Ecosystem modelling as a tool for marine coastal management

By

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Dr. Marco Zavatarelli y Dra. Nadia Pinardi, profesores en la Universidad de Bologna (Italia), como sus directores,

HACEN CONSTAR: que esta Memoria, titulada *"Ecosystem modelling as a tool for marine coastal management"* presentada por Da. Giulia Mussap, resume su trabajo de Tesis Doctoral y, considerando que reúne todos los requisitos legales, autorizan su presentación y defensa para optar al grado de Doctor en Gestión Marina y Costera/Marine and Coastal Management.

SIGNED: .... DATE: aug. 29 2016

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To the people I've met, who have taught me about life

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ABSTRACT

Ecological modeling can be a valid tool to understand, monitor and predict changes and interactions in the ecosystem dynamics. Knowledge on the social and ecological impacts on the environment have dramatically improved during the last decade thanks to the availability of new technologies.

The first steps of this thesis involved the coupling of the Biogeochemical Flux Model to the uni-dimensional version of the Princeton Ocean Model (BFM-POM 1D), as well as the retrieval of available observations from various sources for the Gulf of Trieste (northern Adriatic). Observational data was analyzed and prepared for its use both as forcing functions and validation purposes. The coupled pelagic model was then validated against observations and mechanistic experiments were performed on trophic chain interactions and external forcings. Results demonstrated the model to be stable and qualitatively valid for the area, as well as to have the potential as a management support tool.

Subsequently, an intermediate benthic compartment was added to BFM-POM 1D configuration. Sensitivity analysis on benthic-pelagic processes found best bottom sedimentation and diffusion parameters for the Gulf of Trieste. A mechanistic experiment involving the removal of filter feeders from the benthic system highlighted their important role in trapping pelagic organic matter and regulating benthic-pelagic fluxes in coastal areas.

Finally, a multi-parameter ensemble approach was carried out with the previously tuned BFM-POM 1D. Over 5000 experiments were carried out as a whole with different parametrizations, in view of its effective use as a management tool for stakeholders. The three scenarios considered were: S1 representing a surface temperature increase, S2 representing a decrease in surface phosphate concentrations or river loading and S3 representing a combination of the two. Frequency distribution histograms revealed the uncertainties associated to BFM-POM 1D and the likely reactions of the system to such pressures. Moreover, a simple and visual communication strategy was proposed to ease the communication between scientists and stakeholders. These encouraging results prompt towards a future effective collaboration between the two in order to reciprocally support each other in decision making processes.

Resumen

La modelización ecológica puede ser un herramiento válido para comprender, controlar y predecir los cambios en los flujos e interacciones de la biogeoquímica marina. El conocimiento sobre los impactos sociales y ecológicos en el medio ambiente ha mejorado dramáticamente en la última década, gracias a la disponibilidad de nuevas tecnologías.

Los primeros pasos de esta tesis participan el acoplamiento del Biogeochemical Flux Model a la versión uni-dimensional del Princeton Ocean Model (BFM-POM 1D) , así como la recuperación de las observaciones disponibles de diversas fuentes para el Golfo de Trieste (norte Adriático). Los datos de observación se analizaron y se prepararon para sus uso para obligar a las funciones y validar los resultados.

Despues, el modelo pelágico acopiado fue validado con las observaciones, y se realizaron experimentos mecánicos para investigar las interacciones de la cadena trófica y la relaciòn con los forzamientos externos. Los resultados demostraron que el modelo es estable y cualitativamente válido para la zona, así como tener el potencial como herramienta de apoyo a la gestión.

A continuación, un compartimiento bentónico intermedio se añadió a la configuración del BFM-POM 1D. Una análisi de sensibilidad en los procesos bentónicos-pelágicos encontró los mejores parámetros de sedimentación y difusión del fondo para el Golfo de Trieste. Un experimento mecanicista que implica la eliminación de los organismos filtradores del sistema bentónico, destacó su importante papel en la captura de materia orgánica pelágica y la regulación de los flujos bentónicos-pelágicos en las zonas costeras.

Por último, un enfoque conjunto de multi-parametrización se llevó a cabo con el BFM-POM 1D previamente regolado. Más de 5000 experimentos se llevaron a cabo con diferentes parametrizaciones, en vista de su uso efectivo como una herramienta de gestión para las partes interesadas. Tres escenarios diferentes presiones se tuvieron en cuenta: 1) presión 0 - las condiciones actuales, 2) presión 1 - aumento de la temperatura y 3) presión 2 - la disminución de carga de fosfato del río. Histogramas de distribución de frecuencias revelaron las incertidumbres asociadas a BFM-POM 1D y las posibles reacciones del sistema a tales presiones. Ademàs, se propuso una estrategia de comunicación sencilla y visual para facilitar la comunicación entre los científicos y los grupos de interés. Estos resultados alentadores impulsan a hacer una futura colaboración efectiva entre los dos, con el fin de apoyarse recíprocamente en los procesos de toma de decisiones.

TABLE OF CONTENTS

CHAPTER 1

PROLOGUE

Knowledge of the functioning of coastal ecosystems has dramatically improved during the last four decades, and the importance of the interactions among physico-chemical-biological processes has been widely recognized. The biogeochemical state of the ocean depends on biogeochemical cycling and on fluxes across the ocean boundaries (land, atmosphere and sea floor [20]).

Shallow shelf seas are the most productive regions of the global ocean and play a fundamental role in shaping global biogeochemical dynamics and trophic interactions. The coastal ocean is also directly influenced by anthropogenic pressure and is subject to eutrophication as well as hypoxia/anoxia events. Understanding the biogeochemical interactions and functioning of the system, and the anthropogenically induced changes, is therefore essential [16] in order to be able to correctly face these problems.

Ecological modelling has strongly developed and improved during the last two decades, allowing to test specific hypotheses and investigate the integrated effects of various factors under given assumptions [35]. In fact, it can inform on the behaviour of the ecosystem as a whole [18].

In the present thesis we worked on the understanding of the ecosystem functioning in a shallow shelf sea (Gulf of Trieste, northern Adriatic) in relation to management issues. Sensitivity and mechanistic experiments on the pelagic and benthic realms were carried out with a coupled physical-biogeochemical 1D model (BFM-POM 1D). Trophic interactions were explored via sensitivity and mechanistic experiments, and a multi-model ensemble framework was employed for the management of hypoxia.

1.1 Aims of the thesis

- to establish and test the structure of a coupled (physical-biogeochemical) one-dimensional numerical model (BFM-POM 1D) in order to evaluate its suitability as a tool for testing environmental management options for coastal oceans
- to establish and test the structure of the benthic compartment and provide an understanding of the extent to which the benthic "biogeochemical machinery" determines the sediment-water fluxes
- to provide a range of useful information and contribute to the decision-making process in coastal ecosystem-based management through effective communication with stakeholders

1.2 Data and model overview

In order to fulfill the aims proposed for the thesis, the following datasets and models were used:

- The Biogeochemical Flux Model (BFM), open source (http://bfm-community.eu/)
- The Princeton Ocean Model (POM), open source (http://www.ccpo.odu.edu/POMWEB/index.html
- Wind stress and solar radiation generated by the ECMWF (http://www.ecmwf.int/)
- Temperature, salinity and biogeochemical data from the Regional Environmental Agency (ARPA-FVG, http://www.arpa.fvg.it/cms/) and the Italian National Oceanographic Data Center/IOC (http://nodc.ogs.trieste.it/nodc/)

1.3 Structure of the thesis

The thesis is organized as follows:

- Chapter 2: Introduction

- Chapter 3: A management oriented 1-D ecosystem model: implementation in the Gulf of Trieste (Adriatic Sea)
- Chapter 4: A numerical study of the benthic-pelagic coupling in a shallow shelf sea (Gulf of Trieste)
- Chapter 5: Linking coastal ocean modeling to environmental management: an ensemble approach
- Chapter 6: Conclusions

CHAPTER 2

INTRODUCTION

This thesis describes the implementation of a coupled 1D physical-biogeochemical model (BFM-POM 1D), the experiments carried out to validate the model and investigate ecosystem characteristics, and the discussion on its potential use as a marine coastal management tool. The work began with the coupling of the open source Biogeochemical Flux Model (BFM) with the 1D version of the open source Princeton Ocean Model (POM). *In situ* observations were retrieved from various sources and institutions for the Gulf of Trieste (northern Adriatic), and analysed in order to use them both as external forcings and for model validation.

Chapter 3 focuses on the first big step of this work: the coupling between BFM and POM 1D and its validation against observations in the Gulf of Trieste. The model's robustness and the trophic structure characteristics were investigated via mechanistic experiments involving the alternate isolation of the microbial and herbivorous food webs, and via a sensitivity experiment on external forcing. Results were encouraging and gave the basis for a further development of the model in view of its potential use as a supportive management tool.

As a continuation of the work, the model was further developed in Chapter 4 by introducing a benthic system of intermediate complexity, which was absent from the previous application. The application of the model with these new configurations focused on examining the benthic-pelagic coupling dynamics as well as the benthic organisms interactions with the surrounding system. Sensitivity experiments on sedimentation and diffusion were carried out in order to find the best possible combination to represent the benthic-pelagic coupling dynamics of the Gulf of Trieste. Moreover, the role filter feeders play in regulating benthic-pelagic fluxes was investigated via a mechanistic experiment, revealing interesting results.

Once the fully coupled BFM-POM 1D was validated, an ensemble study was carried out in Chapter 5 to investigate model uncertainty. Scenario studies which dealt with temperature and phosphates concentrations variations were designed and ensemble experiments performed on them. The resulting distributions were observed and compared to the deterministic simulation. The representation of the results was then contextualized and a communication strategy was proposed between the scientific community and the stakeholders.

The following paragraphs introduce the reader to the world of ecological modelling, its potential and its limits. The contribution of ecological modeling to marine coastal management is also discussed, as well as the necessity of new communication strategies.

2.1 Overview

During the last 10 to 20 years, knowledge of social and ecological impacts on the environment has improved dramatically as a result of the advance in technology and the increase of available datasets. At the same time, the use of environmental resources has rapidly accelerated leading to an enhanced pressure on ecosystems. Thus, the human society played and is still playing a crucial role in defining the environmental state of the global ecosystem. However, although scientific knowledge has experienced a sharp rise concurrent to the technological advances, how to deal with such a rapidly changing system is still uncertain. One of the biggest and most difficult effects to deal with such changes is the speed at which they occur. Restructuring the system and understand how it is going to change is not a trivial challenge. Moreover, this is further complicated by the natural variability of a system. Although the unexpected feedbacks are mostly linked to humans, ecology also carries a certain degree of uncertainty due to the fact that it has never experienced before such a rapid change. Because of the multi-scale anthropogenic pressure, it is important to consider also the reciprocal interactions and not just consider them in isolation. Indeed, environmental changes have also implications for trading, human conflicts and movement of people around the world. Managing the ocean therefore deals with new ways of looking at the social and human side, as well as understanding ecosystems and balancing trade-offs.

The dynamics of coastal ecosystems are extremely complex due to the countless interactions between the living and non-living components. Small changes in the pressures acting on the system can lead to large structure shifts, depending on the site specific physical and biogeochemical characteristics. Given that coastal areas are heavily inhabited and are home to very delicate systems, understanding and being able to represent such systems is of tremendous importance. *In situ* measurements and observations cannot cover all the interactions taking place, and can only give a general view of the present situation. Numerical modelling however, offers the possibility of representing the bigger picture by including smaller processes and interactions.

Already in 1993 Costanza et al. [14] were acknowledging both the need to use models for policy evaluation, and their misuse by legitimizing rather than informing the policy decisions. Since then, new and more complete models have been developed and computational performance has improved. However, the use of models in the decision making process is still controversial and this can be partially associated to an ineffective communication strategy. This is mostly because users got used to single values, which imply a certain degree of confidence. However, no simulation is complete without a description of the uncertainty, or likelihood, of a particular event [15]. Presenting results with the associated uncertainties gives the users a certain degree of freedom in the decision making process. Although stakeholders often ask for either black or white answers, science is mostly grey, which is why representing uncertainty is fundamental. Communicating it effectively consequently becomes vital.

2.2 Ecological modelling

Ecological modelling was first explored in the 20s when Lotka [44] and Volterra [74] presented the first simple ecological model, which consisted in a set of simple equations describing the prey-predator population dynamics. Two decades later, Riley presented the first mechanistic numerical ecosystem model which associated the biological rates to environmental factors such as temperature and irradiance [63]. He also managed to combine the phytoplankton and zooplankton in his model with remarkable results.

It is only during the last decades that significant advances were made in ecological modelling, when high computing power became available. In the late 80s modelling was accepted and recognized as a mainstream research tool and their use in coastal management exploded[8].

Nowadays, many types of ecological models from which one can choose are available, depending on the destined use and their limitations. These include: biogeochemical and bioenergetic dynamic models, static models, structural dynamic models, fuzzy models, artificial and neutral networks, individual based models and cellular automata, spatial models, ecotoxicological models, stochastic models and hybrid models [12].

Generally speaking, three main issues are true for all models: 1) the insufficiency of available observed data, fundamental for the validation of the model, 2) a weak parameter calibration and 3) a faulty reflection of the real properties of the ecosystems [42]. The first problem can be potentially solved by organizing more sampling cruises, while the other two problems deal with the model itself and are, to a certain extent, linked.

Since it is not possible to examine each single process taking place in nature, parameters are calibrated based on the final representation of the system. Moreover, single processes behave differently when separated from the dynamic system they originate from. As Allen explained [1], "the whole is greater than the sum of the parts". This is why it is important to carry out the parametrization approximation by looking at the outcome of the "bigger picture" rather than at the specific parameter. However, an erroneous parameter calibration may lead to an inaccurate representation of the system.

Although models will never be able to contain all the features of the real system itself, it is only important that the model contains the characteristics features essential in the context of the problem to be solved or described [41]. In fact, ecological modelling requires a comprehensive knowledge of the functioning of the system, but a balance of their complexity needs to be found based on available data and the issue to be explored [42].

2.3 Communicating modeling to managers

Communicating science to stakeholders is already complicated as it is; communicating science and persuade them to use it for management issues is a challenge. Nonetheless, taking into consideration different aspects of the environment has long been recognized to be crucial for the management of the delicate systems present in coastal areas, and the most effective way to do this is via numerical modeling. An ecosystem-based management (EBM) approach is one that takes into account natural changes and human activities as a whole. The aim is to have an integrated view of complex systems and be able to adopt the most appropriate management strategy considering various aspects from different sectors. In contrast to the management strategies adopted in the past, which did not considered single issues as part of a greater whole, EBM acknowledges the cumulative dynamics, reactions and impacts of different fields in a given system.

One of the major obstacles scientists have to face in the communication process to stakeholders, is the communication of uncertainty of the results. One way to face this is the application of a multi-parametrization ensemble approach. An ensemble is a group of model simulations designed to explore the main sources of uncertainty associated with the output of a simulator [69]. Ensemble forecast methods are well established in meteorology [60], but this is not the case for oceanography, and even less so for ecology, where results tend to give only single-value projections. Single-value projects imply a certain degree of confidence, and this cannot be true in such complex systems where so many fluxes are involved and many parameters have been subject to guess work. In order to have an effective communication strategy, ensemble prediction techniques are therefore fundamental.

Finally, attention must be given to the communication strategy of these results with the associated uncertainties. A visual approach would be considered to be the best one as it would be the most intuitive.

CHAPTER 3

A MANAGEMENT ORIENTED 1-D ECOSYSTEM MODEL: IMPLEMENTATION IN THE GULF OF TRIESTE (ADRIATIC SEA)

This chapter shows the results of the sensitivity and mechanistic experiments on the pelagic ecosystem structure carried out with the numerical model BFM-POM 1D in the Gulf of Trieste (northern Adriatic). The BASE (reference) experiment results were qualitatively validated against available observations. The findings of this chapter demonstrated the model's suitability as a supportive tool for marine coastal management. The main output of this chapter set the basis for a further development of the model to include benthic dynamics (Chapter 4).

The preliminary results of the experiments were presented as oral presentation in AMEMR IV - Advances in Marine Ecosysytem Modelling Research held in Plymouth, UK, in 2014, and in IMBIZO IV - Marine and human systems: Addressing multiple scales and multiple stressors held in Trieste, Italy, in 2015. The final results of the experiments were communicated in *Regional Studies of Marine Science* with the following referencing:

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A management oriented 1-D ecosystem model: Implementation in the Gulf of Trieste (Adriatic Sea)

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HIGHLIGHTS

- The BFM–POM 1D system successfully replicated the observed seasonal variability.
- The microbial food web dominates the Gulf of Trieste trophic structure.
- External inputs variability can change the trophic web structure.
- A first step for developing a modelling system supporting environmental management.

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ABSTRACT

In this paper a coupled physical–biogeochemical one-dimensional numerical model (BFM–POM 1D) was implemented in the Gulf of Trieste, (northern Adriatic Sea) and its structure was tested in order to evaluate its usability as a tool to support coastal management and planning. The evaluation concerned the ability of the model to reproduce the main trophic pathways, as well as their temporal variability, in terms of seasonal variations. The ecosystem structure comprised three phytoplankton groups, four zooplankton groups, one bacterial group, and a simple benthic return in order to parametrise benthic processes. The dynamics and interactions between groups were studied, as well as the model's sensitivity to different trophic web configurations. Results showed that the model was capable of replicating the behaviour of seasonal vertical profiles of the major biogeochemical elements, and the prevalence of the microbial food web shaping the trophic chain in the Gulf of Trieste. The model also responded to strong forcings at the surface and different trophic arrangements, thus providing initial evidence of its potential as a scientific tool aimed at marine coastal management.

1. Introduction

The biogeochemical state of the ocean depends on biogeochemical cycling and on fluxes across the ocean boundaries (land, atmosphere and sea floor, Doney, 2010). In shallow coastal waters (the most productive regions of the global ocean), the role of such fluxes is amplified. These areas therefore play a fundamental role in shaping global biogeochemical dynamics and trophic interactions. However, they are also very vulnerable and subject to strong anthropogenic pressure that significantly affects the major marine biogeochemical cycles.

In order to define and implement ecosystem-based options and strategies, a deep understanding of the functioning and dynamics of the ecosystem is required (Curtin and Prellezo, 2010). Observational and modelling tools can be used to assess the current state of the system, its main ecosystem attributes exposed to the joint action of direct and indirect anthropogenic pressure, and subsequently to explore the effects related to the implementation of a specific management plan. Thus, the modelling tool (supported by an adequate observational base), plays a critical role to envision how the major biogeochemical fluxes could change and/or modify their interactions in response to the drivers (e.g. climatic and/or anthropogenic) of change.

In 2003 Vichi et al. implemented the biogeochemical model ERSEM (Baretta et al., 1995), from which the BFM was later developed, in three sites in the northern Adriatic. Apart from our overall aim, the major differences of our study with respect to

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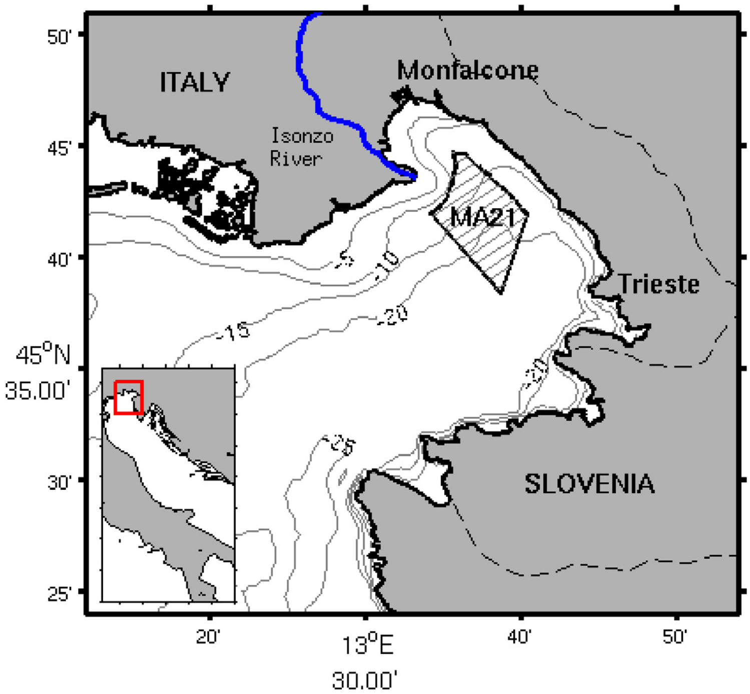

Fig. 1. Map and bathymetry (in metres) of the Gulf of Trieste with location of the implementation area MA21.

Vichi et al. (2003) were the use of the latest version of BFM and the implementation of the hydrodynamical model in a diagnostic mode. The aim of this paper is to establish and test the structure of a coupled (physical–biogeochemical) one-dimensional numerical model (BFM–POM 1D) in order to evaluate its suitability as a tool for testing environmental management options for coastal oceans. We studied the ecosystem structure of lower trophic levels (primary producers and consumers) and their interactions by investigating the sensitivity of the simulated fluxes with respect to different configurations of the trophic web and to a stronger surface forcing. Mechanistic experiments were thus carried out and results are discussed with emphasis on the changes in the fluxes determined by such configurations. The experiments comprised the alternating activation/deactivation of the herbivorous and microbial foodwebs and the amplification of surface nutrient forcing. A qualitative study of system reactions was carried out in order to understand the extent to which different compartments determine carbon fluxes and biogeochemical cycling.

As an initial testbed, the model was implemented and tested in the Gulf of Trieste (northern Adriatic Sea). The reason for this choice is twofold: the Gulf has been the focus of previous modelling efforts (Vichi et al., 2003; Butenschon et al., 2012) and a rich dataset is available, thus enabling the definition of a valid and reliable hydrological climatology.

2. Materials and methods

2.1. Model implementation

Bordering Italy and Slovenia on the northern-east coast of the Adriatic sea (Fig. 1), the Gulf has an average depth of 20 m. The whole area is strongly affected by river runoff, especially along the shallow northwestern coast (Isonzo River). The implementation area was chosen on the basis of the Gulf's macroareas identified by the regional environmental agency (ARPA-FVG), on the basis of the distance from the coast, geomorphology, hydrological characteristics (water column stability) (Butenschon, 2012) and freshwater inputs. Following the definition of the area types, the hydrological bodies were identified on the basis of the environmental status highlighted in previous monitoring campaigns, the limits of the protected areas, and the pressures influencing the achievement of the quality objectives.

The model implementation area is code-numbered MA21 and is situated in the centre of the Gulf (Fig. 1). Monitoring data for to the whole area were analysed and used to set initial conditions, surface boundary conditions, and to validate the model's performance.

The hydrological features of the Gulf show a very large interannual and seasonal variability (Vichi et al., 2003). Although the circulation is very variable, the Gulf is generally characterised by a cyclonic circulation mainly driven by freshwater inputs by the Isonzo and Po rivers, while tidal currents play a small role in the circulation (Guarnieri et al., 2013). The biogeochemical characteristics of the Gulf of Trieste are also subject to a significant interannual variability depending mostly on the variability of the land based nutrient inputs conveyed to the sea above all by the discharge of the Isonzo river and by anthropogenic pressure. This gives rise, for instance, to a wide qualitative and quantitative variability in the phytoplankton population structure (Mozetic et al., 1998, 2010; Tedesco et al., 2007). Nonetheless, generally speaking the Gulf, as with most of the Mediterranean, is P-limited. As a result of such physical features, primary production is characterised by a winter bloom and by high concentrations near the seabed during spring and summer.

2.2. Coupled numerical model set-up

The one-dimensional coupled numerical model used is composed of the one-dimensional version of the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) and the Biogeochemical Flux Model (BFM) (Vichi et al., 2007).

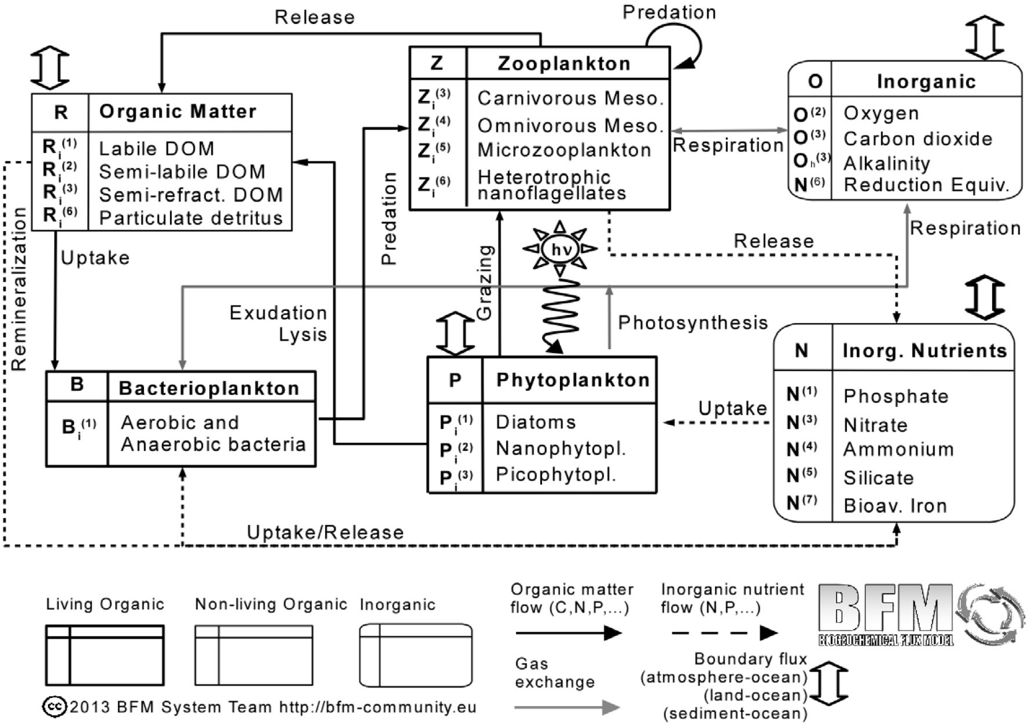

Fig. 2. General overview of the matter fluxes between the BFM state variables. Square boxes represent the model functional groups exchanging Carbon (C), Nitrogen (N), Phosphorus (P), Silicon (Si) and Oxygen (O). Organic matter (C, N, P, Si) flows are indicated by solid black arrows; N, P and Si nutrient uptake/remineralisation flows are represented by the dashed black arrows. Solid grey arrows mark the gas C (Carbon dioxide) and O flows. Purely biochemical processes are indicated by the dashed grey arrows. Small double arrows above the boxes mark boundary (water–atmosphere and water–sediment) flow. After Vichi et al. (2007).

