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ORIGINAL ARTICLE

Beneath the Surface: How Climate Change Intensifies Erosion and Suspended Sediment Loads

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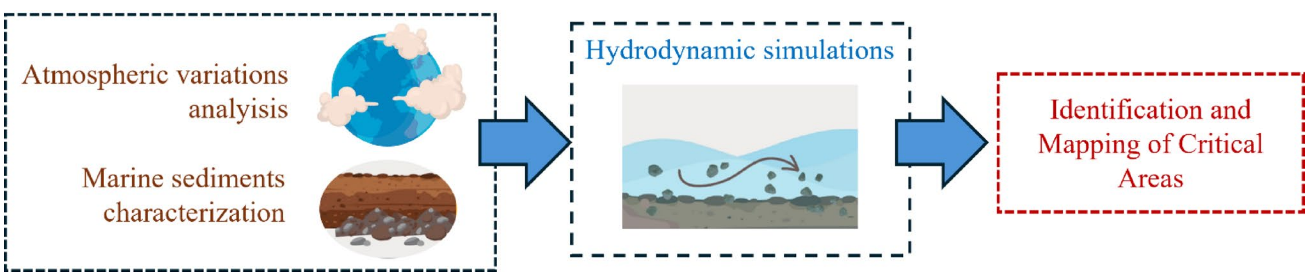
Abstract
This study leverages high-resolution climate datasets and advanced hydrodynamic modelling tools to propose a methodological procedure for assessing the potential impact of changes in atmospheric patterns on marine bottom stress and erosion processes occurring on the seabed. The analysis focuses on the Mar Piccolo basin of Taranto, a coastal area in southern Italy where marine sediments are heavily impacted by both past and ongoing anthropogenic pollution. Hydrodynamic simulations performed to define medium-term future scenarios indicate that, starting from 2035, a marked increase in current intensity is expected in both surface and bottom layers. This shift in current dynamics can be mainly attributed to changes in the wind regime. The enhanced current intensity is expected to lead to stronger shear stresses at the sediment-water interface, exceeding the critical thresholds for sediment resuspension, favouring sediment mobilization. These outcomes highlight the importance of analysing climate-related processes for understanding expected coastal dynamics and designing targeted remediation strategies for contaminated coastal sites.

Graphical Abstract


The graphical summary provides a concise overview of the research, emphasizing the data utilized and the methodologies applied. It effectively synthesizes the analytical approach designed to identify areas likely to be affected by potential changes in atmospheric patterns, particularly in terms of marine bottom stress and seabed erosion processes. The visual abstract leads the reader through the following steps: first, the system under investigation is characterized by (i) analyzing climate data to assess expected changes in atmospheric variables, and (ii) defining sediment size and granulometric distribution. Then, hydrodynamic simulations are conducted to model medium-term scenarios of current intensity at both surface and bottom layers. Finally, based on simulation results, hotspot areas, ei., sites exhibiting stronger shear stresses at the sediment-water interface, are identified. These zones, prone to enhanced sediment mobilization, may also experience increased pollutant

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dispersion. Overall, the study demonstrates how analyzing climate-driven processes can support the analysis of future coastal dynamics and support the development of targeted remediation strategies for contaminated coastal sites.

Highlights

- Climate data are exploited in hydrodynamic simulations for environmental analysis.
- Sediment samples characterization allowed the definition of critical shear stress.
- Starting from 2035, a marked increase in current intensity is expected.
- Stronger shear stresses at the sediment-water interface are assessed.

Keywords Polluted sediments · Wind pattern · Currents simulation · Taranto, Italy

1 Introduction

The Mediterranean coastal areas host numerous industrial sites, including oil refineries, petrochemical plants, shipyards, military facilities and steel mills, often located near major ports for ease of transportation. While these industries contribute to economic growth and employment, they also pose remarkable environmental risks, including marine pollution, habitat destruction, and air quality degradation (Carreño and Lloret 2021; El Zrelli et al. 2021; Romano et al. 2021; Mejjad et al. 2022; Lacoste et al. 2023). In Italy, since the second half of the last century, the territory of Taranto has been characterized by a high concentration of industrial districts, including the largest steel plant in Europe, inaugurated in 1965, the ENI refinery, completed in 1964 and operational since 1967, the thermoelectric power plant (formerly Enipower S.p.A.), the Cemitaly cement plant (formerly Cementir), various landfills, and numerous small and medium enterprises. Since the end of the 19th century, Taranto has also been home to the largest naval base of the Italian Navy, along with its associated maritime shipyard. The long-term extended human settlement and the impact of two centuries of the activity of industrial facilities have caused severe issues in the area, with consequences affecting the different environmental matrices (soil, air, water, and marine sediments - Trizio et al. 2016; Todaro et al. 2018, 2019; Rizzo et al. 2022a; Niccolini et al. 2025). Due to those characteristics, Taranto is considered one of the most polluted cities in Western Europe and it is included in the Italian list of the Sites of National Interest (SIN), for which the remediation process (Article 242 of the Italian Legislative Decree n. 152/06 and subsequent amendments) falls under the responsibility of the Italian Ministry of the Environment and Energy Security – MASE.

As shown in Fig. 1, the coastal area of Taranto is divided into two basins, called Mar Grande MG) and Mar Piccolo (MP). The latter is divided into two connected bays - the First Bay (Bay I) and the Second Bay (Bay II) - by the Punta Penne promontory (Valenzano et al. 2018). The inlet (rias - sensu Evans, 2003) of Mar Piccolo, with its typical lagoonal features and scarce hydrodynamics, is extremely vulnerable to environmental modifications (De Serio et al. 2020). Especially in the case of shallow basins subjected to strong anthropization and urban discharges, it is fundamental to monitor the basins' hydrodynamics and water quality (De Carolis et al. 2013; De Padova et al. 2017a, b; Armenio et al. 2018, 2019; Mossa et al. 2021). Such monitoring efforts have proven to be essential tools for local authorities and stakeholders, allowing them to deepen their understanding of the physical processes at work in the basin and track their real-time evolution. Moreover, they support the management of sediment transport and effluent discharges—phenomena that are closely linked to current speed and direction. To monitor the local hydrodynamic patterns, in December 2013, the first meteo-oceanographic station in the MP basin was mounted at the geographical coordinates 4027.6 N, 1712.9E. It was funded by the Italian national project PON R&C 2007–2013 "Magna Grecia" and the RITMARE Flagship Project (Italian Research for the Sea, where we operated as the research unit CoNISMa-Polytechnic University of Bari) provided by the Italian Ministry of Education, University and Research. In May 2014, funded by the Flagship Project RITMARE, the station Mar Piccolo was also placed in the target area. Namely, it was installed in the navigable channel, at the geographyical coordinates 4028.38 N, 1714.08E, because at present it is the main exchange between MP and MG excavated during the 19th century (Mastronuzzi et al. 2013, 2014). Further details on the MG and MP meteo-oceanographic stations can be found in Mossa et al. (2015).

Despite the high urbanization and industrialization, the area of Taranto has a remarkable ecological and biological importance, hosting peculiar coastal habitats and some threatened marine species (Cardellicchio et al. 2016). As summarized in Rizzo et al. (2022b), the area has been subject to several characterization activities aimed at providing the scientific base for the operative reclamation process. With regard to studies aimed at the environmental characterization of the Taranto site, a review of the scientific literature reveals a large number of studies focusing on the Mar Piccolo basin. Investigations carried out over the past

