorosi A, Lo Presti V, Mastronuzzi G, Deiana G, De Falco G, Fontolan G, Fontana A, Lisco S, Marsico A, Moretti M, Orru P, Sannino GM, Serpelloni E, Vecchio A (2017) Sea-level rise and potential drowning of the Italian coastal plains: Flooding risk scenarios for 2100, Quat. Sci. Rev. 158:29-43.

Archetti R (2009) Quantifying the evolution of a beach protected by low crested structures using video monitoring. J. Coastal Res., 25(4):884 – 899.

Archetti R, Zanuttigh B (2010) Integrated monitoring of the hydro-morphodynamics of a beach protected by low crested detached breakwaters. Coast. Eng. 57(10):879-891.

Archetti R, Gaeta MG (2012) Wave run-up observation and 2DV numerical investigation on beaches protected by structures. Proceedings of the Coastal Engineering Conference 33: 1-12.

Archetti R, Paci A, Carniel S, Bonaldo D (2016) Optimal index related to the shoreline dynamics during a storm: the case of Jesolo beach, Nat. Hazards Earth Syst. Sci. 16:1107-1122. doi:10.5194/nhess-16-1107-2016.

Ashton AD, Hutton EWH, Kettner AJ, Xing F, Kallumadikal J, Nienhuis J, Giosan L (2013) Progress in coupling models of coastline and fluvial dynamics, Computers & Geosciences, 53:21-29, doi: http://dx.doi.org/10.1016/j.cageo.2012.04.004.

Baart F, Van Der Kaaij T, Van Ormondt M, Van Dongeren A, Van Koningsveld M, Roelvink JA (2009) Real-time forecasting of morphological storm impacts: A case study in the Netherlands, J. Coastal Res. 56:1617-1621.

Baart F, van Ormondt M, van Thiel de Vries JSM, van Koningsveld M (2016) Morphological impact of a storm can be predicted three days ahead. Computers & Geosciences, 90, Part B:17-23, doi: http://dx.doi.org/10.1016/j.cageo.2015.11.011.

Balica SF, Wright NG, van der Meulen F (2012) A flood vulnerability index for coastal cities and its use in assessing climate change impacts, Nat Hazards 64 (1):73-105. doi:10.1007/s11069-012-0234-1

Barbariol F, Benetazzo A, Carniel S, Sclavo M (2013) Improving the assessment of wave energy resources by means of coupled wave-ocean numerical modeling. Renew. Energy 60: 462–471. doi:10.1016/j.renene.2013.05.043

Bellafiore D, Bucchignani E, Gualdi S, Carniel S, Djurdjevic V, Umgiesser G (2012) Assessment of meteorological climate models as inputs for coastal studies. Ocean Dyn 62(4):555–568

Benetazzo A, Fedele F, Carniel S, Ricchi A, Bucchignani E, Sclavo M (2012) Wave climate of the Adriatic Sea: a future scenario simulation. Nat Hazards Earth Syst Sci 12:2065–2076. doi:10. 5194/nhess-12-2065-2012

Benetazzo A, Carniel S, Sclavo M, Bergamasco A (2013) Wave-current interaction: Effect on the wave field in a semi-enclosed basin. *Ocean Modell. 70*:152–165. doi:10.1016/j.ocemod.2012.12.009

Beltrami GM, Bellotti G, De Girolamo P, Sammarco P (2001) Treatment of wave breaking and total absorption in a Mild-Slope Equation FEM Model. J. Waterw. Port, Coast. Ocean Eng. 127:263–271.

Blum MD, Roberts HH (2009) Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nature Geoscience 2:488-491, doi:10.1038/ngeo553

Boero F (2014) The future of the Mediterranean Sea Ecosystem: towards a different tomorrow. Rend. Fis. Acc. Lincei 26:3–12. doi:10.1007/s12210-014-0340-y

Bonaldo D, Archetti R, Carniel S (2014) Monitoring Northern Adriatic seashore at Jesolo Resort. Sea Technology Magazine 55(2)_55-58.

Bonaldo D, Benetazzo A, Bergamasco A, Campiani E, Foglini F, Sclavo M, Trincardi F, Carniel S (2016) Interactions among Adriatic continental margin morphology, deep circulation and bedform patterns. Mar. Geol. 375:82–98. doi:10.1016/j.margeo.2015.09.012

Bonaldo D, Bucchignani E, Ricchi A, Carniel S (2017) Wind storminess in the Adriatic Sea in a climate change scenario. Acta Adriatica 58(2):195-208.

Bonaldo D, Orlic M, Carniel S (2018) Framing Continental Shelf Waves in the southern Adriatic Sea, a further flushing factor beyond dense water cascading. Sci. Rep. 8(1). http://dx.doi.org/10.1038/s41598-017-18853-2.

Bonaldo D, Benetazzo A, Sclavo M, Carniel S (2015) Modelling wave-driven sediment transport in a changing climate: a case study for northern Adriatic Sea (Italy). *Regional Environmental Change 15*:45–55. doi:10.1007/s10113-014-0619-7

Bondesan M, Castiglioni GB, Elmi C, Gabbianelli G, Marocco R, Pirazzoli P, Tomasin A (1995) Coastal areas at risk from storm surges and sea-level rise in north-eastern Italy. J. Coast. Res. 11:1354–1379. doi:10.2307/4298437

Booij N, Ris RC, Holthuijsen LH (1999) A third-generation wave model for coastal regions: 1. Model description and validation. J. Geophys. Res. 104, 7649. doi:10.1029/98JC02622

Brown JM, Davies AG (2009) Methods for medium-term prediction of the net sediment transport by waves and currents in complex coastal regions, Continental Shelf Research 29:1502-1514. doi: 10.1016/j.csr.2009.03.018

Bucchignani E, Montesarchio M, Zollo AL, Mercogliano P (2015) High-resolution climate simulations with COSMO-CLM over Italy: Performance evaluation and climate projections for the 21st century. Int. J. Climatol. 36(2):735-756. doi:10.1002/joc.4379

Bucchignani E, Sanna A, Gualdi S, Castellari S, Schiano P (2013) Simulation of the climate of the XX century in the Alpine space. Nat Hazards 67: 981. doi:10.1007/s11069-011-9883-8

Burchard H (2002) Applied turbulence modelling in marine waters, vol. 100 of Lecture Notes in Earth Sciences, Springer, Berlin, Heidelberg, New York, 229 pp.

Burcharth HF, Lykke Andersen T, Lara JL (2014) Upgrade of coastal defence structures against increased loadings caused by climate change: A first methodological approach, Coast. Eng. 87:112-121. doi: http://dx.doi.org/10.1016/j.coastaleng.2013.12.006.