The open source BFM (http://bfm-community.eu/) describes the physiological and population processes of lower trophic levels in the marine environment. Biota is described by means of three main functional groups: producers, decomposers and consumers, each one defined by internal constituents: carbon, nitrogen, phosphorous, oxygen and (in the case of diatoms) silicon (Vichi et al., 2007). The model includes three phytoplankton groups (diatoms, nanophytoplankton and picophytoplankton), four zooplankton groups (carnivorous mesozooplankton, omnivorous mesozooplankton, microzooplankton and heterotrophic nanoflagellates) and one bacterial group. Trophic and chemical interactions are represented through chemical functional families (CFFs) and Living Functional Groups (LFGs) (Vichi et al., 2007). CFFs are defined as the inventory of a certain biogeochemical element contained in complex living and non-living components, and are divided into three main groups: non-living organic, living-organic and inorganic. These groups are measured based on the major chemical elements (C, N, P, Si, O) or on molecular weight units as with chlorophyll. The living organic group represents the LFGs, which are made up of producers (phytoplankton), consumers (zooplankton) and decomposers (bacteria). The dynamics of each of these are described by population processes (growth, migration, mortality) and physiological processes (photosynthesis, ingestion, respiration, excretion, egestion). Regarding the benthic compartment, a simple benthic return was used (see Table A.7). This choice was made in order to simplify an already fairly complex system. Since the focus was directed towards the interactions in the pelagic realm, a simple benthic return was considered initially sufficient to support major biogeochemical dynamics. In fact, this configuration was already found to be a valid replacement to complex benthic dynamics (Vichi et al., 2003). Fig. 2 shows the biogeochemical model structure and a detailed description of each model component can be found in Appendix A.

POM is a primitive equation ocean circulation model formulated in sigma coordinates that computes diffusivity by means of a second-order turbulence closure scheme proposed by Mellor and Yamada (1982). We used the one-dimensional version of the model implemented with 30 σ layers ($\sigma = z/H$) logarithmically distributed near the bottom and surface. In this implementation, the bottom depth is $H = 16$ m, corresponding to a typical depth for area MA21. At each model timestep, the hydrodynamics computed by POM provides the BFM with information on the physical environment. The coupled model combines physics with biology to compute the temporal rate of change of a generic biogeochemical variable (expressed in terms of concentration, see Appendix A). The two components of the modelling system are coupled online using the source-splitting method described in Butenschon et al. (2012).

Following Bianchi et al. (2006) we used POM in diagnostic mode: the climatological time dependent (monthly varying) temperature and salinity vertical profiles, obtained from data, were prescribed, while the vertical profiles of vertical diffusion coefficients were computed by the model through the (Mellor and Yamada, 1982) second order turbulent closure scheme. The coefficients are used to compute the vertical profiles of the BFM state variables. The use of the "diagnostic" mode eliminates possible drifts in temperature and/or salinity due to the use of a "non zero" surface heat and/or mass surface fluxes or to the lack of a proper parametrisation of the lateral advective fluxes, which are by necessity not contained in a one-dimensional model implementation. The use of the diagnostic mode with climatological data, provides a stable (non-drifting) annual cycle of the vertical density structure, which is particularly suitable when using the numerical model to evaluate possible options of environmental management. Clearly, the reliability of the simulations relies on the quality of the assembled climatology. Therefore, a 1-D modelling system relying on the

Table 1
Summary of available measured data, source, period and application. Climatologies were used as model forcings and for validation purposes. The model derives the Photosynthetic Available Radiation (PAR) from the total solar radiation.

Variable	Units	Period	Climatology
Forcings			
Temperature	°C	2000–2011, 2013	Monthly
Salinity	psu	2000–2011, 2013	Monthly
Wind stress	N m^{-2}	2000–2013	Monthly
Solar radiation	W m^{-2}	2000–2013	Monthly
Inorganic suspended matter	mg m^{-3}	1997–2000	Seasonal
Phosphate	mmol m^{-3}	1998–2001	Monthly
Nitrates	mmol m^{-3}	1998–2001	Monthly
Ammonium	mmol m^{-3}	2000–2001	Monthly
Silicate	mmol m^{-3}	2009–2012	Monthly
Validation data			
Phosphate	mmol m^{-3}	1998–2001	Seasonal
Nitrates	mmol m^{-3}	1998–2001	Seasonal
Ammonium	mmol m^{-3}	2000–2001	Seasonal
DOC	mg m^{-3}	2000–2001	Seasonal
POC	mg m^{-3}	2000–2001	Seasonal
PON	mmol m^{-3}	2000–2001	Seasonal
Oxygen	mmol m^{-3}	2000, 2002–2011, 2013	Seasonal
Chlorophyll-a	mg m^{-3}	2000–2011, 2013	Seasonal

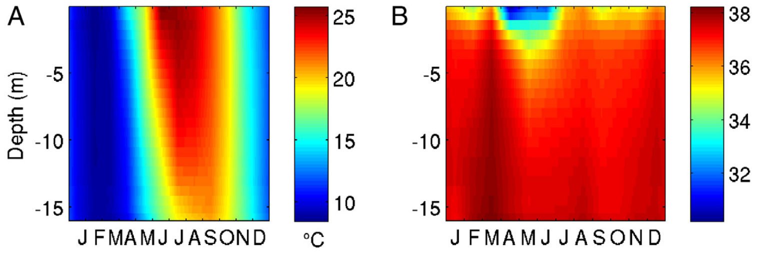

Fig. 3. Temperature (A) and salinity (B) monthly climatological profiles calculated from available *in situ* data (Table 1) fed to the model and interpolated on its time step.

diagnostic description of the density vertical structure entails the implementation in a hydrological "data-rich" area such as areas where observing systems are in place. The hydrological data (temperature and salinity profiles) used to compose the prescribed climatology originate from the monitoring activities carried out in the MA21 by ARPA-FVG and OGS from 2000 to 2013 (see Table 1).

The climatological annual cycles of the vertical temperature and salinity are shown in Fig. 3(A) and (B), respectively. They show a seasonal cycle characterised by well-mixed conditions in the winter and by vertical thermal stratification in the summer. Surface salinity is affected by pulses of freshwater mostly due to the Isonzo river discharging in the Gulf, while below the surface, there are periodical increases in the salinity value, most probably due to the ingression of saltier water in the Gulf (Malacic and Petelin, 2009).

2.3. *Forcing functions and initial conditions*

The use of the diagnostic mode for the physical component of the modelling system, entails specifying the surface wind stress as the only surface forcing function. The annual, monthly-varying, climatology used here was obtained from the 6-hour ECMWF ERA-interim reanalysis (Berrisford et al., 2009) for 2000–2013 (Fig. 4(A) and Table 1). Wind stress is highest and more variable (higher standard deviations) during winter and autumn, reflecting the prevalence of the typical strong Bora (northeasterly) and Scirocco (southeasterly) winds, respectively (Kourafalou, 1999; Zavatarelli et al., 2002). Winds are weaker during spring and summer.

The daily surface incident shortwave radiation necessary to force the BFM primary production module also originates from the ECMWF data (Fig. 4(B) and Table 1). The ECMWF solar radiation arriving at the sea surface penetrates the vertical column as photosynthetically available radiation (PAR). The PAR vertical profile is then calculated using the Lambert–Beer equation (see Appendix A) using a vertical extinction coefficient composed of the time-dependent prognostic phytoplankton and particulate detritus concentrations. In addition extinction is used depending on the inherent optical properties of the seawater and the concentration of inorganic suspended matter (ISM), whose seasonally averaged profiles originate from direct measurements in area MA21 (Fig. 4(C), Table 1). Observations were collected monthly over the period 1997–2000 (Vichi et al., 2003). The inconsistency of the time period used between other physical forcings (2000–2013) and ISM (1997–2000) is due to the scarce climatological information available concerning seasonal mean concentrations. This degree of uncertainty was taken into account in the general performance of the model.

In order to parametrise the external (land based) nutrient input, we defined a surface nutrient flux by relaxing the surface value to a monthly varying climatology of phosphate, nitrate, ammonia and silicate (Table 1, Fig. 4(D)). The surface boundary conditions used are detailed in Appendix A (see Eq. (A.5)).

The initial climatological conditions for biogeochemical pelagic components were set for a vertically-homogeneous profile consistent with the observed winter concentrations. The benthic system was initialised with an educated guess regarding the detrital organic matter based on the literature (Giordani et al., 1992). Tests to determine the spin up period showed that a five year integration period yielded a repeating seasonal cycle after three years. Therefore, results were analysed from the fifth year of simulation, where the first four years were considered as the specific spin-up time necessary for the model to find equilibrium.

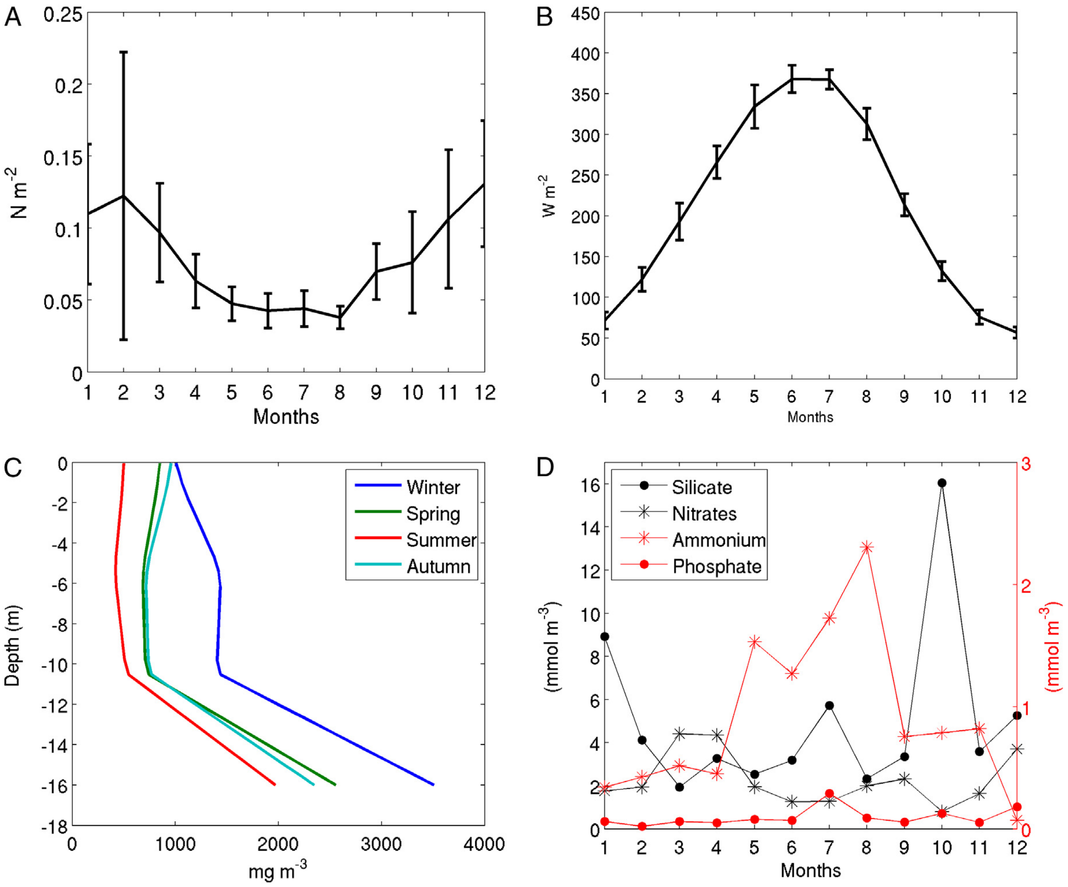

Fig. 4. Climatological forcing functions (A) Wind stress monthly varying climatology from the 6-h ECMWF ERA-interim reanalysis relative to the period 2000–2013. (B) Solar radiation daily varying climatology from the 6-h ECMWF ERA-interim reanalysis relative to the period 2000–2013. (C) Inorganic Suspended Matter (ISM) monthly varying climatological concentrations for the period 1997–2000. (D) Surface monthly varying climatological concentrations of nutrients for the period 1998–2012 (see Table 1).

2.4. Validation data

Tables 1 and 2 summarise the biogeochemical observations used to validate the model results at the seasonal climatological level (winter: January to March, spring: April to June, summer: July to September, autumn: October–December).

The biogeochemical data used to force the model are scarce but temporally consistent with the profiles used for validation. Chlorophyll and oxygen validation profiles were computed from a longer time period compared to the other variables, resulting in a relatively more robust seasonal climatology.

Seasonal climatological vertical profiles were computed from the available data, along with the corresponding standard deviations (unless lack of data prevented its calculation). Seasonal profiles and corresponding standard deviations are shown in Fig. 5 for comparison with the model results.

2.5. Numerical experiments

Mechanistic experiments were performed in order to understand the low level trophic ecosystem structure and test the capacity of the model as a scientific tool aimed at tackling coastal management issues. As Kiørboe (2008) and Azam and Long (2001) argue, our knowledge on the lower level trophic system is rudimentary and there is the need for a mechanistic understanding of the system. With the mechanistic methodology we intend to modify trophic interactions in order to demonstrate the importance of the different functional ecosystem components in the organic carbon flux dynamics.

The overall response of the model was assessed. In particular, we evaluated the sensitivity of the system to different levels of nutrient forcing as well as to the presence/absence of a full herbivorous chain and microbial loop in the simulated ecosystem. Table 3 presents the simulations carried out.

The BASE experiment was carried out with the full BFM, and the results were used to validate the modelling system. With the MICRO and HERB experiments, the role of the two trophic structures – classical herbivorous food chain versus microbial food web – were studied. The aim of the experiments was to understand to what extent the microbial web, previously proven to be key to certain fluxes and dynamics (Fonda Umani and Beran, 2003), shapes the trophic structure in relation to the herbivorous food web. The two food chains were isolated one at a time, and details of the resulting trophic structures are provided below. The HERB experiment configuration simplifies the system thus making it a more classical NPZD model, where microbial dynamics are absent and the system is closed by a constant remineralisation rate. Organic matter remineralisation is thus computed by introducing a constant remineralisation rate, which is not temperature dependent, while the grazing pressure on the primary producers is entirely dependent on the herbivorous mesozooplanktonic group.

Finally, experiment BASE × 5 examined the model's sensitivity to different surface nutrient forcing scenarios. Testing the model's response to different drivers is fundamental in order to

Table 2
Number of samples per biochemical variable divided by season in the depth intervals indicated. For chlorophyll and oxygen, numbers refer to 1 m vertical resolution casts.

Variable	Depth (m)	Winter Jan–Mar	Spring Apr–Jun	Summer Jul–Sep	Autumn Oct–Dec
Chlorophyll	Casts	62	66	65	66
Oxygen	Casts	56	63	60	60
Nitrates	0–3	19	17	15	13
	3–6	5	12	9	3
	6–9	3	4	2	3
	9–12	11	7	7	5
	12–15	0	7	5	3
	15–18	0	0	6	0
Phosphate	0–3	10	11	11	8
	3–6	3	8	5	2
	6–9	0	2	1	2
	9–12	7	5	5	4
	12–15	0	3	3	1
	15–18	0	0	3	0
Ammonium	0–3	8	6	6	4
	3–6	2	4	4	1
	6–9	2	2	1	1
	9–12	4	2	2	1
	12–15	0	4	2	2
	15–18	0	0	3	0
DOC	0–3	7	6	6	4
POC	3–6	2	4	4	1
PON	6–9	2	2	1	1
	9–12	4	2	2	1
	12–15	0	4	2	2
	15–18	0	0	3	0

Table 3
Summary of numerical experiments: BASE (complete BFM), MICRO (only microbial food web), HERB (only herbivorous food web) and BASE × 5 (multiplies by 5 the surface nutrient forcing). P1: diatoms, P2: nanophytoplankton, P3: picophytoplankton, Z3: carnivorous, Z4: omnivorous mesozooplankton, Z5: microzooplankton, Z6: heterotrophic, B1: bacteria.

Experiment	Herbivorous (P1, P2, Z3, Z4)	Microbial (P3, B1, Z5, Z6)	Surface nutrients
BASE	Yes	Yes	clim.
MICRO	No	Yes	clim.
HERB	Yes	No	clim.
BASE × 5	Yes	Yes	clim. × 5

provide consistent predictions regarding changes in the major biogeochemical fluxes. In this experiment, the surface nutrient data fed to the model were multiplied by five, thus dramatically increasing the nutrient concentrations.

3. The BASE experiment and its sensitivity

3.1. Seasonal validation

The BASE experiment was designed to validate the model results from the full blown BFM. Simulated seasonally averaged vertical profiles of chlorophyll, oxygen, phosphate, nitrates, dissolved organic carbon (DOC), particulate organic carbon (POC) and particulate organic nitrogen (PON) were compared to the corresponding seasonal profiles observed (see Table 1).

The simulated and observed seasonal profiles are compared in Fig. 5. The results indicate that the model replicates chlorophyll and oxygen seasonal variability within one standard deviation (Fig. 5, rows A and B respectively). Seasonal profiles always fall within the observed standard deviation, except for the simulated spring chlorophyll profile, which is underestimated. The simulated vertical profiles of phosphate and nitrates (Fig. 5, rows C and D respectively) lie close to the mean or fall within one standard deviation of the specific observations. However, the simulated seasonal variability of ammonium (Fig. 5, row E) for winter and spring is characterised by a concentration increase in depth which does not match the observed data. This overestimation is certainly one aspect of the model's configuration that requires careful attention. The constant benthic remineralisation rate and the absence of a complex benthic chamber could be the reason behind this mismatch.

The simulated vertical profiles of DOC, POC and POM (Fig. 5, rows F, G, H respectively) show points of agreement and disagreement with observations. In the majority of the observed vertical points, the data were so scarce that it was not possible to compute the standard deviations, and an evaluation of the model's reliability is therefore difficult. Although simulated concentrations are underestimated, DOC seasonal profiles show a qualitative agreement with observations (homogeneous vertical profiles in winter and autumn, and concentrations decreasing in depth in spring and summer). On the other hand, the POC and POM simulated profiles show vertical structures that differ from the vertical profiles observed, with a nearly constant increase from the surface to the bottom. Concentration magnitudes however fell within the bulk values. Again, the mismatch in the vertical structure could be connected to the simplified benthic boundary condition, which does not account for major benthic processes.

3.2. Sensitivity of the forcings

Given the temporal non-homogeneity in the datasets used to define the model forcings (see Table 1), a sensitivity test was

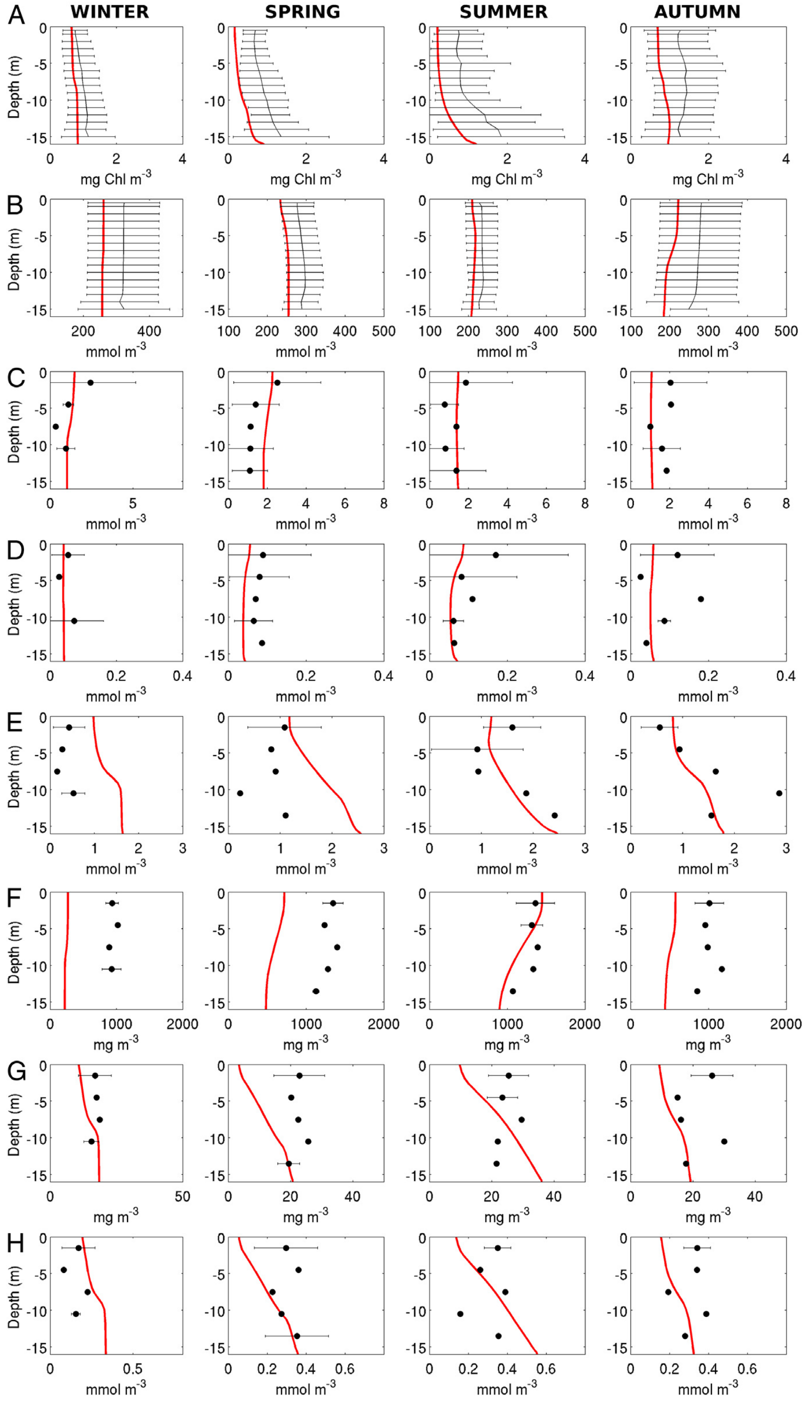

Fig. 5. Model and data comparison for (A) chlorophyll, (B) oxygen, (C) nitrates, (D) phosphate, (E) ammonium, (F) DOC, (G) POC and (H) PON as climatological seasonal profiles for site MA21. The continuous red line is the simulated mean seasonal profile, while observations are plotted as seasonal means with the standard deviation (where data allows it). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

carried out using different time averaged surface biochemical and physical fields. It was decided to force the model only with temperature, salinity, wind stress and solar radiation from the overlapping period, 2000–2001. Biogeochemical seasonal vertical profiles were compared to the BASE experiment and the results are shown in Figure S1. This sensitivity experiment showed that the average forcings of temperature, salinity, solar radiation and wind stress for 2000–2001 produced seasonal profiles that fell within a 25% difference compared to those obtained in the BASE experiment.

The results show that the different time-averaged forcings produced qualitatively the same ecosystem response. The largest dif-

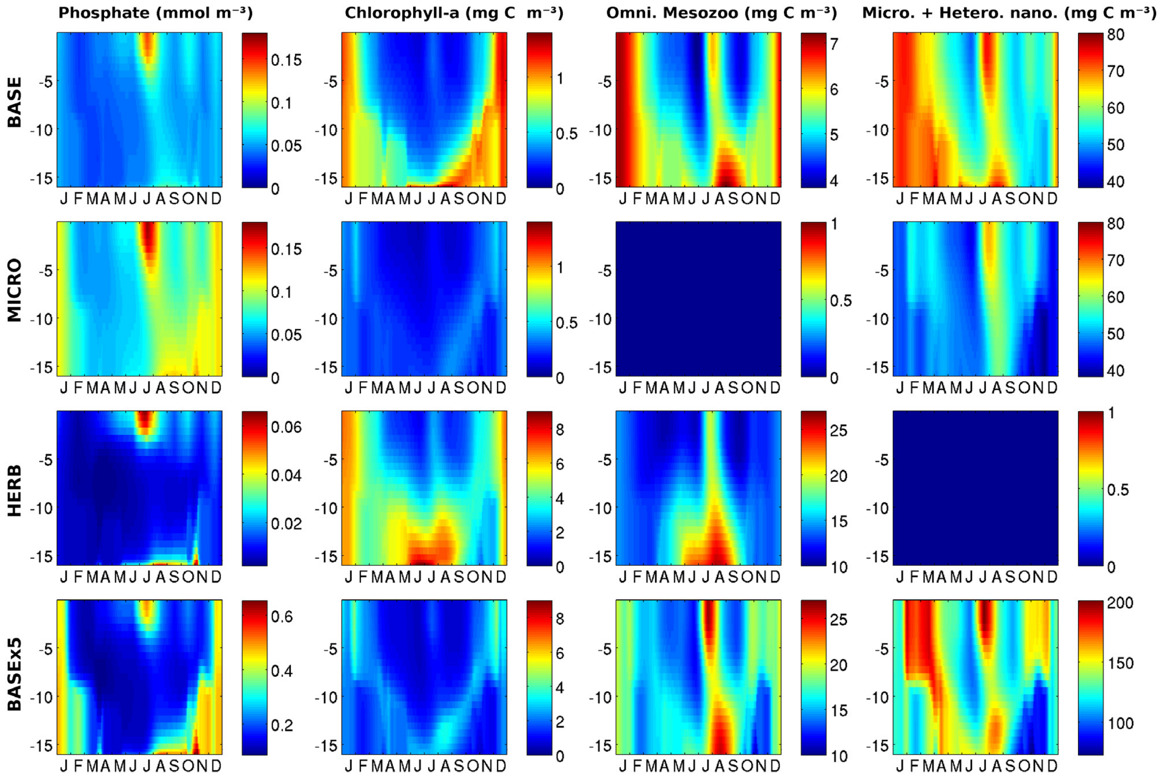

Fig. 6. Hovmöller plots of modelled results of phosphate, chlorophyll-a, omnivorous mesozooplankton and microzooplankton with heterotrophic nanoflagellates for the BASE, MICRO, HERB and BASE × 5 experiments (top to bottom). Depth on the *y*-axis, months on the *x*-axis. Note the differences in scales.

ferences were in oxygen and nitrates in summer, and in ammonia in winter and autumn due to the sensitivity to chemical rates to different temperature conditions. We believe that such differences do not affect the conclusions regarding the identification of the carbon pathways in the mechanistic experiments because the changes revealed by those experiments are much larger than the changes between the BASE and the sensitivity experiment.

4. Mechanistic experiments

4.1. MICRO experiment

In the MICRO experiment (Table 3, Fig. 6) the herbivore components of the trophic web (diatoms, nanophytoplankton, carnivorous and omnivorous zooplankton) were removed from the model. The model was run with only the microbial food web active. The absence of a herbivorous chain results in an increase in the available phosphate concentrations compared to the BASE experiment, most probably due to the reduced competition for nutrients. On the other hand, chlorophyll and microzooplankton (microzooplankton and heterotrophic nanoflagellates) concentrations decrease. This result could be due to fewer photosynthetic organisms in the system, which cause both a lower primary production and less prey available for microzooplankton. Despite these system changes, however, the temporal evolution and distribution of concentrations in the water column throughout the year is comparable to that of the BASE experiment. The fact that concentrations and distribution do not greatly differ from the BASE experiment highlights the importance of the microbial trophic web in this area.