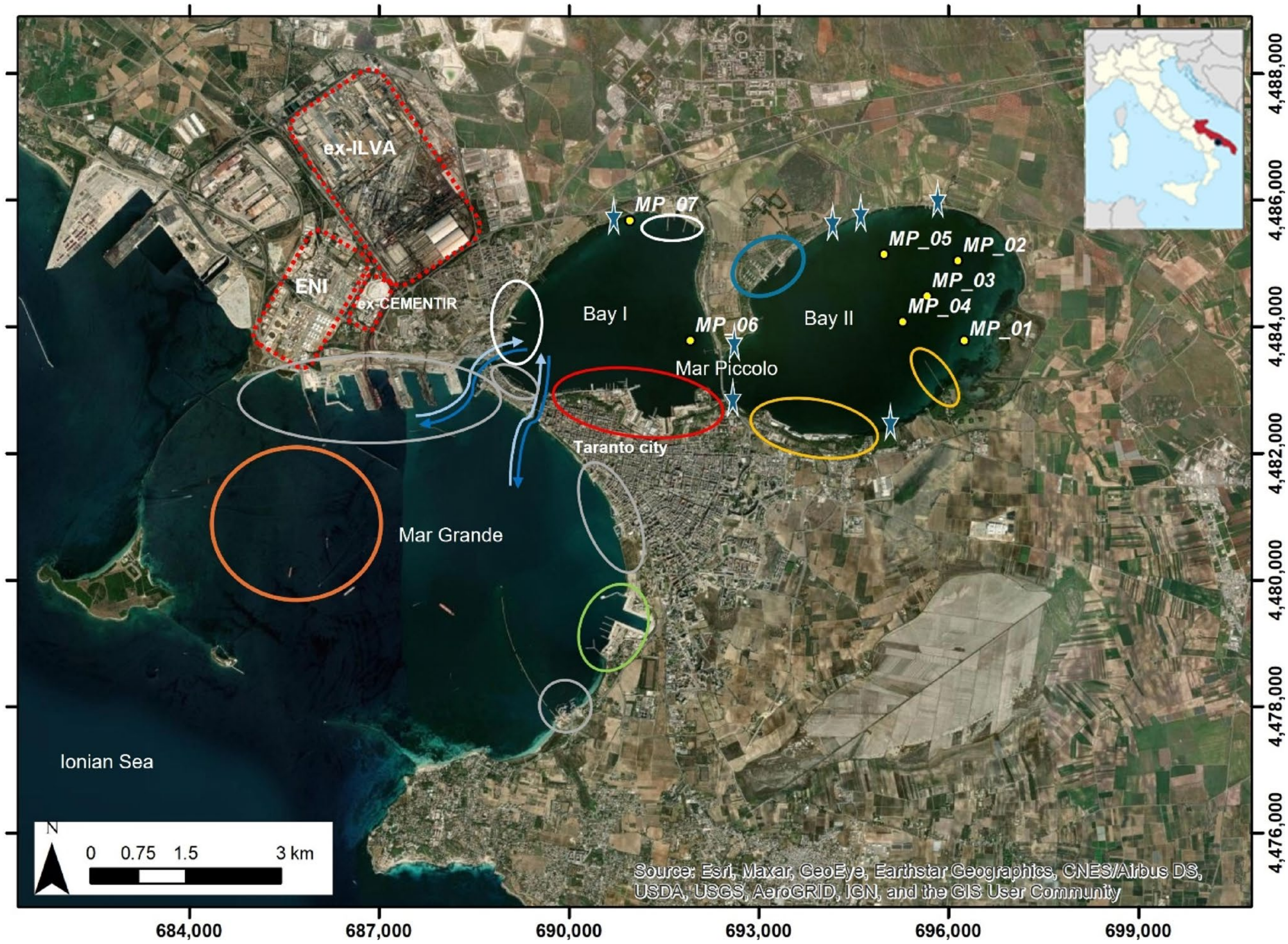


Fig. 1 Study area location. The polygons represent the sites hosting the main anthropogenic activities located along the Taranto coastal sector. Red dotted polygons: industrial sites. Ellipses: yellow - arsenal and air force depot; grey - harbours; white - shipyards; red - Italian navy arsenal. Orange circle: refinery buoy field. Stars: mussel farms. Arrows represent deep and superficial currents. Yellow bullets refer to the sediment sampling points.
Source background image: ESRI

25 years have highlighted a significant deterioration in the quality of marine sediments, particularly in the area of the First Bay, where high concentrations of various organic compounds and heavy metals have been detected (ISPRA 2010; ARPA PUGLIA 2014; Cardellicchio et al. 2007, 2009, 2016; Todaro et al. 2019; Cotecchia et al. 2021; Massari et al., 2021; Marsico et al. 2023). The results of the multidisciplinary analyses conducted in the area of Taranto showed that the First Bay of Mar Piccolo is affected by widespread contamination, due both to the high concentrations of trace metals and organotin compounds - often exceeding national limits - and to their presence at high levels within the same site. The most heavily contaminated areas are located in the central and southern parts of the First Bay, near industrial sites and navy arsenals. A detailed synthesis of the contamination affecting the two inlets is provided in Labianca et al. (2021) who, based on the result of the coring campaign performed by ARPA Puglia in 2014, highlighted that the two inlets present a macroscopic difference, with more serious, widespread, and deep contamination in the First Bay. In the Second Bay, only the first layers of the sea bottom (up to 50 cm) are characterized by spread contamination.

Recent investigations have highlighted the need to include the evaluation of expected morphodynamic changes induced by ongoing climate change in the characterization plans of the coastal contaminated sites (Rizzo et al. 2024). In this context, several studies focused on the identification of areas prone to be affected by future relative sea level rise (RSLR) and related erosion and inundation processes. By way of example, in Scardino et al. (2020), shoreline changes as consequence of sea level variation are assessed for the coastal area of Taranto Gulf while in Marsico at al. (Marsico et al. 2017) and Scardino et al. (2022) the submersion scenarios based on future local sea level projections are proposed for the industrial area of Taranto and Manfredonia, respectively.

Nevertheless, an analysis of the scientific literature shows that, to date, no studies are available on the potential direct and indirect effects of climate change on the local hydrodynamic conditions in the Taranto area. The only exception is represented by studies focusing on the effects of recent extreme meteorological events. One such event is the devastating "Tornado di Sava," which struck the Taranto area on 19 August 1976. Another major tornado, with an intensity of A3 on the Thompson scale, hit the western side of the city on 28 November 2012. Although it did not produce significant rainfall (approximately 35 mm in one hour), it swept across the whole Apulia region, reaching the Adriatic Sea (Venerito et al. 2013). Since 2000, annual precipitation levels have generally remained above 500 mm, peaking in 2009 (726.6 mm) and 2015 (670.4 mm). Regarding intense rainfall events, in 2003, just west of Taranto, in Castellaneta, rainfall reached peaks of 142 mm/hour and 244 mm over 12 h. This event caused extensive damage, overflowed coastal river sections, and resulted in three fatalities. On 16 October 2015, a meteorological event brought 137 mm of rain in three hours and 201.8 mm over 12 h.

The Mar Piccolo area of Taranto is not new to such phenomena. In the past 150 years, in addition to the aforementioned event, two extreme weather events stand out. In 1883, around 170 mm of rain fell between 14 and 15 September, causing the water level in the Mar Piccolo to rise significantly, flooding the coastal downtown area and damaging the Byzantine Castle of Raimondello Orsini, which was later demolished. On 23 October 1940, another intense rainfall event occurred, with 184 mm falling in about 2 h (Mastronuzzi et al. 2013; Parabita et al. 2020).

Based on the assumption that the current availability of very high-resolution climate data, both in space and time, is transforming our ability to analyze local atmospheric dynamics and their spatial and temporal evolution in the context of climate change, this study represents a pioneering initiative to assess how the variation in the atmospheric variables could affect the sediment bottom stress, favoring the erosion process and the consequent mobilization of polluted sediments. To this aim, the very high-resolution climate datasets, such as VHR-REA_IT (Raffa et al. 2021; Adinolfi et al. 2023), developed in the farmwork of the *Highlander* project (Bottazzi et al. 2024) to support impact assessments across several key sectors, have been exploited to define future scenarios of hydrodynamic conditions in the Taranto coastal area. Through the use of state-of-the-art regional climate models, including configurations at convection-permitting scale, it is now possible to more accurately represent local-scale climatic phenomena, especially in morphologically complex areas such as the Adriatic region. This area, characterized by strong interactions between orography, local circulations, and marine influences, is particularly sensitive to the effects of climate change, notably the increasing frequency and intensity of extreme events such as heatwaves, intense precipitation, and coastal storms (IPCC 2024; Coppola et al. 2021; Pichelli et al. 2021; Lionello et al. 2022). The integration of high-resolution data into climate analysis therefore, enables a more robust assessment of local impacts and provides essential scientific support for the design of effective adaptation strategies, particularly in vulnerable territories along the Adriatic coast.

2 Materials and methods

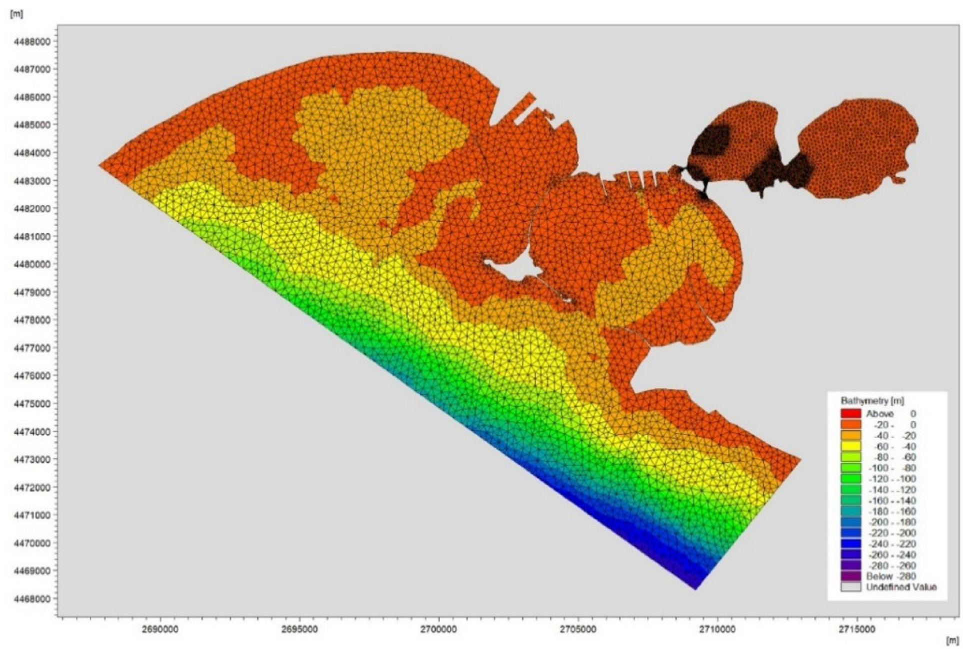
2.1 Study Area

The domain under investigation in the present work is the MP inlet, located in the northeastern area of the Ionian Sea in southern Italy, within the Gulf of Taranto. The MP basin is composed of two bays (the first Bay – Bay I and the second Bay – Bay II) with a total surface area of about 20.7 km^2 and an average depth of about 7.0 m. The basin is connected to the MG by two channels, i.e., the Navigable Channel and the Porta Napoli Channel, which cross the hystorical center of Taranto city (Fig. 1) (Mastronuzzi et al. 2013, 2014).

From a geological point of view, the area presents a well-known stratigraphical setting, characterized by the Mesozoic limestone (calcare di Altamura unit) and Upper Pliocene–Lower Pleistocene calcarenite (calcarenite di Gravina unit) which are overlaid upwards and laterally by the argille subappennine unit (Lisco et al. 2016). As highlighted in Mastronuzzi and Sansò (1998) and in Valenzano et al. (2018), the current geomorphological patterns of the area are the results of the interplay between the eustatic sea-level rise during the post Last Glacial Maximum (LGM) transgression and the low-rate regional uplift. The Mar Piccolo basin presents a particular seawater circulation trigged by the presence of submarine and subaerial freshwater springs, locally called "*citri*". The peculiar hydrogeological and geomorphological features of the area have led to the development of typical lagoonal characteristics. Combined with the semi-enclosed nature of the basin, this results in limited seawater circulation, further exacerbating the environmental challenges faced by the area (De Pascalis et al. 2016).