Carniel S, Benetazzo A, Bonaldo D, Falcieri FM, Miglietta MM, Ricchi A, Sclavo M (2016) Scratching beneath the surface while coupling atmosphere, ocean and waves: Analysis of a dense water formation event. Ocean Model. 10:101–112. doi:10.1016/j.ocemod.2016.03.007

Cavaleri L, Bertotti L, Lionello P (1989) Wind-waves evaluation in the Adriatic and Mediterranean Seas. International Journal for Numerical Methods in Engineering 27:57-69.

Church, JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D, Unnikrishnan AS (2013) Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cialone MA, Stauble DK (1998) Historical findings on ebb shoal mining. J. Coastal Res. 14 (2):537-563.

Cooper NJ, Pontee NI (2006) Appraisal and evolution of the littoral 'sediment cell' concept in applied coastal management: Experiences from England and Wales (2006) Ocean and Coastal Management 49(7-8):498-510.

Correggiari A, Remia A, Foglini F, Gallerani A, Miserocchi S, Moscon G, Piazza R, Bertaggia R (2013) *Riorganizzazione dei dati geofisici, geognostici ed ambientali relativi ai depositi sabbiosi sommersi presenti nelle aree denominate RV_A, RV_B, RV_C, RV_D, RV_G, RV_JC nella piattaforma nord adriatica per implementare il geodatabase in_Sand. Attività nell'ambito del Progetto IPA–Adriatico SHAPE n.167.* (in Italian). Technical Report, Istituto di Scienze Marine, Bologna, Italy.

Correggiari A, Perini L, Remia A, Luciani P, Foglini F**,** Grande V, Moscon G, Calabrese L**,** Lorito S (2016) *Sistema Informativo per* *l'utilizzo della risorsa Sabbia offshore nei progetti di protezione costiera: geodatabase in_Sand. Rapporto tecnico.* (in Italian) 36 pp. Centro Stampa della Regione Emilia-Romagna ISBN 978-88-8186-012-8.

Davolio S, Stocchi P, Benetazzo A, Bohm E, Riminucci F, Ravaioli M, Li XM, Carniel S (2015a) Exceptional Bora outbreak in winter 2012: validation and analysis of high-resolution atmospheric model simulations in the northern Adriatic area. Dynamics of Atmospheres and Oceans 71:1-20, doi:10.1016/j.dynatmoce.2015.05.002.

Davolio S, Silvestro F, Malguzzi P (2015b) Effects of Increasing Horizontal Resolution in a Convection Permitting Model on Flood Forecasting: The 2011 Dramatic Events in Liguria (Italy). J. Hydrometeorology 16:1843-1856, doi:10.1175/JHM-D-14-0094.1.

De Falco G, Budillon F, Conforti A, De Muro S, Di Martino G, Innangi S, Perilli A, Tonielli R, Simeone S (2014) Sandy beaches characterization and management of coastal erosion on western Sardinia island (Mediterranean Sea). J. Coastal Res. 70:395-400.

Duong TM, Ranasinghe R, Walstra D, Roelvink D (2016) Assessing climate change impacts on the stability of small tidal inlet systems: Why and how? Earth-Science Reviews 154:369-380. doi: http://dx.doi.org/10.1016/j.earscirev.2015.12.001.

Eurosion (2004) Living with coastal erosion in Europe: sediment and space for sustainability. PART III – Methodology for assessing regional indicators. 20 May 2004. Available at: http://www.eurosion.org/reports-online/part3.pdf (last access: 20.10.2017).

Ferranti L, Antonioli F, Amorosi A, Dai Prà G, Mastronuzzi G, Mauz B, Monaco C, Orrù P, Pappalardo M, Radtke U, Renda P, Romano P, Sansò P, Verrubbi V (2006) Elevation of the last interglacial highstand in Italy: A benchmark of coastal tectonics Quat. Int. 145-146:3-18. doi:10.1016/j.quaint.2005.07.009

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 Modell. 61:38-48.

Foglini F, Campiani E, Trincardi F (2016) The reshaping of the South West Adriatic Margin by cascading of dense shelf waters. Mar. Geol. 375, 64–81.

Fontolan G, Pillon S, Delli Quadri F, Bezzi A (2007) Sediment storage at tidal inlets in northern Adriatic lagoons: ebb-tidal delta morphodynamics, conservation and sand use strategies, Estuarine Coastal and Shelf Science 75:261-277.

Fontolan G, Bezzi A, Pillon S (2011) *Rischio da mareggiata*. (in Italian) In: Atlante Geologico della Provincia di Venezia. Cartografie e Note illustrative. Ed. A.Vitturi. Provincia di Venezia: pp. 581-600 + Plate 16. ISBN 978-88-907207-0-3.

Fontolan G, Bezzi A, Martinucci D, Pillon S, Popesso C, Rizzetto F (2015) Sediment budget and management of the Veneto beaches, Italy: an application of the modified Littoral Cells Management System (SICELL). Coastal and Maritime Mediterranean Conference CM 47-50, Ferrara 25-27 November 2015. Revue Paralia online, http://dx.doi.org/10.5150/cmcm.2015.010.

Furlani S, Cucchi F (2013) Downwearing rates of vertical limestone surfaces in the intertidal zone (Gulf of Trieste, Italy). Mar. Geol 343:92-98.

Furlani S, Cucchi F, Forti F, Rossi A (2009) Comparison between coastal and inland Karst limestone lowering rates in the north-eastern Adriatic Region (Italy and Croatia). Geomorphology 104:73-81.

Furlani S, Ninfo A, Zavagno E, Paganini P, Zini L, Biolchi S, Antonioli F, Coren F, Cucchi F (2014a) Submerged notches in Istria and the Gulf of Trieste: results from the Geoswim Project. Quat. Int. 332:37-47.

Furlani S, Pappalardo M, Gomez-Pujol L, Chelli A (2014b) The rocky coasts of the Mediterranean and Black Sea. In: Kennedy, D.M., Stephenson, W.J., Naylor, L.A. (Eds), Rock coast Geomorphology: A Global Synthesis. Geological Society, London, Memoirs 40:89-123.

Gabrié C, Lagabrielle E, Bissery C, Crochelet E, Meola B, Webster C, Claudet J, Chassanite A, Marinesque S, Robert P, Goutx M, Quod C (2012) The Status of Marine Protected Areas in the Mediterranean Sea. MedPAN & RAC/SPA. Ed: MedPAN Collection. 256 pp.

Gaeta MG, Samaras AG, Federico I, Archetti R, Maicu F, Lorenzetti G (2016) A coupled wave-3-D hydrodynamics model of the Taranto Sea (Italy): A multiple-nesting approach. Nat. Hazards Earth Syst. Sci. 16:2071-2083. https://doi.org/10.5194/nhess-16-2071-2016.

Galea A , Grifoll M, Roman F, Mestres M, Armenio V, Sanchez-Arcilla A, Zammit Mangion L (2014) Numerical simulation of water mixing and renewals in the Barcelona harbour area: the winter season. Environ Fluid Mech 14:1405-1425.