4.2. HERB experiment

In the HERB experiment (Table 2, Fig. 6), the simulated trophic web was reduced to the herbivore branch by removing all the microbial functional groups (bacteria, picophytoplankton, microzooplankton and heterotrophic nanoflagellates). To some extent, this configuration simplifies the system by making it a more classical NPZD (nutrients–phytoplankton–zooplankton–detritus) model, where the remineralisation is at a constant rate, substituting the roles of the bacteria and heterotrophic nanoflagellates (Fasham et al., 2000). Organic matter remineralisation was thus computed by introducing a constant remineralisation rate, while the grazing pressure on the primary producers was entirely dependent on the herbivorous mesozooplanktonic group.

The variety of remineralisation rates found in the literature (Table 4) prompted us to carry out various sensitivity runs to test the responsiveness of the BFM to a constant remineralisation rate applied to dissolved and particulate matter. We ran simulations adopting a constant remineralisation parameter of 0.05, 0.1 and 0.2 d^{-1}. The progressive increase in the constant remineralisation parameter always yielded a much higher phytoplankton biomass compared to that obtained in the BASE experiment. The increase was roughly proportional to the increase in the magnitude of the constant remineralisation parameter. Here we show results obtained using a constant remineralisation parameter of 0.1 d^{-1}.

The removal of all the microbial components from the system leads to a decrease in phosphate concentrations, but an increase in ammonium and nitrates. The high nutrient standing stock results in a very strong phytoplankton biomass (diatoms and nanophytoplankton). Very high chlorophyll concentrations (>8 mg Chl-*a* m^{-3}) occur between June and July in the lower part of the water column, close to the seabed. The temporal and

Table 4
Remineralisation rates found in literature.

Author	Year	Remineralisation rate (d^{-1})
Davis and Steele (1994)	1994	0.2
Fasham (1995)	1995	0.05
Doney et al. (1996)	1996	0.1
Stickney et al. (2000)	2000	0.05
Edwards (2001)	2001	0.1
Fennel et al. (2001)	2001	0.05
Lima and Olson (2002)	2002	0.25
Schartau and Oschlies (2003)	2003	0.048
Lima and Doney (2004)	2004	0.2
Powell et al. (2006)	2006	1.03
Fennel et al. (2006)	2006	0.01/0.03
Fiechter et al. (2009)	2009	1.0
Dorman et al. (2011)	2011	0.1
Scott et al. (2011)	2011	0.1
Kriest and Oschlies (2011)	2011	0.05
Kriest et al. (2012)	2012	0.05
Heinle and Slawig (2013)	2013	0.048

spatial distribution of mesozooplankton reflects that of primary production, as expected. This rather different state of the system obtained by forcing the trophic web to be only "herbivorous", appears to depend on the lack of competition for nutrients between primary producers and bacteria, and on the reduced grazing pressure (removal of microzooplankton). Under these conditions, the primary producers underwent a very strong development, with much higher phytoplankton biomass than obtained in the BASE and MICRO experiments. This is also reflected by the concentrations of omnivorous mesozooplankton, which increased dramatically compared to the BASE experiment. These results highlight the importance of the microbial system in controlling the availability of the limiting nutrient via competition.

4.3. BASE × 5 experiment

The BASE × 5 experiment involved a significant change in surface nutrient forcing (concentrations were quintupled) and was designed to test the model's sensitivity to external changes. This is mandatory when developing a management tool, and can also be considered as a first attempt to investigate the response of the ecosystem to coastal eutrophication.

Results of the BASE × 5 experiment are shown in Fig. 6 (bottom row). The enhanced surface nutrient flux boosted the primary production processes, as indicated by the much higher (with respect to the BASE Experiment) chlorophyll concentrations. The strongly increased phytoplankton biomass determined the overall increase in the consumers biomass and the phosphate accumulation near the bottom in summer, as a result of the large organic matter sinking. However, the changes induced by the increased nutrient input are not simply quantitative, but also involve a strong remodulation of the main mass and energy flux through the trophic web. In fact, in order to highlight the outcome of the experiment, several indexes of ecosystem functioning were also considered. Indexes relating to the BASE × 5 experiment were compared to the corresponding indexes from the BASE experiment (Fig. 7) in order to observe system reactions in such conditions. The indexes considered were: the ratio between herbivorous (phytoplankton to zooplankton) and microbial (from bacterioplankton to zooplankton) grazing (Legendre and Rassoulzadegan, 1995), the phosphorus flux between bacteria and phosphate, the ratio between micro–nano phytoplankton and picophytoplankton, and the ratio between meso- and microzooplankton.

The grazing ratio in Fig. 7(A) helps to identify the prevailing trophic web pattern. Index values greater than one indicate a prevailing "herbivorous" trophic web, while values smaller than one indicate a prevailing "microbial" pathway. It should be noted that in the BASE experiment, the trophic structure is persistently "microbial" from May to November, and "herbivorous" for the rest of the year. For a significant part of the year, a larger nutrient input (BASE × 5 experiment) leads to a restructuring of the trophic web thus making it a more "herbivorous" structure, with a shorter and weaker "microbial" period during the warmest months.

The bacterial functional role was also examined via the phosphorus flux between bacteria and phosphate (Fig. 7(B)). In concomitance with a shift in the trophic web structure, the bacterial functional role also changed. Generally speaking, bacteria tend to act as net organic matter remineralizers (positive flux) when the herbivorous trophic web is dominant, and competitors for inorganic phosphorus (negative flux) when microbes prevail. In BASE × 5, this structure was enhanced and the shift in the bacterial roles is very evident. While in the BASE experiment bacteria always acted as phytoplankton competitors (with the flux close to zero during winter months) for nutrients, in BASE × 5, fluxes were stronger and the switch between roles is clear. From December to April bacteria act as remineralizers, with fluxes reaching >0.02 mmol m^{-3} d^{-1}. During warmer months however, they compete with phytoplankton for nutrients. Therefore, higher nutrients concentrations cause the system to shift towards a more herbivorous trophic structure and a more varied bacterial activity.

Phytoplankton and zooplankton ratios (Fig. 7(C) and (D)) give an indication of the size distribution in these communities. Results show how, as a consequence of higher nutrient concentrations in the system, larger phytoplankton and zooplankton groups develop (higher ratios). In fact, it is clear how the more modest nutrient concentrations of the BASE experiment lead to a system mainly composed of smaller organisms.

The results of the BASE × 5 experiment support the theory advanced by Legendre and Rassoulzadegan (1995), that the reduction in the limiting nutrient influences the type of the prevailing food web. This was also found by Thingstad and Sakshaug (1990) in their idealised, steady-state, mathematical model, and by Samuelsson et al. (2002) in their microcosm experiments. Riegman et al. (1993) also found that small algae are better competitors for light and nutrients than larger algae. Thus, the model demonstrated its capability to respond appropriately to nutrient forcing, thus capturing the major food web dynamics.

5. Discussion

5.1. Trophic interactions

The mechanistic experiments were designed to achieve a qualitative understanding of the lower trophic level web dynamics, and of the role played by different functional groups in determining the trophic web structure. The comparison with the available observations indicated that the model is able to capture (within one standard deviation) the observed seasonal dynamics of biogeochemical variables.

The results of the MICRO and HERB experiments highlighted that the importance of the microbial and herbivorous food webs is mostly governed by environmental conditions (Legendre and Rassoulzadegan, 1995; Danger et al., 2007).

When only the microbial web was kept active (MICRO experiment), the vertical structure and the temporal variability of the biogeochemical state variables differed little from the reference simulation (BASE Experiment). On the contrary, concentrations increased unrealistically in the HERB experiment.

Such results confirm the findings of Fonda Umani et al. (2006) about the importance of the microbial food web even in a coastal environment. The microbial food web prevalence appears to be dictated by the nutrient limitation condition as suggested by the

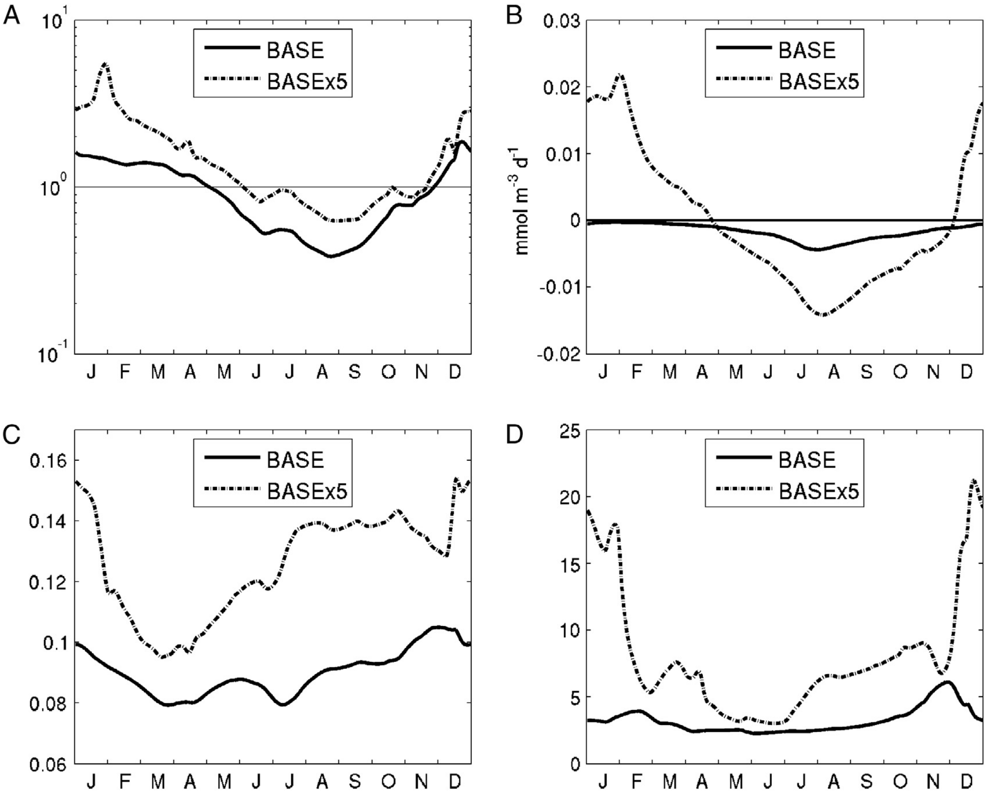

Fig. 7. Indices of ecosystem functioning and matter-transfer pathways. (A) Ratio between the carbon flow due to herbivorous grazing (from autotrophs to zooplankters, values greater than one) and the one due to microbial grazing (from bacterioplankton to zooplankters, values smaller than one; in semi-logarithmic scale). (B) Phosphorus flux between bacteria and dissolved inorganic phosphorus (Positive flux when remineralising, negative flux when competing). (C) Ratio between micro–nano phytoplankton and picophytoplankton. (D) Ratio between omnivorous mesozooplankton and microzooplankton.

BASE × 5 experiment. In fact, the substantial increase of the nutrient external input indicated a shift of the main mass and energy flow through the trophic web. The system responded to the change in the external forcing by shifting from a prevailing microbial structure to an alternating microbial and herbivorous structure. Similarly, Hardman-Mountford et al. (2013) also observed an alteration of the plankton community towards larger organisms in response to surface nutrient enrichment.

These results support the theory advanced by Legendre and Rassoulzadegan (1995), that the reduction in the nutrient limitation conditions influence the type of prevailing food web. This was also found by Thingstad and Sakshaug (1990) in their idealised, steady-state, mathematical model, and by Samuelsson et al. (2002) in their microcosm experiments.

5.2. Management questions addressed

Experiment results demonstrated that the BFM–POM 1D system is able to correctly simulate the lower level trophic interactions and carbon pathways of the Gulf of Trieste.

Furthermore, it proved to be able to modify its main trophic structure in response to changes in the external forcing. From a quantitative point of view, model performance is still relatively low mainly because the Gulf of Trieste physical dynamics is not well captured by a 1-D model which neglects horizontal advection and horizontal patchiness. Thus the study was directed towards a more holistic assessment, focusing on the overall system characteristics rather than on specific state variables. As already stressed above, seasonal structures and trends were generally correctly captured and ecosystem functions were appropriately represented. This opens the way for the use of the model to explore and discover causal relationships (de Mora et al., 2016).

With the increased complexity of marine legislation, the need to have available cost-effective decision tools is urgent in order to understand the state of the environment (Hyder et al., 2015).

We believe that BFM–POM 1D could potentially help in answering some of the questions regarding the Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD). In fact, our study addresses, at least partially, questions regarding the interactions between food web structure and other GES descriptors, the impacts of changes in shelf seas biogeochemistry on ecosystem state and the potential efficiency gains from redesigning monitoring programmes.

In particular, BFM–POM 1D can provide information regarding food web structure and eutrophication (descriptors 4 and 5 respectively), which are of particular interest to the MSFD. The model shows to have an overall robust structure (see supplementary material, Appendix C), which is recommended for the study of the low level trophic food web structure. Moreover, experiment BASE × 5 highlighted changes induced by variations on nutrient inputs.

Therefore, a science-based modelling tool, such as the one developed here, could help decision makers to understand lower trophic web interactions in a given area (if backed up by extensive and reliable hydrodynamical data), and to study the sensitivity of the system to external forcings. This could be considered a first step in the definition of a science-based tool, which exploits the structure of a complex biogeochemical model for exploring environmental issues.

5.3. Improvements and future work

Overall, BFM–POM 1D shows some weaknesses in the representation of certain variables such as chlorophyll, oxygen and DOC, which are on the whole underestimated. Similarly, ammonium tends to be overestimated near the seabed. This could be the result of the parametrisation of nitrification, which is not mediated by bacteria.

Future work should be directed towards the inclusion of a fourth phytoplanktonic functional group (large phytoplankton) and a more complete benthic model, rather than a simple benthic return. In such shallow areas, the benthic environment can potentially play a critical role in the carbon cycle dynamics and in shaping the pelagic realm.

Work is currently being carried out in order to satisfy these improvements and further investigate and understand the Gulf of Trieste area.

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Appendix A

The coupled numerical model BFM–POM

The BFM–POM 1D combines the physical with the biological processes to compute the temporal rate of change of a generic biogeochemical variable expressed in terms of concentration $A_j(z,t)$, where $j = 1, 2, 3, \ldots, n_{state}$ and n_{state} corresponds to the total number of pelagic state variables. Tables A.1–A.5 give the specific state variables with the parameters' values used in the equations as written in Vichi et al. (2007). The temporal rate of change of A_j is therefore defined as:

$$\frac{\partial A_j}{\partial t} = \left.\frac{\partial A_j}{\partial t}\right|_{phys} + \left.\frac{\partial A_j}{\partial t}\right|_{bio} \tag{A.1}$$

where the rate of change due to physical processes is defined as

$$\left.\frac{\partial A_j}{\partial t}\right|_{phys} = -W_s\frac{\partial A_j}{\partial z} + \frac{\partial}{\partial z}\left[K_H\frac{\partial A_j}{\partial z}\right]. \tag{A.2}$$

Here, W_s is he settling velocity of the variable, and $W_s = 0$ for the dissolved constituents. K_H is the diffusion coefficient.

The surface boundary conditions are:

$$K_H\left.\frac{\partial A_j}{\partial z}\right|_{z=0} = 0 \tag{A.3}$$

for all the LO and NO state variables type,

$$K_H\left.\frac{\partial A_j}{\partial z}\right|_{z=0} = F_j \tag{A.4}$$

for the (see Table A.1) $O^{(2)}$ (dissolved oxygen), $O^{(3)}$ (carbon dioxide) and $O^{(5)}$ (alkalinity) state variables, where F_j is the flux computed at the air–sea interface according to Wanninkhof (1992).

For the nutrient IO state variables ($N^{(1)}$, $N^{(3)}$, $N^{(4)}$, $N^{(5)}$) the surface boundary condition is:

$$K_H\left.\frac{\partial A_j}{\partial z}\right|_{z=0} = \lambda(A_j - A_{js}) \tag{A.5}$$

where A_j is the current nutrient surface value, A_{js} is the corresponding climatological value and λ is the relaxation velocity (here set to 0.6 m d^{-1}).

At the bottom ($z = -H$) the boundary conditions are:

$$K_H\left.\frac{\partial A_j}{\partial z}\right|_{z=-H} = 0 \tag{A.6}$$

for all LO and NO state variables, while for the IO is:

$$K_H\left.\frac{\partial A_j}{\partial z}\right|_{z=-H} = \omega_{remin} \bigtriangleup z_{bot} \tag{A.7}$$

where $\bigtriangleup z_{bot}$ is the depth of the bottommost layer of the vertical grid and ω_{remin} is a calculated sediment–water exchange rate at the bottom interface for A_j. This is defined as

$$\omega_{remin} = A_{j_{ben}}\ \alpha_{rmn} \tag{A.8}$$

where $A_{j_{ben}}$ is the concentration of detritus in the benthic environment and α_{rmn} is the specific prescribed remineralisation rate.

Oxygen consumption is stoichiometrically associated to carbon remineralisation rates and the nitrogen remineralisation is partitioned into ammonium and nitrate flux with a constant value. Table A.6 summarises the values used for the concentration of detritus and the remineralisation rates.

Regarding light in the biological model, phytoplankton's self-shading effect is taken into consideration and the irradiance, used as forcing functions for the calculation of production rates, is defined as

$$E_{PAR} = \varepsilon_{PAR} Q_S e^{\lambda_w z + \int_z^0 \lambda_{bio}(z')dz'} \tag{A.9}$$

where ε_{PAR} is the coefficient determining the portion of PAR,

$Q_S e^{\lambda_w z + \int_z^0 \lambda_{bio}(z')dz'}$ is the incoming solar radiation at the surface, λ_w is the visible extinction coefficient and

$$\lambda_{bio} = \sum_i c_{P_i} P_i + c_D D + c_M M \tag{A.10}$$

where P_i is the carbon content of phytoplankton groups in the model, D the carbon content of particulate detritus and M the suspended inorganic sediments (ISM). The c constants are the specific contributions to the total extinction coefficient of each suspended substance (Vichi et al., 2003). Surface PAR is prescribed through daily values means.

The POM

POM is a free surface, hydrostatic, primitive equation, finite difference model (Blumberg and Mellor, 1983). In this "diagnostic" one dimensional implementation, the model prognostically computes the vertical velocity (u, v) and turbulent diffusivity profiles (K_M, K_H) for tracers and momentum. The temperature and salinity (and therefore density) vertical profiles are dynamically interpolated in time from climatological monthly profiles. The prognostic equations for the velocity profiles are:

$$\frac{\partial U}{\partial t} - fV = \frac{\partial}{\partial z}\left(K_M\frac{\partial U}{\partial z}\right) \tag{A.11}$$

$$\frac{\partial V}{\partial t} + fU = \frac{\partial}{\partial z}\left(K_M\frac{\partial V}{\partial z}\right) \tag{A.12}$$

where $f = 2\Omega \sin\phi$ is the Coriolis parameter and ϕ is the latitude. The vertical diffusivity coefficients are calculated assuming the closure hypothesis $K_M(z) = qlS_H$, where S_H is an empirical function (Mellor and Yamada, 1982). The change in time of turbulent kinetic energy is then

$$\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right)=\frac{\partial}{\partial z}\left(K_M\frac{\partial q^2/2}{\partial z}\right)+P_s+P_b-\varepsilon \tag{A.13}$$

where $q^2/2$ is the turbulent kinetic energy, K_M diffusion, P_s the turbulent kinetic energy production by shear, P_b the buoyant production/dissipation and ε the dissipation due to turbulence.

The turbulent length scale is defined as:

$$\frac{\partial}{\partial t}(q^2 l)=\frac{\partial}{\partial z}\left(K_M\frac{\partial q^2 l}{\partial z}\right)+E_1[P_S+P_b]-\frac{q^3}{B_1}\tilde{W} \tag{A.14}$$

where $\tilde{W}$ is a function of the distance between rigid boundaries, and E_1 and B_1 are empirical constants.

Boundary conditions

To solve Eqs. (A.11)–(A.14), we need to define vertical boundary conditions for $U, V, q^2, q^2 l$.

The U and V vertical boundary conditions are:

$$K_M\left.\frac{\partial U}{\partial z}\right|_{z=0}=\tau_w^{(x)} \tag{A.15}$$

$$K_M\left.\frac{\partial V}{\partial z}\right|_{z=0}=\tau_w^{(y)} \tag{A.16}$$

$$K_M\left.\frac{\partial \vec{U}}{\partial z}\right|_{z=-H}=\vec{\tau}_b \tag{A.17}$$

where $\vec{\tau_w}=(\tau_w^{(x)},\tau_w^{(y)})$ is the wind stress prescribed through interpolation between adjacent monthly values and $\vec{\tau_b}$ is the bottom drag coefficient defined as

$$\vec{\tau_b}=C_b\left|\vec{U_b}\right|\vec{U_b} \tag{A.18}$$

where C_b is the bottom drag coefficient, and $\vec{U_b}=(U_b,V_b)$ is the velocity at the bottommost layer.

The boundary conditions for turbulent kinetic energy at the surface ($z=0$) depend on the wind stress intensity and are represented by the following semi-empirical equation:

$$\left.q^2\right|_{z=0}=B_1^{\frac{2}{3}}\frac{|\vec{\tau}_w|}{C_d}. \tag{A.19}$$

The bottom boundary condition ($z=-H$) is

$$\left.q^2\right|_{z=-H}=B_1^{\frac{2}{3}}\frac{|\vec{\tau}_b|}{C_b}. \tag{A.20}$$

Appendix B

Description and values of the parameters of BFM–POM 1D used in the BASE experiment. The parameter choice originates from a calibration exercise carried out based on model defaults, Vichi et al. (2007) and personal communication.

Table A.1

List of the reference state variables A_i for the pelagic model. The subscript i indicates the basic components (if any) of the variable, e.g. $P_i^{(1)}\equiv(P_c^{(1)},P_n^{(1)},P_p^{(1)},P_s^{(1)},P_l^{(1)},P_f^{(1)})$.

n_{state}	Variable	Type	Const.	Units	Description
1	$N^{(1)}$	IO	P	mmolP m^{-3}	Phosphate
2	$N^{(3)}$	IO	N	mmolN m^{-3}	Nitrate
3	$N^{(4)}$	IO	N	mmolN m^{-3}	Ammonium
4	$N^{(5)}$	IO	Si	mmolSi m^{-3}	Silicate
5	$N^{(6)}$	IO	R	mmolS m^{-3}	Reduction equivalents, HS^-
6	$O^{(2)}$	IO	O	mmolO_2 m^{-3}	Dissolved oxygen
7	$O^{(3)}$	IO	C	mgC m^{-3}	Carbon dioxide
8	$O^{(5)}$	IO	–	mmol Eq m^{-3}	Total alkalinity
9	$P_i^{(1)}$	LO	C N P Si Chl	mgC m^{-3}, mmolN–P m^{-3}, μmol, mg Chl-*a* m^{-3}	Diatoms
10	$P_i^{(2)}$	LO	C N P Chl	mgC m^{-3}, mmolN–P m^{-3}, μmol, mg Chl-*a* m^{-3}	Flagellates
11	$P_i^{(3)}$	LO	C N P Chl	mgC m^{-3}, mmolN–P m^{-3}, μmol, mg Chl-*a* m^{-3}	Picophytoplankton
12	$P_i^{(4)}$	LO	C N P Chl	mgC m^{-3}, mmolN–P m^{-3}, μmol, mg Chl-*a* m^{-3}	Picophytoplankton
13	B_i	LO	C N P	mgC m^{-3}, mmolN–P m^{-3}	Pelagic bacteria
14	$Z_i^{(3)}$	LO	C N P	mgC m^{-3}, mmolN–P m^{-3}	Carnivorous mesozooplankton
15	$Z_i^{(4)}$	LO	C N P	mgC m^{-3}, mmolN–P m^{-3}	Omnivorous mesozooplankton
16	$Z_i^{(5)}$	LO	C N P	mgC m^{-3}, mmolN–P m^{-3}	Microzooplankton
17	$Z_i^{(6)}$	LO	C N P	mgC m^{-3}, mmolN–P m^{-3}	Heterotrophic Flagellates
18	$R_i^{(1)}$	NO	C N P	mgC m^{-3}, mmolN–P m^{-3}	Labile dissolved organic matter
19	$R_c^{(2)}$	NO	C	mgC m^{-3}	Semi-labile dissolved organic carbon
20	$R_i^{(3)}$	NO	C	mgC m^{-3}	Semi-refractory dissolved organic carbon
21	$R_i^{(6)}$	NO	C N P Si	mgC m^{-3}, mmolN–P–Si m^{-3}	Particulate organic detritus

Legend: IO = Inorganic; LO = Living organic; NO = Non-living organic.

Table A.2

List of the parameters in the BFM pelagic equations for phytoplankton.

