

Three-dimensional modeling of the lower trophic levels in the Ria de Aveiro (Portugal)

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ABSTRACT

The water and the ecosystem dynamics of the Ria de Aveiro, a shallow, multi-branch lagoon located on the northwest coast of Portugal, are simulated using a new fully coupled 3D modeling system. This model couples the hydrodynamic model SELFE (semi-implicit Eulerian-Lagrangian finite element) and an ecological model extended from EcoSim 2.0 to represent zooplankton dynamics. The model application is based on an unstructured grid spatial discretization, which is particularly appropriate for this system given its complex geometry. The baroclinic circulation is calibrated and validated for different environmental conditions, leading to velocity errors smaller than 5 cm/s across the lagoon. Ecological simulations, focused on zooplankton dynamics represented by a site-specific formulation, are then presented and compared against field data for two contrasting environmental conditions: Autumn 2000 and Spring 2001. Results show that the fully coupled model is able to reproduce the dynamics of the ecosystem in the Spring 2001, fitting the model results inside the range of data variation. During this period zooplankton differences between data and model results are of about 0.005 mg C/l (60%), while other ecological tracers' differences are generally smaller than 20–30% along the several branches of the lagoon. In the Autumn 2000, the model tends to overestimate zooplankton by a factor of 10 and to underestimate phytoplankton and ammonium, with discrepancies of about 0.1 mg C/l and 4.8 $\mu\text{mol N/l}$, respectively. Factors like the ecological conditions imposed at the boundaries, the input parameters of the ecological model and the simplification of the ecosystem structure, since phytoplankton is the only primary producer considered, may explain the observed differences.

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1. Introduction

The Ria de Aveiro is a shallow temperate coastal lagoon located on the Northwest (NW) coast of Portugal (40°38'N, 8°45'W). The lagoon is about 45 km long and 10 km wide (Fig. 1) and has an average depth of about 1 m (Dias et al., 2000). It is separated from the ocean by a sand spit, interrupted by an artificial tidal inlet about 20 m deep. The artificial inlet channel is connected to four main branches, the Mira, Ílhavo, Espinheiro and S. Jacinto channels (Fig. 1), through which the main sources of freshwater flow into

the lagoon. The rivers Vouga and Antuã discharge to the Espinheiro channel, being the major sources of freshwater to the lagoon (Dias et al., 2000; Dias and Lopes, 2006). Smaller sources of freshwater flow into the system through other channels, namely the Boco river in the Ílhavo channel, the Caster River in the S. Jacinto channel and several small rivers in the Mira channel. Freshwater flows are poorly known due to a severe lack of data: Dias and Lopes (2006) refer average annual flows of 50 and 5 m³/s, while Dias et al. (2000) refer average annual flows of 29 and 2 m³/s, respectively, for the Vouga and the Antuã rivers; for the Vouga river, Vaz and Dias (2008) refer an average annual flow of 31.45 m³/s, based on field measurements in the Espinheiro channel from September 2003 to August 2004. Tides at the mouth of the lagoon are semi-diurnal, with a mean tidal range of about 2 m (Dias et al., 2000). More detailed descriptions of the lagoon can be found in Dias et al. (2000) and references herein.

This lagoon plays an important ecological role, being the habitat of several species of flora and fauna (Hermoso et al., 2001) that are supported by the dynamics of the lagoon. In the lower trophic levels, in particular, zooplankton is a very important biological community. Zooplankton is responsible for the secondary productivity

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Fig. 1. Synthetic map of the Ria de Aveiro.

of the estuaries, which supports several vital functions for fishes or shrimps. The study of the factors that affect this community is thus fundamental for the management of the ecosystem (David et al., 2006). In the Ria de Aveiro, the copepoda community represents 62% of the total zooplanktonic biomass, playing an important role in the secondary production of the lagoon (Leandro, 2008).

There are also several economic and social activities (e.g. industries, agriculture) in the Ria de Aveiro and it supports a population of about 250 000 habitants (Ferreira et al., 2003). In the last few decades, these activities have reduced the ecological quality of the lagoon (Lopes and Silva, 2006; Lopes et al., 2005). Some human interventions, like the construction of a submarine outfall, reduced the nutrient loads and improved its quality (Silva et al., 2000), but there are still problems.

There is, thus, a need to develop strategies that contribute to an integrated management of the Ria de Aveiro, supported by a detailed and updated knowledge of the system and by tools and monitoring programs that improve this knowledge. In particular, it is important to assess the impact of the human interventions in this water system (e.g. outfall construction). Numerical models, integrated and validated with field data, are important tools for supporting management policies.

Most of the past ecological and water quality studies in the Ria de Aveiro were based on field data. The focus of these studies include the oxygen consumption (e.g. Cunha et al., 1999), the variability of nutrients and chlorophyll *a* along the lagoon (e.g. Almeida et al., 2005, 2007; Lopes et al., 2007), the effects of the mercury contamination (Válega et al., 2008; Pato et al., 2008) and the zooplankton (Leandro et al., 2006a). The studies based on water quality and eco-

logical models (e.g. Lopes et al., 2005, 2008; Saraiva, 2005; Trancoso et al., 2005; Lopes and Silva, 2006) are still scarce. The hydrodynamics of the lagoon has been characterized through both field data (e.g. Dias et al., 1999; Vaz and Dias, 2008) and numerical modeling (e.g. Dias et al., 2003; Oliveira et al., 2006), but past numerical applications were limited by insufficient horizontal or vertical resolution. Indeed, among these studies, only one uses unstructured grids, which are fundamental to solve the complex geometry of the lagoon and the relevant spatial scales. However, this study, from which was built the 3D model presented here, is based on a depth-averaged approach (Oliveira et al., 2006). An integrated analysis that is able to tackle the adequate spatial scales is yet to be performed both to increase the knowledge of the system and to create the basis for an operational forecast system to support the lagoon's management.

The present work aims at implementing a new, fully coupled, three-dimensional hydrodynamic and ecological model, ECO-SELFE (Rodrigues et al., 2008), in the Ria de Aveiro and validate it with field data measured in the several branches of the lagoon under different environmental conditions. This model allows for the representation of the hydrodynamic and the biological processes at the relevant time and space scales, through the use of unstructured discretizations of the domain. The ecological model allows the simulation of the cycles of carbon, nitrogen, phosphorous, silica and iron, and includes a site-specific formulation for zooplankton, based on the field work of Leandro et al. (2006a,b) in the Ria de Aveiro. This application of ECO-SELFE constitutes its first validation in a real system.

2. Methodology

A two-stage methodology is adopted in this study. First, the hydrodynamic model is calibrated with field data, in order to establish the numerical conditions of the simulations (e.g. horizontal and vertical grids, time step). This approach optimizes the computational time as the coupled model is twice more CPU demanding than the hydrodynamic module alone. The implementation of the 3D hydrodynamic model builds on the work of Oliveira et al. (2006). Secondly, the fully coupled 3D hydrodynamic and ecological model is validated. This validation is performed for two contrasting environmental conditions, also allowing the analysis of the effects of the seasonal conditions on the ecosystem dynamics. For both stages, the simulation periods were defined based on the data available for the validation of the coupled model. Thus, the structure of the paper reflects the methodology adopted: the description of the model and its set-up for both stages are presented in the following subsections. Section 3 presents and discusses the results for the hydrodynamic model assessment and the ECO-SELFE model application together with a preliminary analysis on the importance of the environmental factors; the main conclusions and the directions for further research are summarized in Section 4.