According to literature data, Bay I of the MP basin is characterized by relatively high sediment accumulation rates, with values ranging from 1 mm/year to 3 mm/yr (Cotecchia et al. 2021). Furthermore, as emerged from the sediment core described in Valenzano et al. (2018) and Niccolini et al. (2025), the upper part of the sediment layer in

Fig. 2 Bathymetry of the simulated domain and computation mesh



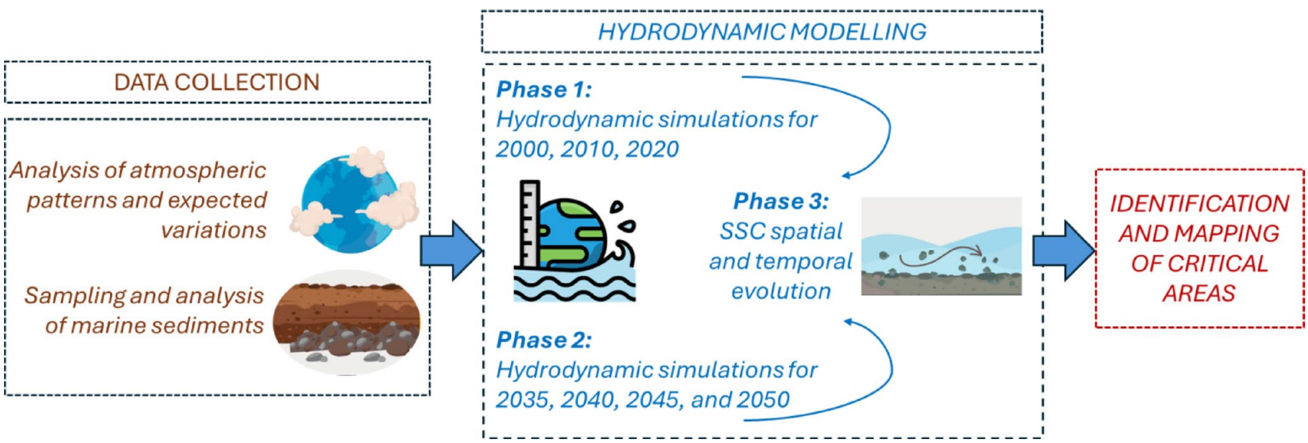


Fig. 3 Flow chart of the methodological procedure applied to model the expected impact of climate change on the suspended solid concentration and evolution

the MP basin corresponds to specific litho-facies, consisting of very soft, grey, structureless silts with an abundant organic content and bioclasts, indicating deposition in a semi-enclosed basin with low hydrodynamicity. Based on the investigations performed by De Pascalis et al. (2016), Armenio et al. (2016), De Serio e Mossa (2016), the entering current directed towards the MP characterize the deeper layers (light blue arrows in Fig. 1), while in the more superficial layers, the current is mostly directed towards the MG (outgoing – dark blue arrows in Fig. 1). As regards the erosion and accumulation phenomena resulting from the interaction between sediment and bottom sea currents, De Serio et al. (2018) showed that the MP - MG connection channels and the area across the ex-ILVA water pumping station (which brings water to the industrial area) are characterized by the maximum tangential load (responsible for erosion) at the bottom of the seabed. A tendency towards sediment deposition has been observed in the remaining parts of the inlets. Finally, Pierri et al. (2024) describe unusual rhodolith beds along the W coast of the Punta Penne peninsula: this data indicates that, locally, there are bottom currents able to move such centimetric (quasi-spheroidal) particles covered by red calcareous algae.

2.2 Grain-size Analysis

In order to define the grain-size characteristics of the seabottom, sediment samples were collected in both bays of the

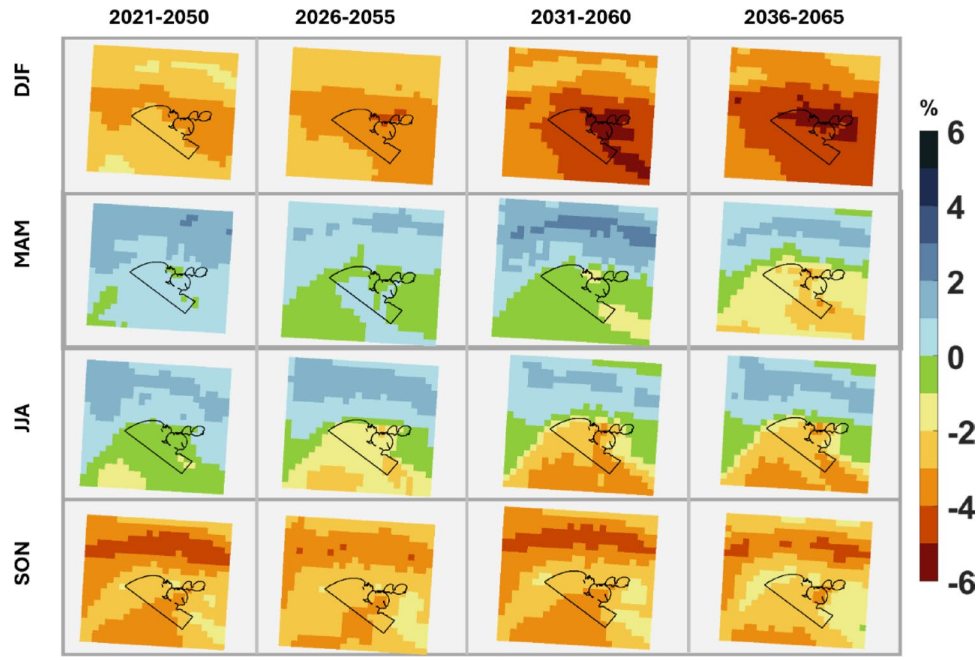


Fig. 4 Seasonal climate variations of the mean daily wind speed obtained starting from VHR-PRO_IT dataset for four periods analyzed (2021–2050, 2026–2055, 2031–2060 and 2036–2065) by considering as a reference period 1981–2010. The seasons are indicated as DJF (winter), MAM (spring), JJA (summer), and SON (autumn)

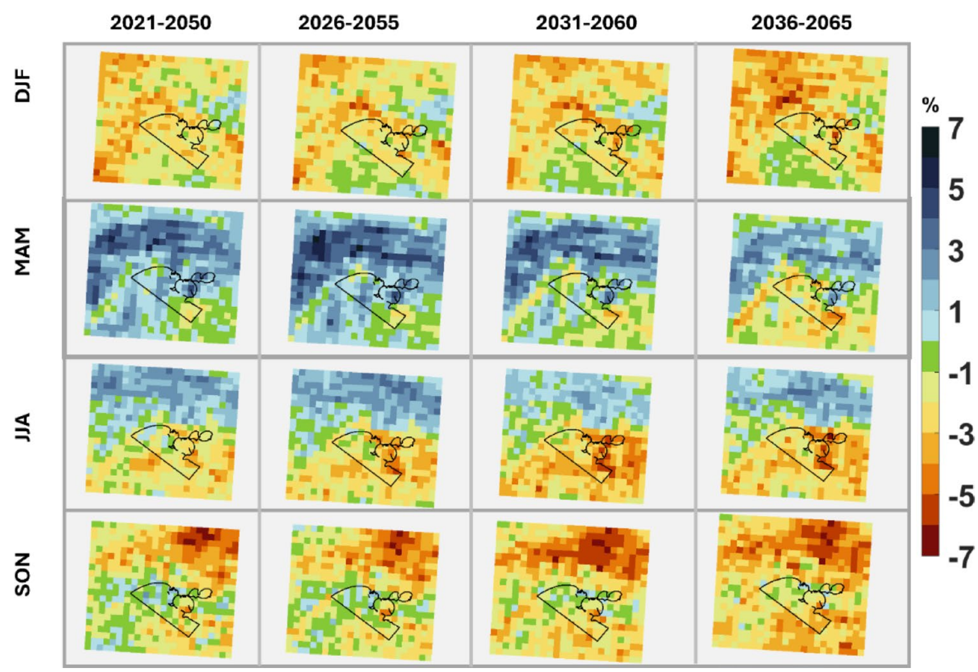


Fig. 5 Seasonal climate variations of the 98-percentile of the maximum daily wind speed obtained starting from VHR-PRO_IT dataset for four periods analyzed (2021–2050, 2026–2055, 2031–2060 and 2036–2065) by considering as a reference period 1981–2010. The seasons are indicated as DJF (winter), MAM (spring), JJA (summer), and SON (autumn)

MP basin. Samples were manually collected in December 2022 by means of a Veen grab sampler and then analyzed in the laboratory to obtain their granulometric characteristics. The grain-size analyses were carried out by using the standard procedures provided by the American Society for Testing and Materials and the British Standard. A set of ASTM sieves with meshes of ½ phi from 2 mm to the minimum granulometric fraction (<0.125 mm) was used to sieve the samples. According to this procedure, the samples were first dried in the oven at a temperature of 80° for 24 h. Then, each sample was quartered and set in a sieve column. Sediments from 2.0 mm to 0.125 mm were sieved with the vibrating screen for 20 min. Subsequently, each held fraction was weighed. The laboratory results were then processed with a specific application for Microsoft Excel (Gradistat© v8), which yield the cumulative curves, histograms, and statistically evaluate the main textural parameters (mean size (Mz), sorting (σ), skewness (S_k), and kurtosis (K_G).