Parameter	Symbol	$P^{(1)}$	$P^{(2)}$	$P^{(3)}$
Characteristic Q10 coefficient (–)	p_q10	2.0	2.0	2.0
Cut-off threshold for temperature factor (–)	p_qtemp	0.0	0.0	0.0
Maximal productivity at 10 °C (day^{-1})	p_sum	2.5	3.0	3.5
Respiration rate at 10 °C (day^{-1})	p_srs	0.05	0.05	0.05
Max.specific nutrient-stress lysis rate (day^{-1})	p_sdmo	0.01	0.01	0.01
Half saturation constant for nutrient stress lysis (–)	p_thdo	0.1	0.1	0.1

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Table A.2 (*continued*)

Parameter	Symbol	$P^{(1)}$	$P^{(2)}$	$P^{(3)}$
Extra lysis rate (biomass density-dependent) (day^{-1})	p_seo	0.0	0.0	0.0
Half saturation constant for extra lysis (mgC m^{-3})	p_sheo	0.0	0.0	0.0
Excreted fraction of primary production (–)	p_pu_ea	0.01	0.1	0.1
Activity respiration fraction (–)	p_pu_ra	0.1	0.1	0.2
Membrane affinity for N (m^3/mgC/day)	p_qun	0.025	0.025	0.025
Half saturation constant for NH_4 uptake preference over NO_3 (mmolN/m^3)	p_lN4	1.0	0.5	0.1
Minimum quotum N:C (mmolN/mgC)	p_qnlc	6.87×10^{-5}	6.87×10^{-5}	6.87×10^{-5}
Reference quotum N:C (mmolN/mgC)	p_qncPPY	0.0126	0.0126	0.0126
Multiplication factor for luxury storage (–)	p_xqn	2.0	2.0	2.0
Membrane affinity for P (m^3/mgC/day)	p_qup	2.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
Minimum quotum P:C (mmolP/mgC)	p_qplc	4.29×10^{-4}	4.29×10^{-4}	4.29×10^{-4}
Reference quotum P:C (mmolP/mgC)	p_qpcPPY	7.86×10^{-4}	7.86×10^{-4}	7.86×10^{-4}
Multiplication factor for luxury storage (–)	p_xqp	2.0	2.0	2.0
Half saturation conc. for dissolved Si limitation (mmolSi m^{-3})	p_chPs	1.0	0.0	0.0
Membrane affinity for Si (m^3/mgC/day)	p_qus	0.0	0.0	0.0
Minimum quotum Si:C (mmolSi/mgC)	p_qslc	4.3×10^{-3}	0.0	0.0
Reference quotum Si:C (mmolSi/mgC)	p_qscPPY	8.5×10^{-3}	0.0	0.0
Nutrient stress threshold for sinking (–)	p_esNI	0.7	0.75	0.75
Maximum Sinking velocity (m day^{-1})	p_res	5.0	0.5	0.5
Specific turnover rate for Chla (day^{-1})	p_sdchl	0.2	0.2	0.2
Initial slope of the P-E curve (mgC s m^2/mgChl/uE)	p_alpha_chl	1.1×10^{-5}	0.46×10^{-5}	0.7×10^{-5}
Reference quotum Chla:C (mgChla/mgC)	p_qlcPPY	0.035	0.02	0.02
Chla-specific extinction coefficient (m^2/mgChla)	p_epsChla	0.03	0.03	0.03
Relaxation rate towards maximum Chla:C (day^{-1})	p_tochl_relt	0.25	0.25	0.25
Optimal value of E_PAR/E_K (–)	p_EpEk_or	3.0	3.0	3.0

Table A.3
List of the parameters in the BFM pelagic equations for microzooplankton.

Parameter	Symbol	$Z^{(5)}$	$Z^{(6)}$
Q10 value for physiological rates (–)	p_q10	2.0	2.0
Potential growth rate (day^{-1})	p_sum	2.0	5.0
Respiration rate at 10 °C (day^{-1})	p_srs	0.02	0.02
Mortality rate due to oxygen limitation (day^{-1})	p_sdo	0.25	0.25
Temperature independent mortality (day^{-1})	p_sd	0.0	0.0
Assimilation efficiency (–)	p_pu	0.5	0.3
Fraction of activity excretion (–)	p_pu_ea	0.25	0.35
Half-saturation oxygen concentration (mmolO_2 m^{-3})	p_chro	0.5	0.5
Half-saturation food concentration for Type II (mgC m^{-3})	p_chuc	200.0	200.0
Half-saturation food concentration for preference factor (mgC m^{-3})	p_minfood	50.0	50.0
Maximum quotum N:C (mmolN/mgC)	p_qncMIZ	1.67×10^{-2}	1.67×10^{-2}
Maximum quotum P:C (mmolN/mgC)	p_qpcMIZ	1.85×10^{-3}	1.85×10^{-3}

Table A.4
List of the parameters in the BFM pelagic equations for mesozooplankton.

Parameter	Symbol	$Z^{(3)}$	$Z^{(4)}$
Q10 value for physiological rates (–)	p_q10	2.0	2.0
Respiration rate at 10 °C (day^{-1})	p_srs	0.01	0.02
Potential growth rate (day^{-1})	p_sum	2.0	2.0
Specific search volume (m^3 mgC d^{-1})	p_vum	0.0025	0.0025
Assimilation efficiency (–)	p_puI	0.6	0.6
Fraction of faeces production (–)	p_peI	0.3	0.35
Specific density-dependent mortality (m^3 mgC d^{-1})	p_sdo	0.01	0.01
Background natural mortality (day^{-1})	p_sd	0.02	0.01
Exponent of density-dependent mortality (–)	p_sds	2.0	2.0
Maximum quotum P:C (mmolP/mgC)	p_qpcMEZ	1.67×10^{-3}	1.67×10^{-3}
Maximum quotum N:C (mmolN/mgC)	p_qncMEZ	0.015	0.015
Half-saturation O_2 concentration (mmolO_2 m^{-3})	p_clO2o	30.0	30.0

Table A.5
Pelagic bacteria parameters description and value.

Parameter	Symbol	$B^{(1)}$
Characteristic Q10	p_q10	2.95
Half saturation constant for O_2 (mmol/m^3)	p_chdo	30.0
Specific mortality rate (day^{-1})	p_sd	0.0
Density dependent specific mortality rate (day^{-1})	p_sd2	0.0
Specific potential uptake fro nutrient-rich DOM (day^{-1})	p_suhR1	0.5
Specific potential uptake fro nutrient-poor DOM (day^{-1})	p_sulR1	0.0
Specific potential uptake for semi-labile DOC (day^{-1})	p_suR2	0.05

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Table A.5 (*continued*)

Parameter	Symbol	$B^{(1)}$
Specific potential uptake for semi-refractory DOC (day^{-1})	p_suR3	0.01
Specific potential uptake for POM (day^{-1})	p_suR6	0.1
Specific potential growth rate (day^{-1})	p_sum	8.38
Activity respiration fraction (–)	p_pu_ra	0.4
Additional respiration fraction at low O_2 (–)	p_pu_ra_o	0.2
Specific rest respiration (day^{-1})	p_srs	0.01
Optimal N/C ratio (mmolN/mgC)	p_qncPBA	0.0167
Optimal P/C ratio (mmolP/mgC)	p_qpcPBA	0.00185
Minimal N/C ratio (mmolN/mgC)	p_qlnc	0.0167
Minimal P/C ratio (mmolP/mgC)	p_qlpc	0.00095
Membrane affinity for N (mmolN/mgC/day)	p_qun	0.05
Membrane affinity for P (mmolP/mgC/day)	p_qup	0.005
Half saturation ammonium conc. for uptake (mmolN/m^3)	p_chn	5.0
Half saturation ammonium conc. for uptake (mmolP/m^3)	p_chp	0.5
Relaxation timescale for N uptaken/remin. (day^{-1})	p_ruen	1.0
Relaxation timescale for P uptaken/remin. (day^{-1})	p_ruep	1.0
Relaxation timescale for semi-labile excretion (day^{-1})	p_rec	1.0
Excretion of semi-refractory DOC (–)	p_pu_ea_R3	0.015

Table A.6
Pelagic food matrix.

Predators	Preys							
	$P_i^{(1)}$	$P_i^{(2)}$	$P_i^{(3)}$	$Z_i^{(3)}$	$Z_i^{(4)}$	$Z_i^{(5)}$	$Z_i^{(6)}$	$B_i^{(1)}$
$Z_i^{(3)}$	0.0	0.0	0.0	1.0	1.0	1.0	0.0	0.0
$Z_i^{(4)}$	1.0	0.75	0.7	0.0	1.0	1.0	0.0	0.0
$Z_i^{(5)}$	1.0	1.0	0.1	0.0	0.0	1.0	1.0	0.1
$Z_i^{(6)}$	0.0	0.2	1.0	0.0	0.0	0.0	0.2	1.0

Table A.7
Benthic nutrient concentrations, remineralisation rates and partitioning coefficient.

Symbol	Value	Units	Description
$p\_reminQ_c^{(6)}$	0.005	d^{-1}	Specific remineralisation rate of carbon
$p\_reminQ_n^{(6)}$	0.005	d^{-1}	Specific remineralisation rate of nitrate
$p\_reminQ_p^{(6)}$	0.005	d^{-1}	Specific remineralisation rate of phosphate
$p\_reminQ_s^{(6)}$	0.005	d^{-1}	Specific remineralisation rate of silicate
p_pQIN3	0.1	–	Partitioning coefficient between NO_3 and NH_4

Appendix C. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.rsma.2016.03.015.

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CHAPTER 4

A NUMERICAL STUDY OF THE BENTHIC-PELAGIC COUPLING IN A SHALLOW SHELF SEA (GULF OF TRIESTE)

In this chapter the model BFM-POM 1D was further developed in order to include an intermediate complexity benthic system and a benthic-pelagic coupling. Most biogeochemical models for water column processes either neglect the sediments or apply a rather crude approximation for the benthic response [65]. A sensitivity analysis on the benthic-pelagic coupling was carried out investigating the roles of diffusion and sedimentation. A mechanistic experiment investigated the role of filter feeders in a typical shallow shelf sea. The findings of this chapter further discussed the model's suitability as a supportive tool for marine coastal management and the importance of the inclusion of the benthic realm for this scope. The main outputs of this chapter set the basis for the development of an ensemble framework (Chapter 5).

Results were presented as poster at the European Geosciences Union General Assembly 2016 held in Vienna, Austria, and at the EcoClim5 Summer School held in Natal, Brazil, in 2016. Moreover, results were presented as oral presentation at the 8th International Workshop on Modeling the Ocean held in Bologna, Italy, in 2016.

Final results were presented in the following manuscript entitled "A numerical study of the benthic-pelagic coupling in a shallow shelf sea (Gulf of Trieste)" by Giulia Mussap and Marco Zavatarelli, which was submitted to *Regional Studies in Marine Science* and is in the process of being reviewed.

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A numerical study of the benthic–pelagic coupling in a shallow shelf sea (Gulf of Trieste)

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HIGHLIGHTS

- Benthic–pelagic coupling successfully simulated with BFM–POM 1D.
- Sensitivity experiments revealed best reference parameters.
- Mechanistic experiment highlighted the role of filter feeders in a shallow shelf sea.
- Results recognize BFM–POM 1D potential as a support to ecosystem management.

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ABSTRACT

A coupled physical–biogeochemical 1D model (BFM–POM 1D) with an intermediate complexity benthic formulation was used to carry out sensitivity tests on the coupling parameters (sedimentation and diffusion at the sediment–water interface). Moreover, a mechanistic experiment was designed to investigate the role of filter feeders in regulating the biogeochemical state of the system in a coastal sea. Best reference parameters of sedimentation and diffusion were chosen from the sensitivity experiments carried out based on available observations. The mechanistic experiment revealed the importance of filter feeders' role in trapping pelagic organic matter and regulating benthic–pelagic nutrient fluxes, as well as controlling pelagic primary production. The model demonstrated to be able to qualitatively reproduce the biogeochemical characteristics of the system and adapt to different trophic configurations. The results shown are encouraging and foresee its possible use as a tool to study causal relationships and help in finding solutions for management issues.

1. Introduction

Coastal waters are among the most productive ecosystems in the world (Marcus and Boero, 1998). Their exposure to anthropogenic pressures has led to important system changes and has triggered increasing interest and concern within the scientific community. Hence, a lot of effort is spent in studying and understanding regulating processes and system feedbacks to various conditions and pressures.

The processes connecting the pelagic and benthic realms define the so-called "benthic–pelagic coupling" (hereafter BPC). This term comprises the two-way exchange of matter (particulate and dissolved) physically and biologically mediated, between the bottom sediment and the overlying water column (Marcus and Boero, 1998; Raffaelli et al., 2003; Soetaert et al., 2000). Coastal environmental dynamics of shallow seas are greatly influenced by benthic biogeochemical processes (Burdige, 2011), as the intensity of the BPC mainly depends on water depth (Suess, 1980).

The processes defining the BPC dynamics related to organic matter and nutrients are schematized in Fig. 1. The physically mediated sediment–water exchanges contributing to structure the BPC entirely depend on the sinking and resuspension fluxes of particulate organic matter (POM) and on the diffusive oxygen, carbon dioxide and inorganic nutrients at the sediment–water interface. On the other hand, the biological process consists of the grazing of the "filter feeders" functional group on the sinking organic particles. Such group includes the non-moving benthic organisms feeding directly on the pelagic system by filtering the suspended particles (e.g. bivalve molluscs). The particle feeding complements the transfer of organic matter from the water column to the sediment operated by the sedimentary flux, thereby adding to the BPC processes a highly active component (Gili and Coma, 1998). Such process is sometimes defined as biodeposition (Haven and Morales-Alamo, 1966) and consists of the sequestration of

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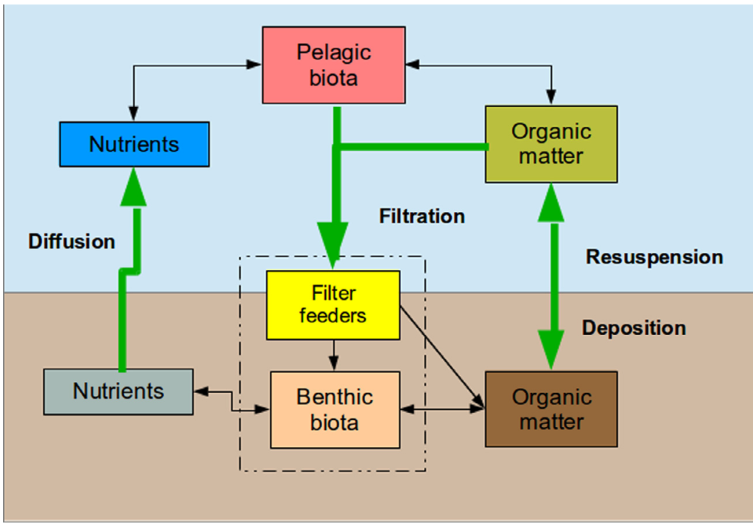

Fig. 1. A scheme representing the organic and inorganic matter related benthic–pelagic coupling. Green double-headed arrows represent the benthic–pelagic processes of diffusion, filtration, deposition and resuspension. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

organic matter from the pelagic system and its deposition into the benthic domain in the form of faeces and pseudo-faeces. Biodeposition has therefore a twofold and opposite impact on the pelagic dynamics: it removes living phytoplankton (Herman et al., 1999) and it contributes to the oxygen and nutrient pool via the bacterial organic matter recycling processes (Dame, 1993; Norkko et al., 2001), modulated by the diffusion at the benthic–pelagic interface. Such impact causes biodeposition to be considered as a possible process controlling eutrophication (Grall and Chauvaud, 2002; Officer et al., 1982) under given environmental conditions. Bacterial activity on the deposited organic matter causes the interstitial waters to be enriched in inorganic nutrients and carbon dioxide, and depleted in oxygen. The difference in concentration between interstitial waters and the overlying water column leads to an effective diffusive exchange back into the water column (Herndl et al., 1989) modulated by biological processes such as bioturbation, bioirrigation and particle reworking (Aller, 1988, 1994; Bertuzzi et al., 1997).

The strong interactions between pelagic primary production, benthic communities and detritus are thus crucial in defining the trophic conditions in coastal regions. Being relatively fixed in place and long lived, the benthos integrates environmental influences at a particular site over a relatively long timespan (Herman et al., 1999). This is important because the presence, spatial distribution and trophic structure of the fauna significantly influences the physical and chemical characteristics of the sediments and sediment–water exchange (Heip, 1995).

It is therefore essential to study the role of the benthos in coastal areas, especially those affected by problems such as eutrophication and bottom oxygen depletion (hypoxia/anoxia).

Numerical modelling allows to test specific hypotheses and to investigate the integrated effects of various factors under given assumptions (Henderson et al., 2001). Moreover, it can inform on the behaviour of the ecosystem as a whole (De Mora et al., 2016). With an appropriate validation against field data, this method may have a key role in developing a strategy for environmental management and sustainability. However, modelling the benthic system has always been a challenge within the scientific community due to the scarcity of information available (Capet et al., 2016). The reason for this is related to the difficulty of sampling the benthos, which is problematic and time consuming (Cardoso et al., 2010; Ebenhöh et al., 1995). Most biogeochemical models for water column processes either neglect the sediments or apply a rather crude approximation for the benthic response (Soetaert et al., 2000). In fact, models of pelagic and benthic biogeochemistry are typically not coupled or connected (Capet et al., 2016; Mussap et al., 2016).

As a continuation of a previous work with the pelagic model BFM–POM 1D implemented in the Gulf of Trieste (northern Adriatic Sea, Mussap et al., 2016), the implementation has been extended to include the benthic realm and the BPC, by coupling the pelagic model with a benthic model of intermediate complexity.

The aim of this paper is to establish and test the structure of the benthic compartment and its interactions with the water column. We aim to provide an understanding of the extent to which the benthic "biogeochemical machinery" determines the sediment–water fluxes. We start by investigating the sensitivity of the system with respect to deposition and diffusive fluxes, and subsequently we carry out a mechanistic experiment involving the removal of the filter feeders functional group in order to understand their role in the BPC.

2. Materials and methods

2.1. The model

The coupled numerical model used in its pelagic component is the Biogeochemical Flux Model (BFM, Vichi et al., 2007). In the model, the trophic and chemical interactions are represented through the concepts of chemical functional families (CFFs) and living functional groups (LFGs Vichi et al., 2007). With respect to the previous implementation form (Mussap et al., 2016), an additional phytoplankton LFG was added (the "large" phytoplankton, i.e. dinoflagellates). Such functional group is characterized by a low growth rate and low grazing pressure, and is known to develop in the Gulf of Trieste (Mozetic et al., 1998). The pelagic BFM is coupled "on-line" to the one-dimensional version of the Princeton Ocean Model (POM 1D, Blumberg and Mellor, 1987). A full description of the coupling between the two models can be found in Mussap et al. (2016). As in Mussap et al. (2016), the implementation of the hydrodynamical model is diagnostic, with prescribed climatological, time dependent (monthly varying) temperature and salinity vertical profiles (obtained from *in situ* data).

The surface wind stress is the only surface forcing function needed for the physical component of the modelling system (given the diagnostic implementation). On the other hand, the BFM primary production is forced by the surface incident shortwave radiation penetrating the water column. Vertical extinction is calculated on the basis of phytoplankton (self-shading) and detritus concentration (both prognostically computed), and seasonal inorganic suspended matter (ISM) profiles which are fed to the model. Surface boundary conditions for nutrients are defined by relaxing surface concentrations to monthly varying climatologies of phosphate, nitrates, ammonium and silicate (Mussap et al., 2016). Climatological initial conditions for biogeochemical pelagic components are vertically-homogeneous and consistent with observed winter concentrations. The climatological annual cycles and forcing functions are the same as in Mussap et al. (2016). The one-dimensional coupled model does not account for any lateral flux of BFM state variables. The underlying assumption is that the implementation area is in steady state from the biogeochemical state variables lateral flux point of view. This assumption (and possible limitation) is justified by the fact that the model is implemented in the centre of an area that observational programs for the Gulf of Trieste defined as rather uniform (see Section 2.3).

In Mussap et al. (2016) the benthic domain was not represented and a simple benthic nutrient cycling procedure was adopted as a "bottom" closure of the pelagic domain. The implementation described here adopts an intermediate complexity benthic model directly coupled to the pelagic component. The model is based on the extensive model effort of Ebenhöh et al. (1995) and Ruardij and Raaphorst (1995), and includes a LFG based description of the benthic fauna and the organic matter recycling processes. Fig. 2 schematizes the structure of the benthic model, where large double-headed arrows indicate BPC processes.

The sediment vertical structure resolves two dynamical layers (oxic and anoxic, Fig. 3) where different processes take place. Organic matter has an implicit vertical distribution and sediment oxygen dynamics are resolved, including the dynamical shifting of the oxic layer.

The benthic LFGs taken into account (Fig. 2) are: epifaunal predators ($Y_i^{(1)}$), deposit feeders ($Y_i^{(2)}$), filter feeders ($Y_i^{(3)}$), meiobenthos ($Y_i^{(4)}$), infaunal predators ($Y_i^{(5)}$) and aerobic and anaerobic bacteria ($H_i^{(1)}$ and $H_i^{(2)}$). Similarly, the CFFs are: phosphate in the oxic and anoxic layer ($K^{(1)}$ and $K1^{(1)}$), nitrate ($K^{(3)}$), ammonium in the oxic and anoxic layer ($K^{(4)}$ and $K1^{(4)}$), silicate ($K^{(5)}$) and reduction equivalents ($K^{(6)}$). Dissolved oxygen and dissolved inorganic carbon in the sediments are also taken into account ($G^{(2)}$ and $G^{(3)}$ respectively).

Benthic organic matter is partitioned into particulate (POM, $Q_i^{(6)}$) and dissolved (DOM, $Q_i^{(1)}$), and its dynamics are regulated by biological activity (uptake and release by benthic organisms and bacteria) in addition to the sedimentation process. The dynamics of DOM in the sediment are mainly controlled by production/consumption terms and by vertical diffusion.

The average location of bacteria is controlled by either the oxic horizon or the detritus penetration depth. They are allowed to directly uptake/release inorganic nutrients from the sediments. Since bacteria are supposed to have almost constant internal ratios, the inputs are eventually compensated by excretion fluxes if the nutrient uptake is higher than the optimal one.

The main processes affecting the oxygen concentration are the biological oxidation of the organic matter, the nitrification reaction of ammonium and the reoxidation of the reduction equivalents. In this intermediate complexity benthic configuration, nutrients are released to the water column at constant specific rates, according to the pore-water concentration. Nitrogen remineralization is partitioned into ammonium and nitrate flux with a constant value. Bioturbation and bioirrigation are parameterized as enhanced diffusion (Ebenhöh et al., 1995).

2.2. The benthic–pelagic coupling

The pelagic and benthic systems are reciprocally interacting at the sediment–water interface (located at depth $z = -H$ in the pelagic system coordinates, Fig. 3). The main forcing for the benthic system is the particulate matter sedimentary flux from the water column pool.

Benthic–pelagic coupling processes are: POM sedimentary flux and diffusive inorganic Carbon (C), Nitrogen (N), Phosphorus (P), Silicon (Si), Oxygen and reduction equivalents fluxes. Resuspension processes are not included in the current BPC implementation, nor is the benthic primary production. The implementation of such processes is planned as a further continuation of the work. It is assumed that the surface burial velocity is a constant value, which is multiplied by the concentration of the sinking variables (POM and phytoplankton) to give the output rates from the water column to the sediments:

$$\left.\frac{dQ_i^{(6)}}{dt}\right|_{R_i^{(6)}}^{sed} = w_{bur} R_i^{(6)}|_{z=-H} \tag{1}$$

$$\left.\frac{dQ_i^{(6)}}{dt}\right|_{P_i^{(1,4)}}^{sed} = w_{bur}\xi_i \sum_{j=1}^{4}(1-\Psi_{P^{(j)}})P_i^{(j)}|_{z=-H} \tag{2}$$

where $i =$ C, N, P, Si and

$$\left.\frac{dQ_i^{(1)}}{dt}\right|_{P_i}^{sed} = w_{bur}\xi_i \sum_{j} P_i^{(j)}|_{z=-H} \tag{3}$$

in which it is also considered that phytoplankton is fractionated into particulate and dissolved components, mainly for mechanical reasons. The pelagic state variables $R_i^{(6)}$ and $P_i^{(j)}$ are the particulate detritus and the phytoplankton functional groups (diatoms and large phytoplankton). The parameter $\Psi_{P^{(j)}}$ indicates the fraction of the biomass that is considered to be labile and is readily available in dissolved phase (different for each phytoplankton group). Nutrients are considered to be more available than carbon in this phase, therefore the non-dimensional constant ξ_i regulates the C, N, P partitioning into dissolved and particulate detritus ($\xi_i = 1$ for C, $\xi_i > 1$ for N and P).

The diffusive flux is calculated by computing the difference of nutrient concentration in the sediments ($K_i^{(j)}$) and in the bottom layer of the water column ($N_i^{(j)}|_{z=-H}$, converted in mmol m^{-2}), and multiplying the result by a constant rate γ:

$$\left.\frac{dK_i^{(j)}}{dt}\right|^{diff} = -\gamma[K_i^{(j)} - N_i^{(j)}dz|_{z=-H}]. \tag{4}$$

The w_{bur} and γ values adopted for the numerical simulations are given in Table 1 of Section 2.4 below.

2.3. Gulf of Trieste: background information

The northern Adriatic has been recognized for many years as a region of high marine production (Fonda Umani, 1996). However, the area is affected by strong anthropogenic pressure which might trigger or worsen eutrophication and hypoxia/anoxia events. The Gulf of Trieste, situated on the northern-east coast of the Adriatic Sea, is characterized by a shallow depth (∼20 m), a large interannual and seasonal variability and a cyclonic circulation. The circulation is mainly driven by freshwater inputs by the Isonzo river (Vichi et al., 2003). Generally speaking the Gulf, as with most of the Mediterranean, is P-limited (Fonda Umani et al., 2007; Mussap et al., 2016; Puddu et al., 2003). Following Mussap et al. (2016), the implementation site chosen

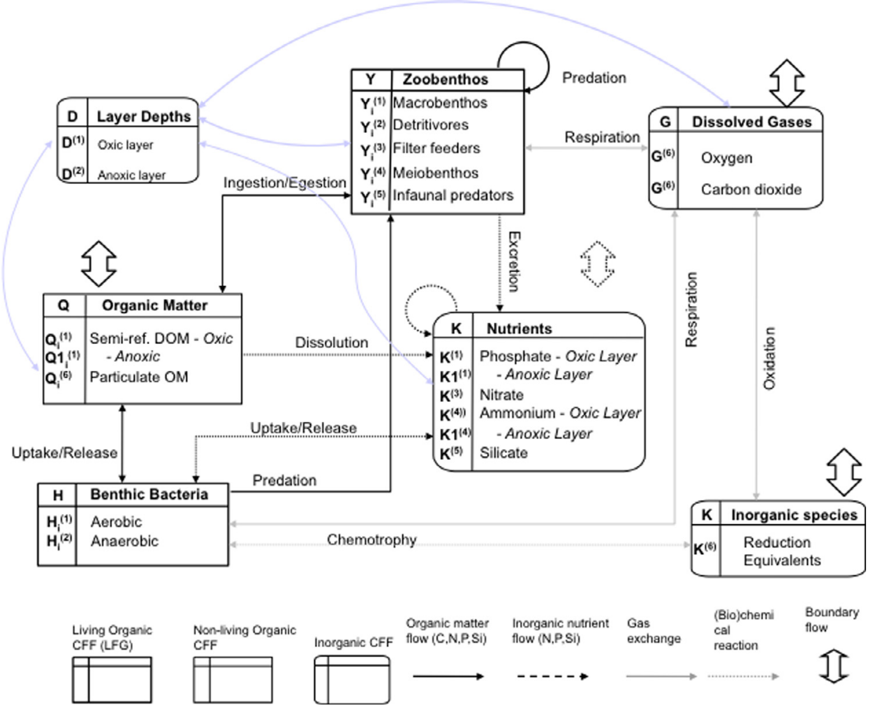

Fig. 2. Scheme of the state variables and benthic interactions of the BFM. Living (organic) Chemical Functional Families (CFFs) are indicated with bold-line square boxes, non-living organic CFFs with thin-line square boxes and inorganic CFFs with rounded boxes. The fat double-headed arrows indicate fluxes of the benthic–pelagic coupling.