2.1. The 3D coupled numerical model ECO-SELFE

ECO-SELFE is a fully coupled three-dimensional hydrodynamic and ecological model. The hydrodynamic model, SELFE (semi-implicit Eulerian–Lagrangian finite-element; Zhang and Baptista, 2008, serial version 1.5k2, available at <http://www.stccmop.org/CORIE/modeling/selfe/>), solves the three-dimensional shallow-waters equations and calculates the free-surface elevation and the 3D water velocity, salinity and temperature. The ecological model results of an extension of the model EcoSim 2.0—ecological simulation (Bisset et al., 2004, available at <http://www.myroms.org/>) to account for the simulation of several groups of zooplankton (Rodrigues et al., 2008). The model includes the cycles of carbon (C),

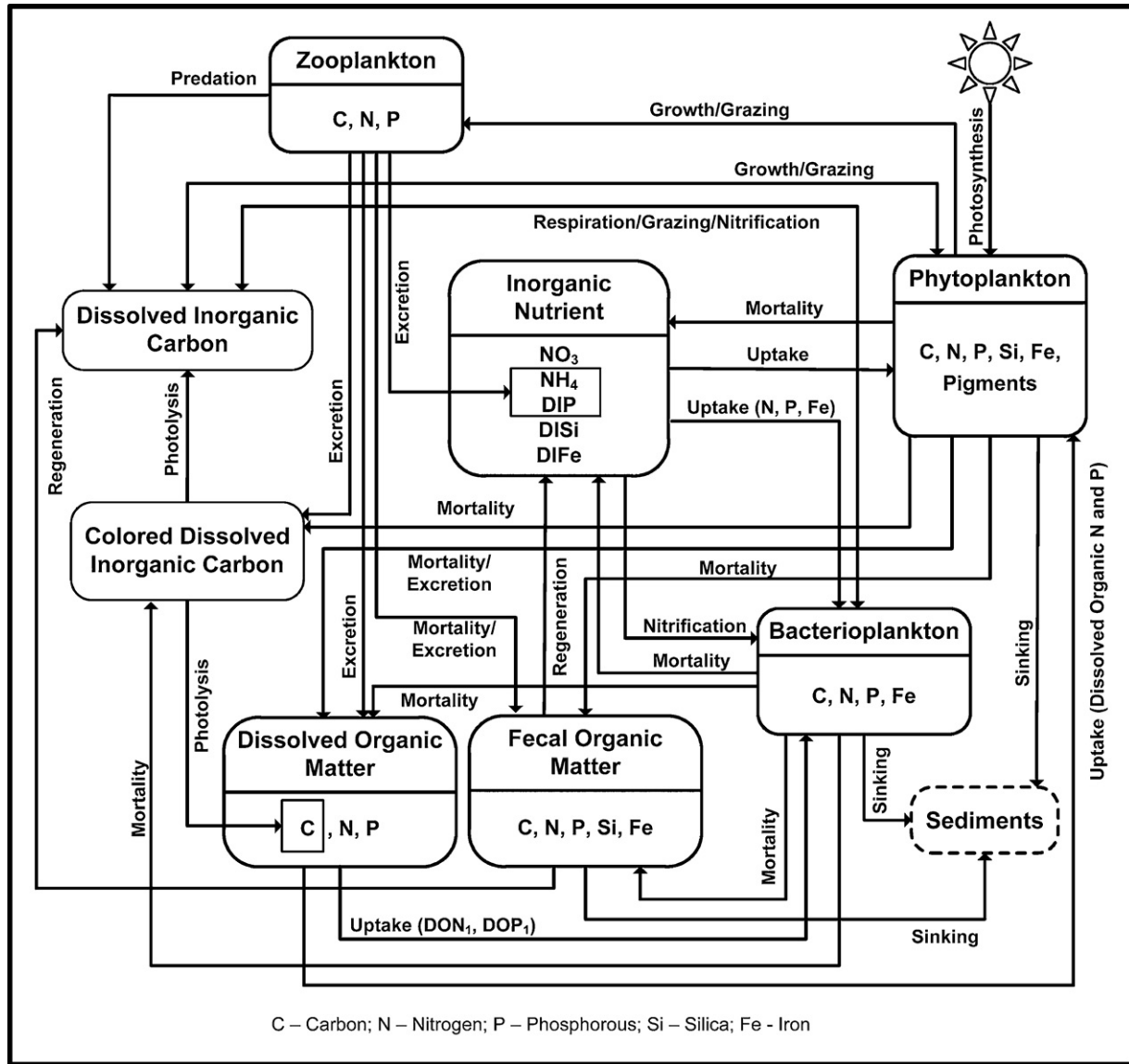


Fig. 2. Sources and sinks of the ecological model.

nitrogen (N), phosphorus (P), silica (Si) and iron (Fe). Besides zooplankton, the model can simulate several phytoplankton groups, bacterioplankton, dissolved and fecal organic matter, inorganic nutrients and dissolved inorganic carbon (DIC).

The integrated model is based on a finite-element/finite-volume numerical scheme (Zhang and Baptista, 2008). For salinity and temperature, advection can be treated with Eulerian–Lagrangian methods (ELM), an upwind or a total variation diminishing (TVD) numerical scheme, while for the ecological tracers upwind and TVD methods are available (Zhang and Baptista, 2008). The domain is discretized horizontally with unstructured triangular grids and vertically with hybrid coordinates (partly terrain-following S-coordinates and partly Z-coordinates), allowing for high flexibility in both vertical and horizontal grids.

The hydrodynamic and the ecological models are integrated through the transport equation:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} = \frac{\partial}{\partial z} \left(\kappa \frac{\partial C}{\partial z} \right) + F_c + \Lambda C \quad (1)$$

where C is a generic tracer, (u, v, w) is the velocity, κ is the vertical eddy diffusivity, F_c is the horizontal diffusion and ΛC are the sources

and sinks calculated with the ecological model. A general overview of the sources and sinks of the ecological tracers is presented in Fig. 2.

Since the zooplankton state variables were added to the base formulation of EcoSim 2.0, the equations that describe the sources and sinks of zooplankton are presented here. Zooplankton is described in terms of carbon (ZC), nitrogen (ZN) and phosphorous (ZP) content according to

$$\Delta ZC_l = \mu_{z,l} ZC_l - e_{z,l} ZC_l - g_{z,l} ZC_l \quad (2)$$

$$\Delta ZN_l = \frac{F_N}{F_C} \mu_{z,l} ZC_l - e_{z,l} ZN_l - g_{z,l} ZN_l \quad (3)$$

$$\Delta ZP_l = \frac{F_P}{F_C} \mu_{z,l} ZC_l - e_{z,l} ZP_l - g_{z,l} ZP_l \quad (4)$$

where the subscript l refers to each functional group of zooplankton, $\mu_{z,l}$ is the zooplankton growth rate (days^{-1}), $e_{z,l}$ is the zooplankton excretion rate (days^{-1}), $g_{z,l}$ is the zooplankton mortality rate due to natural mortality and predation (days^{-1}), and F_c , F_N and F_P are the quantity of food available for zooplankton (mmol m^{-3}) expressed in

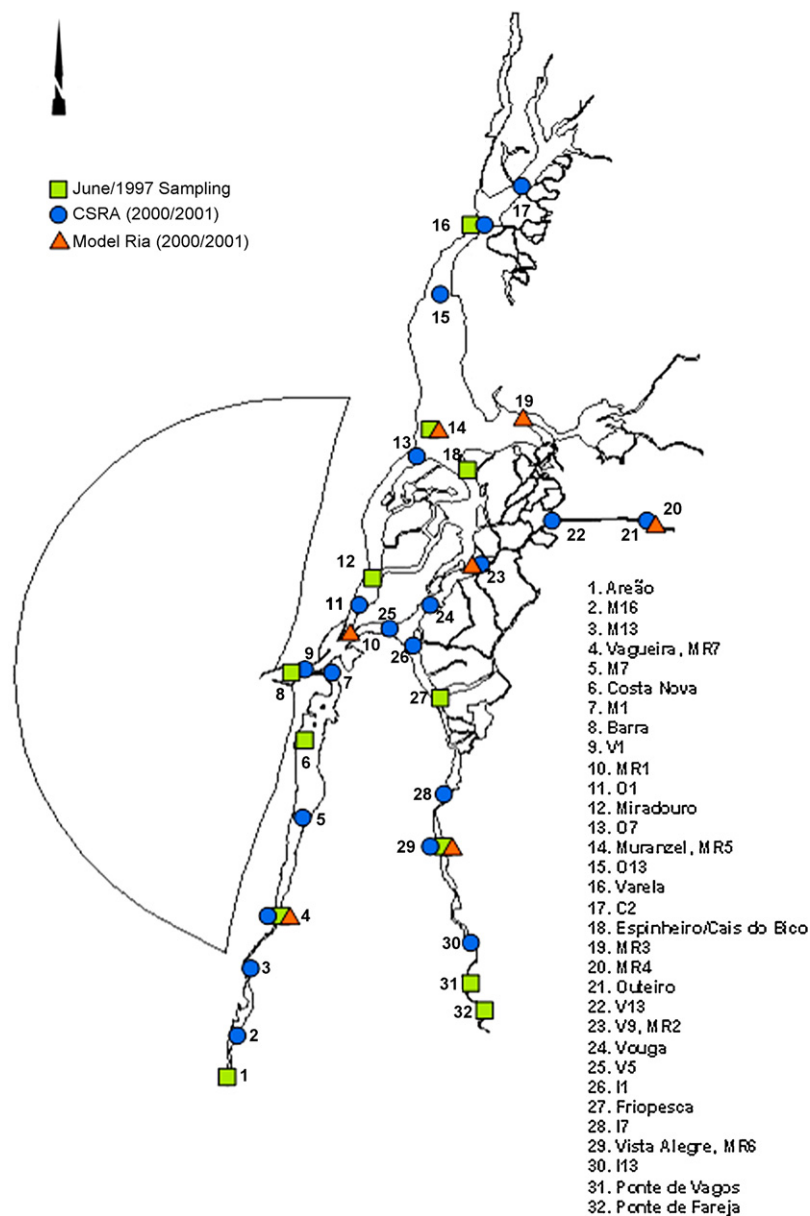


Fig. 3. Location of the sampling stations.