2.3 Climate Data and Analysis

The atmospheric variables used as input for hydrodynamic simulation in the MP basin were taken from two different datasets based on a very high resolution of about 2 km (i.e., Convection Permitting Scale) produced within the Highlander project (https://highlanderproject.eu/). For the curren t climate conditions, the VHR-REA_IT dataset (Raffa et al. 2021) was used. This dataset contains dynamically downscaled ERA5 reanalysis, originally available at ≈31 km x 31 km horizontal resolution, to 2.2 km x 2.2 km. Dynamical downscaling was conducted through the COSMO Regional Climate Model (RCM). Runs cover the whole Italian territory (and neighboring areas according to the necessary computation boundary) so to provide a very detailed (in terms of space-time resolution) and comprehensive (in terms of meteorological fields) dataset of climate data.

2.4 Modelling of Marine Currents

The flow field and sediment transport in the MP basin were computed by using the MIKE 3 FM numerical model (DHI 2016), consisting of two modules. MIKE 3 FM HD model describes the hydrodynamic flow field; the mud transport module (MT) evaluates the sediment dynamics and the effects on sea morphology. Both modules share the same numerical mesh, consisting of 7235 elements and thirteen vertical layers (Fig. 2). Further information regarding the different datasets utilized to generate the mesh is available in De Serio et al. (2020). The hydrodynamic model is based on the numerical solution of three-dimensional incompressible Reynolds-averaged Navier–Stokes (RANS) equations, subject to the assumptions of Boussinesq and hydrostatic

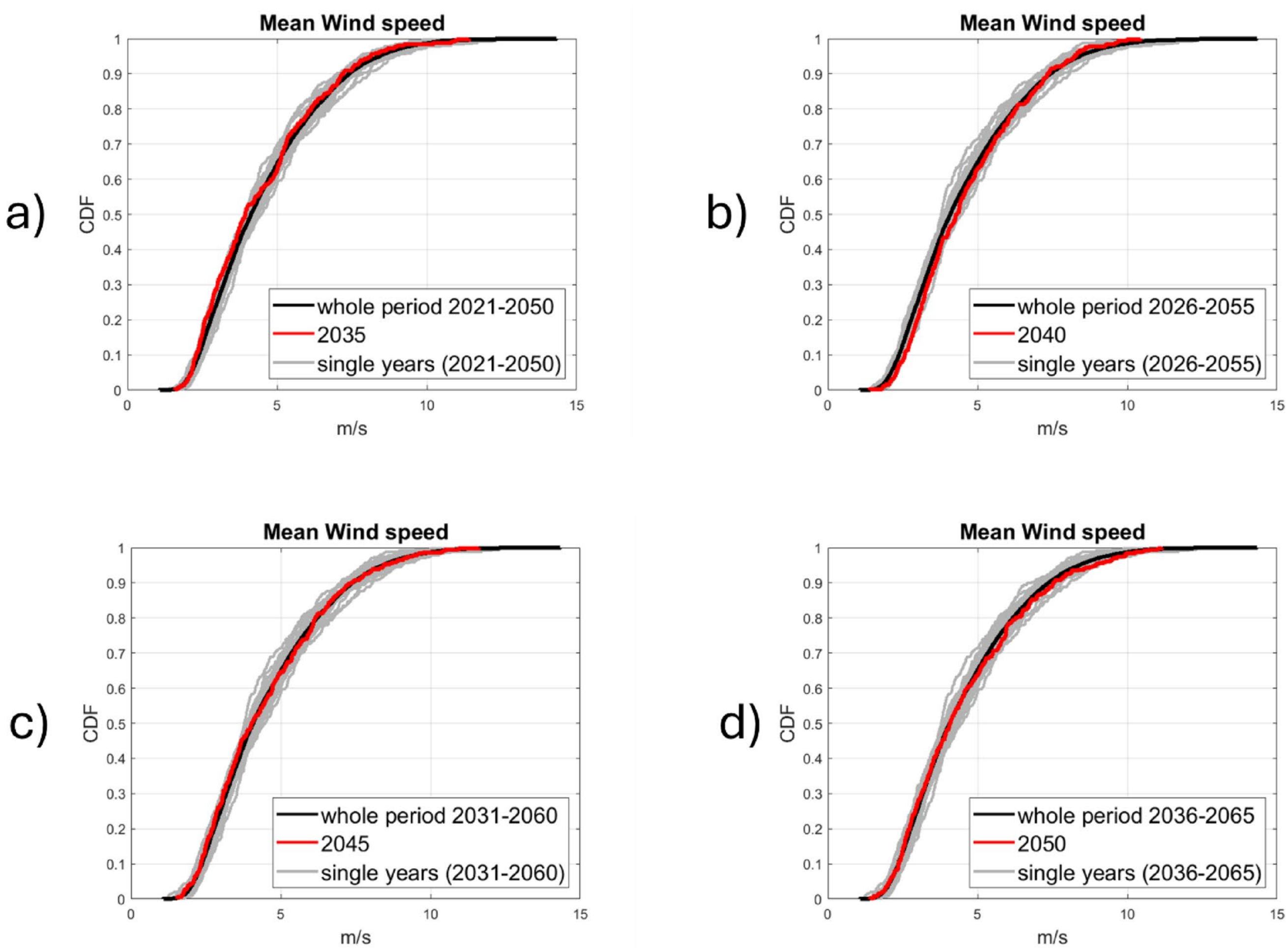


Fig. 6 Cumulative density function F(x) of wind velocity for the following periods: (**a**) 2021–2050; (**b**) 2026–2055 (**c**) 2031–2060 and (**d**) 2036–2065. Grey lines represent F(x) of every single year, the red dashed line is the central year considered for hydrodynamical simulations, and the black thick line represents the whole period of climate analysis. Each plot shows data for VHR-PRO_IT

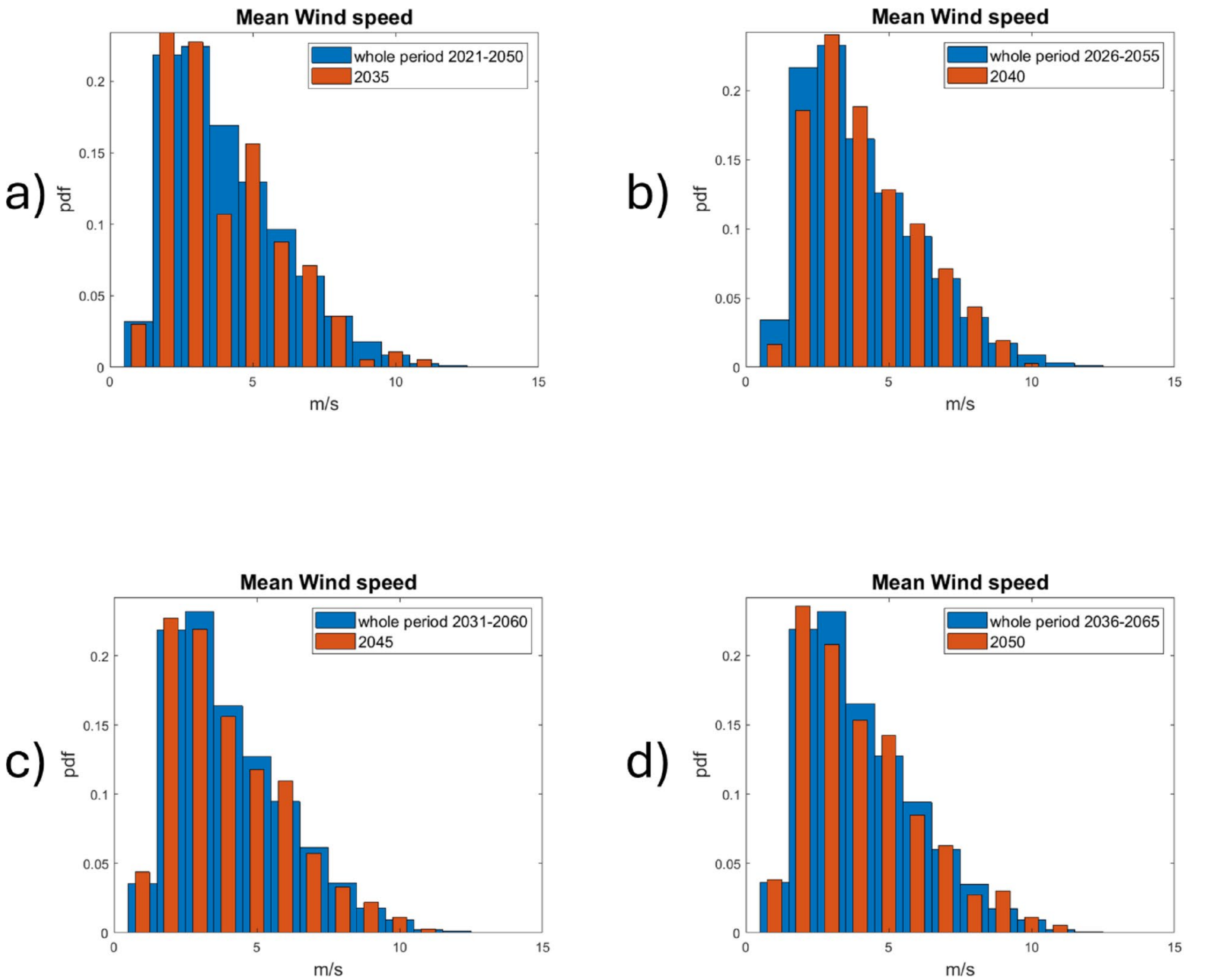


Fig. 7 Probability Density Function (PDF) of wind velocity for the following periods: (**a**) 2021-2050; (**b**) 2026-2055 (**c**) 2031-2060 and (**d**) 2036-2065

pressure. MIKE 3 FM HD model relied on the k-ε formulation for the vertical direction (Rodi 1987) and the Smagorinsky formulation for the horizontal direction (Galperin and Orszag 1993). According to the sensitivity analysis shown in same area (De Padova et al. 2017b), the simulations were performed by adopting the following calibration parameters: a seabed roughness equal to 0.1 m, a wind drag coefficient Cd equal to 0.001. The hydrodynamic simulations were carried out using a baroclinic model with temperature and salinity vertical profiles extracted from the Mediterranean Sea Physics Reanalysis model (horizontal grid resolution of 1/24° and 72 unevenly spaced vertical levels) (Simoncelli et al. 2019), with the aim of modeling more realistic conditions. The hydrodynamic simulations were forced with u and v components of wind [m/s] and atmosphere pressure [Pa] extracted by the climate datasets described in subparagraph 2.3. To model the suspended solid concentration (SSC) and seabed evolution, the mud transport module (MT) coupled with the hydrodynamic model (HD) was used. For more details on this module (MT), the reader can refer to (Partheniades 1965; Lumborg 2005).