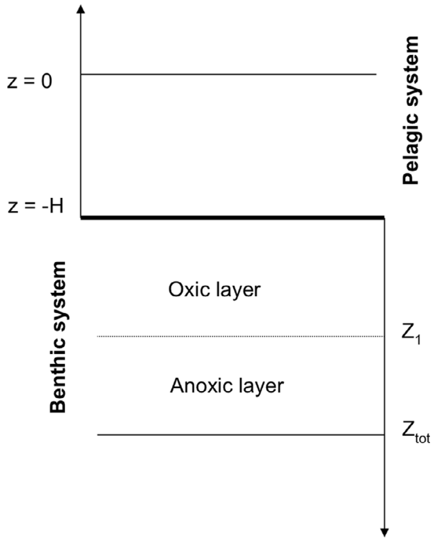

Fig. 3. Scheme of the benthic levels.

was based on the macroareas defined by the regional environmental agency (ARPA-FVG). The implementation area is code-numbered MA21 and is located in the centre of the Gulf (Fig. 4, http://dati.arpa.fvg.it/fileadmin/Temi/Acqua/CW_TW/MA21.pdf). The available *in situ* data relative to the whole area were analysed and used to set initial conditions, surface boundary conditions and to validate pelagic model performance (see Mussap et al., 2016).

In the Gulf of Trieste, soft bottoms are not homogeneous in composition and can vary from sand with patches of beach rocks to muds (Brambati et al., 1983). However, sediments are mostly

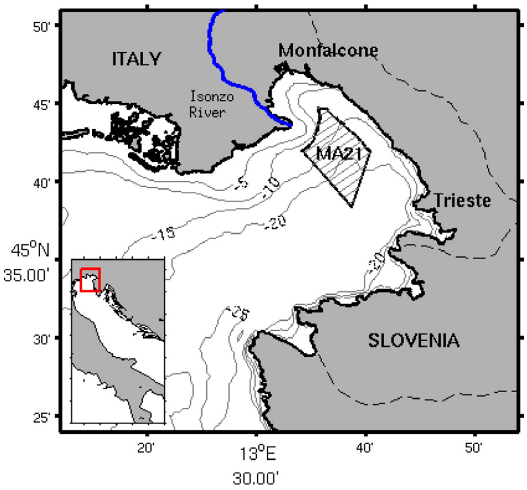

Fig. 4. Map and bathymetry (in meters) of the Gulf of Trieste with location of the implementation area MA21. After Mussap et al. (2016).

composed of silty sands (Ogorelec et al., 1991; Zuschin et al., 1999) with a mean porosity of ∼0.7.

Mean annual sediment–water fluxes measured by (Bertuzzi et al., 1997) with *in situ* benthic chambers can be found in Table 2.

Information concerning the northern Adriatic Sea benthos is sparse and still relies to some extent on the dated assessment carried out by Vatova (1949). In 1969 Orel and Mennea focused on the fauna of the Gulf of Trieste and found it was characterized by a well-developed infauna and epibenthic macrofauna, mostly composed by deposit and filter feeders (∼60% deposit feeders, ∼30% of epibenthos and ∼10% filter feeders). Since then, various authors (Fedra et al., 1976; Solis-Weiss et al., 2004, 2007) have

Table 1
Sensitivity experiments relative γ and w_{bur}.

Experiment	γ (d^{-1})	w_{bur} ($m\ d^{-1}$)
A1	10^{-4}	0.1
A2	10^{-4}	0.5
A3	10^{-4}	1.0
A4	10^{-4}	1.5
A5	10^{-2}	0.1
A6	10^{-2}	0.5
A7	10^{-2}	1.0
A8	10^{-2}	1.5
A9	1	0.1
A10	1	0.5
A11	1	1.0
A12	1	1.5

tried to describe the benthic community biomass composition, all with different results. This could be tied to the fact that since the 1980s the Gulf has been subject to repeated stress such as hypoxia/anoxia and marine snow events, as well as to an increasing anthropogenic pressure. These events have inevitably impacted the benthic community and altered its abundance, distribution and composition. Effects of such events are long-lasting and ecosystem recovery requires a significantly long period of time (Giani et al., 2012; Kollmann and Stachowitsch, 2001). Moreover, benthic fauna is influenced by bottom-water oxygen availability, which is one of the main factors controlling sediment–water exchange fluxes and organic carbon degradation in the sediment (Nestlerode and Diaz, 1998). These stresses, together with the different season, area and sampling method can explain the diverse compositions observed. As a consequence, it is difficult to define the area with a standard composition distribution. Nonetheless, it can be said that overall, polychaetes and molluscs compose ~90% of the Gulf's benthic community, represented deposit and filter feeders respectively. The distribution found by Solis-Weiss et al. (2004), which was derived from an extended dataset (1966–2001) and analysed via an innovative technique (GIS), will be used for the purpose of validating model results (Fig. 7(A)).

2.4. *Numerical experiments*

A set of twelve numerical experiments was designed to test the sensitivity of the model to deposit and diffusive processes. The suite of values for the parameters w_{bur} (Eqs. (1) and (2)) and γ (Eq. (4)) are listed in Table 1. Parameter w_{bur} defines the speed at which organic matter enters the sediment from the lower water column layer. This differs from the sinking velocity, which defines the velocity of organic matter sedimentation through the water column. The sinking velocity for organic detritus was chosen to be 1.5 m d^{-1}, while the sinking velocity for the "diatoms" and "dinoflagellates" functional groups varies from 0 to 5 m d^{-1}, depending on the nutrient stress state. This value lies at the lower end of the known range of the sinking velocity for organic matter, which varies from 0.1 to 10^2 m d^{-1} depending on the mass and size characteristic of the sinking particles. The choice was essentially dictated by a previous experience in modelling the coastal water column.

Parameter γ represents the speed at which inorganic nutrients are released back into the water column after having gone through benthic interactions. In our previous work (Mussap et al., 2016), the value of constant benthic remineralization was chosen so as to fit water column observations. However, once the full benthic system was activated, these values had to be reparameterized for the BPC. In order to do so, a matrix of twelve experiments was designed and results were analysed to find the best combination.

Through the comparison with the available observations, a reference simulation (A10) for BPC parameters was defined. The A10 configuration was used to carry out a mechanistic experiment concerning the role of filter feeders in defining the BPC fluxes. In fact, filter feeders are known to have a key role in shallow coastal environments in regulating fluxes, nutrients and oxygen concentrations. Experiment NO_FF investigated the system's sensitivity to their presence by eliminating the FF functional group from the system.

In all simulations, the model was integrated for 5 years, which was found to be the period of time necessary for the pelagic system to converge with the benthic system (Vichi et al., 2003; Mussap et al., 2016).

3. Results

Sensitivity experiments

The results of the 12 sensitivity experiments are described by the contour plots in Fig. 5, showing the variation in selected model state variables (annual average computed from the last integration year) and fluxes due to the combined change in w_{bur} and γ. The state variables shown are: particulate organic phosphorus concentration in the sediment (POP; mmol m^{-2}), filter feeders biomass (FF; mg C m^{-2} d^{-1}) and the inorganic phosphate concentration in the interstitial waters (mmol P m^{-2}, Fig. 5(B), (C) and (F) respectively); while the fluxes are: vertically integrated net pelagic primary production (NPP; mg C $m^{-2}d^{-1}$), POP FF filtration flux (mmol P m^{-2} d^{-1}) and the difference between the sediment–water P flux and the sedimentary P flux (ΔPflux, mmol P m^{-2} d^{-1}, Fig. 5(A), (D) and (E) respectively). It is stressed that in all the 12 sensitivity experiments the surface nutrient flux differences were in the order of 10^{-9} mmol P m^{-2} d^{-1}. Therefore the differences in the variables examined in Fig. 5 can be completely ascribed to the changes in the w_{bur} and γ parameters.

The results show that both NPP and POP (Fig. 5(A) and (B) respectively) increase as the two w_{bur} and γ rise. However, at a constant w_{bur} value, each of these variables decreases for γ values below 10^{-2}. In fact, it is interesting to note that for $1 \geq \gamma \geq 10^{-2}$, their variation appears insensitive to the change in γ and their value seems entirely dictated by the change in w_{bur}. Conversely, for $\gamma < 10^{-2}$ a progressively smaller γ determines a reduced NPP, which results in a diminished injection of POP in the sediment, thereby reducing organic matter availability for the benthic fauna. This can be seen in the FF abundance (Fig. 5(C)), which decreases with decreasing γ. FF abundance also decreases with the increase in burial velocity (w_{bur}), as progressively less food is available in the water column. This can be reflected in the P filtration flux (Fig. 5(D)), which likewise decreases with increasing w_{bur}. High w_{bur} values also lead to smaller ΔPflux (Fig. 5(E)), which accounts for the difference between sediment P losses (diffusion) and P gains (particulate P sinking), as the inward flux is enhanced. Highest ΔPflux values occur at $w_{bur} = 0.5$ and $1 \geq \gamma \geq 10^{-2}$. However, above and below this range ΔPflux decreases, suggesting a threshold area. At low ΔPflux ($w_{bur} > 0.5$) inorganic P accumulates in the sediments (Fig. 5(F)). Highest concentrations occur at maximum w_{bur} values and minimum γ values. For $\gamma > 0.1$ inorganic P concentrations in the sediments are mainly controlled by γ (although not visually detectable).

It must be noted that in all sensitivity experiments oxic conditions were maintained in both the pelagic and benthic domains.

Definition of the reference BPC parameters

On the basis of the sensitivity experiments, reference BPC parameters were chosen by comparing the simulation results with the available observations relative to water column vertical profiles, benthic biomass and benthic fluxes. The BPC parameters

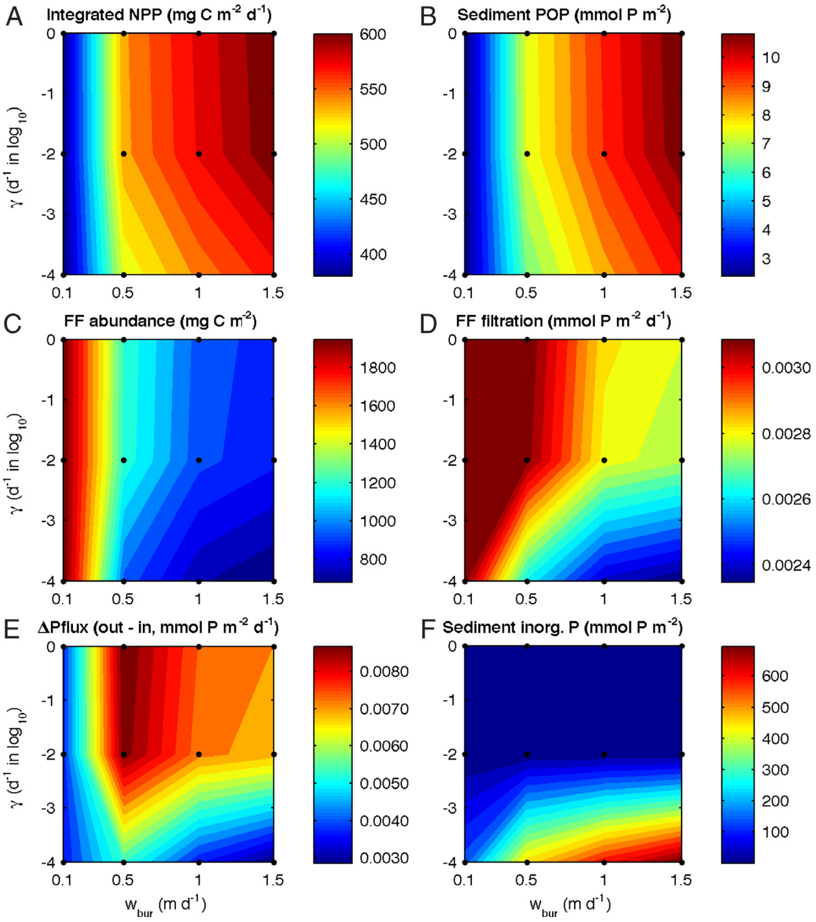

Fig. 5. Sensitivity experiments contour plots of (A) vertically integrated net pelagic primary production, (B) particulate organic phosphorus concentration in the sediment, (C) filter feeders biomass, (D) particulate organic phosphorus filter feeders filtration flux, (E) the difference between the P diffusive flux and the sedimentary P flux, and (F) inorganic phosphate concentration in the interstitial water variation of the annually averaged value is shown in relation to w_{bur} (x-axis) and γ (y-axis, log scale). Black points represent the 12 sensitivity experiments.

that yielded results closer to the observations are those adopted for experiment A10 of Table 1 ($\gamma = 1$ [d^{-1}] and $w_{bur} = 0.5$ [m d^{-1}]). The selected parameters were those that provided the minimum number of profiles characterized by a marked deviation from the observed variability and a composition of the benthic fauna qualitatively closer to the observation data. The vertical profiles obtained with such parameter choice are shown in Fig. 6 and are compared to the corresponding observed average and standard deviation value.

Simulated chlorophyll seasonal profiles (Fig. 6(A)) are in accordance with the observed seasonal trends, showing an increase with depth during spring and summer, and more uniform profiles in winter and autumn. Surface values are overestimated in winter and underestimated in spring and summer, while the autumn simulated profile always falls within one standard deviation. Spring and summer concentrations in the bottom meter sharply decrease, most probably due to the grazing activity of filter feeders.

As in Mussap et al. (2016), oxygen concentrations (Fig. 6(B)) are generally underestimated in respect to the mean observed vertical profile. This is mostly evident in spring, when concentrations are on the limit of the standard deviation. Nonetheless, the profile shapes are well represented.

Simulated nitrates seasonal profiles (Fig. 6(C)) nicely follow the however scarce observational profiles. The same is true for phosphate (Fig. 6(D)), although the simulated summer and autumn profiles show an increase in concentration with depth that is not reflected in the observations. Contrastingly, ammonium (Fig. 6(E)) is overestimated in winter and spring, while it falls closer to observations in summer and autumn. However, it must be noted that very few observations were available for this variable.

Fig. 7 shows the comparison relative to benthic biomass composition between Solis-Weiss et al. (2004) and model results (A and B respectively). For this comparison, the group defined as “polychaetes” in Solis-Weiss et al. (2004) are represented by deposit feeders, while “molluscs” and “crustaceans” are compared with model filter feeders and epibenthos respectively. “Others” were considered to be a mixture of meiobenthos and infaunal predators. The pie charts highlight how the model slightly overestimates deposit feeders and epibenthos, while it underestimates filter feeders.

Finally, Table 2 summarizes the benthic fluxes measured by Bertuzzi et al. (1997) with *in situ* benthic chambers and those simulated in experiment A10. The model slightly overestimates the phosphate flux and greatly underestimates the silicate and oxygen fluxes. However, nitrate and ammonium fluxes are in the range of observations. The slightly high phosphate flux can be echoed in bottom water column concentrations, which, as already seen in Fig. 6(D), are slightly overestimated. The same and opposite is true for oxygen.

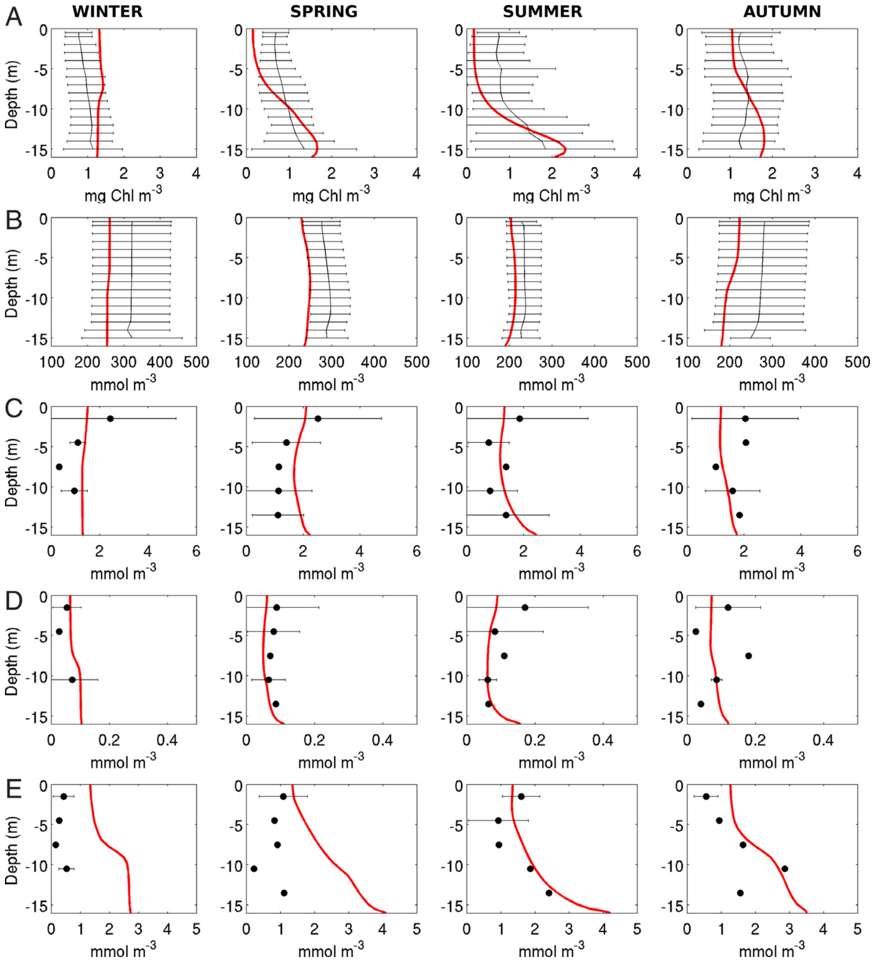

Fig. 6. Model (red) and data (black) comparison for (A) chlorophyll, (B) oxygen, (C) nitrates, (D) phosphate and (E) ammonium as climatological seasonal profiles for site MA21. The continuous red line is the simulated mean seasonal profile, while observations are plotted as seasonal means with the range of variability (where data allows it). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

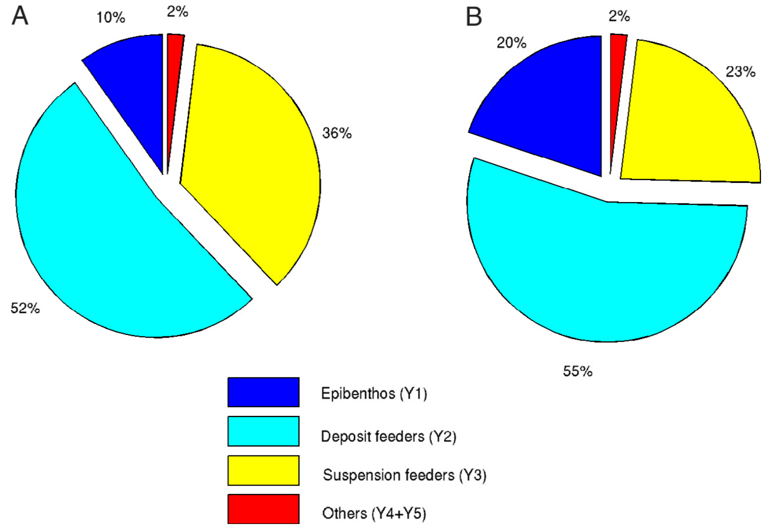

Fig. 7. Observed (A) and modelled (B) benthic fauna distribution pie charts in percentage. Observations after Solis-Weiss et al. (2004).

Table 2
Mean (± standard deviation) annual benthic fluxes of N, P, Si and O_2 (mmol m^{-2} d^{-1}).

Reference	NO_3^-	NH_4^+	PO_4^{3-}	$Si(OH)_4$	O_2
Bertuzzi et al. (1997)	0.17 ± 0.73	0.8 ± 0.7	0.029 ± 0.05	2.59 ± 2.3	-20.4 ± 8.9
BFM–POM 1D	0.27 ± 0.16	0.63 ± 0.38	0.048 ± 0.03	0.47 ± 0.41	-5.14 ± 3.5

Experiment NO_FF

Once a reference experiment was defined relative to the parameterization of the deposit/diffusion parameters (experiment A10), a mechanistic experiment was carried out to evaluate the role of filter feeders in defining benthic–pelagic dynamics. This was achieved by running experiment A10 with the FF functional group excluded. Such experiment will be named NO_FF hereafter.

In order to effectively compare NO_FF results with the A10 experiment, the percentage differences between the two was calculated for several state variables and are reported in Fig. 8. The variables shown are integrated NPP, deposit feeders biomass, bottom P flux (sediment to water column), bottom POC, organic matter in the sediments and benthic aerobic bacteria.

The removal of FF from the system causes NPP to increase throughout the year in respect to the A10 experiment, except for January and December when they coincide (Fig. 8(A)). The deposit feeders biomass is close to that of experiment A10 for the first five months of the year, and then increases of up to 30% until December (Fig. 8(B)). The bottom phosphate flux (Fig. 8(C)) has a very similar behaviour, showing important differences only after May. Bottom POC has slightly higher concentrations in the first months of the year, but a sharp increase occurs between April and May (Fig. 8(D)). Concentration differences reach up to over 110% between July and August and then decrease until December, when they become small.

A different trend can be seen for organic matter and benthic aerobic bacteria in the sediments (Fig. 8(E) and (F) respectively). The removal of FF determines a decrease of both state variables for most year. This behaviour can be related to the annual FF biomass concentration seen in experiment A10 (Fig. 9).

In fact, FF abundance in experiment A10 shows an oscillating trend during the first three months of the year, followed by a strong peak in April. High fluctuating concentrations are maintained until July and rapidly drop from September to November. When compared to the OM in the sediments and benthic aerobic bacteria, it is possible to notice that the period in which differences are nearly null coincides with lowest FF concentrations (March). Similarly, when FF peak, negative differences are stronger (between April and May). Less OM enters the sediments when FF are isolated from the system, and consequently less bacteria are present too. The increase in OM in the sediments around October (and consequently of aerobic bacteria) is given by the increase in NPP, deposit feeders biomass and bottom POC.

4. Discussion and conclusions

In this paper we have shown results from numerical simulations carried out in the Gulf of Trieste with a complex 1D coupled biogeochemical model. The focus was on the interactions between the benthic and pelagic realms and their regulating factors. The sensitivity experiments allowed to test the correct functioning of model dynamics and empirically define the BPC reference parameters. The mechanistic experiment involving the removal of filter feeders from the system acknowledged their role in a shallow shelf sea.

Results of the sensitivity test revealed two main features: (1) at high γ values ($\gamma \geq 10^{-2}$) the BPC dynamics are mostly governed by the w_{bur} value and (2) below this value the diffusive flux plays a constraining role. Small γ values mean a slower return of inorganic nutrients to the water column, which results in an accumulation in the sediments. As seen in Fig. 5, highest concentrations of inorganic phosphate in the sediments coincide with lowest FF abundance (and consequently lowest P filtration flux) and lowest ΔPflux.

When considering the $\gamma \geq 10^{-2}$ domain, as organic matter enters the sediment faster, NPP, POP and inorganic phosphate in the sediments increase. On the other hand, FF abundance, the filtration flux of P and ΔPflux decrease. In fact, the faster velocity of organic matter entering the sediment limits the filter feeders growth, while it causes higher organic and inorganic P concentrations in the sediment. It also causes a decrease in ΔPflux as the inward flux is enhanced. At the same time, the relatively high values of γ send the inorganic phosphate back to the water column, stimulating primary production. Therefore, the faster the organic matter enters the sediment, the higher the nutrients concentrations both in the sediment and the water column. This results in a highly productive system.

Contrastingly, for $\gamma \leq 10^{-2}$, the diffusive flux plays a bigger role than w_{bur}. In fact, the decreasing diffusion determines lower NPP, POP, FF abundance, P filtration flux and ΔPflux. On the contrary, it causes inorganic phosphate to accumulate in the sediment. The decreasing ΔPflux indicates a stronger incoming flux, which gets closer to the value of the outward flux. This highlights how, in order to avoid the accumulation of inorganic nutrients in the sediment and maintain the system balanced, the flux exiting the sediment has to be greater than the one entering it.

The domain of γ and w_{bur} values in which results were best compared to the available observations coincides with the ΔPflux threshold where maximum values are reached. In other words, when the difference between the outgoing flux and the incoming flux is greatest. This happens at $w_{bur} = 0.5$ m d^{-1} and $1 \geq \gamma \geq 10^{-2}$. In fact, experiment A10 was chosen to define the reference BPC parameters, however it must be noted that experiment A6 yielded very similar and equally valid results. Moreover, while carrying out sensitivity experiments it was found that values of diffusion higher than 1 d^{-1} produced unrealistic results.

The reference (A10) experiment reproduced the mean seasonal pelagic biogeochemical characteristics observed in the Gulf of Trieste. Results were qualitatively valid, showing misfits only for surface chlorophyll concentrations (winter, spring and summer), oxygen spring concentrations and ammonium winter and spring concentrations. The model demonstrated to be capable of reproducing the major benthic biota composition, although overestimating epibenthos and deposit feeders, and underestimating filter feeders. This disagreement with observed data could be linked to excess concentrations of organic matter in the lower water column. In fact, high organic matter densities and content in the sediment generally favour deposit feeding organisms (Marinelli and Williams, 2003; Pearson and Rosenberg, 1978). This is supported by benthic fauna distribution results of the sensitivity experiments (not shown), where composition is strongly liked to the burial velocity of organic matter (w_{bur}). In fact, FF abundance is inversely proportional to w_{bur}: with increasing burial velocity, progressively less FF and more deposit feeders are present in the system. Indeed, sedimentation is partially linked to variations in macrofaunal community (Norkko et al., 2001).

The model only partially reproduces observed benthic fluxes, performing quite poorly in the silicate and oxygen fluxes.