carbon, nitrogen and phosphorous, respectively. Zooplankton is not described in terms of its content of silica and iron, which is a reasonable assumption according to Vichi et al. (2007). The zooplankton growth rate is calculated based on Vichi et al. (2007), depending on the water temperature among other factors. The model has several alternative equations to calculate the temperature-dependent growth, based on the work of Leandro et al. (2006a,b) in the Ria de Aveiro. The zooplankton loss terms (excretion and predation) are constant rates defined as a site-specific or as a functional group parameter.

The zooplankton extension of EcoSim 2.0 leads to changes in the equations that represent the sources and sinks of other ecological state variables. These state variables include the ones relative to the phytoplankton groups, labile dissolved organic matter, fecal organic matter, ammonium, inorganic phosphorous and iron, and DIC. More detailed descriptions of the coupled model and of each of its components can also be found in Rodrigues et al. (2008), Zhang and Baptista (2008) and Bisset et al. (2004).

2.2. Model set-up

2.2.1. SELFE set-up

Hydrodynamic simulations were performed first to establish the numerical conditions for the three-dimensional model. These simulations were based on the 2D unstructured grid simulations of Oliveira et al. (2006). Since water level, current velocity and salinity data along the Ria de Aveiro (Fig. 3) are available for June 1997 (Dias et al., 1999), the simulations were performed for 25 days (starting on June 1, 1997) to cover this period and allowing 2 days for spin-up. The horizontal domain was discretized with an unstructured grid of 21 268 nodes, covering the whole lagoon and extending about 10 km to the coastal zone (Fig. 4a). Some salinity data (e.g. Almeida et al., 2007) suggest that tides propagate further than the upper limit of the Caster river considered in the domain. However, the unavailability of bathymetric data prevents the extension of the domain further upstream. The spatial resolution varies from 1.5 km in the coastal area to 3 m in the narrow channels of the

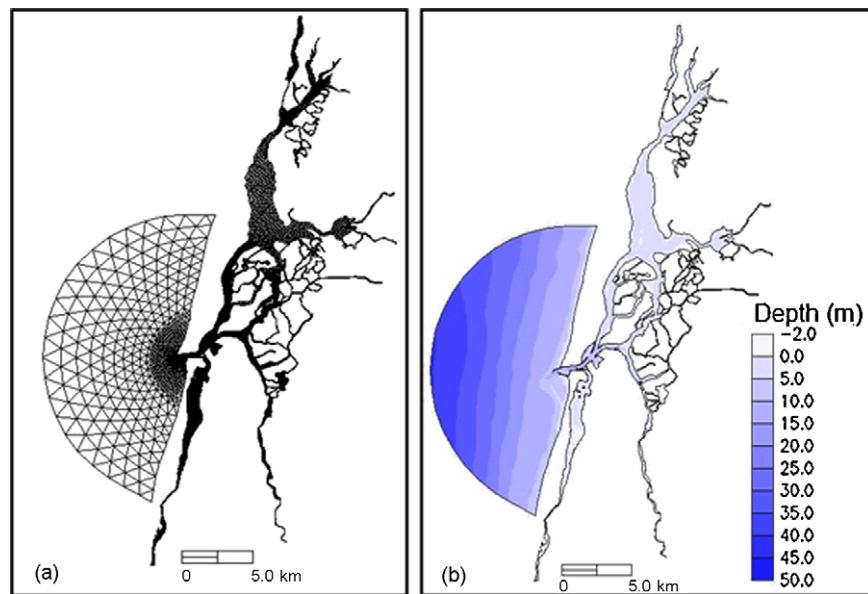


Fig. 4. Horizontal grid (a) and bathymetry (b) of the Ria de Aveiro.

lagoon. The vertical domain was discretized in seven equally spaced vertical S levels, since the lagoon is shallow (Fig. 4b). A drag coefficient of 0.002 was assumed in the whole domain. Because the lagoon is mostly composed by very narrow channels, wind stress was neglected. The time step was set to 90 s.

Five river boundaries were considered: Vouga, Antuã, Boco, Caster and Mira. At the ocean boundary the model was forced by tidal elevations. Eleven tidal constituents, taken from the regional model of Fortunato et al. (2002), were used (Z0, M2, S2, N2, O1, K1, M4, MN4, MS4, MSF and M6).

At the river boundaries, flow measurements are not available at all branches for the period of simulation. Thus, these flows were estimated based on historical data, the basins areas, meteorological data and previous modeling works on the Ria de Aveiro. The flows estimations were based on the time series available at SNIRH (Sistema Nacional de Informação dos Recursos Hídricos; <http://www.snirh.pt>) for the Ponte de Águeda (1935–1990) and the Ponte Minhoteira (1979–1989) stations, and the proportion of the basins areas determined by Saraiva (2005). With this approach, the riverine flows in Vouga, Antuã, Caster, Boco and Mira were, respectively, of $13 \text{ m}^3 \text{ s}^{-1}$, $4.3 \text{ m}^3 \text{ s}^{-1}$, $3.5 \text{ m}^3 \text{ s}^{-1}$, $1.9 \text{ m}^3 \text{ s}^{-1}$ and $1.9 \text{ m}^3 \text{ s}^{-1}$. For the same period of time, Vaz (2007) set a flow of $7 \text{ m}^3 \text{ s}^{-1}$ in the Vouga river based on a calibration procedure. An analysis of the river flows and the precipitation during the period for which SNIRH data are available, suggests that for the precipitation regime observed during June 1997 the Vouga river flow could be smaller than $13 \text{ m}^3 \text{ s}^{-1}$. Preliminary simulations using the $13 \text{ m}^3 \text{ s}^{-1}$ and the $7 \text{ m}^3 \text{ s}^{-1}$ flows in the Vouga river were performed. Based on the results of these simulations, the present study used a flow of $7 \text{ m}^3 \text{ s}^{-1}$ in the Vouga river and reduced the other river's flows accordingly. Thus, the river flows at the boundaries were set as:

$7 \text{ m}^3 \text{ s}^{-1}$ in the Vouga, $2.3 \text{ m}^3 \text{ s}^{-1}$ in the Antuã, $1.9 \text{ m}^3 \text{ s}^{-1}$ in the Caster, $1 \text{ m}^3 \text{ s}^{-1}$ in the Boco and $1 \text{ m}^3 \text{ s}^{-1}$ in the Mira. The flows used in the calibration of the hydrodynamic model were then assumed as characteristics of the environmental conditions, namely the precipitation regimes, of June 1997. Thus, for other periods of simulation where river flows are not available at SNIRH, the flows were estimated based on a ratio between the precipitation in the period of simulation and the precipitation in June 1997 and the flows determined previously for June 1997. The precipitation data were also obtained from SNIRH (station Gafanha da Nazaré).

Initial conditions of salinity were set to spatially decrease gradually from 36 in the open ocean boundary to 0 in the river boundaries. Salinity was set constant at all boundaries and equal to 36 in the ocean boundary and to 0 in the river boundaries.