Giorgi F, Lionello P (2008) Climate change projection for the Mediterranean region. Glob. Planet Change 63:90-104.

Giorgi F, Gutowki jr WJ (2015) Regional Dynamical Downscaling and the CORDEX initiative. Annu. Rev. Environ. Resour. 40:467-490. Doi: 10.1146/annurev-environ-102014-021217

Gornitz VM, White TW, Cushman RM (1991) Vulnerability of the U.S. to future sea-level rise. In Proceedings of Seventh Symposium on Coastal and Ocean Management: 2354-2368. Long Beach, CA (USA)

Grande V, Proietti R, Foglini F, Remia A, Correggiari A, Paganelli D, Targusi M, Franceschini G, La Valle P, Berducci MT, La Porta B, Lattanzi L, Lisi I, Maggi C, Loia M, Pazzini A, Gabellini M, Nicoletti L (2015) *Sistema Informativo per il monitoraggio ambientale della risorsa sabbia offshore nei progetti di protezione costiera: geodatabase* env_Sand. ISPRA, Manuali e Linee guida, 127/2015: 63 pp. In Italian

Greco M, Martino G (2016) Vulnerability assessment for preliminary flood risk mapping and management in coastal areas. Nat. Hazards 82:7–26. doi:10.1007/s11069-016-2293-1

Guerrero M, Rüther N, Szupiany RN (2012) Laboratory validation of acoustic Doppler current profiler (ADCP) techniques for suspended sediment investigations. Flow Measurement and Instrumentation 23(1): 40–48. doi:10.1016/j.flowmeasinst.2011.10.003.

Guerrero M, Rüther N, Archetti R (2014) Comparison under controlled conditions between multi-frequency ADCPs and LISST-SL for investigating suspended sand in rivers. Flow Measurement and Instrumentation 37:73-82.

Hervouet JM (2007) Hydrodynamics of Free Surface Flows: Modelling with the finite element method, John Wiley & Sons, Ltd, 360 pp.

High C, Hanna, FK (1970) Method for the direct measurements of erosion on rock surfaces. British Geomorphol. Research Group. Technical Bull. 5:1-25.

Hinkel J (2005) DIVA: an iterative method for building modular integrated models. Advances in Geosciences 4:45–50.

Hinkel J, Klein R (2009) The DINAS-COAST project: developing a tool for the dynamic and interactive assessment of coastal vulnerability. Global Environ Chang 19(3):384 – 395.

Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, Marzeion B, Fettweis X, Ionescu C, Levermann A (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. Proceedings of the National Academy of Sciences of the United States of America 111(9):3292–7. doi:10.1073/pnas.1222469111

Holman RA, Stanley J (2007) The history and technical capabilities of Argus. Coast. Eng. 54:477–491

Horton, BP, Rahmstorf S, Engelhart SE, Kemp AC (2014) Expert assessment of sea-level rise by AD 2100 and AD 2300. Quat Sci Rev. 841(6).

Inman DL (2005) Littoral Cells. In: Schwartz M.L. (eds) Encyclopedia of Coastal Science:594-599. Encyclopedia of Earth Science Series. Springer, Dordrecht. DOI: https://doi.org/10.1007/1-4020-3880-1_196

Jäger WS, Christie EK, Hanea AM, den Heijer C, Spencer T (2018) A Bayesian network approach for coastal risk analysis and decision making. Coast. Eng. 134:48-61.

Jiménez JA, Osorio A, Marino-Tapia I, Davidson M, Medina R, Kroon A, Archetti R, Ciavola P, Aarnikhof S (2007) Beach Recreation Planning Using Video-derived Coastal State Indicators. Coast. Eng. 54:507-521.

Kaminsky GM, Gelfenbaum G (2000) The southwest Washington coastal erosion study: a scientific research project to address management-scale *objectives*. In: Proceedings of Coastal Society 17th Conference "Coasts at the Millennium". 9-12 July 2000, Portland, Oregon.

Karambas TV, Samaras AG (2014) Soft shore protection methods: The use of advanced numerical models in the evaluation of beach nourishment. Ocean Eng. 92:129-136, doi: 10.1016/j.oceaneng.2014.09.043.

Kroon A, Davidson MA, Aarninkhof SGJ, Archetti R, Armaroli C, Gonzalez M, Medri S, Osorio A, Aagaard T, Holman RA, Spanhoff R (2007) Application of remote sensing video systems to coastline management problems. Coast. Eng. 54:493-505. doi:10.1016/j.coastaleng.2007.01.004.

Lambeck K, Antonioli F, Anzidei M, Ferranti L, Leoni G, Scicchitano G, Silenzi S (2011). Sea level change along Italian coast during Holocene and a projection for the future Quat. Int. 232(1-2):250-257 doi:10.1016/j.quaint.2010.04.026

Lamberti A, Archetti R, Kramer M, Paphitis D, Mosso C, Di Risio M (2005) European experience of low crested structures for coastal management, Coast. Eng. 52(10–11):841-866.

Ličer M, Smerkol P, Fettich A, Ravdas M, Papapostolou A, Mantziafou A, Strajnar B, Cedilnik J, Jeromel M, Jerman J, Petan S, Sofianos S (2016) Modeling the ocean and atmosphere during an extreme bora event in northern Adriatic using one-way and two-way atmosphere–ocean coupling. *Ocean Science 12*:71–86. doi:10.5194/os-12-71-2016.

Luo J, Li M, Sun Z, O'Connor BA (2013) Numerical modelling of hydrodynamics and sand transport in the tide-dominated coastal-to-estuarine region, Mar. Geol. 342:14-27. doi: http://dx.doi.org/10.1016/j.margeo.2013.06.004.

Marsico A, Lisco S, Lo Presti V, Antonioli F, Amorosi A, Anzidei M, Deiana G, De Falco G, Fontana A, Fontolan G, Moretti M, Orrù P, Serpelloni E, Sannino G, Vecchio A, Mastronuzzi G (2017) Flooding scenario for four Italian coastal plains using three relative sea-level rise models. Journal of Maps 13(2):961-967.

McLaughlin S, Cooper JAG (2010) A multi-scale coastal vulnerability index: A tool for coastal managers? Environmental Hazards 9(3):233-248(16).

Mendoza PET, Jimenez QJA (2008) Vulnerability assessment to coastal storms at a regional scale. Proc. 31st ICCE Conference, ASCE, Hamburg.

Mihanović H, Vilibić I, Carniel S, Tudor M, Russo A, Bergamasco A, Bubić N, Ljubešić Z, Viličić D, Boldrin A, Malačič V, Celio M, Comici C, Raicich F (2013) Exceptional dense water formation on the Adriatic shelf in the winter of 2012. *Ocean Science 9*(3):561–572. doi:10.5194/os-9-561-2013

Milliman JD, Syvitski JPM (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. J. Geol. 100:525-544.