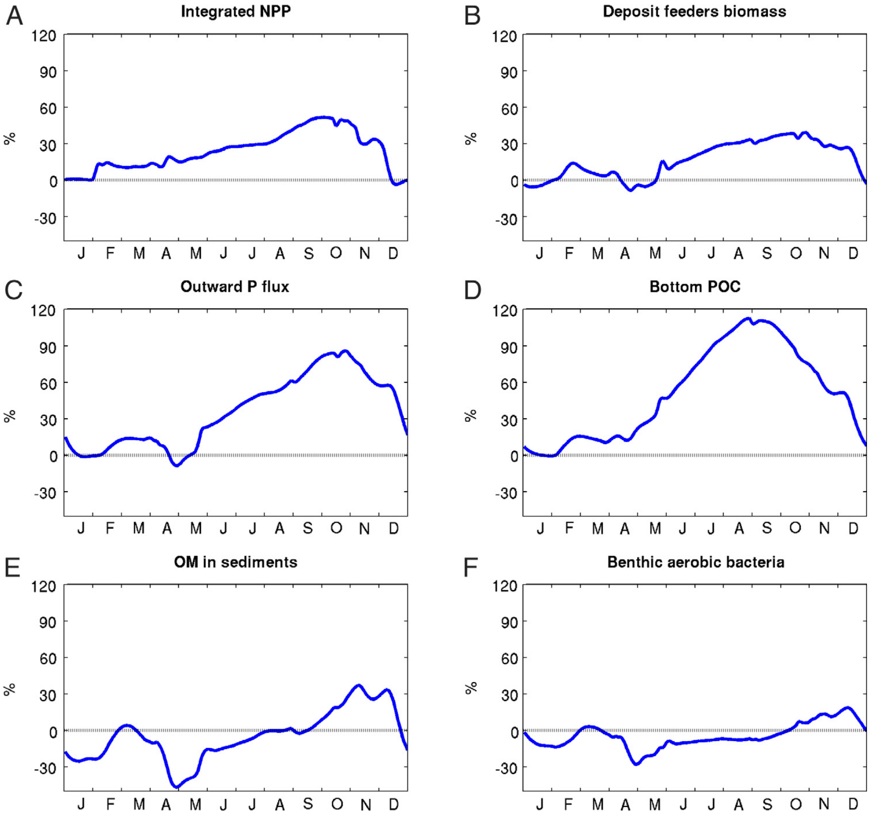

Fig. 8. Percentage difference between the A10 experiment and experiment NO_FF for (A) integrated NPP, (B) deposit feeders abundance, (C) bottom P flux, (D) bottom POC, (E) organic matter in the sediments and (F) benthic aerobic bacteria.

Concerning the silicate flux, it is well known that dissolution of biogenic silica in the sediment is significantly impacted by the faunal density and composition (Marinelli and Williams, 2003). The difference in the modelled benthic fauna with respect to the known observed structure of the Gulf of Trieste benthic communities might be responsible for the unsatisfactory silicate flux at the interface. Obviously this is an issue that requires more investigation. Also, it might be that the model overestimates the benthic organisms abundance, however this could not be checked against observations. On the other hand, the simulated low oxygen flux could be linked to an exaggerated oxygen demand and bacterial activity in the sediments. Overall, benthic model results point to an overestimation of OM in the water column bottom layer, which leads to imprecise simulation of benthic fauna distribution and benthic–pelagic fluxes.

The mechanistic experiment, consisting in the removal of the FF functional group from the system, yielded interesting results highlighting the role of FF in a shallow shelf sea. The removal of FF leads to a general increase in NPP throughout the year and in deposition being the only process defining the entrance of POC in the sediments. This supports the theory that FF play an important role in the sequestration of suspended particles from the water column, regulating primary production in coastal systems (Gili and Coma, 1998) and acting as a natural eutrophication control. Moreover, the presence of FF affects production in the water column by enhancing rates of pelagic recycling (Doering, 1989). Results highlight the importance of the role of FF in the sequestration of OM in the sediments in a shallow shelf sea, and the strong interconnection between the benthic and pelagic realms. Moreover, they underline how the dynamics of the whole system change based on the presence/absence of FF.

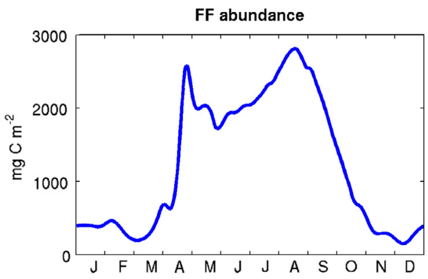

Fig. 9. Filter feeder abundance for experiment A10.

Overall, the experiments carried out in this work demonstrate a good capacity of the model to qualitatively simulate current benthic–pelagic conditions and to adapt to different trophic configurations (i.e. without FF). Seasonal trends were generally captured and ecosystem functions were appropriately represented. Our model is in line with Soetaert et al. (2000) conclusions that the best modelling choice in terms of BPC complexity to be one where the evolution of particulate matter is part of the solution and the bottom fluxes of dissolved constituents are parameterized based on mass budget considerations.

As already mentioned, modelling the BPC is still a marine biogeochemical modelling still affected by many (and large) uncertainties (Capet et al., 2016). The scarce and non-homogeneous observational datasets represent an important obstacle that must be overcome in view of using BPC modelling as a useful tool for management-related questions. Having available cost-effective decision tools is urgent in order to understand the state of the environment (Hyder et al., 2015). BFM–POM 1D has the potential to inform us on the trophic interactions and dynamics between the benthic and pelagic realms, explaining and understanding causal relationships (De Mora et al., 2016).

Improvements and future work

The Gulf of Trieste has been subject to many natural and anthropogenic pressures during the last four decades, which have caused modifications of the environmental conditions (Giani et al., 2012). The scarce observational dataset is therefore an important limit in the validation of model performance. Also, representing benthic organisms with functional groups is not an easy task as some species may change their feeding habits depending on life cycle stages and environmental conditions (Marinelli and Williams, 2003). Moreover, benthic primary producers and physical sediment resuspension processes are not included in the current formulation, representing a limit which we intend to fulfil in future works.

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CHAPTER 5

LINKING COASTAL OCEAN MODELING TO ENVIRONMENTAL MANAGEMENT: AN ENSEMBLE APPROACH

In this chapter BFM-POM 1D was used to carry out multi-parametrization ensemble experiments in order to investigate the relevance of different parameters in defining the system. Scenario studies dealing with a decrease in phosphate surface concentrations and an increase in water temperature (leading to a stronger stratification) were considered and performed with ensembles. Also, this chapter tries to communicate modeling results to stakeholders in a comprehensible manner, so to effectively contribute to marine coastal management.

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Linking coastal ocean modeling to environmental management: an ensemble approach

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Abstract The use of a one-dimensional interdisciplinary numerical model of the coastal ocean as a tool contributing to the formulation of ecosystem based management (EBM) is explored. The focus is on the definition of an experimental design based on ensemble simulations, integrating variability linked to scenarios (characterised by changes in the system forcing) and to the concurrent variation of selected, and poorly constrained, model parameters.

Ensembles determined by changes in the simulated environmental (physical and biogeochemical) dynamics, under joint forcing and parameterisation variations, highlight the uncertainties associated to the application of specific scenarios that are relevant to EBM, providing an assessment of the reliability of the predicted changes.

The work has been carried out by implementing the coupled modeling system BFM-POM1D in the Gulf of Trieste (northern Adriatic Sea) and forcing it by changing climatic (warming) and anthropogenic (reduction of the land based nutrient input) pressure. Model parameters affected by considerable uncertainties (due to the lack of relevant observations) were varied jointly with the scenarios of change.

The resulting large set of ensemble simulations provided a general estimation of the

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model uncertainties related to the joint variation of pressures and model parameters. The information of the model result variability aimed at conveying efficiently and comprehensibly the information on the uncertainties/reliability of the model results to non-technical EBM planners and stakeholders, in order to have the model based information effectively contributing to EBM.

Keywords Marine biogeochemical modelling · Ecosystem based management · BFM · Model uncertainties · Adriatic Sea · Gulf of Trieste

1 Introduction

The global coastal ocean is an intensively studied part of the global ocean, because of its complex dynamics, its ecological and socio-economical importance and its to changes (Mackenzie et al, 2004; Robinson and Brink, 2006). This delicate system is often subject to strong, and continuously increasing, anthropogenic pressures. Moreover, climate variability and change interacts with the anthropogenic pressures, potentially amplifying ecosystem degradation (Artioli et al, 2008). Detecting and predicting the possible response of the system to anthropogenic and climate pressures is therefore a scientific challenge of major interest (Harley et al, 2006). Moreover, understanding and managing the ecological alterations occurring under anthropogenic pressure is a major challenge for managers and policy makers (Hoegh-Guldberg and Bruno, 2010). The adoption of a marine ecosystem-based management (EBM) approach has therefore become essential. EBM (Slocombe, 1993) involves the management and sustainable use of the marine resources (Atkins et al, 2011), considering natural changes and human activities as components of the larger ecosystem (Arkema et al, 2006; Coll and Libralato, 2012).

Ecological models can effectively contribute to the implementation of EBM, providing insight and understanding on the functioning of the ecosystem to be managed, and contributing to predict consequences of potential impacts and pressures. The proper use of models as coastal management support tools requires the validation of the results against available observations and analysis to investigate the consequences of parameters choices that are poorly constrained by observations and/or oftern referred to very general "average values" (Harley et al, 2006). In addition to that, communicating findings arising from the simulations to managers and policy makers requires adequate procedures and protocols to define the prediction uncertainty. In fact, the uncertainty linked to the parametrization of processes is a major constraint for their use at management level (Fiechter, 2012). Developing a reliable and comprehensible communication system is therefore essential to provide information on complex topics with a degree of simpleness. The general idea is to deliver results with associated estimated uncertainty ranges, enabling stakeholders and managers to take the most appropriate decisions. One effective way to do this is by implementing a multi-parametrization ensemble approach, involving a large number of numerical experiments, considering, in an integrated way, the sensitivy of the model results to parameters and forcing conditions, and defining scenarios of change that include the combined effect of climatic change and anthropogenic pressure (as detailed below).

Ensemble simulations are now routinely carried out in the weather and climate forecast fields, where a single forecast is replaced by an ”ensemble” of forecasts, produced by varying the forecast initial conditions and/or the model parameters (Slingo and Palmer, 2011), so that the forward in time effective state of the (weather/climate) system should lie within the ”spread” generated by the different time dependent evolution of the ensemble members. The larger the ”spread”, the larger the uncertainty of the forecast/prediction should be. Such approach is adopted here and applied to the dynamics of the coastal ocean ecosystem, retaining the parameters variability approach, but analyzed jointly with variability in the forcing (scenario) conditions. In such a framework the ensembles spread (variability between ensembles) provides a measure of the overall effect of the projected scenario conditions, while the spread within the individual ensembles provides an indication of the uncertainty of the scenario projection due to the model parameterization. This way, if a model scenario simulation is particularly sensitive to a model parameter choice, the ensemble simulations for such scenario will show large spread of its members in the values of the response, thus giving indications of the (reduced) reliability of the projection.

In this work, this approach is explored by using a one-dimensional physical-biogeochemical model (BFM-POM 1D) previously developed, implemented and tested in the Gulf of Trieste (Mussap et al, 2016; Mussap and Zavatarelli, 2017). The site choice is motivated by the extensive monitoring activities carried out in the gulf. The model implementation in this site is then proposed here as a "pilot effort" in the implementation of a relatively simple model tool. In fact, as stated in the previous papers, the modeling system is aimed to complement and integrate the scientific knowledge for coastal ocean sites interested by monitoring activities (data rich areas). The objective is to provide a tool allowing to test the effectiveness of management options, accounting also for concurrent changes in the climatic characteristics. The previous efforts validated the model, defined the suitability of the system to replicate the changes in the biogeochemical functioning induced by the general variability of the physical environment and explored the role of the benthic-pelagic coupling in the general biogeochemical dynamics of the site.

Here the crucial issue of the model reliability in projections determined by different policy actions is finally investigated. The ensemble approach applied to simulations of the marine food web dynamics is rather new (Fiechter, 2012) and the general aim is to go beyond a purely model sensitivity study and have a support tools for decision making in presence of uncertainties (Ravetz, 1986) Furthermore our effort is a starting point for emulation research in the field of marine biogeochemistry. As Ratto et al (2012) state: Despite the stunning increase in computing power over recent decades, computational limitations remain a major barrier to the effective and systematic use of large-scale, process-based simulation models in rational environmental decision-making. Our effort proposes a reduced order numerical model to be used for emulator-like studies where sensitivity to model parameterizations is considered to be necessary to advance toward an usable environmental management tool.

A conceptual scheme of the work and methodology carried out is given in Figure

1. Adopting a DPSIR (Drivers, Pressures. State, Impact, Response) related (Rapport and Friend, 1979; Oesterwind et al, 2016) terminology, the changing forcing applied in each scenario represent the "pressure", while some model state variables (bottom oxygen concentration, , benthic biomass and integrated dissolved organic carbon, DOC) have been selected as representative of the system "state", while the integrated net primary productivity have been chosen to investigate the "impact" on the system.

Three pressure scenarios were taken into consideration corresponding to an increase in temperature (S1), a decrease in phosphate surface concentrations (S2) and a combination of the two (S3). The choice of the state variables listed above as representative of the system "state" was dictated by the following general consideration: bottom oxygen variability is indicative of the ventilation condition of the coastal environment, as it is well known that relatively high trophic conditions and strong vertical stratification might lead to anoxia phenomena in the coastal ocean (Rabalais et al, 2010, 2014). The dynamics of the benthic fauna (in particular the filter feeders component: Gili and Coma, 1998) has a strong influence on the dynamics of the pelagic environment, as it can significantly constrain the primary production process (Mussap and Zavatarelli, 2017). Variation in the concentration level of dissolved organic matter can be indicative of the importance of the "microbial" food web (Kujawinski, 2011) in the overall pelagic ecosystem functioning.

The chosen process experiencing an "impact" is the net primary productivity (hereafter NPP) expressed in mg C m^{-2} d^{-1}, i.e. the balance between the photosynthesis process operated by the phytoplankton functional groups and their carbon losses due to rest and activity respiration. NPP can be considered as the main process fueling the flow of matter and energy in the coastal marine ecosystem (Cloern et al, 2014). The choice was motivated by the kind of temperature and nutrient related scenarios adopted, that are directly acting on the NPP process (Falkowski et al, 1998).

Multi-parametrization ensemble experiments were performed for each of these scenarios, by varying four BFM parameters: bacterial Carbon (C) to Nitrogen (N) to Phosphorus (P) ratio (hereafter C:N:P), the phytoplankton Carbon to Phosphorus ratio (hereafter C:P), the daily specific rate of water volume filtered by benthic filter feeders (V_f in m^3 mgC d^{-1}) and the zooplankton specific mortality d_z (d^{-1}). Details on the motivation and the rationale underlying the scenarios definitions, as well as the selection of the parameters to be systematically modified for the ensemble simulations, are given in section 2.3 devoted to the description of the experimental design. The application of different scenarios to generate ensenbles jointly with the parameterts variation is expected to entail important uncertainties linked to both the parametrization of the major biogeochemical processes under projected changes of the system forcing functions.

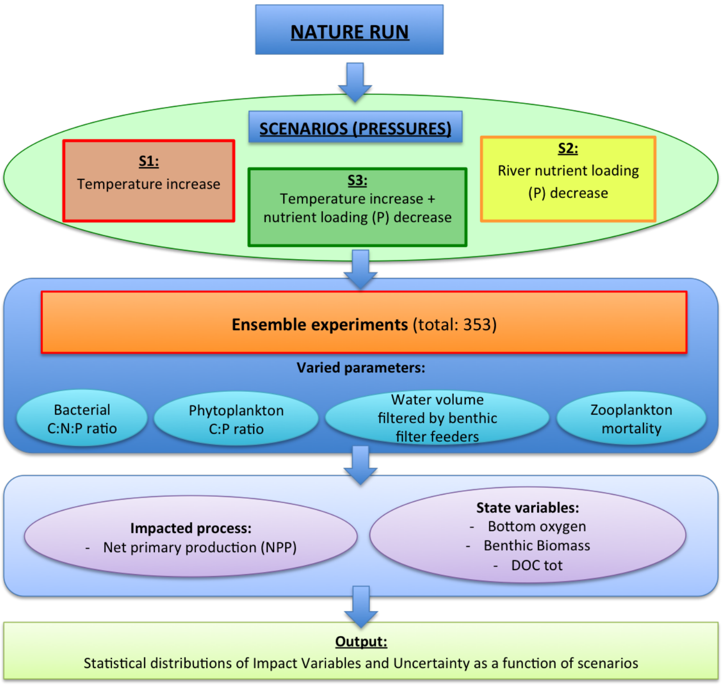

Fig. 1 Conceptual scheme representing of the structure of this study: the three scenarios, the impact variables analyzed for each of them and the statistical distributions developed as a function of the scenarios.

2 Materials and methods

2.1 Study site: the Gulf of Trieste

As for the previous studies (Mussap et al, 2016; Mussap and Zavatarelli, 2017), the one-dimensional modeling exercise has been carried out by implementing the model in the Gulf of Trieste, a shallow semi-enclosed basin ($\sim$ 20m) in the northern Adriatic Sea (Figure 2). The main freshwater input is the Isonzo river, which regulates circulation and acts as a source of nutrients. The circulation is generally cyclonic, but intense and frequent wind events (from the northeastern quadrant) produce an east-to-west surface current (Malacic and Petelin, 2009). River inputs and wind conditions are major factors in defining the trophodynamics of this area (Fonda Umani et al, 2007; Solidoro et al, 2007) influencing stratification and nutrient availability.

The Gulf is subject to strong anthropogenic pressure and is characterised by high productivity (Fonda Umani, 1996). In fact, the coast of the Gulf of Trieste is heavily populated and is site of important harbours and activities related to tourism, fishing and aquaculture, making it one of the most polluted areas in the Adriatic Sea (Faganeli and Ogrinc, 2009). Nutrient loads impact primary production and community composition, and consequently biological activity strongly depend on the Isonzo river discharge, which may vary from year to year. This anthropogenic influence contributes to the interannual variability of chemical parameters (Mozetic et al, 1998).

Generally speaking, the Gulf, as most of the Mediterranean, is P-limited. Changes in ecology and chemistry have been observed as a consequence of the stress the Gulf is constantly under, which leads to excess nutrient loads and therefore eutrophication. In fact, bottom waters have been observed to be episodically depleted in oxygen, experiencing anoxic conditions (Faganeli et al, 1991).

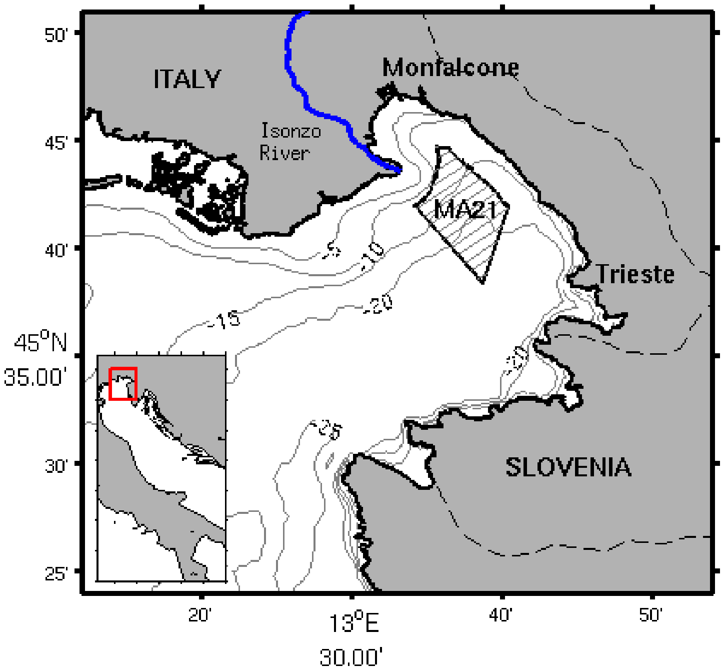

Fig. 2 Coastline and bathymetry of the Gulf of Trieste. The area labeled "MA21" is the region defined by ARPA-FVG as characterised by homogeneous hydrologic conditions.

2.2 Model description

The coupled numerical model implemented here (BFM-POM 1D) is composed by the open source Biogeochemical Flux Model (BFM, http://bfm-community.eu/) and the one-dimensional version of the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987), coupled "on-line". The equations describing the coupling between the two models can be found in (Mussap et al, 2016).
The BFM pelagic component is described in (Vichi et al, 2007), while the benthic component, based on Ebenhöh et al (1995) and Ruardij and Raaphorst (1995), has been implemented in the BFM-POM 1D by Mussap and Zavatarelli (2017).
The 1-D coupled physical and biogeoochemical model was implemented in the center of the Gulf (Figure 2), at a site included in the area MA21, covered by 6 sampling stations of the Regional Environmental Protection Agency (ARPA-FVG),

and considered as homogeneous from the point of view of the hydrological characteristics (uniform spatio-temporal distribution and coherent variability of the hydrological properties). The ARPA-FVG monitoring activities have identified several "homogeneous" areas in the Gulf (see http://www.arpaweb.fvg.it/daamc/gmapsdamc.asp). The MA21 area is representative of river influenced waters, it covers an area 3km offshore from the coastline and it is called offshore coastal because it is under the direct influence of nutrient inputs from the Isonzo river but it does not directly include the coastal current. Thus our choice of the MA21 area to do scenario studies for different nutrient inputs. The proposed methodology can be easily replicated in other areas, as the one-dimensional structure of the model allows for the extensive realisations of the ensemble simulations, an effort that would result in a prohibitive computational load if carried out with a three-dimensional model.

The bottom depth was set at 16m (average depth of the Gulf of Trieste), and the vertical resolution is defined by 30 levels, with a logarithmic distribution near the surface and bottom boundaries. As detailed in Mussap et al (2016), the implementation of the hydrodynamic model was chosen to be diagnostic for the temperature and salinity profiles (prescribed monthly climatological temperature and salinity vertical profiles). This is made possible by the extensive observational activities carried out by the Regional Environmental Protection Agency that allows for the reconstruction of a reliable climatology of the hydrological properties. The prescribed monthly varying temperature and salinity profiles eliminate the problem of model drift and reduce the problem of an incorrect representation of the spatio-temporal variability linked to the model lack of horizontal resolution. Moreover the biogeochemical state variable have been validated against independent data Mussap et al, 2016; Mussap and Zavatarelli, 2017 and results indicate that the model, despite its simple structure, has skill in reproducing the observed seasonal variability of marine trophic structure at MA21.

Under this implementation characteristics, the only surface physical forcing function applied is the monthly-varying climatological wind stress, which was obtained from the 6-hour ECMWF ERA interim reanalysis (Berrisford et al, 2009) relative to the period 2000-2013, in order to be coherent with the observational period of the hydrological data (see below).

The biogeochemical system component is forced by monthly values of surface solar radiation composed also in this case from ERA-interim (Berrisford et al, 2009), surface nutrients and seasonally varying inorganic suspended matter vertical profiles (ISM). Surface incident shortwave radiation (photosynthetically available radiation, PAR) is forcing the Primary production process. PAR penetrating the water column is attenuated on the basis of phytoplankton (self-shading) and detritus concentration (both prognostically computed), and prescribed observed ISM profiles.

The surface nutrient boundary condition is a surface nudging term (Haney, 1971; Vichi et al, 1998a,b, 2003a,b, 2004; Carniel et al, 2007) constraining the surface nutrient concentrations (phosphate, nitrate, ammonium and silicate) to monthly varying observed values:

$$K_v \frac{\partial N}{\partial t}\bigg|_{z=0} = -\gamma(N - N^*) \tag{1}$$

where N is a generic dissolved nutrient state variable, K_v is the turbulent vertical diffusion coefficient (m^2/s), N^* is the observed value and γ is an empirical relaxation velocity chosen to be 0.6 m/d. The chosen nudging surface boundary condition accounts for the external nutrient inputs from rivers.

The initial conditions for biogeochemical pelagic components are vertically-homogeneous (see Mussap et al 2016). The temperature, salinity, surface nutrient concentrations monthly climatologies were compiled from observations collected in the gulf in the period 2000-2013. Information regarding the climatologies and sources of the forcing functions can be found in Mussap et al (2016).

It has to be stressed that the model forcing functions, as well as the prescribed ISM vertical profiles are climatological (long term averages) values, therefore the obtained results should be considered as indicative of an average system behaviour.

The BFM structure is based on chemical functional families (CFFs) and Living Functional Groups (LFGs) (Vichi et al, 2007, Figure 3).

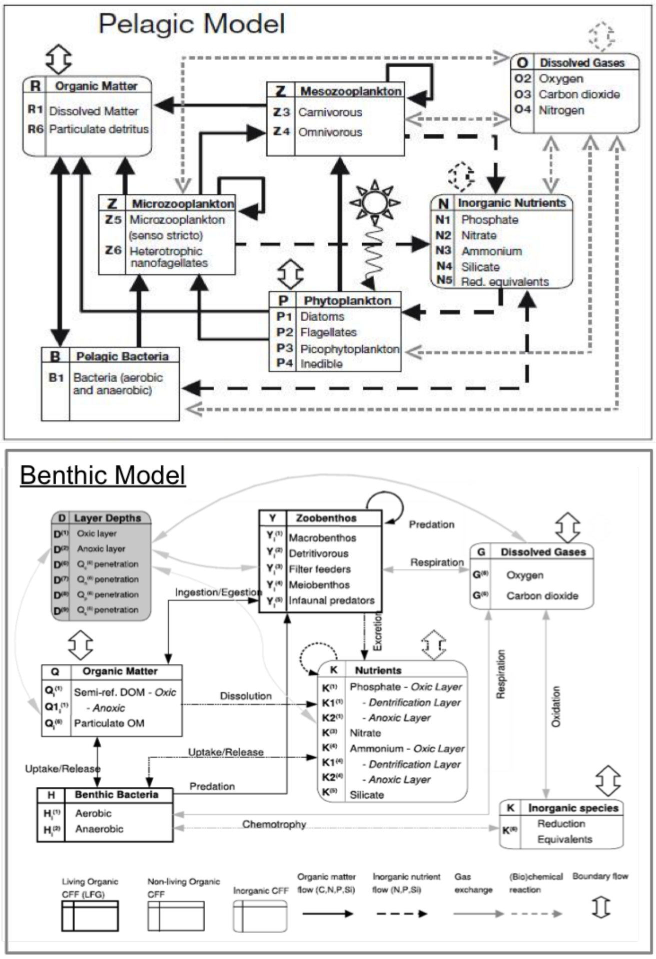

Fig. 3 Scheme of the pelagic and benthic state variables and interactions of the BFM. Living (organic) Chemical Functional Families (CFFs) are indicated with bold-line square boxes, non-living organic CFFs with thin-line square boxes and inorganic CFFs with rounded boxes. The fat double-headed arrows indicate fluxes of the benthic-pelagic coupling.

The LFGs are producers (eg. phytoplankton), consumers (eg. zooplankton) and decomposers (bacteria). The dynamics of each LFG are defined by population (growth, migration, mortality) and physiological (photosynthesis, ingestion, respiration, excretion, egestion) processes. The model resolves 4 phytoplankton LFGs, 4 zooplankton LFGs, 1 pelagic bacteria LFG, 5 benthic organisms LFGs and 2 benthic bacteria LFGs.