2.2.2. ECO-SELFE set-up

ECO-SELFE simulations were performed for two different periods: a period denoted as “Autumn 2000”, lasting from 05/September/2000 to 04/October/2000, and a period denoted as “Spring 2001”, lasting from 01/March/2001 to 04/April/2001, and allowing 2 days for spin-up. These periods were chosen based on the chemical and ecological data available, in particular zooplankton data, and in order to evaluate the influence of different environmental conditions. In the Ria de Aveiro there is a lack of zooplankton data and one of the few studies where this data were collected along all the branches of the lagoon (Fig. 3) is the project ModelRia (Universidade de Aveiro, 2003; Almeida et al., 2005; Saraiva, 2005). Data of salinity, temperature, chlorophyll a and nutrients concentrations are also available from the ModelRia project. To complement this data and validate the scalar transport of the tracers along the lagoon, salinity and temperature data from the

Table 1

Flow, salinity and temperature considered at the river boundaries for Autumn 2000 and Spring 2001.

River	Autumn 2000			Spring 2001		
	Flow (m^3/s)	Salinity	Temperature ($^{\circ}\text{C}$)	Flow (m^3/s)	Salinity	Temperature ($^{\circ}\text{C}$)
Vouga	3.92	0	19.2	31.33	0	14.0
Antuã	1.29	0	19.9	10.29	0	15.4
Caster	1.06	33.1	22.6	8.5	0	18.3
Boco	0.56	0	20.4	4.48	0	17.0
Mira	0.56	0	22.4	4.48	0	15.5

Table 2

Ecological tracers input parameters.

Parameter	Value	References
<i>Phytoplankton</i>		
Half-saturation for NO_3 uptake ($\text{mmol NO}_3 \text{ m}^{-3}$)	0.824	Bisset et al. (2004)
Half-saturation for NH_4 uptake ($\text{mmol NH}_4 \text{ m}^{-3}$)	0.141	Bisset et al. (2004)
Half-saturation for SiO uptake (mmol SiO m^{-3})	1.824	Bisset et al. (2004)
Half-saturation for PO_4 uptake ($\text{mmol PO}_4 \text{ m}^{-3}$)	0.0515	Bisset et al. (2004)
Maximum phytoplankton 24 h growth rate (d^{-1})	0.4	Lalli and Parsons (1997)
Base temperature for exponential growth ($^{\circ}\text{C}$)	27	Bisset et al. (2004)
Phytoplankton exponential temperature factor ($^{\circ}\text{C}^{-1}$)	0.0633	Bisset et al. (2004)
Nitrate uptake inhibition for NH_4 (μmol^{-1})	1.28	Bisset et al. (2004)
Maximum phytoplankton C:N ratio ($\mu\text{mol C}/\mu\text{mol N}$)	14	Bisset et al. (2004)
Balanced phytoplankton C:N ratio ($\mu\text{mol C}/\mu\text{mol N}$)	6.625	Bisset et al. (2004)
Absolute minimum phytop.C:N ratio ($\mu\text{mol C}/\mu\text{mol N}$)	5.500	Bisset et al. (2004)
Maximum phytoplankton C:Si ratio ($\mu\text{mol C}/\mu\text{mol Si}$)	5.521	Bisset et al. (2004)
Balanced phytoplankton C:Si ratio ($\mu\text{mol C}/\mu\text{mol Si}$)	5.521	Bisset et al. (2004)
Absolute minimum phytop. C:Si ratio ($\mu\text{mol C}/\mu\text{mol Si}$)	4.5831	Bisset et al. (2004)
Maximum phytoplankton C:P ratio ($\mu\text{mol C}/\mu\text{mol P}$)	106.0	Bisset et al. (2004)
Balanced phytoplankton C:P ratio ($\mu\text{mol C}/\mu\text{mol P}$)	106.0	Bisset et al. (2004)
Absolute minimum phytop. C:P ratio ($\mu\text{mol C}/\mu\text{mol P}$)	88.0	Bisset et al. (2004)
Maximum quantum yield ($\mu\text{mol C}/\mu\text{mol quanta}$)	0.0833	Bisset et al. (2004)
Compensation light level ($\mu\text{mol quanta}$)	10.0	Bisset et al. (2004)
Light level for photoinhibition ($\mu\text{mol quanta}$)	10 000.0	Bisset et al. (2004)
Maximum lighted limited C:Chl ratio	60.0	Bisset et al. (2004)
Rate of change in light limited C:Chl ratio	0.12	Bisset et al. (2004)
Minimum lighted limited C:Chl ratio	25.0	Bisset et al. (2004)
Rate of change in nutrient limited C:Chl ratio	12.2	Bisset et al. (2004)
Minimum nutrient limited C:Chl ratio ($(\mu\text{g C}/\mu\text{g Chl})^{-1}$)	60.0	Bisset et al. (2004)
Rate of change in package effect ($(\mu\text{g C}/\mu\text{g Chl})^{-1}$)	0.01429	Bisset et al. (2004)
Maximum package effect ($(\mu\text{g C}/\mu\text{g Chl})^{-1}$)	0.05	Bisset et al. (2004)
Fraction of DOM released by phytoplankton	0.3333	Bisset et al. (2004)
Fraction of fecal matter released by phytoplankton	0.3333	Bisset et al. (2004)
Fraction of inorganic matter released by phytoplankton	0.3333	Bisset et al. (2004)
Phytoplankton excretion rate (d^{-1})	0.005	Bisset et al. (2004)
Phytoplankton natural mortality rate (d^{-1})	0.0025	Bisset et al. (2004)
Refuge population ($\text{mmol C}/\text{m}^{-3}$)	0.02	Bisset et al. (2004)
Half-saturation for DOP uptake (mmol DOP m^{-3})	0.00001	Bisset et al. (2004)
C:P ratio where DOP uptake begins ($\mu\text{mol C}/\mu\text{mol DOP}$)	500.0	Bisset et al. (2004)
Half-saturation for DON uptake (mmol DON m^{-3})	0.00001	Bisset et al. (2004)
C:P ratio where DON uptake begins ($\mu\text{mol C}/\mu\text{mol DON}$)	500.0	Bisset et al. (2004)
Half-saturation constant DOC uptake (mmol DOC m^{-3})	130.0	Bisset et al. (2004)
Maximum 24 h bacterial growth rate (d^{-1})	2.0	Bisset et al. (2004)
<i>Bacterioplankton</i>		
Base temperature for exponential growth ($^{\circ}\text{C}$)	27	Bisset et al. (2004)
Bacteria exponential temperature factor ($^{\circ}\text{C}^{-1}$)	0.092	Bisset et al. (2004)
C:N ratio of bacteria ($\mu\text{mol C}/\mu\text{mol N}$)	5.0	Bisset et al. (2004)
C:P ratio of bacteria ($\mu\text{mol C}/\mu\text{mol P}$)	60.0	Bisset et al. (2004)
Fraction of DOM released by bacterioplankton	0.4583	Bisset et al. (2004)
Fraction of fecal matter released by bacterioplankton	0.0834	Bisset et al. (2004)
Fraction of inorganic matter released by bacterioplankton	0.4583	Bisset et al. (2004)
Bacterial gross growth carbon efficiency	0.3	Bisset et al. (2004)
Maximum nitrification rate (d^{-1})	0.4	Bisset et al. (2004)
Half-saturation for nitrification ($\text{mmol NH}_4 \text{ m}^{-3}$)	0.1	Bisset et al. (2004)
<i>Fecal organic matter</i>		
Fecal regeneration temperature base ($^{\circ}\text{C}$)	27	Bisset et al. (2004)
Fecal regeneration exponential temperature factor ($^{\circ}\text{C}^{-1}$)	0.092	Bisset et al. (2004)
Fecal carbon regeneration rate (d^{-1})	0.1	Bisset et al. (2004)
Fecal nitrogen regeneration rate (d^{-1})	0.1	Bisset et al. (2004)
Fecal silica regeneration rate (d^{-1})	0.13	Bisset et al. (2004)
Fecal phosphorous regeneration rate (d^{-1})	0.1	Bisset et al. (2004)
<i>Zooplankton</i>		
Fraction of DOM released by zooplankton	0.25	Saraiva (2005)
Fraction of fecal matter released by zooplankton	0.5	Set
Fraction of inorganic matter released by zooplankton	0.25	Saraiva (2005)
Availability of prey to predator	0.75	Set
Capture efficiency of zooplankton	1	Vichi et al. (2007)
Half-saturation for total food ingestion (mmol C m^{-3})	1.042	Vichi et al. (2007)
Assimilation efficiency of zooplankton's predators	0.5	Set
Zooplankton excretion rate	0.15	Arhonditsis et al. (2000)
Zooplankton mortality rate (d^{-1})	0.15	Arhonditsis et al. (2000)

water, which was estimated based on the application of Saraiva (2005). The boundary conditions are listed on Tables 3 and 4. The initial conditions were set as spatially varying based on the values determined for each boundary.