Milliman JD, Bonaldo D, Carniel S (2016) Flux and fate of river-discharged sediments to the Adriatic Sea. Advances In Oceanography and Limnology 7(2):106-114. DOI: 10.4081/aiol.2016.5899.

Montereale Gavazzi G, Madricardo F, Janowski L, Kruss A, Blondel P, Sigovini M, Foglini F (2016) Evaluation of seabed mapping methods for fine-scale classification of extremelyshallow benthic habitats – Application to the Venice Lagoon, Italy, Est, Coast Shelf S 170:45-60. doi: 10.1016/j.ecss.2015.12.014

Nelson B (1970) Hydrography, sediment dispersal, and recent historical development of the Po River delta, Italy, in Deltaic Sedimentation Modern and Ancient, edited by J. P. Morgan and R. H. Shaver, Spec. Publ. Soc. Econ. Paleontol. Mineral. 15:152–184.

Nicholls RJ, French JR, van Maanen B (2015) Simulating decadal coastal morphodynamics. Geomorphology 256:1–2. doi:10.1016/j.geomorph.2015.10.015

Özyurt G (2007) Vulnerability of coastal areas to sea level rise: a case of study on Göksu Delta. Thesis submitted to the Graduate School of Natural and Applied Sciences of Middle-East Technical University. January 2007. Available on-line at: http://etd.lib.metu.edu.tr/upload/12608146/index.pdf (last access: 10.08.2011).

Palmer BJ, van der Elst R, Mackay F, Mather AA, Smith AM, Bundy SC, Thackeray Z, Leuci R, Parak O (2011) Preliminary coastal vulnerability assessment for KwaZulu-Natal, South Africa. J. Coast. Res. 1390–1395.

Payo A, Hall JW, French J, Sutherland J, van Maanen B, Nicholls RJ, Reeve DE (2016) Causal Loop Analysis of coastal geomorphological systems. Geomorphology 256:36–48. doi:http://dx.doi.org/10.1016/j.geomorph.2015.07.048

Peckham SD, Hutton EWH, Norris B (2013) A component-based approach to integrated modeling in the geosciences: The design of CSDMS. Computers & Geosciences 53:3-12. doi: http://dx.doi.org/10.1016/j.cageo.2012.04.002.

Petronio A, Roman F, Nasello C, Armenio V (2013) Large-Eddy Simulation model for wind driven sea circulation in coastal areas. Nonlinear Processes in Geophysics 20:1095-1112.

Rahmstorf S (2007) A Semi-Empirical Approach to Projecting Future Sea-Level Rise. Science 315:368-370. http://dx.doi.org/10.1126/science.1135456.

Ramieri E, Hartley A, Barbanti A, Duarte Santos F, Gomes A, Hilden M, Laihonen P, Marinova N, Santini M (2011) Methods for assessing coastal vulnerability to climate change, European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC CCA) Technical Paper, Bologna (IT) 93, October 2011

Ranasinghe R, Larson M, Savioli J (2010) Shoreline response to a single shore-parallel submerged breakwater, Coast. Eng. 57:1006-1017. doi: http://dx.doi.org/10.1016/j.coastaleng.2010.06.002, 2010.

Regione Emilia-Romagna (2011) *Nuovi strumenti per la gestione dei litorali in Emilia – Romagna, SICELL il sistema gestionale delle celle litoranee*. (In Italian). Servizio Difesa del Suolo della Costa e Bonifica, 61 p.

Reikard G (2009) Forecasting ocean wave energy: Tests of time-series models. Ocean Eng. 36:348-356. doi: http://dx.doi.org/10.1016/j.oceaneng.2009.01.003.

Renault L, Chiggiato J, Warner JC, Gomez M, Vizoso G, Tintoré J (2012) Coupled atmosphere-ocean-wave simulations of a storm event over the Gulf of Lion and Balearic Sea. *J Geophys Res*-Oceans 117(C9). doi:10.1029/2012JC007924.

Ribas F, de Swart HE, Calvete D, Falqués A (2012) Modeling and analyzing observed transverse sand bars in the surf zone. J Geophys Res 117(F2), F02013. doi:10.1029/2011JF002158

Ricchi A, Miglietta MM, Falco PP, Benetazzo A, Bonaldo D, Bergamasco A, Sclavo M, Carniel S (2016) On the use of a coupled ocean-atmosphere-wave model during an extreme Cold Air Outbreak over the Adriatic Sea. Atmospheric Research 172-173:48–65. doi:10.1016/j.atmosres.2015.12.023

Richards J, Nicholls RJ (2009) Impacts of climate change in coastal systems in Europe. PESETA- Coastal Systems study. JRC Scientific and Technical Reports.

Russo A, Coluccelli A, Carniel S, Benetazzo A, Valentini A, Paccagnella T, Ravaioli M, Bortoluzzi G (2013) Operational models hierarchy for short term marine predictions: the Adriatic Sea example. OCEANS 2013 MTS/IEEE Bergen: The Challenges of the Northern Dimension, 0–5.

Samaras AG, Koutitas CG (2012) An integrated approach to quantify the impact of watershed management on coastal morphology, Ocean and Coastal Management 69:68-77. doi: 10.1016/j.ocecoaman.2012.08.010.

Samaras AG, Koutitas CG (2014a) The impact of watershed management on coastal morphology: A case study using an integrated approach and numerical modelling. Geomorphology 211:52-63, doi: 10.1016/j.geomorph.2013.12.029.

Samaras AG, Koutitas CG (2014b) Modeling the impact of climate change on sediment transport and morphology in coupled watershed-coast systems: A case study using an integrated approach, International Journal of Sediment Research 29:304-315. doi: 10.1016/s1001-6279(14)60046-9.

Samaras AG, Gaeta MG, Moreno Miquel A, Archetti R (2016) High resolution wave and hydrodynamics modelling in coastal areas: operational applications for coastal planning, decision support and assessment, Nat. Hazards Earth Syst. Sci 16:1499-1518.

Santoro F, Tonino M, Torresan S, Critto A, Marcomini A (2013) Involve to improve: A participatory approach for a Decision Support System for coastal climate change impacts assessment. The North Adriatic case. Ocean Coast. Manag. 78, 101–111. doi:10.1016/j.ocecoaman.2013.03.008

Sclavo M, Benetazzo A, Carniel S, Bergamasco A, Falcieri FM, Bonaldo D (2013) Wave-current interaction effect on sediment dispersal in a shallow semi-enclosed basin. *J. Coastal Res.* (65), 1587–1592. doi:10.2112/SI65-268.1

Signell RP, Carniel S, Cavaleri L, Chiggiato J, Doyle, J D, Pullen J, Sclavo M (2005) Assessment of wind quality for oceanographic modelling in semi-enclosed basins. *Journal of Marine Systems*, *53*(1-4), 217–233. doi:10.1016/j.jmarsys.2004.03.006

Siegle E, Huntley DA, Davidson MA (2007) Coupling video imaging and numerical modelling for the study of inlet morphodynamics, Mar. Geol. 236:143-163.