The pelagic CFFs are: phosphate, nitrate, ammonium, silicate and reduction equivalents The benthic CFFs are: phosphate and ammonium in the oxic and anoxic layers, nitrate, silicate and reduction equivalents. Dissolved oxygen and CO_2 are also taken into account in both the pelagic and benthic domain. Organic matter is divided into particulate (POM) and dissolved (DOM), and its dynamics are regulated by biological activity (uptake and release).

The BFM pelagic and benthic domains are directly coupled through sedimentary and diffusive fluxes at the water-sediment interface. The benthic model resolves the oxic and anoxic layers; within the total sediment thickness, the Carbon, Nitrogen, Phosphorus and Silicon detrital components have different penetration depths. the model describes the benthic fauna dynamics (determining bioturbation and bioirrigation) and the microbially mediated organic matter mineralization. Benthic primary production and sediment resuspension processes are not considered in the current formulation.

2.3 Experimental design

All the ensemble simulations were performed by forcing the modeling system in perpetual year mode (monthly varying surface forcing functions and prescribed temperature, salinity and suspended sediment vertical profiles). Using a climatological perpetual forcing for the control simulations allowed us to validate the modeled marine food web in the previous paper (Mussap et al., 2016). Thus generating food web changes by altering the characteristics of a current realistic climatological state of the system appears to be a consistent experimental design aimed to evaluate uncertainties (Milliken, 1987). Moreover, by constraining the model to the observed (or coherently altered) climatologies, the uncertainties estimation arising from the ensemble runs should be mostly depending on the purely biogeochemical dynamics, i.e. the most important (and critical) from an environmental management point of view. On the other hand, the importance and the extent of this uncertainties estimation effort should be considered in a climatological (long term averaged system state) perspective.

The scenarios were chosen as representative of two important "pressures" acting on the coastal ocean: the climate and the land based input mediated pressure. Both pressures can be considered as "anthropogenic", but their action on the coastal ocean can be considered as respectively "indirect" and "direct" (Oesterwind et al, 2016).

The climate pressure is represented by the warming of the surface ocean waters as a consequence of the global warming induced by the anthropogenic increase of atmospheric greenhouse gases (S.H., 1990; IPCC, 2014). It can be considered as a pressure acting indirectly on the coastal ocean, since it is mediated by the complex and non linear dynamics of the climate system. The latest projections about the increase of the surface temperature (IPCC, 2014) states that "Surface temperature is projected to likely exceed 1.5^{o}C" (IPCC, 2014). Therefore the temperature related scenarios applied (S1, see figure 1) were generated by progressively increasing the sea surface temperature (SST) monthly values by +0.5^{o}C from the climatological value up to to +1.5^{o}C, and by applying a corresponding subsurface warming linearly decreasing with depth, so that the temperature at the bottommost sigma layer remains identical to the climatological value. The S1 temperature related scenario group (Figure 1) is then constituted by a set of 4 scenarios, each of them characterised of a SST increase, $\varDelta\mathrm{T}_{SST}$=0.0, 0.5, 1.0, 1.5 ^{o}C.

Figure 4 reports as an example the climatological (defined as "Nature" condition) and the modified scenarios temperature profiles for the months of February and August. The scenarios choice of applying a depth (inversely) dependent warming was motivated by the willingness to enquire into one aspect of the possible warming related system modification: the increase of the vertical stratification, that is thought to influence quantitatively and qualitatively the marine primary production (Scavia et al, 2002; Behrenfeld et al, 2006) and the coastal marine ecosystem dynamics (Coma et al, 2009).

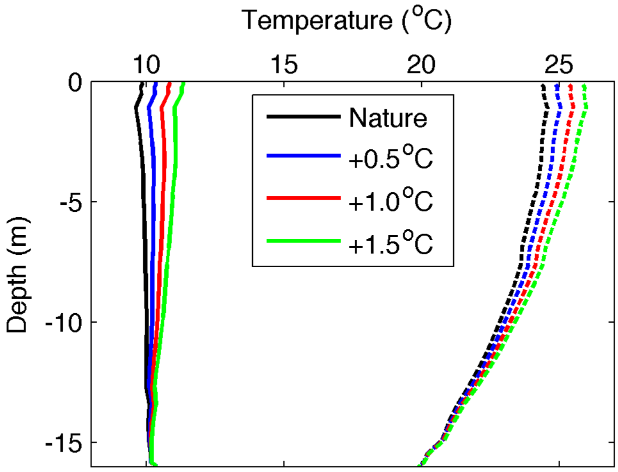

Fig. 4 January (continuous line) and August (dashed line) temperature vertical profiles of present day conditions and of the S1 scenario (increase in surface temperature).

It has to be stressed that climatic change will not affect the coastal ocean only in terms of purely temperature related changes, but the wind forcing will also be affected. In this study we did not consider climatic scenarios based on changes in the wind forcing because of a missing consensus view about a scenario of change such as the one proposed by IPCC (2014). The pressure determined by the nutrient land based input can be considered as directly acting on the coastal ocean environmental dynamics. The exclusive focus on the reduction of the land based nutrient load conveyed to the coastal ocean is motivated by the successful application of the EU regulations (648/2004 and 259/2012) concerning the abatement of phosphate (the limiting nutrient in the Mediterranean, including the northern Adriatic Sea: Marty et al, 2002; Krom et al, 2004; Solidoro et al, 2009) and phosphorus compounds in detergents. The implementation of such abatement policy contributed to a marked reduction of the phosphate riverload affecting the Mediterranean Sea (Ludwig et al, 2009, 2010) and resulting, for the northern Adriatic Sea, in a rearrangement of its trophic state towards more oligotrophic conditions (Solidoro et al, 2009; Djakovac et al, 2012). The S2 scenario group (figure 1) is then constituted by a set of 10 scenarios obtained by progressively decreasing the monthly climatological surface phosphate concentrations (used to formulate the surface boundary conditions) in 10% steps, from the climatological values to a value being just 10% of it. The interacting effect of these two pressures has been then evaluated in the S3 scenario (Figure 1) by simultaneously applying them to the system. These scenarios were run singularly as well as jointly, resulting in a set of 40 scenario experiments (4 temperature and 10 phosphare surface concentrations), including the simulation carried out under current climatological forcing and that is defined as the "nature" run.

Subsequently 15 scenario runs were were sub-sampled in order to develop ensembles considering variation in the forcing condition and in the model parameters. The sub-sampling affected the number of surface phosphate concentration scenarios, that was reduced from 10 to 4 (climatological value and reduction of 25, 50 and 75%) in order to have a manageable number of ensemble simulatons runs to be carried out.

The parameters to be varied in the ensemble simulations (Bacterial C:N:P, Phytoplankton C:P, V_f, d_z) were selected because their value is either very often referred to average conditions (Bacterial C:N:P, Phytoplankton C:P) or is poorly constrained by specific in-situ or laboratory based observations (V_f, d_z), and because of their importance in modulating the biogeochemical processes of the marine ecosystem. They act then as a source of uncertainty due to lack of knowledge and/or to their inherent natural variability. Obviously, this selected suite of parameters is not exhaustive of the problem of poorly known parameter values, but are however, crucial to define important biogeochemical processes such as net primary production, nutrient bacterial re-mineralization/utilization, secondary production and benthic/pelagic predation.

The baseline value for the adopted bacterial molar C:N:P ratio is the Goldman et al (1987) ratio (45:9:1). The BFM representation of the bacterial dynamics (Baretta-Bekker et al, 1997; Polimene et al, 2006) allows bacteria to act as inorganic nutrient remineralizers or as utilisers (and therefore as phytoplankton competitors for nutrients) on the basis of their C:N:P ratios: higher/lower C:P and/or C:N bacterial ratios (compared to Goldman et al, 1987) determine the bacterial utilisation/remineralisation of inorganic nutrients. The different biogeochemical functionality of the bacteria is associated to the establishment of the herbivorous or microbial trophic web and on trophic conditions shifting from eutrophic to oligotrophic (Legendre and Rassoulzadegan, 1995; Fagerbakke et al, 1996; Vrede, 1998; Vichi et al, 2003a). Given the "average" meaning of the Goldman et al (1987) ratio, the establishment of a threshold value for the definition of the functional role of the bacteria in a numerical model is therefore subject to uncertainties, depending on the characteristics of the bulk bacterial population and on the trophic state of the system under analysis.

The selection of the phytoplankton C:P ratio as a parameter to be varied for the ensemble simulation is essentially due to the same reasons. The average ratio is the Redfield (1934) ratio (106:1). In BFM this ratio is used to define the Droop (1973, 1975) and Nyholm (1977) nutrient dynamics in phytoplankton, implemented according to Baretta-Bekker et al (1997). The implementation allows a partial decoupling of the carbon and the nutrient dynamics, allowing the internal phytoplankton C:P ratio to vary up to to 50% of the Redfield (1934) value, therefore allowing phosphorus luxury storage/consumption. The same considerations would apply to the phytoplankton C:N ratio, but given the overall P-limited nature of the implementation site, the variation of the parameterized reference ratio was applied only to the C:P ratio of all the 4 phytoplankton functional groups considered by BFM.

The filter feeder activity constitutes an important element of the benthic pelagic coupling, capturing suspended particles and directly regulating primary production (Winter, 1978; Officer et al, 1982; Gili and Coma, 1998). A previous modeling effort (Mussap and Zavatarelli, 2017) demonstrated the importance of such processes in constraining the trophic characteristics of the implementation site and the adopted (validated reference run) baseline value for the V_f parameter was

2 10^{-3} m^3 (mgC d^{-1}), a value which is in line with the estimates of Winter (1978); Mohlenberg and Riisgard (1979); Officer et al (1982); Ricciardi and Bourget (1998). However, the estimates point to a significant variability (and therefore uncertainty) in dependence of the different macroinvertebrates that in BFM are represented by the single "filter feeders" functional group.

The background (non-predation) specific mesozooplankton mortality (d_z), that accounts for 25-35 % of the total zooplankton mortality (Hirst and Kiorboe, 2002), is the fourth and last parameter whose variation compose the set of the ensemble simulations. The baseline value for the two mesozooplankton functional groups resolved by BFM (carnivorous and onnivorous mesozooplankton) is 0.02 and 0.01 d^{-1} respectively (Dubovskaja et al, 2014). Including the variation of such parameter into the general ensemble simulation generation implies a modification of the top down control exerted by the ecosystem on the "impacted" primary productivity and therefore an estimation of the uncertainties associated to such parameterized process.

All four parameters listed above were varied in the ±20% range with respect to be baseline value, as schematised in table 1. When only single parameters were varied, the variation step was of 1% (i.e. -20%, -19%, -18%, ...,+20%), while when two parameters were simultaneously modified, the step was of 5% (i.e. -20%, -15%, -10%, ...,+20%). Each ensemble (Fig. 1) was then constituted by 352 runs. Here, the ensemble results are represented by means of frequency distribution histograms for integrated NPP, bottom oxygen, total benthic biomass and integrated DOC.

The scenarios characteristics selected for the ensemble development are schematized in Table 2. Overall, 16 ensembles were generated for a total of 5632 ensemble members, each of which was numerically stable. Note that ensemble A1 indicates the ensemble development from the "nature" run and is hereafter defined as the "control" ensemble.

Each simulation composing each ensemble had a 5 years integration time length, as previous work with the same implementation of the BFM-POM1D system (Mussap et al, 2016; Mussap and Zavatarelli, 2017) indicated that such integration time was ensuring the achievement of a stable seasonal cycle. The results shown were extracted from the last year of integration.

Table 1 Table of multi-parametrized ensemble experiments involving bacterial C:N:P ratio, phytoplankton C:P ratio, the volume filtered by the filter feeders and zooplankton mortality. Variations involved ±20% of the nature run values. The steps were of 1% for variations of single variables, and of 5% when different variables were crossed. In total, each ensemble was composed by 352 members. Shaded cells are duplicate crossings.

	Bacterial C:N:P ratio	**Phytoplankton C:P ratio**	**Zooplankton mortality**	**Volume filtered by filter feeders**
Bacterial C:N:P ratio	±20% -20:1:20 Experiments: 40	▨	-	▨
Phytoplankton C:P ratio	±20% -20:5:20 Experiments: 64	±20% -20:1:20 Experiments: 40	-	-
Zooplankton mortality	±20% -20:5:20 Experiments: 64	-	±20% -20:1:20 Experiments: 40	▨
Volume filtered by filter feeders	-	-	±20% -20:5:20 Experiments: 64	±20% -20:1:20 Experiments: 40
Total number of experiments: 352				

Table 2 Table of the scenario multi-parametrized ensemble experiments and their reference number. Ensemble number 1 is the control ensemble.

Temperature	**Multiples of phosphate**			
increase (^{o}C)	**1.0**	**0.75**	**0.5**	**0.25**
+0.0	A1	A2	A3	A4
+0.5	B1	B2	B3	B4
+1.0	C1	C2	C3	C4
+1.5	D1	D2	D3	D4

3 Simulation experiments

3.1 Control ensemble experiments

The control ensemble carried out with "present day" forcing (A1, Figure 5) was developed by varying the parameters listed in Section 2.3 and according to Table

1. Results are shown relatively to the selected "state" variables and "impacted" process listed in Section 2.3 by means of histograms, in order to highlight their distribution and variability with respect to the "nature" run (Figure 5). The continuous red line indicates the nature run value.

A t-test performed on the ensembles revealed a normal distribution at 5% significance level for all four histograms shown in Figure 5. The means, standard deviation and ranges for each distribution listed in Table 3 and compared with the A1 ensemble means are virtually indistinguishable from the nature run values, confirming an appropriate parameterisation of the former. In fact, both the ensemble mean and the nature run fall within the highest frequency bin. Standard deviations and ranges are, relatively to the average values, very similar to each other, with the exception of the bottom oxygen which shows smaller standard deviation and range.

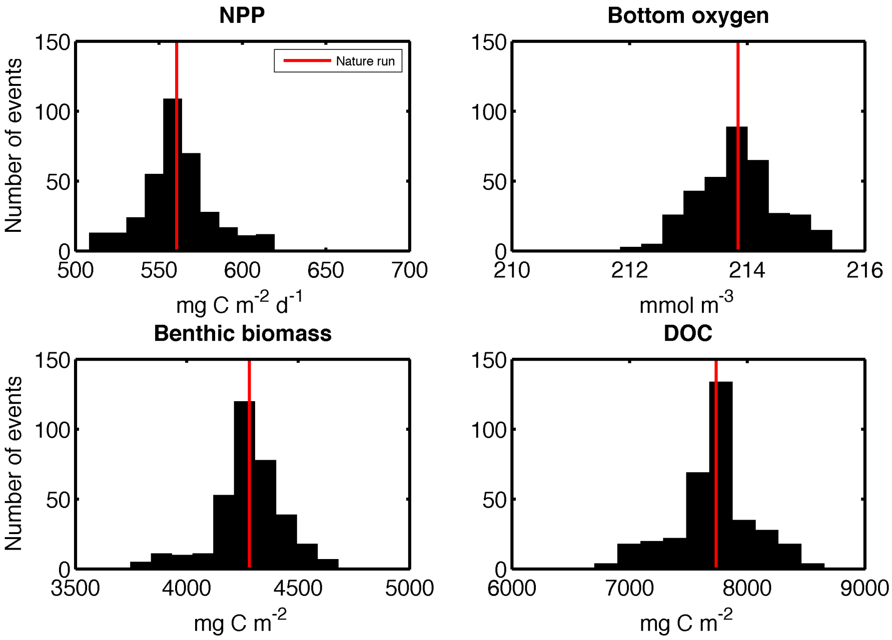

Fig. 5 Histograms of the control ensemble, computed from the 352 members of the multi-parameter ensemble. The red continuous line represents the nature run value. Panels correspond to integrated NPP, bottom oxygen, benthic biomass and total DOC.

3.2 Scenario simulations

In order to understand how the uncertainty due to the parameter choices for A1 reflects on the scenario studies, 39 simulations were carried out under scenario conditions S1, S2 and S3 with the nature run parametrization. Results of the 39 scenario experiments (plus the nature run) are described by the contour plots of Figure 6, which shows the annually averaged value obtained from each scenario. The characteristic that immediately emerges from Figure 6 is how little temperature (y-axis) and how much phosphate concentration (x-axis) determine changes in the system. In fact, temperature does not seem to play a major changing role influencing NPP, benthic biomass and integrated DOC (Figure 6A, C and D respectively). This is not true for bottom oxygen concentrations (Figure 6B), that decrease with increasing temperature. This decrease could be explained by the fact that oxygen solubility is inversely proportional to temperature (Henry's law). However, this can also be attributed to the conditions of increased stratification, which limits the ventilation of the lower water column, rather than to the increased organic matter to be respired. While bottom oxygen reaches its maximum values when no change in temperature is applied and phosphate is strongly decreased, all other variables have highest average values when phosphate concentrations are maintained at today's concentrations. In fact, they do not seem to be strongly influenced by a temperature increase, except for the integrated DOC, which slightly increases with increasing temperature. Overall, Figure 6 suggests that a reduction

Table 3 Nature run: annually averaged values. Control ensemble (A1): mean, standard deviation and range of variation computed. The numbers in parenthesis refer to the standard deviation percentage computed with respect to the mean value.

	Nature run	**Control ensemble (A1)**			
Variable	**Average**	**Average**	**Std. Dev.**	**Range**	**Units**
Integrated NPP	560.7	560.7	21.5 (3.8%)	110.9 (19.8%)	mg C m^{-2} d^{-1}
Bottom O_2	213.8	213.8	0.7 (0.3%)	3.6 (1.7%)	mmol m^{-3}
Benthic biomass	4281.2	4281.6	155.3 (3.6%)	933.9 (21.8%)	mg C m^{-2}
Integrated DOC	7735.5	7735.9	341.5 (4.4%)	1953.4 (25.3%)	mg C m^{-2}

in phosphate concentration may cause a stronger system alteration than an increase in temperature (and therefore stratification).

The 40 scenario experiments (depicted in Figure 6), were sub-sampled by choosing to select 15 temperature and surface nutrients forcing conditions to be run with the 352 parameter combinations of the ensemble exercise. The ensemble scenario characteristics and the corresponding ensemble run name are reported in table 2.

The variation of the ensemble averages corresponding to the scenarios adopted (and depicted in Figure 7), provides an indication of the overall sensitivity of the modeled system to the changing forcing conditions. It can be easily noted that the variation of the ensemble averages with respect to the changing forcing conditions is essentially identical to the average values obtained when only forcing conditions

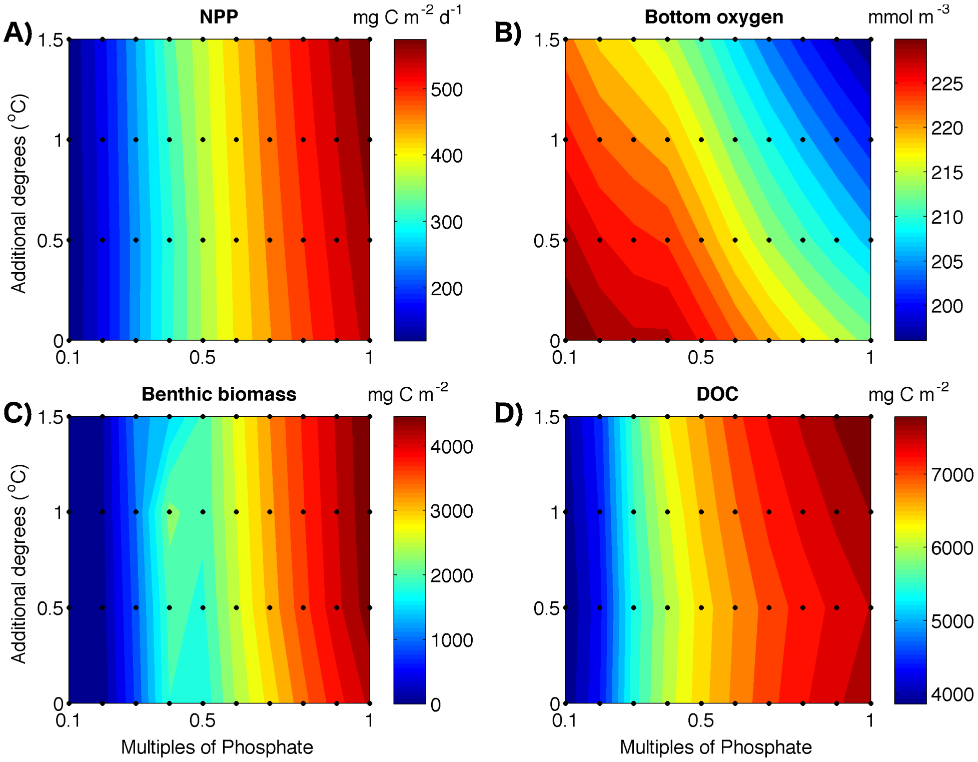

Fig. 6 Contour plots of the 39 (+ nature run) scenario experiments (represented with black dots). Multiples of phosphate on the x-axis and additional degrees on the y-axis. Panels correspond to integrated NPP, bottom oxygen, benthic biomass and integrated DOC

were changed (see table 3 and figure 6). Therefore an analysis of the ensemble runs results based solely on the shift of the ensemble average value provides little insight about the uncertainties associated to the joint variability of the forcing and the parameter choices. More important are the changing characteristics of the ensemble distributions determined by the joint variation of the forcing and the parameter values, i.e. the ΔP and C values. For instance, Figure 8 shows the frequency distribution of the values relative to the same properties shown in Figure 7, arising from the S1 (temperature variation) scenarios (A1, B1, C1 and D1 of Table 2). Similarly, Figure 9 shows the histograms corresponding to the S2 (surface phosphate flux) scenarios (A1, A2, A3, A4 of Table 2). Both figures provide a further confirmation of the finding previously described: phosphate input is a major

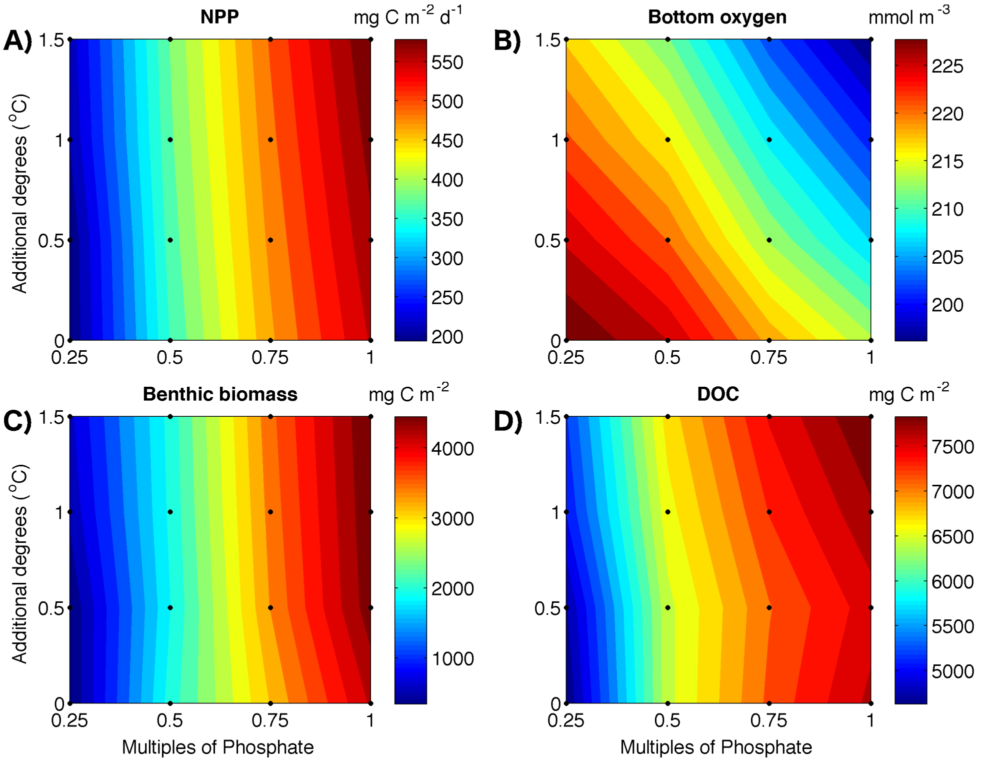

Fig. 7 contour plots of the ensemble average value obtained from the 15 Ensemble runs. X and Y axis values and properties plotted as in Figure 6

driver of change, with temperature playing a relevant role only with respect to the bottom oxygen concentration. The frequency distribution of the ensembles was checked for normality (t test) and was confirmed at the 5% significance level with the only - albeit notable - exception being the frequency distribution of the benthic biomass (discussed later) for A3 (Figure 9C). However, the roughly normal shape of each ensemble distribution associated to specific scenarios distribution changes considerably, indicating that the uncertainty affecting the simulated state variables and processes, is related to the joint role of variability in the pressures and to the parameter choices.