For the calculation of the spectral irradiation, the atmospheric parameters were considered constant in each of the two periods simulated and were estimated based on the values measured at a meteorological station located in the University of Aveiro (Table 5).

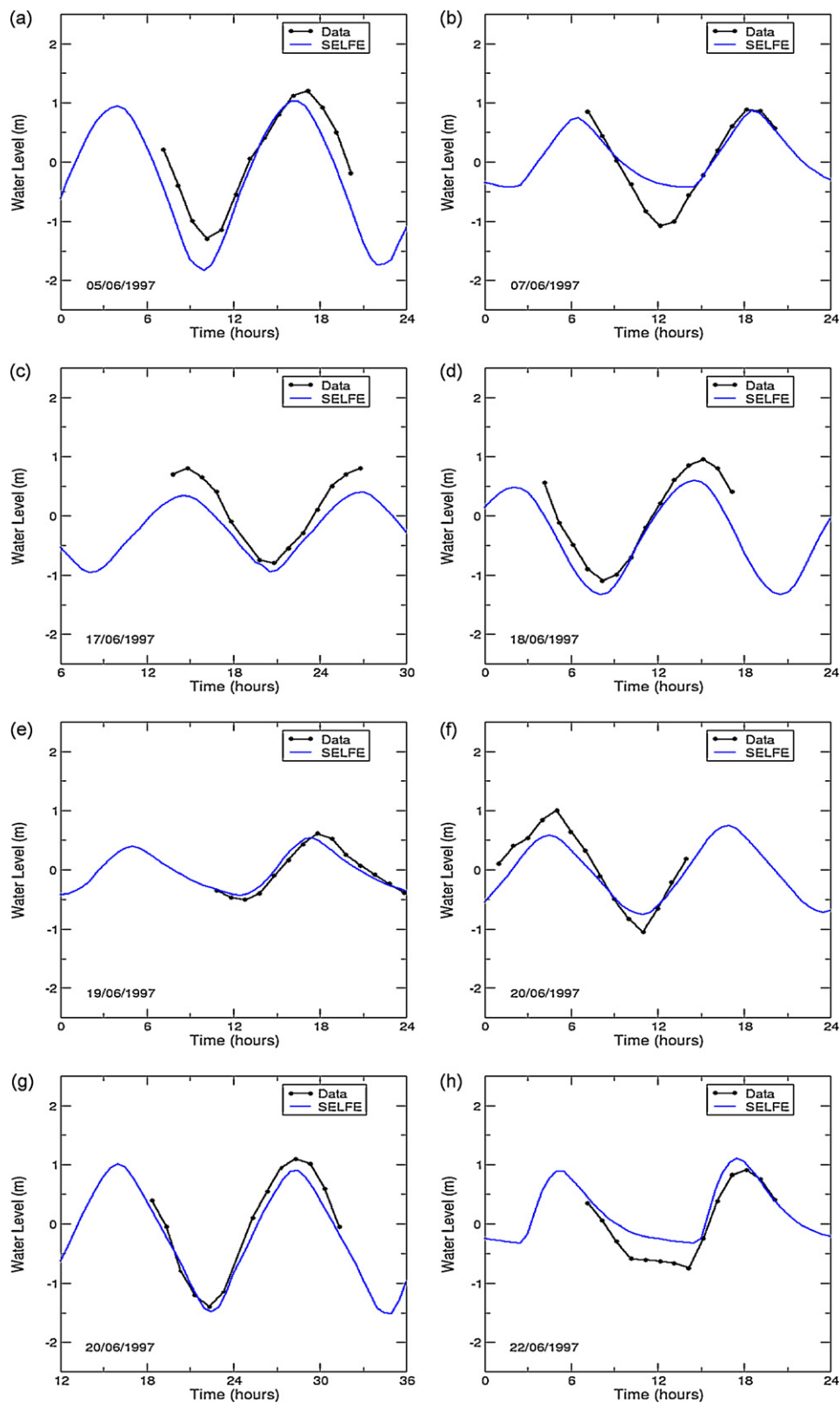


Fig. 5. Comparison between data (Dias et al., 1999) and SELFE results for water level in June/1997: (a) Friopescas, (b) Vista Alegre, (c) Espinheiro/Cais do Bico, (d) Miradouro, (e) Varela, (f) Muranzel, (g) Costa Nova and (h) Vagueira.

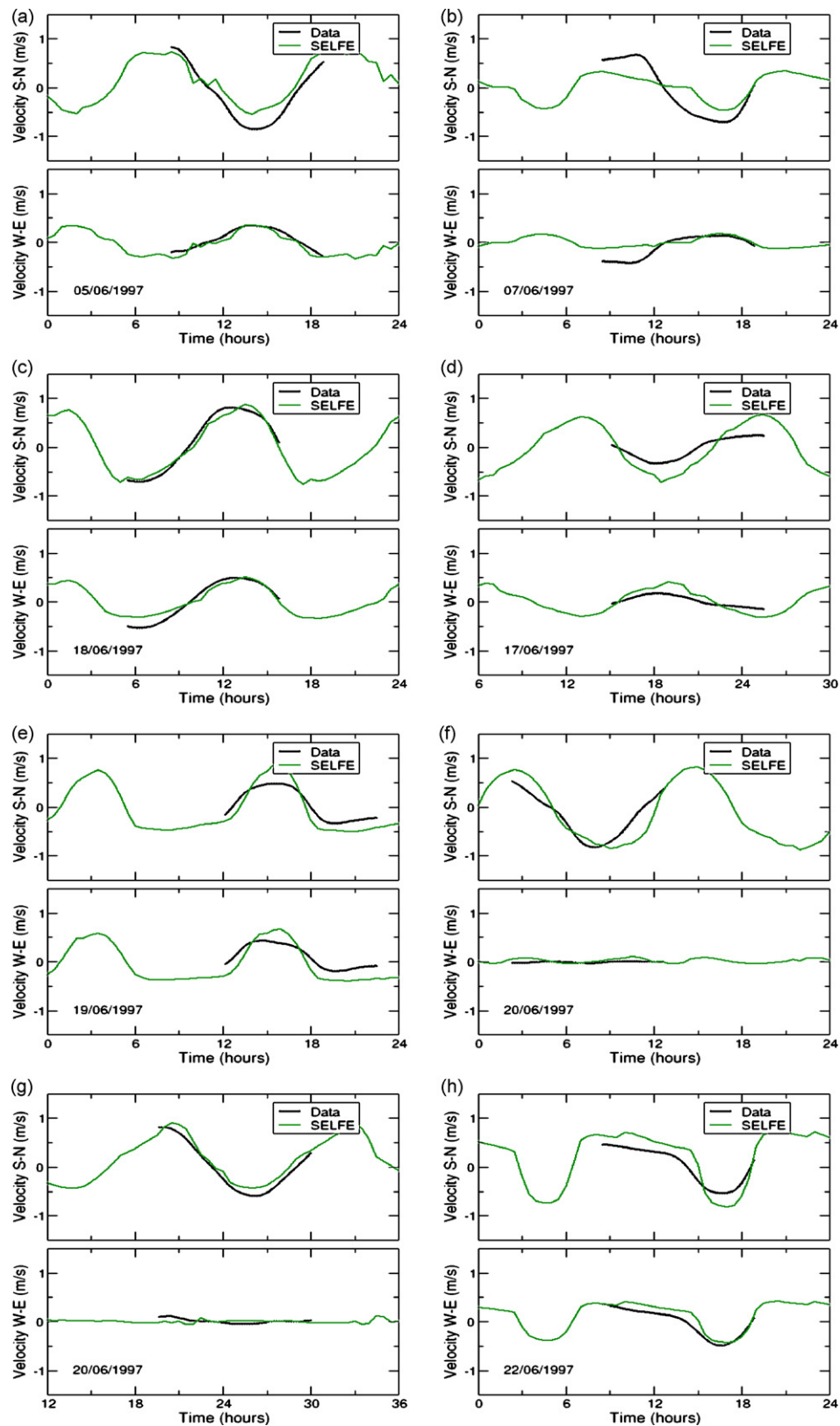


Fig. 6. Comparison between data (Dias et al., 1999) and SELFE results for velocity in June/1997: (a) Friopesca, (b) Vista Alegre, (c) Espinheiro/Cais do Bico, (d) Miradouro, (e) Varela, (f) Muranzel, (g) Costa Nova and (h) Vagueira.