Simeone S, De Falco G, Quattrocchi G, Cucco A (2014) Morphological changes of a Mediterranean beach over one year (San Giovanni Sinis, western Mediterranean). J. Coastal Res. 70:217-222.

Simeone S, De Falco G (2012) Morphology and composition of beach-cast Posidonia oceanica litter on beaches with different exposures. Geomorphology 151-152:224-233.

Simon TP, Morris CC, Argyilan EP (2016) Characterization of Coastal Drift-Cell Sediment Processes Effecting the Restoration of the Southern Lake Michigan Shoreline. Environmental Management, 58(6):1059-1073.

Soomere T, Bishop SR, Viska M, Raamet A (2015) An abrupt change in winds that may radically affect the coasts and deep sections of the Baltic Sea. Climate Research, 62(2):163–171.

Stephenson WJ, Kirk RM, Kennedy DM, Finlayson BL, Chen Z (2012) Long term shore platform surface lowering rates: Revisiting Gill and Lang after 32 years. Marine Geology 299-302:90-95.

Stockdon HF, Doran KJ, Thompson DM, Sopkin KL, Plant NG, Sallenger AH (2012) National assessment of hurricane-induced coastal erosion hazards-Gulf of Mexico, U.S. Geological Survey Open-File Report 2012–1084, 51 pp.

Syvitski JPM, Kettner AJ (2007) On the flux of water and sediment into the Northern Adriatic Sea. Continental Shelf Research 27:296–308. doi:10.1016/j.csr.2005.08.029

Szlafsztein C, Sterr H (2007) A GIS-based vulnerability assessment of coastal natural hazards, State of Para, Brazil. J Coast Conserv 11(1):53–66.

Tolman HL, Group WD (2014) User manual and system documentation of WAVEWATCH III version 4.18. NOAA / NWS / NCEP / MMAB Technical Note, p. 311.

Torresan S, Zabeo A, Rizzi J, Critto A, Pizzol L, Giove S, Marcomini A (2010) Risk assessment and decision support tools for the integrated evaluation of climate change on coastal zones. In Swayne D.A., Wanhong Yang, Voinov A.A., Rizzoli A. and Filatova T. (eds.). Proceedings of the International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting, Ottawa, Canada.

Torresan S, Critto A, Rizzi J, Marcomini A (2012) Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic sea. Nat. Hazard. Earth Sys. 12, 2347e2368.

Trudgill ST, High CJ, Hanna KK (1981) Improvements to the micro-erosion meter (MEM). British Geomorphol. Research Group, Technical Bulletin 29:3–17.

Turner IL, Anderson DJ (2007) Web-based and 'real-time' beach management system. Coast. Eng. 54(6–7):555–565.

Uunk L, Wijnberg KM, Morelissen R (2010) Automated mapping of the intertidal beach bathymetry from video images. Coast. Eng., 57 (4):461-469.

van Maanen B, Nicholls RJ, French JR, Barkwith A, Bonaldo D, Burningham H, Murray B, Payo A, Sutherland J, Thornhill G, Townend IH, van der Wegen MJA, Walkden M (2016) Simulating mesoscale coastal evolution for decadal coastal management: A new framework integrating multiple, complementary modelling approaches. Geomorphology *256:*68–80. https://doi.org/10.1016/j.geomorph.2015.10.026

Villaret C, Hervouet JM, Kopmann R, Merkel U, Davies AG (2013) Morphodynamic modeling using the Telemac finite-element system, Computers and Geosciences 53:105-113. doi: 10.1016/j.cageo.2011.10.004.

Warner JC, Armstrong B, He R, Zambon JB (2010) Development of a Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) Modeling System. Ocean Model. 35(3):230–244. doi:10.1016/j.ocemod.2010.07.010.

Figure 1 rev

Vertical movements due to tectonics and isostasy (mm/y)