As summarized in Fig. 3, the modeling procedure is composed of three steps.

As first step, the numerical simulations are performed by considering the different atmospheric variables provided by the VHR-REA_IT dataset (Raffa et al. 2021) for recent climate developed by dynamically downscaling ERA5 reanalysis, originally available at ≃31 km horizontal resolution, to ≃2.2 km resolution (i.e., convection permitting scale). In this case, hydrodynamic simulations were performed for the years 2000, 2010, and 2020 in order to reproduce the current climate.

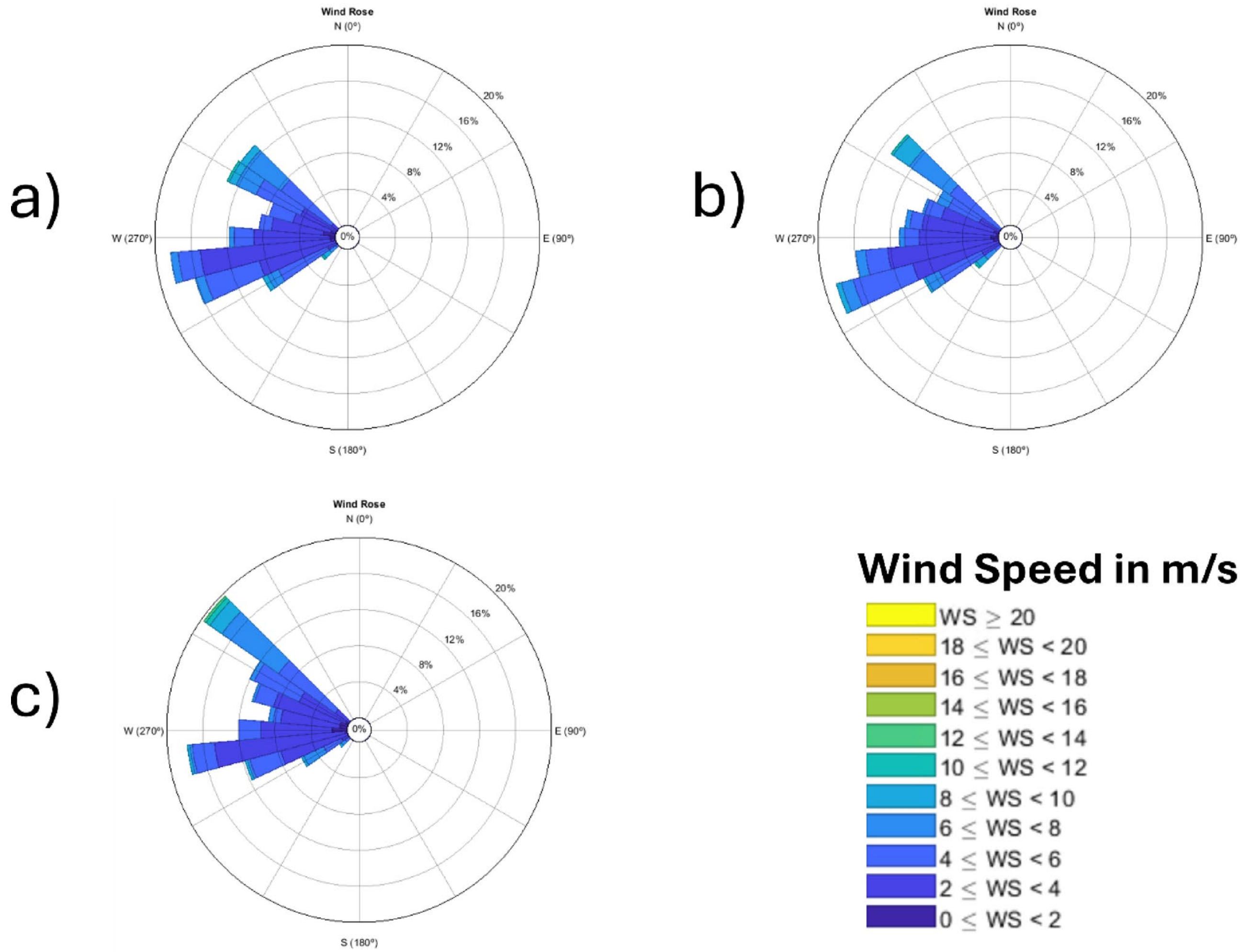


Fig. 8 Wind rose for the following years: (**a**)2000; (**b**) 2010 (**c**) 2020. Each plot shows data for the VHR-REA_IT dataset

Table 1 Sample textural characteristics. Mz = mean, σ = sorting, S_k = skewness, K_G = kurtosis

SAMPLE	Mz (ϕ)	Description	σ (ϕ)	Description	S_k (ϕ)	Description	K_G (ϕ)	Description
MP_1	4.431	Very Coarse Silt	1.452	Poorly sorted	0.514	Very Fine Skewed	1.105	Mesokurtic
MP_2	5.454	Coarse Silt	2.778	Very Poorly Sorted	−0.448	Very Coarse Skewed	1.669	Very Leptokurtic
MP_3	6.588	Medium Silt	2.282	Very Poorly Sorted	−0.394	Very Coarse Skewed	2.335	Very Leptokurtic
MP_4	6.789	Medium Silt	1.593	Poorly Sorted	−0.271	Coarse Skewed	1.463	Leptokurtic
MP_5	3.883	Very Fine Sand	3.403	Very Poorly Sorted	−0.393	Very Coarse Skewed	0. 679	Platykurtic
MP_6	4.246	Very Coarse Silt	3.630	Very Poorly Sorted	−0.523	Very Coarse Skewed	1.738	Very Leptokurtic
MP_7	2.473	Fine Sand	3.51	Poorly Sorted	−0.289	Coarse Skewed	0.73	Platykurtic

In the second step, the numerical simulations are performed by considering as input atmospheric variables provided by the climate projection VHR-PRO_IT dataset (Raffa et al. 2023), developed at ≃ 2.2 km resolution (i.e., Convection Permitting Scale) by dynamically downscaling CMCC-CM global model, adopting the IPCC RCP4.5 scenarios. In this case, hydrodynamic simulations were performed up to 2050.

Finally, in the last step, SSC spatial and temporal evolution is assessed by the exploitation of the mud transport module (MT) coupled with the hydrodynamic model (HD). To this aim, characterization of the bed sediment composition is crucial.

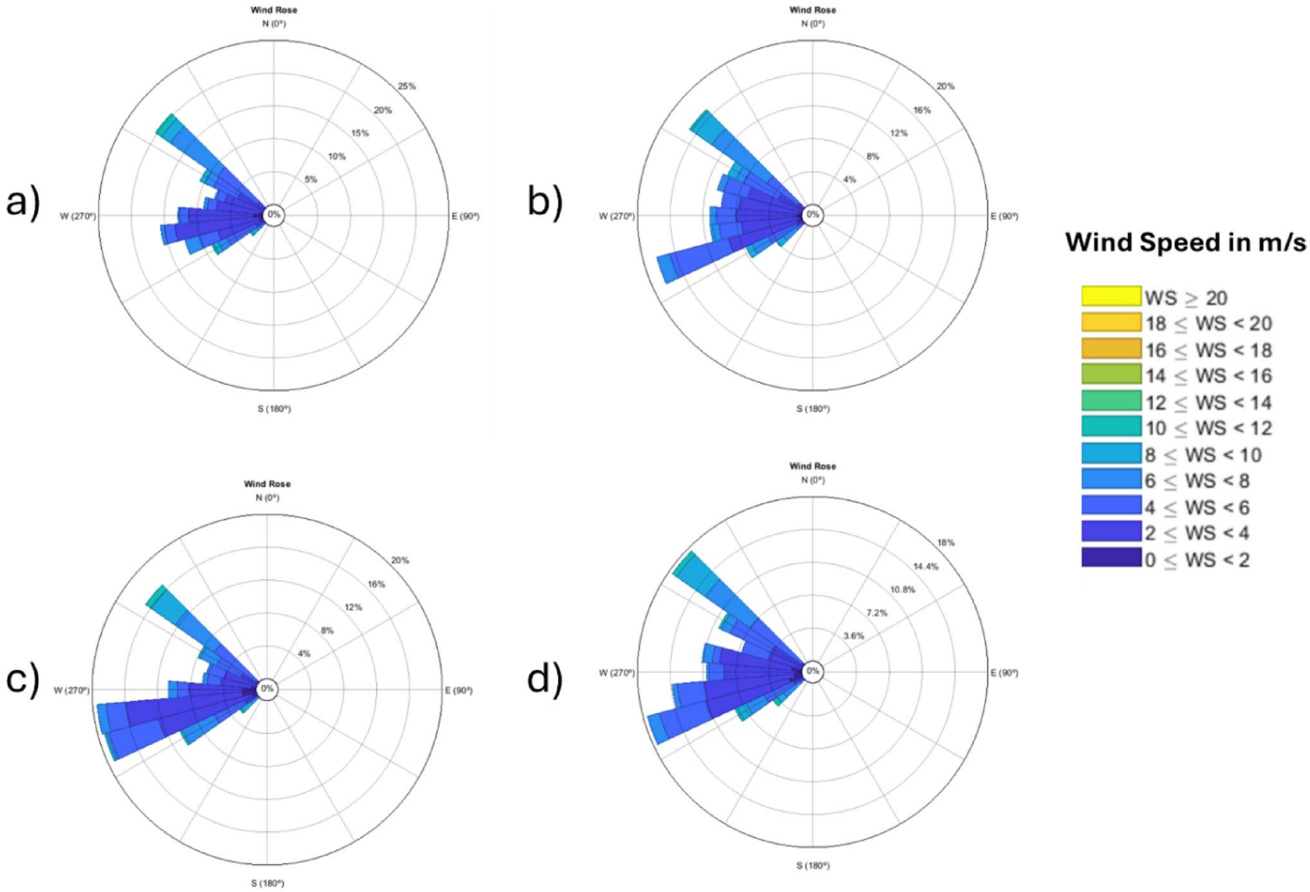


Fig. 9 Wind rose for the following years: (**a**)2035; (**b**) 2040 (**c**) 2045 and (**d**) 2050. Each plot shows data for the VHR-PRO_IT dataset