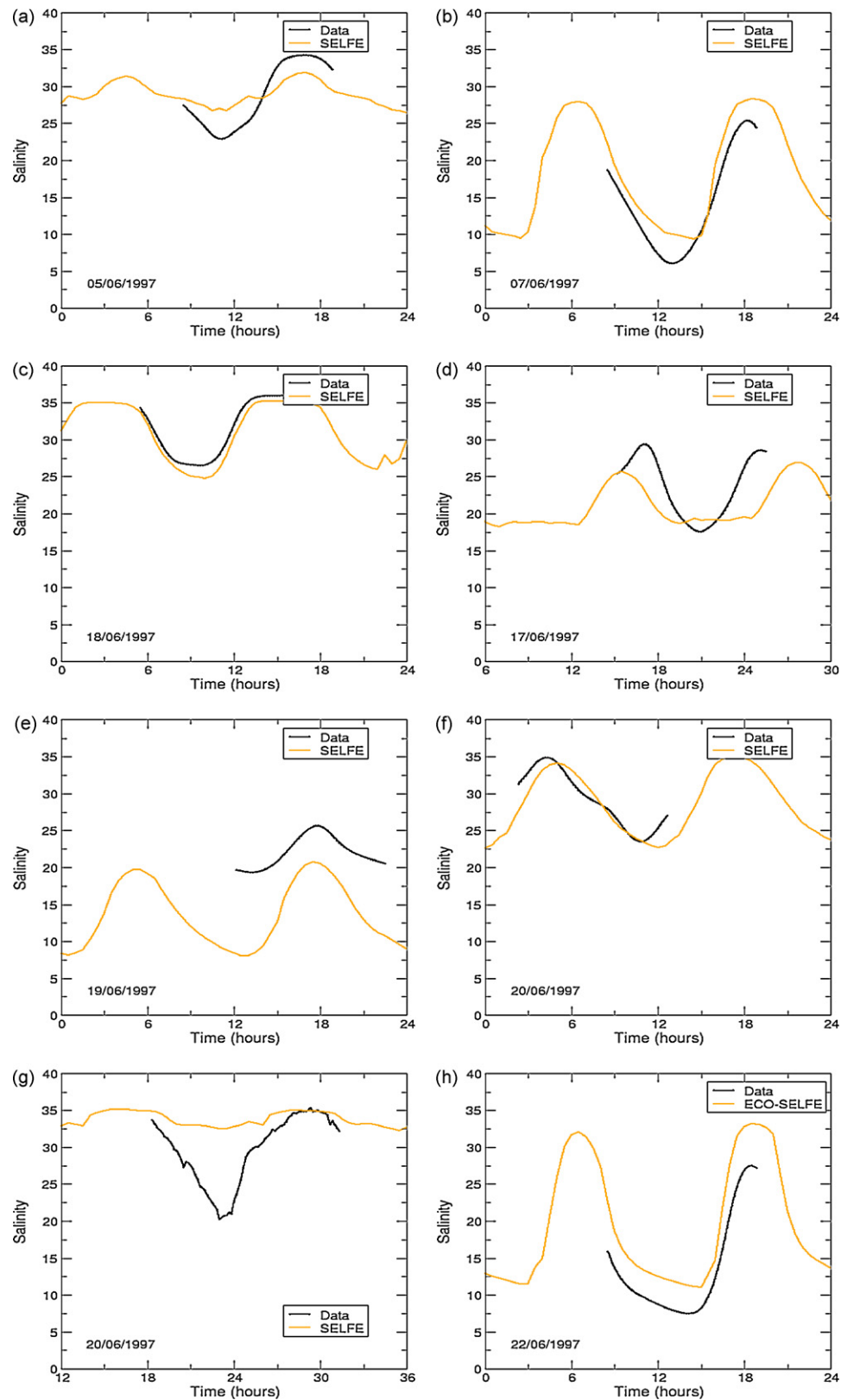


Fig. 7. Comparison between data (Dias et al., 1999) and SELFE results for salinity in June/1997: (a) Friopesca, (b) Vista Alegre, (c) Espinheiro/Cais do Bico, (d) Miradouro, (e) Varela, (f) Muranzel, (g) Costa Nova and (h) Vagueira.

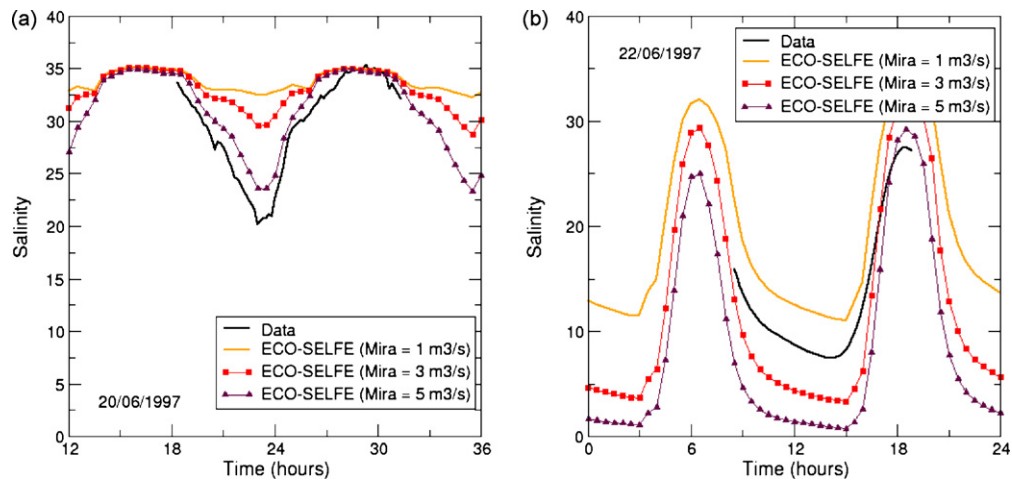


Fig. 8. Influence of the river flow in the Mira channel: (a) Costa Nova station and (b) Vagueira station.

Table 5
Atmospheric conditions considered for the calculation of the spectral irradiation.

Parameter	Autumn 2000	Spring 2001
Wind	6.7 m/s, N	5.2 m/s, SW
Air temperature	18.5 °C	12.5 °C
Atmospheric pressure	1021.0 mbar	1014.75 mbar
Relative humidity	85.6%	85.4%
Cloud cover	0.2	0.5

3. Results and discussion

3.1. SELFE simulations assessment

These simulations were performed for the June 1997 period. Simulations to calibrate the horizontal and vertical grids' refinement, time step and the drag coefficient were done previously. The

following validation analysis is based on the best results from the calibration procedure.