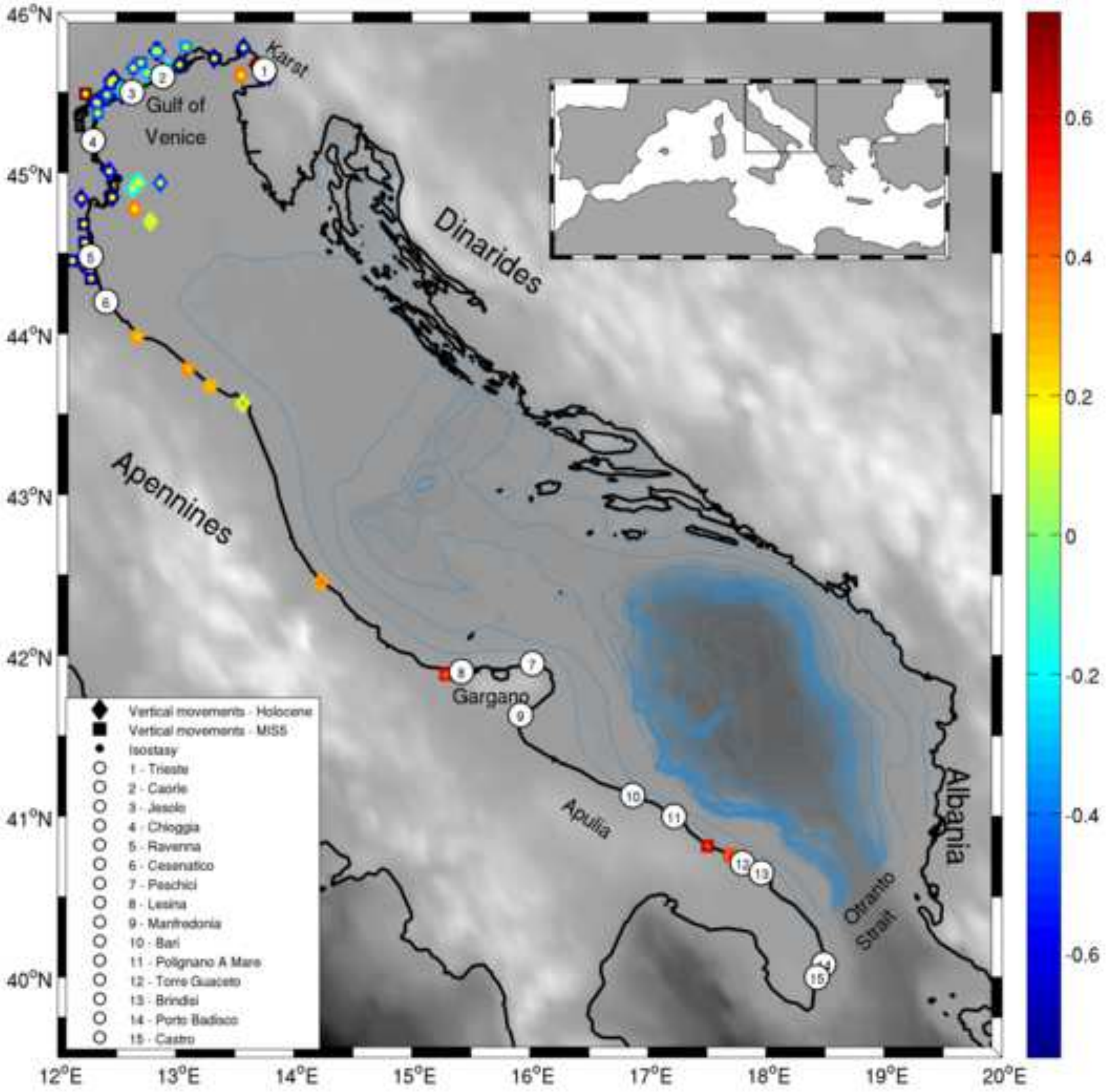

Figure 2

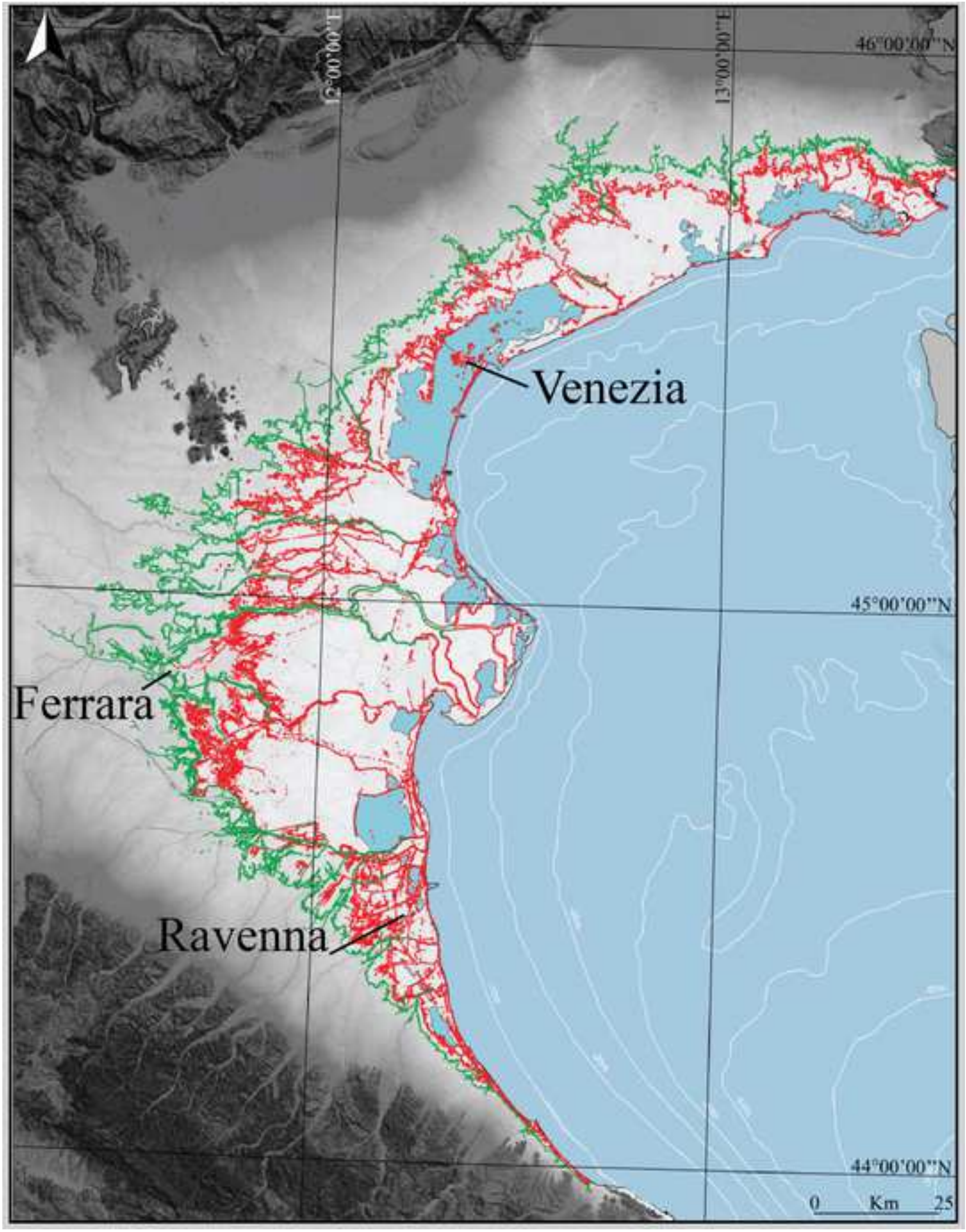
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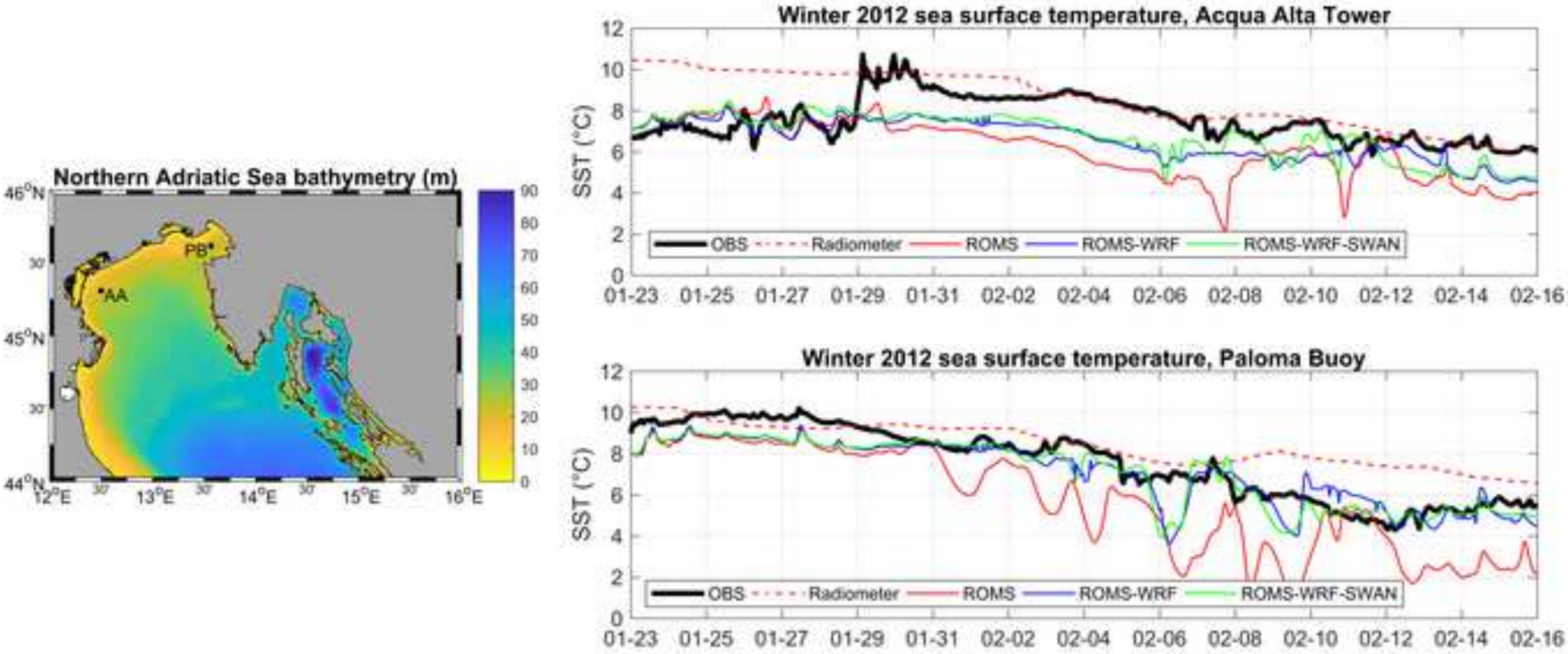
Figure 3 rev