3 Results and Discussion

3.1 Climate re-analysis and Future Projections for the Area of Taranto

The use of the high spatial-temporal resolution dataset allows for more precise analysis of local atmospheric dynamics and their future evolution, providing useful support for planning effective adaptation strategies in vulnerable territories such as the Adriatic coast. To introduce the climate context, the seasonal climate variations in terms of mean values (mean daily wind speed) and in terms of extremes (98th percentile of the maximum daily wind speed) have been obtained starting from the VHR-PRO_IT dataset for the four future periods analyzed (2021–2050, 2026–2055, 2031–2060 and 2036–2065) using 1981–2010 as a reference period. The seasonal climate variations reveal a duality between the evolution of mean values (Fig. 4) and extreme values (Fig. 5), with important implications for currents and sediment dynamics in the study area. Specifically, the general trend toward a reduction in mean wind speed, particularly marked in winter (DJF) and autumn (SON) seasons, could influence the basic hydrodynamic circulation of the system. Conversely, the intensification of extreme events (98th percentile), particularly evident in the spring season (MAM), with increases reaching 4–6%, is of critical relevance for the mobilization of contaminated sediments.

Climate variations results can be further enriched by subsequent analyses in terms of Cumulative Distribution Function (CDF) and Probability Density Function (PDF), analyses described in detail below. Specifically, the probability distribution of wind speeds in 2035, 2040, 2045, and 2050 shows the minimum difference with the mean probability distribution computed for the periods 2021–2050,2026–2055,2031–2060,2036–2065, compared to any other year within the same time interval (Fig. 6).

In general, the results show that the Cumulative Distribution Function (CDF) of the central year does not differ significantly from the CDF of the whole period (except for the tail of the extremes). This result is more evident when analyzing the distribution of values through the Probability Density Function (PDF) (Fig. 7), where considering a single year leads to the loss of some extreme values (particularly for the year 2040). This result is consistent because we are comparing one year with a thirty-year period. Since this work concerns average trends, it is possible to assume

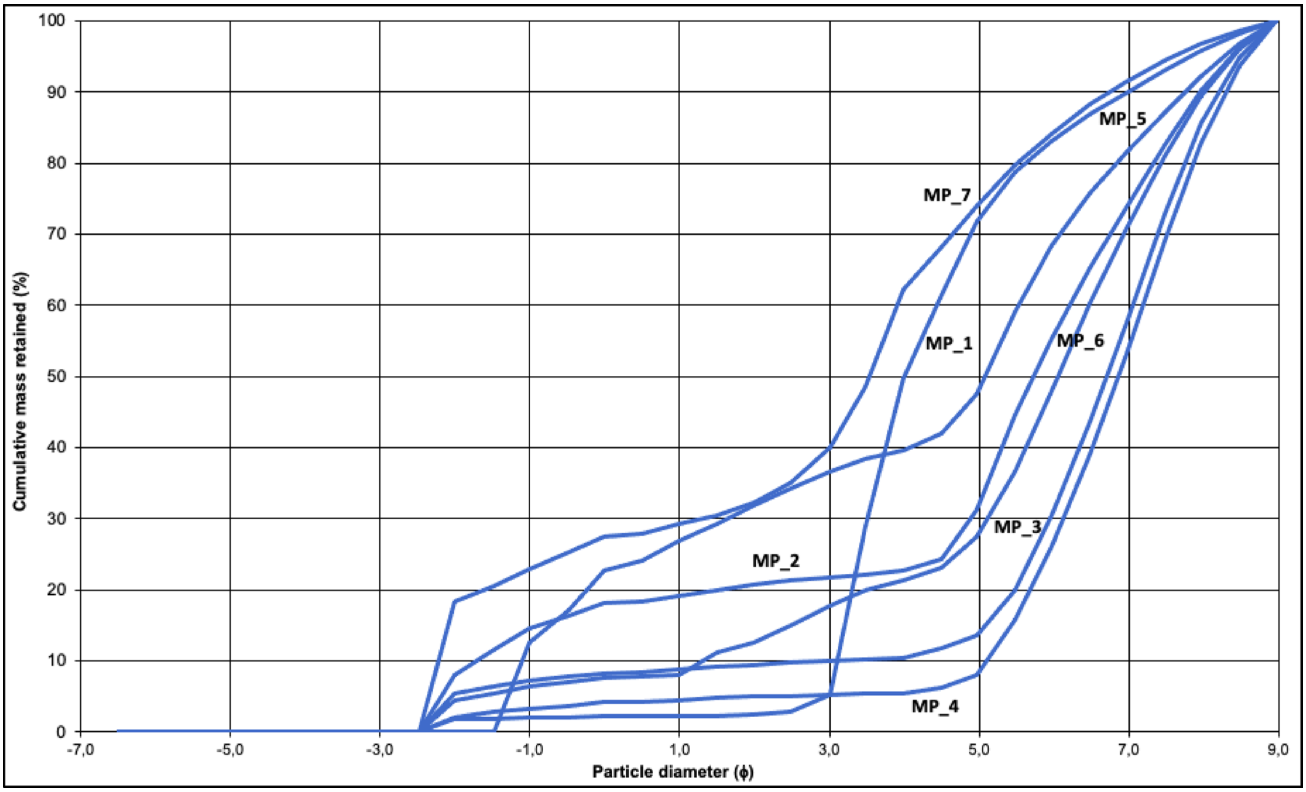


Fig. 10 Grain distribution cumulative curves of the MP sediment samples

that the central year is representative of the entire period and, consequently, significantly reduces the computational burden. In addition, the wind regime was analyzed in terms of wind rose for the years considered in the hydrodynamic simulations, to synthetically represent the wind speed distribution by direction of origin for the MP basin (obtained starting from the VHR-REA_IT dataset shown in Fig. 7 and from the VHR-PRO_IT climate projections shown in Fig. 8). The results highlight an increase in the intensity and frequency of winds coming from directions between W and NNW.

3.2 Granulometric Characteristics

Two samples were collected in Bay I while five samples in Bay II. Their location was chosen to represent the variability of different morpho-sedimentary sectors of the MP (submerged beaches, delta bars, marginal and depocentral areas, etc.). The seabottom of the MP is characterized by sediments with granulometry varying from coarse silt to fine sands. They present a generally low sorting and are from coarse skewed to very coarse skewed (except for sample MP_1), with very variable kurtosis (from platykurtic to very leptokurtic). Coarse-grained, very coarse skewed and very leptokurtic sediments (e.g., MP_6) indicate the presence of tractive currents on the seabed.

3.3 Future Hydrodynamic Characteristics of the Mar Piccolo Basin

As described in subparagraph 2.4, the hydrodynamic simulations were performed using as input the atmospheric variables provided by the climate projection VHR-PRO_IT dataset (Raffa et al. 2023) with a resolution of ≃2.2 km (i.e., Convection Permitting Scale) up to 2050, covering the Italian peninsula and some neighboring areas. VHR-PRO_IT dataset is produced by dynamically downscaling the Italy8km-CM climate projection (spatial resolution ≃8 km) with the Regional Climate Model COSMO-CLM under the IPCC RCP4.5 and RCP8.5 scenarios. Considering the future pattern of the wind data (cf. subparagraph 3.1), hydrodynamic simulations were performed up to 2050 by considering a single year (2035,2040,2045,2050) as a representative for the entire period (2021–2050, 2026–2055, 2031–2060, 2036–2065), generally used for climate study (at least 30 years) according to the IPCC guidelines. All configurations were forced with atmospheric variable of a single year because the cumulative distribution frequency of wind velocity in a single year is the closest to that of the whole period of thirty years (as applied in D'Alpaos et al. 2024) and, consequently, can be considered a representative year for the wind climate of the MP basin. Furthermore, based on the sediment characterization, a critical shear