Water levels phase are represented by the model along the branches of the lagoon (Fig. 5). In terms of amplitude, the model represents the data with average errors smaller than 10–15 cm (Fig. 5). In a few stations (e.g. Vista Alegre, Fig. 5b; Vagueira, Fig. 5h) the model tends to underestimate by 25–50 cm the elevations at low tide. These differences may be due several factors. The boundary conditions, which were taken from a regional model, have some errors as they do not include all frequencies. The drag coefficient may also be a source of errors, since a constant value in the whole domain is considered. However, adequate information is unavailable for a detailed spatial characterization. Recent studies also suggest that bathymetric changes in the inlet channel affect the response of the M2 constituent (Araújo et al., 2008). Since the bathymetry that is used in the model combines data from 1987 and 2004 and is not from the June 1997 period this may also con-

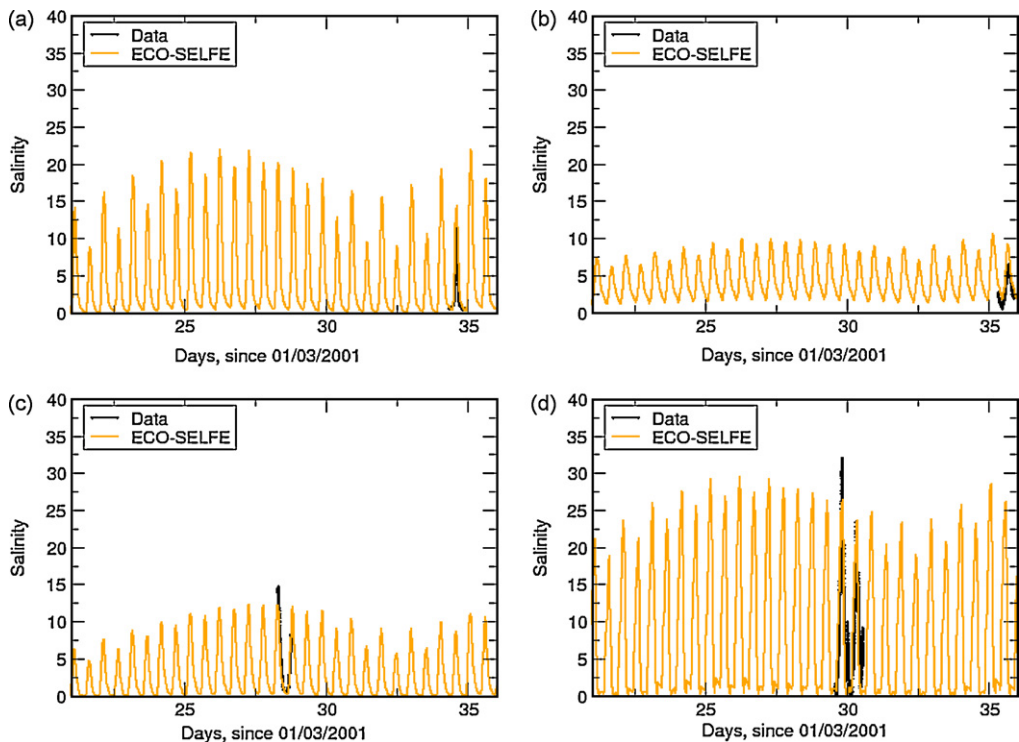


Fig. 9. Comparison between data (CSRA data, 13 h time series) and ECO-SELFE results for salinity in Spring 2001: (a) Vagueira, (b) Varela, (c) Vista Alegre and (d) Vouga.

tribute for the differences observed. There are also several wetting and drying areas in the lagoon poorly represented in the grid, due to its shallowness, in particular in the Mira channel. An increase in the grid resolution in this channel could also lead to an improvement in the water levels results. Tests done in the Mira channel showed that refining the grid resolution by splitting the elements by four significantly improved the water levels representation. However, refining the grid considerably increases the CPU times, which may be limiting when running the coupled hydrodynamic-ecological model.

Velocities phase differences between model and data are generally smaller than 5–10 min along the lagoon (Fig. 6). Magnitude errors are generally smaller than 5 cm/s (Fig. 6). The largest differences between the model results and field data occur in the Vista Alegre (Ílhavo channel) and Varela (S. Jacinto channel) stations, but

these are generally smaller than 10–15 cm/s. These differences may be due to the bathymetry data that are used, which, as mentioned before, are not from June 1997.

Salinities (Fig. 7) are represented by the model for most of the stations with average differences smaller than 5. At the Varela station (upper northern position of the S. Jacinto) the model underestimates salinity by 5–10, which may be due to the uncertainty associated with the river flows at the Caster river boundary. Since a salinity of zero was imposed here, the proximity of this station to the nearby boundary suggests that the grid should be extended further north, to the limit of tidal propagation. However, the lack of bathymetric data prevents the extension of the domain. The largest salinities errors, of about 15, were observed in the Mira channel (Costa Nova station, Fig. 7h). These errors may be due to the river flow boundary conditions, which present an important uncer-

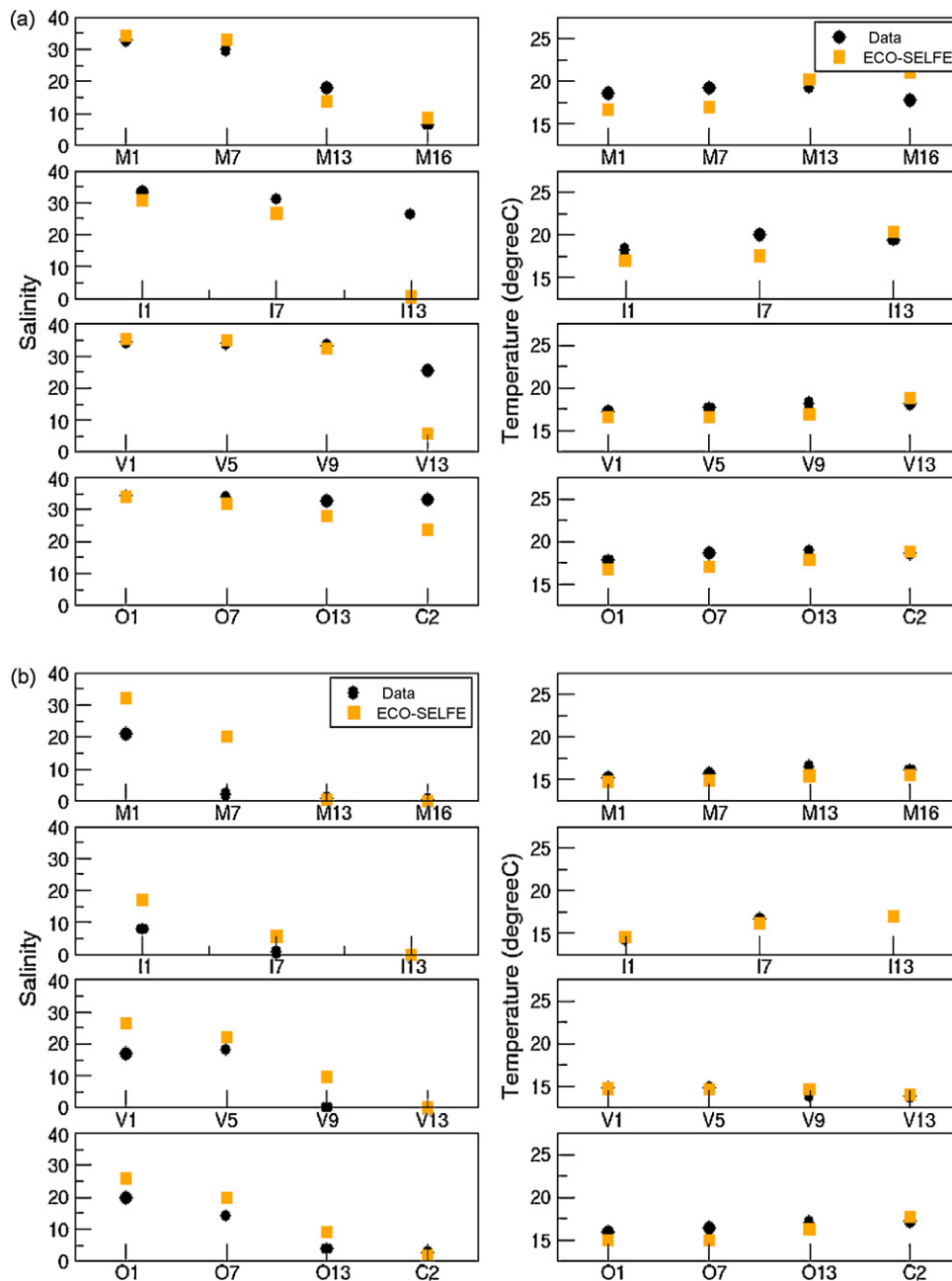


Fig. 10. Comparison between data (CSRA data, point measurements along the four branches of the lagoon) and ECO-SELFE results for salinity and temperature along the four main branches: (a) Autumn 2000 and (b) Spring 2001. Mira channel: M1, M7, M13 and M16 stations. Ílhavo channel: I1, I7 and I13 stations. Espinheiro channel: V1, V5, V9 and V13 stations. S. Jacinto channel: O1, O7, O13 and C2 stations.

Table 6

Relative deviation (ΔR) between data and model results for salinity and temperature during Autumn 2000 and Spring 2001. Data variation range and mean value (in parentheses) are presented.