Northern Adriatic Sea bathymetry (m)
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44°N
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15°E
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16°E
PB
AA
90
80
70
60
50
40
30
20
10
0
Winter 2012 sea surface temperature, Acqua Alta Tower
SST (°C)
12
10
8
6
4
2
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OBS
Radiometer
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ROMS-WRF
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01-23
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Winter 2012 sea surface temperature, Paloma Buoy
SST (°C)
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Figure 4 rev

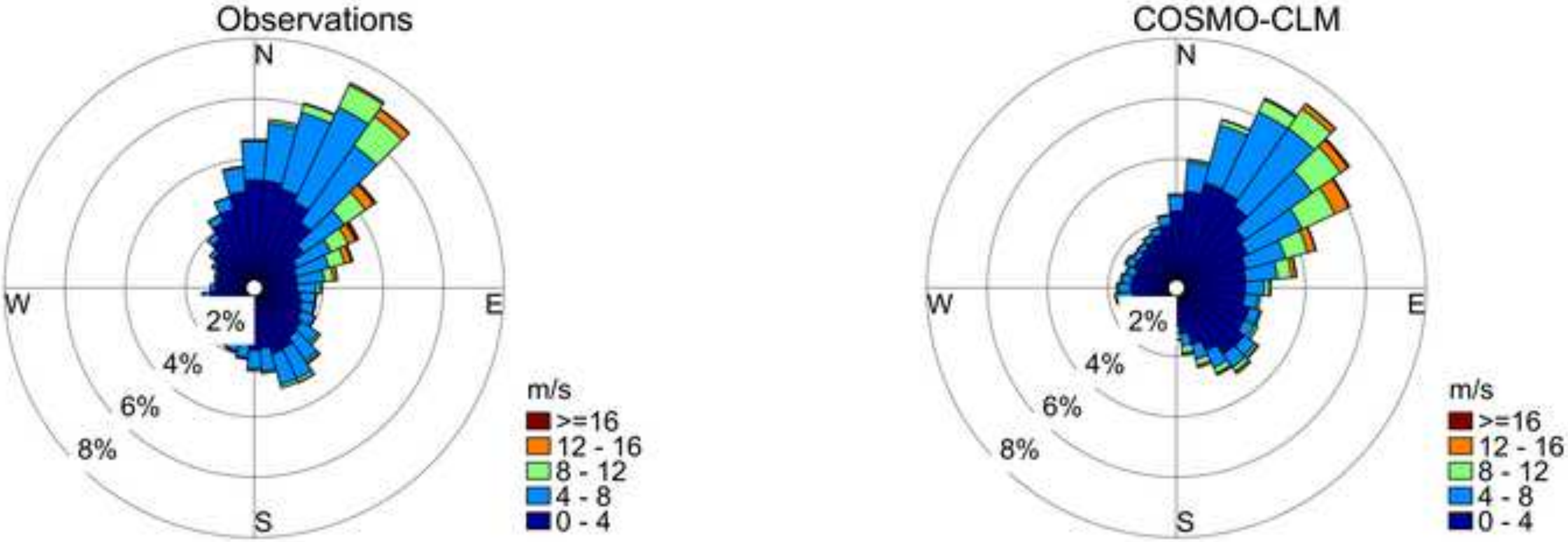
Observations
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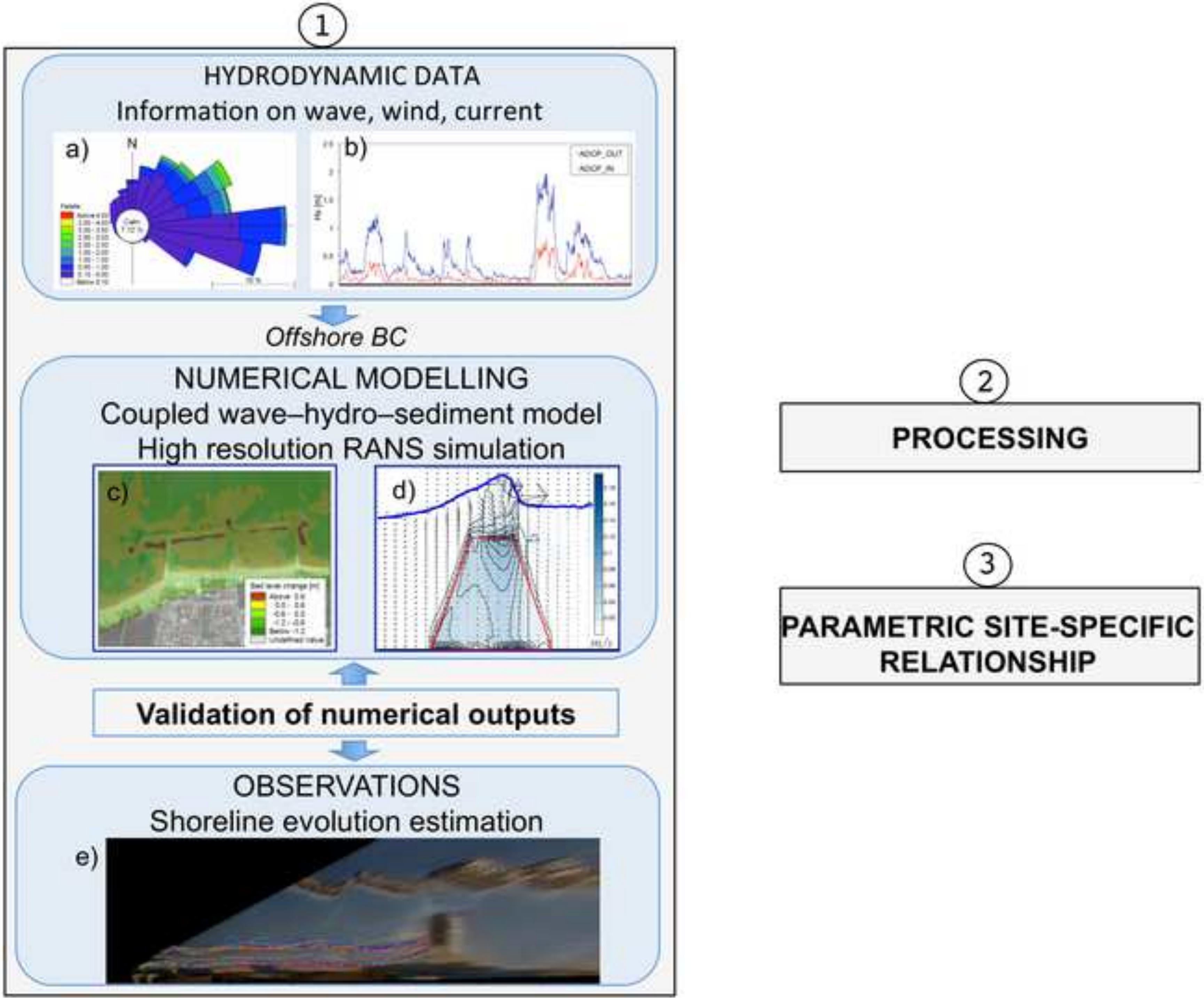
Figure 5 rev