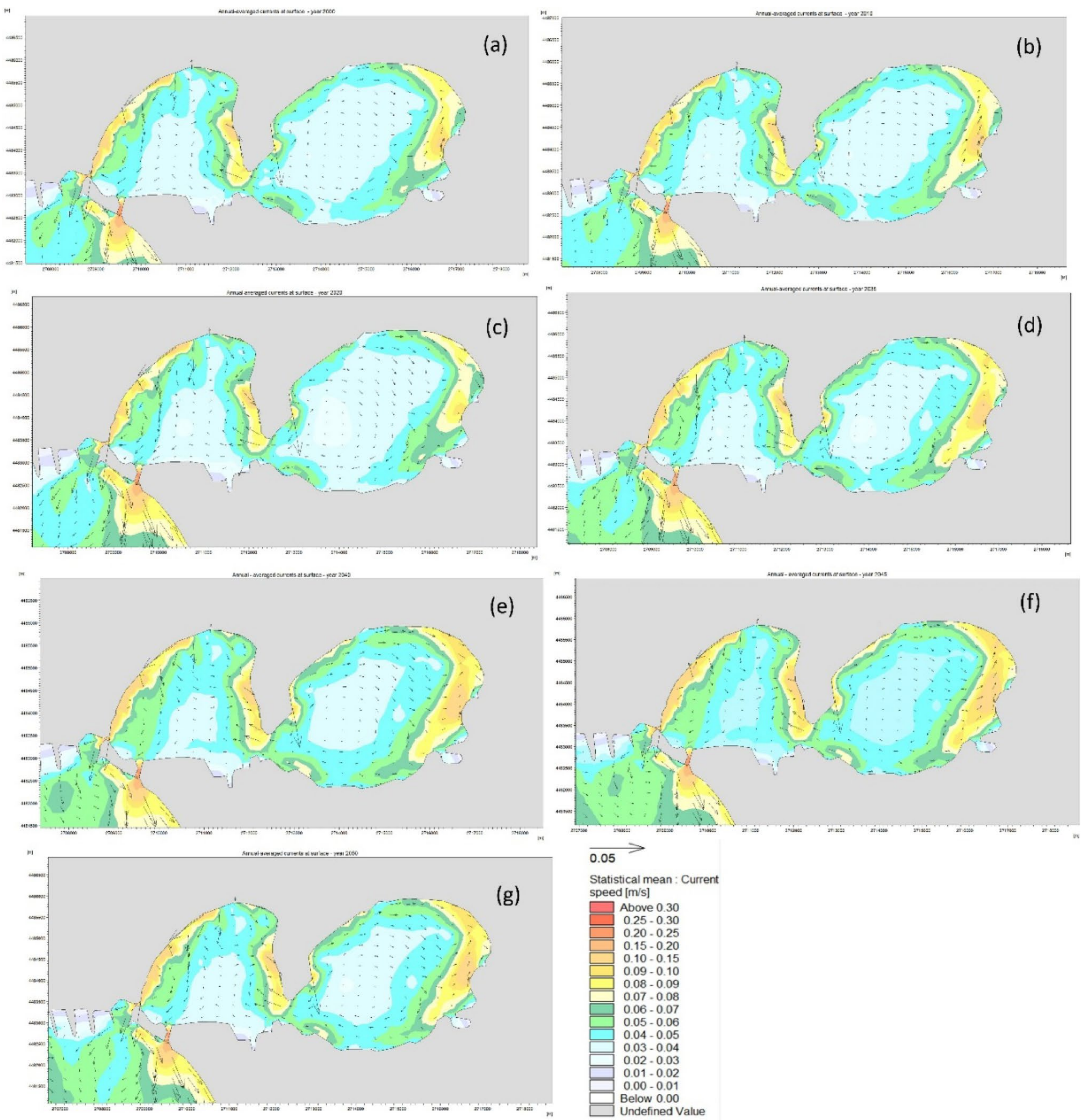


Fig. 11 Computational maps of the annual-averaged currents at the surface referred to (**a**) 2000; (**b**) 2010; (**c**) 2020; (**d**) 2035; (**e**) 2040; (**f**) 2045, and (**g**) 2050

stress $\tau ce = 0.2\ N/m^2$ was derived. The patterns of the surface and bottom annual averaged currents were examined for the investigated years (2000, 2010, 2020, 2035, 2040, 2045, and 2050, as shown in Figs. 10 and 11). All investigated years confirmed the main characteristics of the basin circulation in the MP shown in (De Serio et al. 2020; Padova et al. 2023). General circulation is characterized by a dual mechanism of water-mass exchange. At the bottom, the current flows toward the second inlet of the MP basin, while at the surface, the flow behaves oppositely. The simulated velocity values reveal a peak of 0.3 m/s along the navigable channel of the basin. Between MG and MP, two key

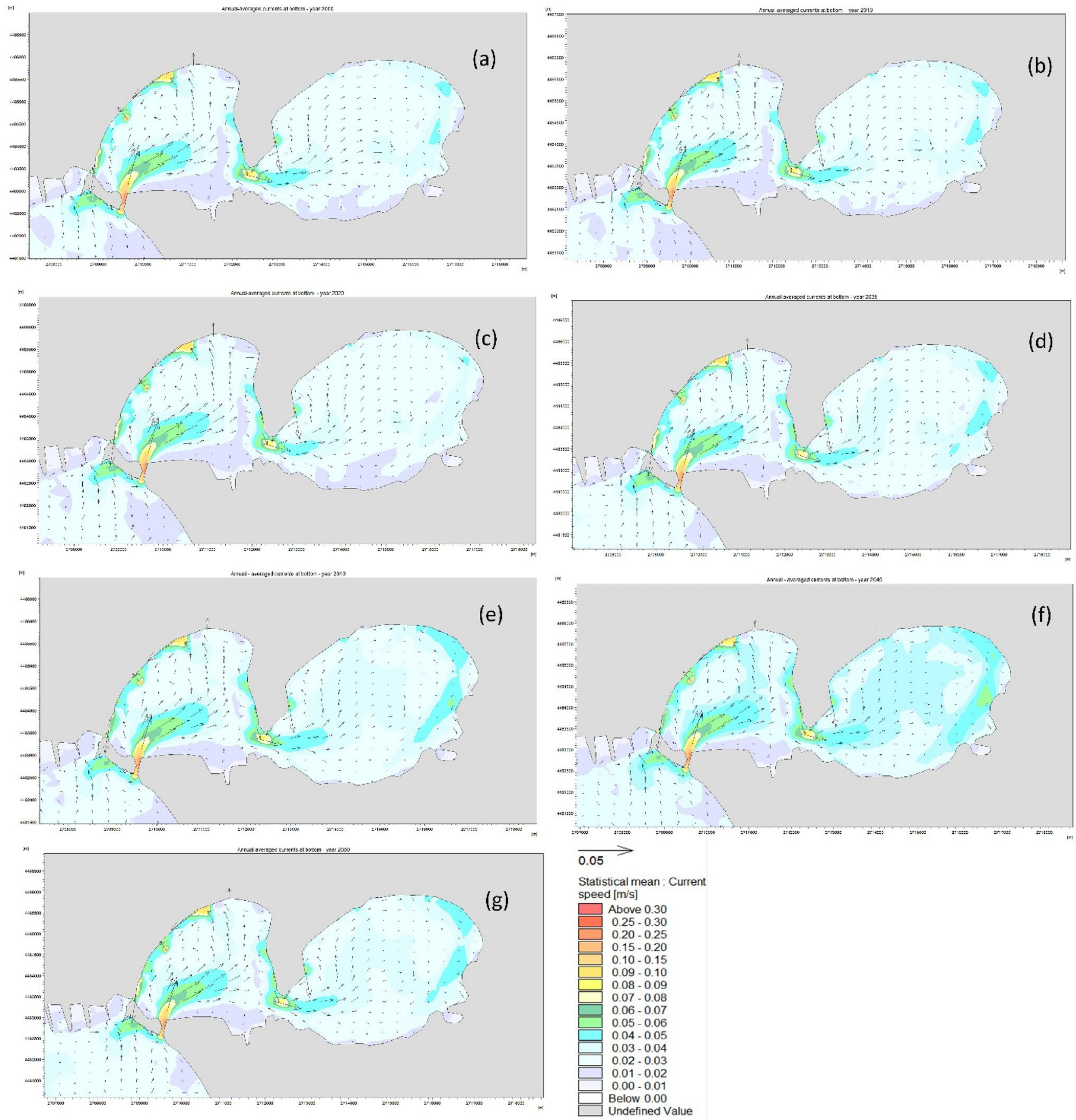


Fig. 12 Computational maps of the annual-averaged currents at the bottom referred to s (**a**) 2000; (**b**) 2010; (**c**) 2020; (**d**) 2035; (**e**) 2040; (**f**) 2045, and (**g**) 2050. (**f**) 2045, and (**g**) 2050

phenomena are observed: (i) the inflow of salty and cold water at the bottom layer and (ii) the outward movement of less salty and warmer water on the surface. However, a change in the intensity of the currents in the surface and bottom layers could already be observed from 2035 and became more evident from 2040. This shift in current dynamics can be attributed to changes in the wind regime (Fig. 8). Figures 12 and 14 present the maps of SSCmean (Suspended Sediment Concentration mean) for the surface and bottom layers, respectively. Obtained results highlight the extent of sediment transport throughout the MP basin. The increased current intensity has resulted in enhanced shear stress at the