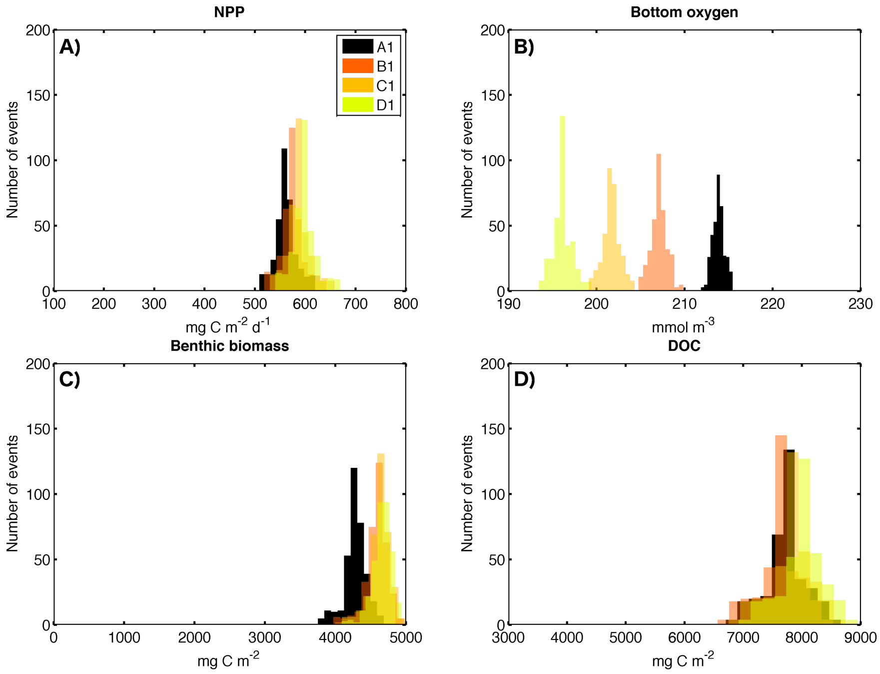

Fig. 8 Histograms of the 352 members ensemble runs carried out for S1 scenarios (+ control ensemble in black). Variables represented are A) integrated NPP, B) bottom oxygen, C) benthic biomass and D) integrated DOC. Refer to Table 2 for information on the scenario associated to the ensemble number

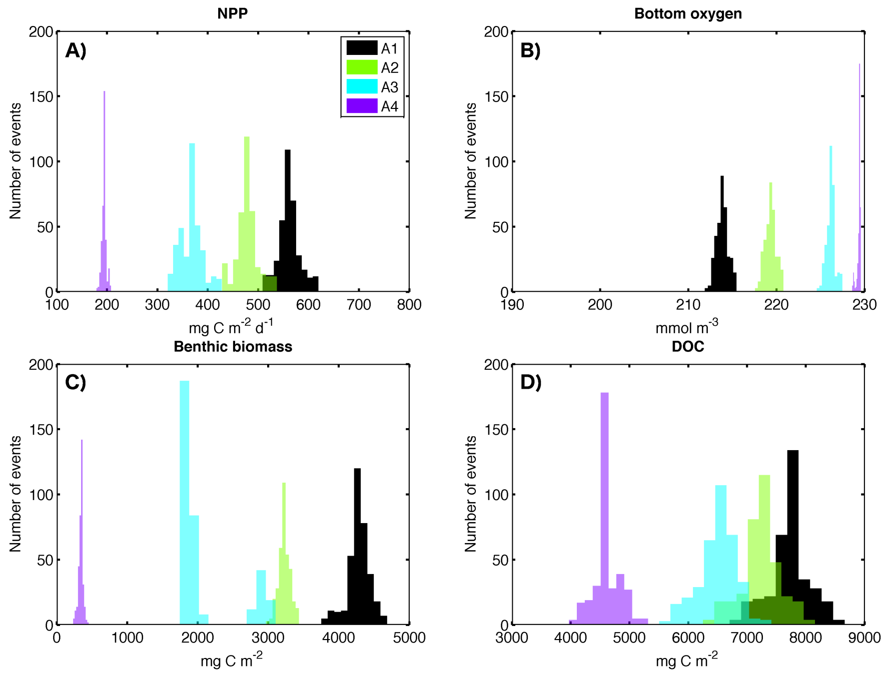

Fig. 9 Histograms of the 352 members ensemble runs carried out for the S2 scenarios (+ control ensemble in black). Variables represented are A) integrated NPP, B) bottom oxygen, C) benthic biomass and D) integrated DOC. Refer to Table 2 for information on the scenario associated to the ensemble number

3.3 Assessing uncertainties

We investigate this issue by showing in Figure 10 the coefficient of variation (standard deviation normalised by the value of the respective ensemble mean). Such coefficient is indicative of the ”spread” affecting the results of each ensemble: the larger the spread the less robust are the results pertinent to each scenario, being affected by the choice of the parameter set.

A preliminary inspection of Figure 10 already indicates that the ensemble variability of the state variables and processes investigated, show different values. It is very low for the bottom oxygen (Figure 10B) concentration (order of 10^{-3}%), it has relatively low values for the NPP (Figure 10A) and the DOC (Figure 10D) concentration (ranging between 2 and 6% and between 4.5 and 5.5% respectively), while significant variability is shown by the total benthic biomass values (ranging

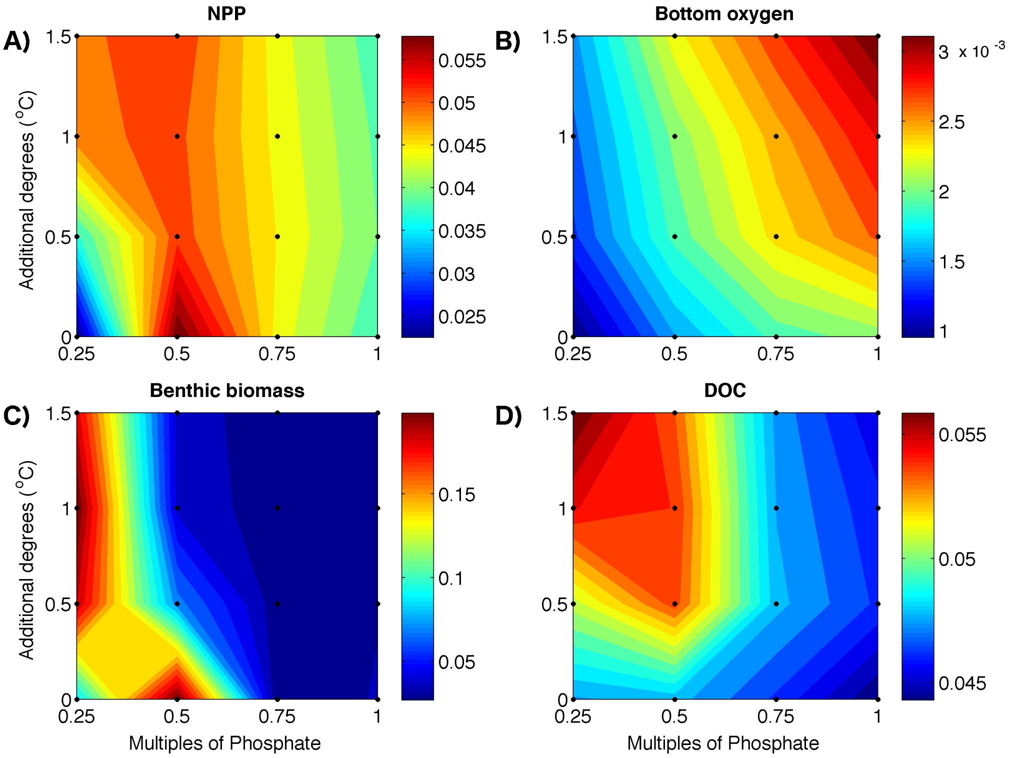

Fig. 10 Contour plot of the coefficient of variation (standard deviation normalised by the value of the respective ensemble mean). X and Y axis values and properties plotted as in Figure 6

between 4 and 20%). This finding indicates that the effect of the joint variation of the forcing functions and model parameters, produces different degrees of uncertainty on the components of the modeled system. The impact on the analyzed state variables and process is, however, not only merely quantitative. Figure 10 suggests that, for the set of scenario adopted to carry out the ensemble experiments, the pattern of uncertainty variation is peculiar. The (relatively low) NPP (Figure 10A) uncertainty shows a pattern indicating that most of the changes are related to changes in the surface nutrient forcing with a reduced role of the temperature. This is similar to the ensemble mean variation of Figure 7, but the uncertainty peaks in correspondence of an halving of the nutrient forcing with a somewhat mitigating effect of increasing temperatures.

It has already been stated above that the uncertainty variation affecting bottom oxygen (Figure 10B) concentration can be considered as negligible, given the very low changes relative to the ensemble mean. The pattern of the oxygen concentration coefficient of variation is inversely related to the changes in concentration. However the magnitude of the coefficient of variations is so small that it can be considered non significant. The model projection for bottom oxygen concentration is then "robust" with respect changes in model parameters in all scenarios.

The benthic biomass (Figure 10C) experience the largest pattern of uncertainty variability. Maximum uncertainty occurs in general in correspondence of the lower biomass values (see Figure 7) and under mimimal surface load and higher temperature warming. The plot in Figure 10C marks also a considerable uncertainty increase corresponding to a nutrient load halving under current temperature conditions.

Finally the (relatively low) uncertainty of the DOC concentration in the control ensemble scenario increases as a function of the increasing temperature and the decreasing nutrient load. This indicates (for the DOC state variable) a progressive increase of the uncertainty for more stratified and oligotrophic trophic conditions, i.e. the system is progressively shifting toward a "microbial" food web system.

Since phosphate is the limiting nutrient in the Gulf of Trieste (Fonda Umani et al, 2007), a scenario of, for instance, increased climatic change (warming) and decreased anthropic input (external nutrient input) would be characterized by a decrease in NPP. This would then lead to a reduced DOC production and to a reduced overall benthic biomass (depending on the primary produced sinking organic matter). The uncertainty related to this pattern is then negligible for what concerns the bottom oxygen concentration, while for the other state variables and processes it has different patterns of variation. However, all of them roughly point to an increase of the uncertainty corresponding to increased temperature and reduced nutrient load.

It has been stated above that each ensemble simulation is characterized by normal values distribution, with the only exception of the benthic biomass that, for the ensemble simulations characterised by a halving of the surface phosphate concentration and irrespective of the temperature change (see as an example Figure 9C), gave a roughly bimodal distribution. This seems to be associated to the presence/absence of the filter feeders functional group (Mussap and Zavatarelli, 2017). Below a certain food source availability, their presence totally depends on the volume of water filtered, which is one of the parameters involved in the ensemble exercise (see Table 1). In fact, below a certain threshold imposed by both the phosphate concentration and the water volume filtered, this faunal group disappears determining a decrease in the total faunal concentration and the observed bimodal behaviour. When S1 and S2 are combined together to form scenario S3, results tend to organize into three clear groups with respect to the control ensemble (except for bottom oxygen). As previously seen, such organization is mainly determined by the phosphate surface concentration, given that a temperature increase does not cause large changes in the system. Moreover, as already seen in scenarios S1 and S2, the ensemble range (uncertainty) does not change much when temperature increases, while it reduces when surface phosphate decreases. For bottom oxygen, results are not clearly grouped like the other variables. The histograms of Figure 11B are the product of the two opposite reactions driven by the increase in temperature and the decrease in phosphate concentration. When surface phosphate concentrations are only slightly decreased (B2, C2, D2), it is temperature that defines the shift. In fact, means decrease in respect to A1, while ranges remain similar. Vice versa, when surface phosphate is strongly decreased (B4, C4, D4), it becomes the dominant factor in defining the changes in mean and range values. B2 and D3 fall closest to the control ensemble, showing a balance between the increase in temperature and the decrease in phosphate.

It can be preliminarily concluded then that the parameter related model uncertainties in predicting the state variable evolution under changing forcing scenarios is effectively scenario depending. For the Gulf of Trieste test case investigated here the most important scenario change is related to the reduction in the nutrient load that clearly shift the system towards more oligotrophic conditions. Such variability between scenarios is associated to a variability within the scenarios, characterized by a reduction of the model results uncertainties directly related to the nutrient load reduction. This seems to be associated to the general reduction in NPP that is impacting the whole biogeochemical system functioning toward a reduction in the parameter related variability.

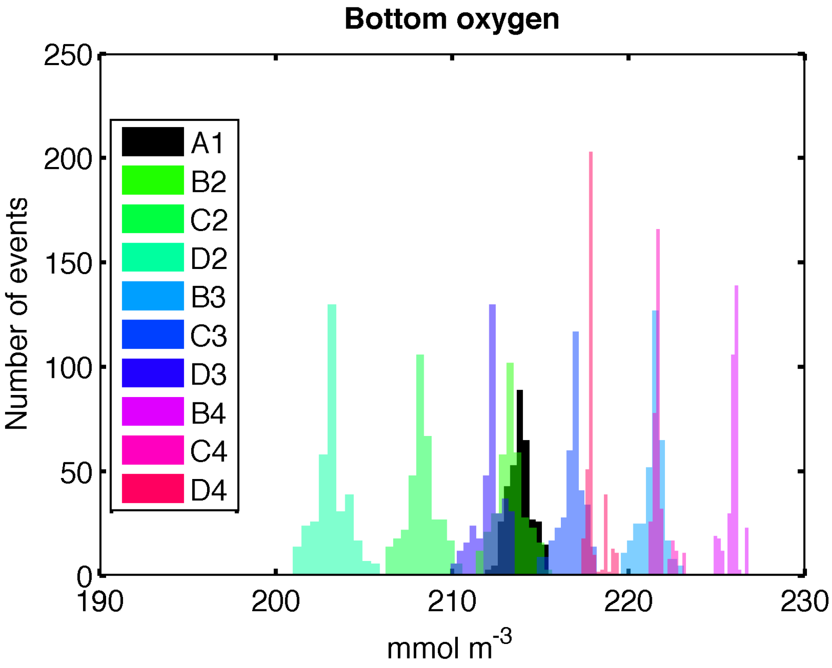

Fig. 11 Histograms of the bottom oxygen 352 members ensemble runs carried out for the S3 scenarios (+ control ensemble in black). Refer to Table 2 for information on the scenario associated to the ensemble number

4 Conclusions

In this paper we have shown results of a multi-parameter ensemble, multi-scenario exercise carried out with a coupled physical-biogeochemical 1D model. The parameter choice was based on low level trophic variables that were considered to be important in defining system dynamics, but affected by considerable uncertainty because of poor observational evidence.

The purpose of this study was to assess the possible use of numerical models in contributing to the definition of EBM management plans, facing the possible direct or indirect (anthropogenically depending) changes in the forcing functions of the coastal ocean ecosystem.

To achieve the goal, the variability of the simulation results jointly determined by the variation in the forcing functions and by the model parameterisation was explored via an ensemble approach. In fact, a model-based prediction can support coastal management planning, aimed to achieve a "good environmental state", only with a sound estimation of the uncertainties associated to the scenario assumptions made and to the parameter choice, so that a "proactive" and not only a "reactive" (Green et al, 2009) management can be attempted. Recently, vulnerability and risk assessments for the coastal ocean based on comprehensive interdisciplinary three-dimensional modeling have been proposed (Rizzi et al, 2016). The numerical simulations at the base of such assessment adopt the scenario point of view to project into the future the long term consequences of the climatic pressure on the coastal marine environment. It is believed that the insertion of the ensemble based procedure described in this work into such assessment effort, can greatly add value to the information originating from the simulation results, since it can provide, when including the assessment results into the formulation of an environmental management plan, an overall evaluation of the uncertainty associated to the simulation results, thereby enabling the policy maker and/or the environmental manager to evaluate with enhanced objectivity the possible consequences of the implementation of a specific management decision. Inserting this procedure into the wider effort proposed by Rizzi et al (2016) would require a relatively minor effort: a one-dimensional version of the model used to simulate the coupled physical-biogeochemical dynamics, implemented at specific points (covered by observations) of the model domain, could be used to generate ensembles based on the joint variability of forcing functions and parameters. This would allow an overall evaluation of the uncertainty associated to the model parameterisation and the change in the pressures. As previously stated, such evaluation cannot be easily obtained in a fully three-dimensional model implementation due to the large number of simulations required to put together meaningful ensembles. The very high number of experiments carried out (352 runs for each of the 15 ensembles), that are allowed by the fast computational times of BFM-POM 1D, enabled to develop frequency distribution histograms allowing the observation of system shifts, and the evaluation of changes in the parameter related uncertainty (Fiechter, 2012).The choice of the analysed forcing function, state variables and impacted process adopted in this study is not exhaustive, but has shown that such approach is worthwhile to be attempted, since it has demonstrated that the uncertainty of the model predictions is closely associated not only to the chosen parameterisation, but also to the scenarios characteristics and that such changing variability effects (with different magnitude) state variables and impacted processes.

The scenario studies showed the potential impacts of climate change and environmental policies related "pressures" (temperature and nutrient loading) affecting the coastal marine environment. Overall, the results of the ensemble simulations, carried out adopting a wide range of scenarios conditions (from minimal to extreme variations), showed that the system simulation uncertainties are crucially linked (as expected) to the model parameter choice, but also indicates that the uncertainty magnitude is strongly related to the changes in the ecosystem forcing (e.g. temperature and nutrient load). In fact, depending on the scenario, the parametrization acquires or loses importance, increasing or decreasing uncertainty, as witnessed by the change in the ensemble standard deviation. This study is directed also towards the definition of an innovative and effective scientific communication between environmental scientists and stakeholders. Despite the (relative) simplicity of a one-dimensional coupled biogeochemical model, the execution of an ensemble based simulation experiment yields results that are both complicated, due to large number of runs, and complex, due to the interaction between the scenario forcing and the parameter set of variation (Hyder et al, 2015). In order to provide useful information for the development of environmental management plans and/or policies, the results must be conveyed to the interested stakeholders in an effective and comprehensible manner. The main aim is to effectively link numerical modeling to management issues and to provide an assessment of the inherent uncertainty affecting a numerical simulation. The conceptual scheme of the communication plan proposed is schematically shown in Figure 12. Model results (frequency distribution from the ensemble runs) are presented via histograms located in an N-P and N-C space, where N is the number of events, P is the state variable value and C is the variation coefficient characterizing each ensemble (see fig. 10). The shift of the P mean values ($\varDelta$S) is determined by the scenario assumptions with respect to the reference simulation, while the change in the ensemble standard deviation ($\varDelta$P), jointly with the variation coefficient value (C), provide information about the projection uncertainty associated with the model parameters. The larger $\varDelta$P and C, the lower is the model robustness and the results reliability since the results have a large spread around the mean due to the parameter choices. The higher the shift of the P mean value, the larger is the change in the overall system characteristics due to the scenario. On the other hand, the larger/smaller $\varDelta$P the larger/smaller is the uncertainty associated with the modeled scenario response. The proposed method does not define ”good” or ”bad” conditions, but represents results in a way that the interested stakeholder can independently evaluate the magnitude and the model reliability to project the marine food web changes in the future scenarios.

The proposed multi-parameter ensemble modeling strategy can be an effective support to the formulation of adaptive management strategies under combined pressures (Meier et al, 2014). This study aimed at exploring the potential numerical model contribution to EBM. We believe that the proposed new communication

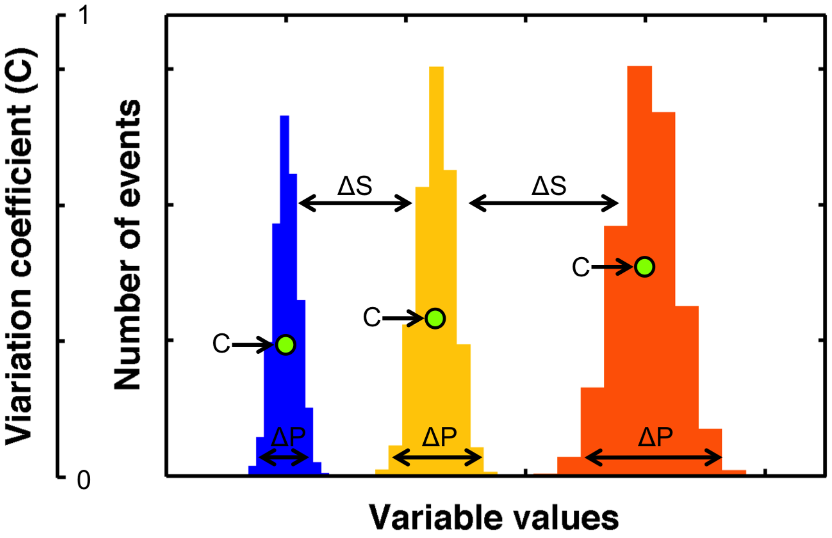

Fig. 12 Conceptual scheme of the strategy proposed to communicate effectively numerical modeling ensemble outputs to stakeholders under changing scenario conditions. Histograms representing ensembles are located in a *N*-*P* space, where *N* is the number of the events and *P* is the state variable value. The second ordinate axis refers to the variation coefficient (*C*) characterizing each ensemble. *Δ*S indicates the shift of the ensemble mean due to the changing scenarios, while the ensemble range (*Δ*P) and the variation coefficient indicate for each ensemble the reliability of the model projection depending on the parameters choices.

strategy can easily and effectively support stakeholders in the decision making process, and we propose it for discussion to the scientific and stakeholder communities.

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CHAPTER 6

CONCLUSIONS

A complex lower trophic level biogeochemical model was successfully coupled to a vertical 1D hydrodynamic model and applied to a coastal area in the northern Adriatic Sea. The coupling and tuning processes of the model in the Gulf of Trieste required an large amount of time. Different and, in some cases, extensive sets of data were analyzed in order to force the model with site specific characteristics and be able to validate model outputs.

The coupled pelagic model was validated against results and the mechanistic studies performed revealed a good functioning of the model. Such experiments highlighted the importance of the microbial food web in the area and revealed how its dynamics are strongly connected to nutrient ratios and availability. In fact, higher nutrient availability caused the system to shift between the microbial and herbivorous food web.

The inclusion of a benthic system of intermediate complexity enlightened on the importance of including these processes in a shallow coastal zone and on the role benthic filter feeders play in determining benthic-pelagic fluxes. The sensitivity experiments carried out acknowledged once again the large uncertainties linked to the modeling of the benthic-pelagic coupling, as well as the need to further developed this aspect of coastal ecological modeling in favor of its use as a supportive management tool.

The multi-parameterization ensemble approach adopted in the last part of this work was fundamental to investigate and understand the range of uncertainties linked to BFM-POM 1D in the Gulf of Trieste. The results of its uncertainties gave the model credit to be used as a supportive tool to coastal management. The scenario experiments revealed interesting results for potential future conditions, uncovering the huge importance of nutrient concentrations in defining the system and the relatively less important changes related to a temperature rise. Moreover, the communication strategy proposed aimed at presenting complex results in a simplified way, comprehensible to stakeholders and the general public.

Overall, the following conclusions can be drawn from the application of BFM-POM 1D in the Gulf of Trieste (norther Adriatic):

- BFM-POM 1D correctly simulates coastal biogeochemical dynamics
- BFM-POM 1D is a stable model, but with a degree of flexibility which allows for it to adapt to new conditions fairly quickly
- the microbial food web prevails in the Gulf of Trieste and trophic interactions are mainly determined by nutrients availability
- the inclusion of a benthic compartment and its sensitivity analysis are important in coastal areas
- Benthic filter feeders play a significant role in coastal areas in determining the benthic-pelagic coupling
- Multi-parametrization ensemble approaches are fundamental for the development of a management tool and for scenario testing
- A change in nutrient concentrations leads to stronger system shifts than an increase in temperature
- new simple ways of communicating science need to be adopted in order to tighten the relationship between stakeholders to scientists, and favor their collaboration

APPENDIX A

APPENDIX A

The peer-review publication resulting from the scientific article *A management oreinted 1-D ecosystem model: implementation in the Gulf of Trieste (Adriatic Sea)* was accompanied by the following supplementary material.

Supplementary material: A management oriented 1-D ecosystem model: implementation in the Gulf of Trieste (Adriatic Sea)

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Abstract

In this paper a coupled physical-biogeochemical one-dimensional numerical model (BFM-POM 1D) was implemented in the Gulf of Trieste, (northern Adriatic Sea) and its structure was tested in order to evaluate its usability as a tool to support coastal management and planning. The evaluation concerned the ability of the model to reproduce the main trophic pathways, as well as their temporal variability, in terms of seasonal variations. The ecosystem structure comprised three phytoplankton groups, four zooplankton groups, one bacterial group, and a simple benthic return in order to parametrize benthic processes. The dynamics and interactions between groups were studied, as well as the model's sensitivity to different trophic web configurations. Results showed that the model was capable of replicating trends of seasonal vertical profiles of the major biogeochemical elements, and the prevalance of the microbial food web shaping the trophic chain in the Gulf of Trieste. The model also responded to strong forcings at the surface and different trophic arrangements, thus providing initial evidence of its potential as a scientific tool aimed at marine coastal management.

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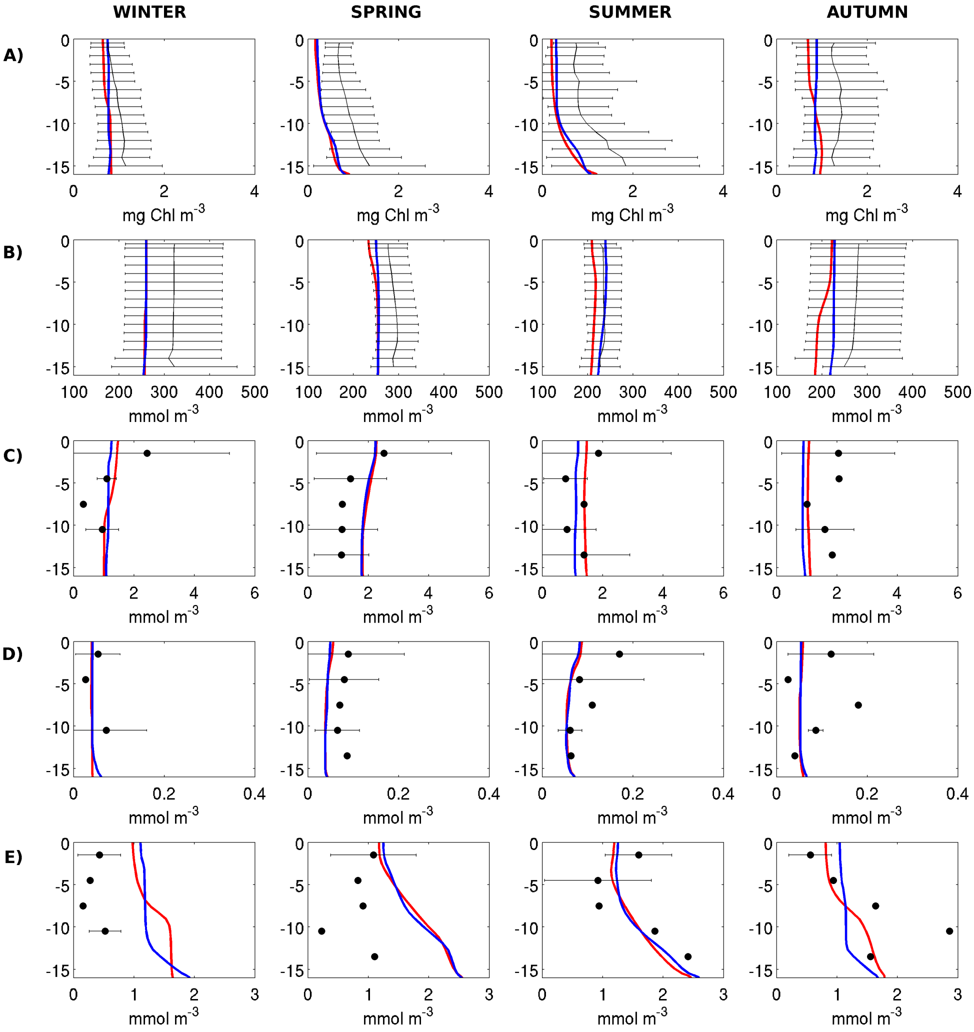

S 1. BASE (red) and sensitivity (blue) experiments compared to *in situ* data as climatological seasonal profiles for area MA21. The sensitivity experiment was forced with physical climatologies (temperature, salinity, wind stress and solar radiation) from the only period for which there is an overlap with biogeochemical data (2000 - 2001). Top to bottom: **A)** chlorophyll, **B)** oxygen, **C)** nitrates, **D)** phosphate and **E)** ammonia. Observations are plotted as seasonal means with standard deviation (where data allows it).

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