①

HYDRODYNAMIC DATA
Information on wave, wind, current

Offshore BC

NUMERICAL MODELLING
Coupled wave–hydro–sediment model
High resolution RANS simulation

Validation of numerical outputs

OBSERVATIONS
Shoreline evolution estimation

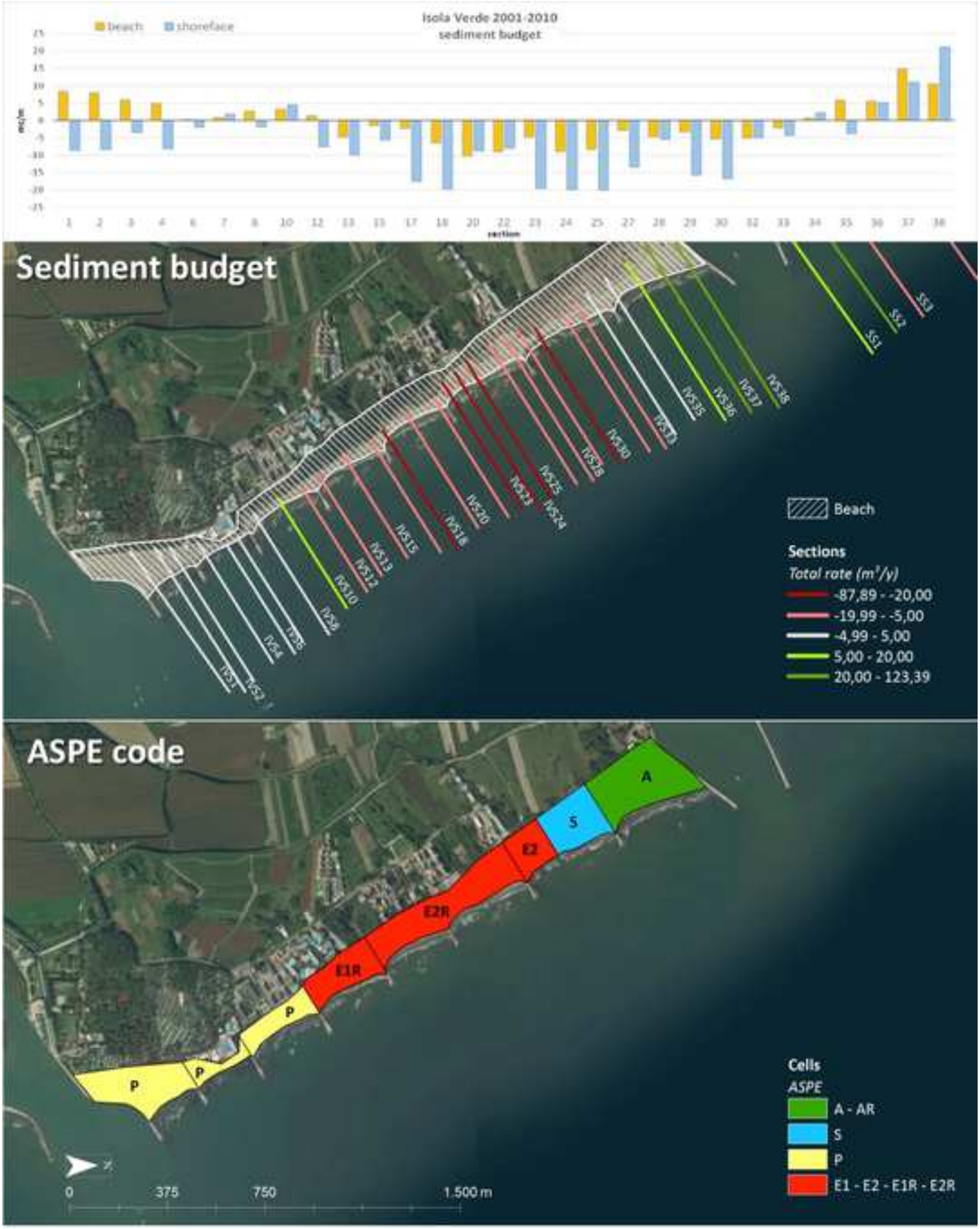
②

PROCESSING

③

PARAMETRIC SITE-SPECIFIC RELATIONSHIP

Figure 6 rev


Isola Verde 2001-2010
sediment budget
beach
shoreface
mc/m
25
20
15
10
5
0
-5
-10
-15
-20
-25
1
2
3
4
6
7
8
10
12
13
15
17
18
20
22
23
24
25
27
28
29
30
32
33
34
35
36
37
38
section
Sediment budget
IVS1
IVS2
IVS4
IVS6
IVS8
IVS10
IVS12
IVS13
IVS15
IVS18
IVS20
IVS23
IVS24
IVS25
IVS28
IVS30
IVS33
IVS35
IVS36
IVS37
IVS38
SS1
SS2
SS3
Beach
Sections
Total rate (m³/y)
-87,89 - -20,00
-19,99 - -5,00
-4,99 - 5,00
5,00 - 20,00
20,00 - 123,39
ASPE code
A
S
E2
E2R
E1R
P
P
P
Cells
ASPE
A - AR
S
P
E1 - E2 - E1R - E2R
N
0
375
750
1.500 m