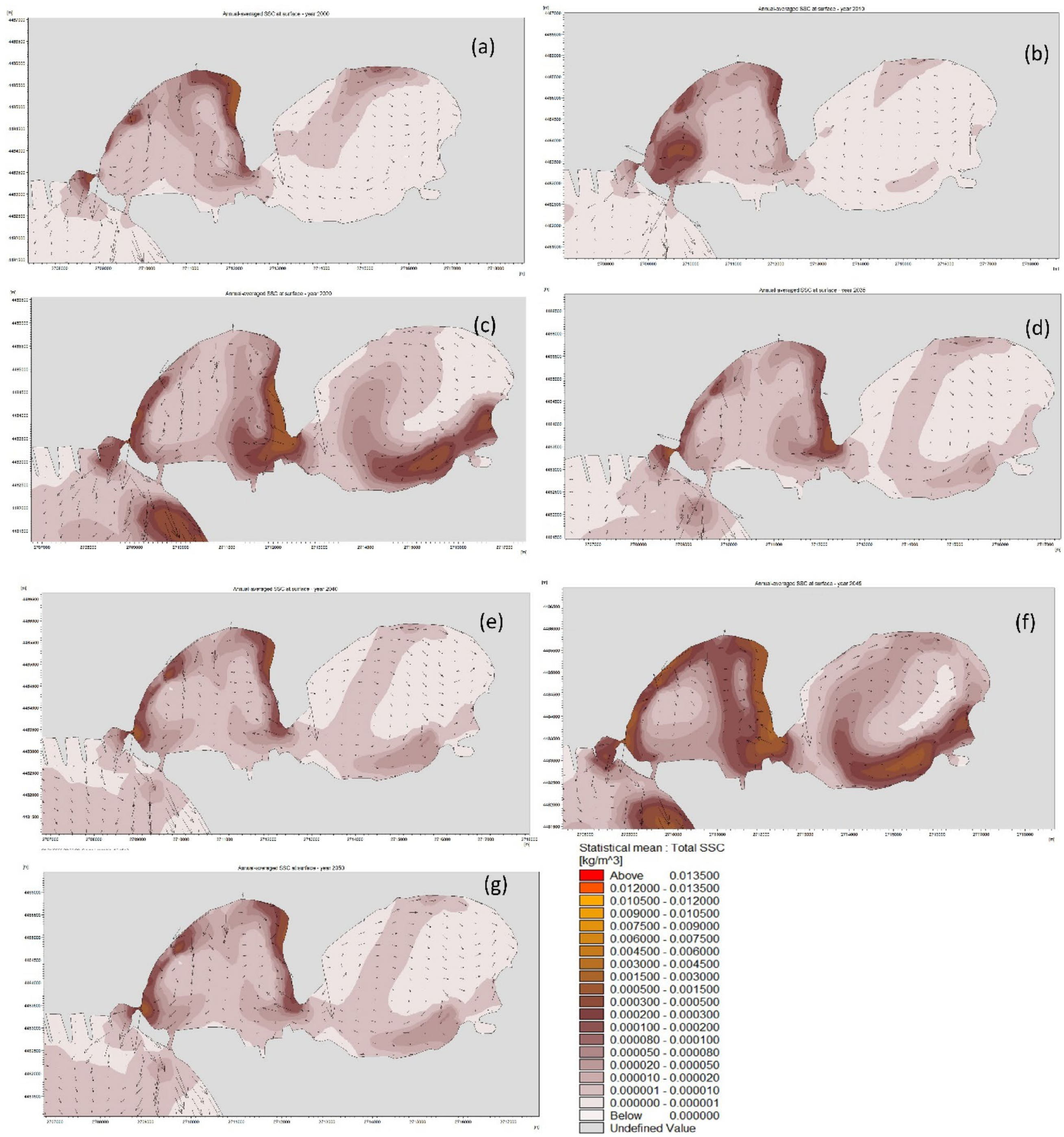


Fig. 13 Computational maps of the annual-averaged suspended solid concentration (SSC) at the surface referred to (**a**) 2000; (**b**) 2010; (**c**) 2020; (**d**) 2035; (**e**) 2040; (**f**) 2045, and (**g**) 2050

sediment-water interface, exceeding the critical thresholds for sediment resuspension. Consequently, a greater mobilization of sediments is expected to be observed across MP, with substantial impacts on sediment distribution and dynamics. This phenomenon is particularly pronounced in Bay II, where intense sediment mobilization is now evident. Such activity was either scarce or entirely absent prior to 2010, suggesting a significant alteration in the local fluid mechanics. The observed sediment dynamics in Bay II may be further amplified by the confined geometry and reduced hydrodynamic exchange of this area, which enhances the trapping and redistribution of fine particles under the influence of the intensified currents.

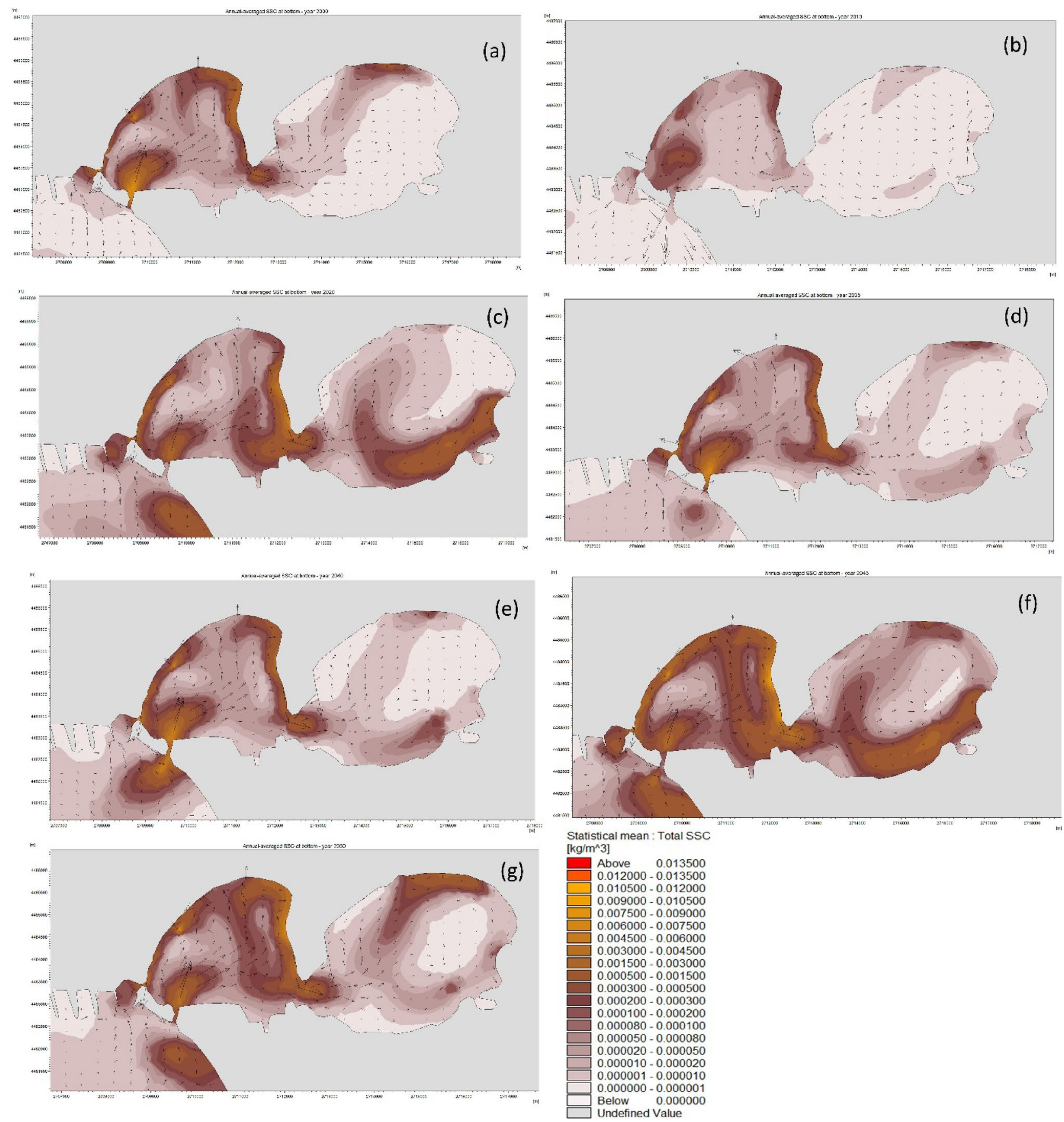


Fig. 14 Computational maps of the annual-averaged suspended solid concentration (SSC) at the bottom referred to (**a**) 2000; (**b**) 2010; (**c**) 2020; (**d**) 2035; (**e**) 2040; (**f**) 2045, and (**g**) 2050

4 Conclusions

This study emphasizes the significant role that high-resolution climate data and advanced hydrodynamic modelling play in understanding the evolving dynamics of coastal ecosystems, particularly in highly impacted areas, such as the MP basin of Taranto.

The MP basin is one of the most complex marine ecosystem models in terms of ecological, social, and economic activities. It is considered highly vulnerable due to the presence of a naval base, the largest refinery in Europe, and an oil refinery. Although it is a sea inlet corresponding to a rias, due to its typical lagoon features and limited water exchange, it is characterized by continued dispersion and accumulation of contaminants, with a strong ecological risk towards marine ecosystems and human health. Considering the shallowness of the MP system, wind is assumed to play a major role in affecting the hydrodynamic and biological processes.

The ability to integrate precise, localized climate information, such as that provided by the VHR-REA_IT and VHR-PRO_IT datasets, has enabled a detailed analysis of how changes in wind regimes could alter the hydrodynamic conditions within the basin, with particular regard to sediment transport and erosion processes.

The results of hydrodynamic simulations presented in the study show that, starting from 2035, a marked increase in current intensity is expected in both surface and bottom layers, primarily attributable to alterations in wind patterns.

This intensified current activity is expected to exert stronger shear stresses at the sediment-water interface, surpassing critical thresholds for sediment resuspension and leading to the mobilization of pollutants already present in the basin. This change is particularly evident in Bay II, where sediment resuspension and redistribution are more pronounced than they were in previous years. These findings highlight the vulnerability of the MP basin to future climate scenarios and the potential for exacerbated ecological risks due to enhanced sediment mobilization.

The outcomes of this research underscore the urgent need for more targeted remediation strategies to address the long-term impacts of climate change on heavily polluted coastal areas. In particular, it is crucial to incorporate climate data into coastal management and pollution control strategies to better prepare for the challenges posed by shifting environmental conditions. This approach can help mitigate further degradation of the marine ecosystems and safeguard both human health and biodiversity in vulnerable coastal regions such as the Taranto area.

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All authors read and approved the final manuscript.

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Declarations

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