Station	Salinity		Temperature (°C)	
	Data	ΔR	Data	ΔR
<i>Autumn 2000</i>				
Vagueira	16.2–30.1 (22.2)	2.2	18.3–20.6 (19.8)	1
Vista Alegre	–	–	–	–
Vouga	–	–	–	–
Varela	31.5–34.3(33.1)	6.6	18.2–20.1 (19.2)	0.8
<i>Spring 2001</i>				
Vagueira	0.4–10.7 (2.4)	1.7	15.3–17.3 (16.6)	1.2
Vista Alegre	0.4–11.5 (3.9)	1.2	14.3–16.2 (15.2)	1.2
Vouga	0.1–19.4 (6.6)	3.3	13.5–14.7 (13.1)	0.2
Varela	0.5–6.1 (3.0)	1.7	15.8–18.6 (17.2)	1.1

tainty (Dias and Lopes, 2006). Sensitivity simulations performed using $5 \text{ m}^3 \text{ s}^{-1}$ (Vaz, 2007) and $3 \text{ m}^3 \text{ s}^{-1}$ (Saraiva, 2005) show that there is a significant influence of the river flow in the salinity along this channel. The use of a larger flow reduces the salinity errors at the Costa Nova station, but increases them at the Vagueira station (Fig. 8). This behavior suggests the existence of an extra source of freshwater between these two stations during this period, with surface or groundwater origin, that was not considered in the model. The analysis of satellite images suggests that agricultural discharge channels may be one of the sources of this freshwater.

Globally, the results suggest that the model is able to reproduce the hydrodynamics along all the branches of the Ria de Aveiro. The magnitude of the observed differences in water levels, velocities and salinities is similar or smaller than those achieved in previous applications in the lagoon for the same period (e.g. Vaz, 2007). In particular, the velocity field, which is fundamental for a good representation of the scalar transport within the ecological model, is simulated by the model with errors of only 5 cm/s.

3.2. ECO-SELFE validation

Results for salinity and temperature of ECO-SELFE simulations are compared with the CSRA data, while ecological tracer's results are compared with the ModelRia data. Results are presented only for the ecological tracers for which data are available: zooplankton, phytoplankton (estimated from chlorophyll *a*), chlorophyll *a*, NH_4^+ , NO_3^- , PO_4^{3-} , SiO_2 and DOC. The relative deviation (ΔR) between the model results and the data was calculated as

$$\Delta R = \frac{1}{N} \sum_{i=1}^N |X_i - C_i| \quad (5)$$

where N is the total number of observations, X_i is the observed value and C_i is the tracer predicted value.

3.2.1. Salinity and temperature

Salinity variations during the tidal cycle are represented by the model with amplitude errors ranging between 2 and 10 in the

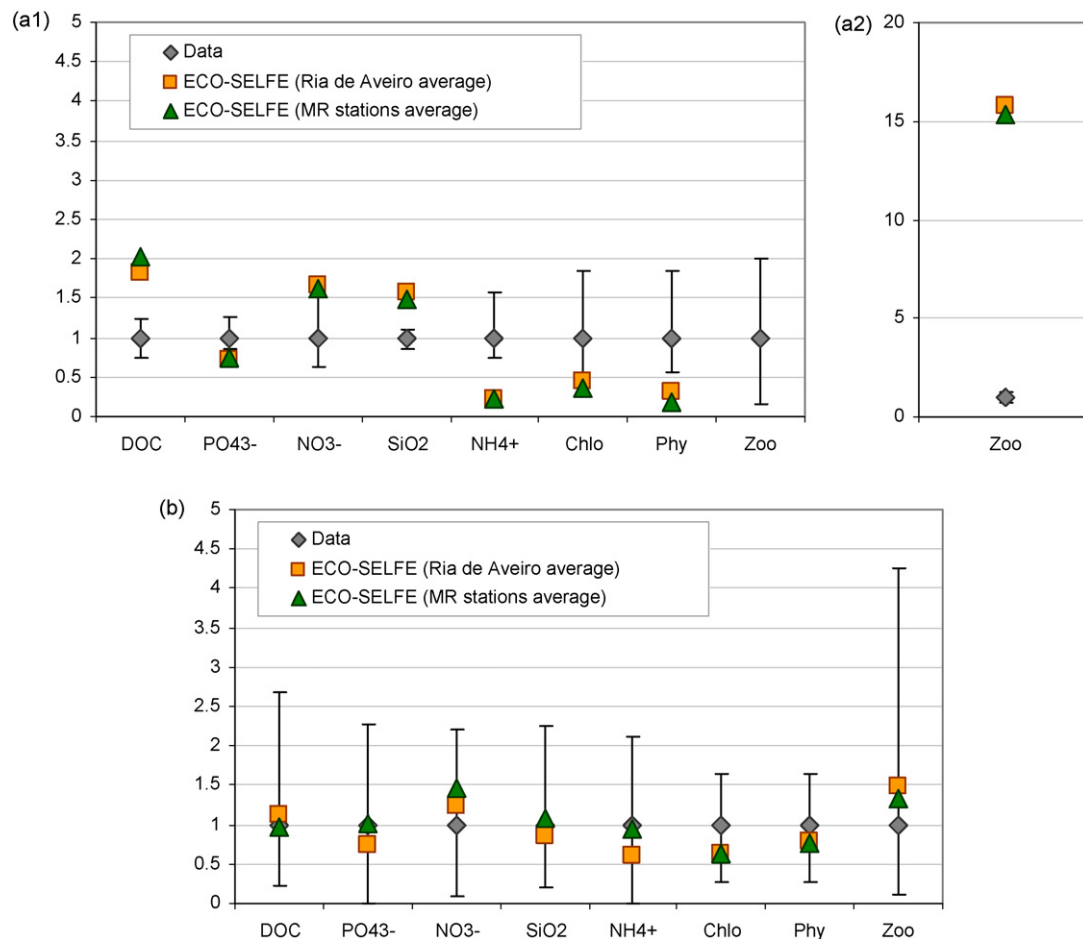


Fig. 11. Average values of the ecological tracers in the Ria de Aveiro in (a) Autumn 2000 (a1) with zooplankton detail (a2) and (b) Spring 2001: comparison between the model results and the field data. The range of variation of each parameter is defined in the upper limit by the maximum value measured in the period and in the lower limit as the minimum value measured in the period. All the values were standardized by the average value of the field data.

Autumn 2000 (Table 6) and 1–4 in the Spring 2001 (Table 6), while phase errors are negligible (Fig. 9, for Spring 2001). In both periods the horizontal variation of salinity in the lagoon is globally represented by the model with differences between the model and the data of about 1–5 (Fig. 10). Exceptions are the upstream stations in the S. Jacinto and Espinheiro channels in the Autumn 2000 (stations C2 and V13, Fig. 10a), with errors of about 10. In the present simulation, a very large value of salinity was used for the Caster river boundary for Autumn 2000 based on the field data for the station C2, but some differences between the coupled model and the data remain. As observed for the SELFE calibration simulation (June 1997), the salinity data from C2 suggest that salinity propagates upstream of the computational domain. The model also overestimates salinity at the M7 and, to a smaller extent, the M1 stations during Spring 2001. Errors in the riverine boundary conditions may cause the observed differences.

Temperature is represented by the model with errors generally smaller than 1.5 °C in both periods (Table 6 and Fig. 10). The model representation of both salinity and temperature horizontal variations along the branches of the lagoon, which is within the range

of data variance measured, confirms the ability of the model to represent the scalar transport in the Ria de Aveiro.

3.2.2. Ecological tracers

Ecological tracers' model results (averaged over the whole Ria de Aveiro and for all ModelRia stations) are first compared with the average values of the data measured in the ModelRia stations and their range of variation, providing a general overview of the model behavior. In the Autumn 2000 period, although the magnitude of the model results for most ecological tracers is roughly within the range of the field data, some tracers are outside this range (Fig. 11a). Zooplankton, in particular, is overestimated by the model in this period. In Spring 2001 the model results fit within the range of variation of the field data for all the ecological tracers evaluated, showing that the model is able to represent these tracers in the Ria de Aveiro during this period (Fig. 11b).

Table 7 summarizes the relative deviation between the observed and the predicted values. These deviations were calculated considering the model results in the instant of the observations and also considering the average of the model results during a tidal cycle

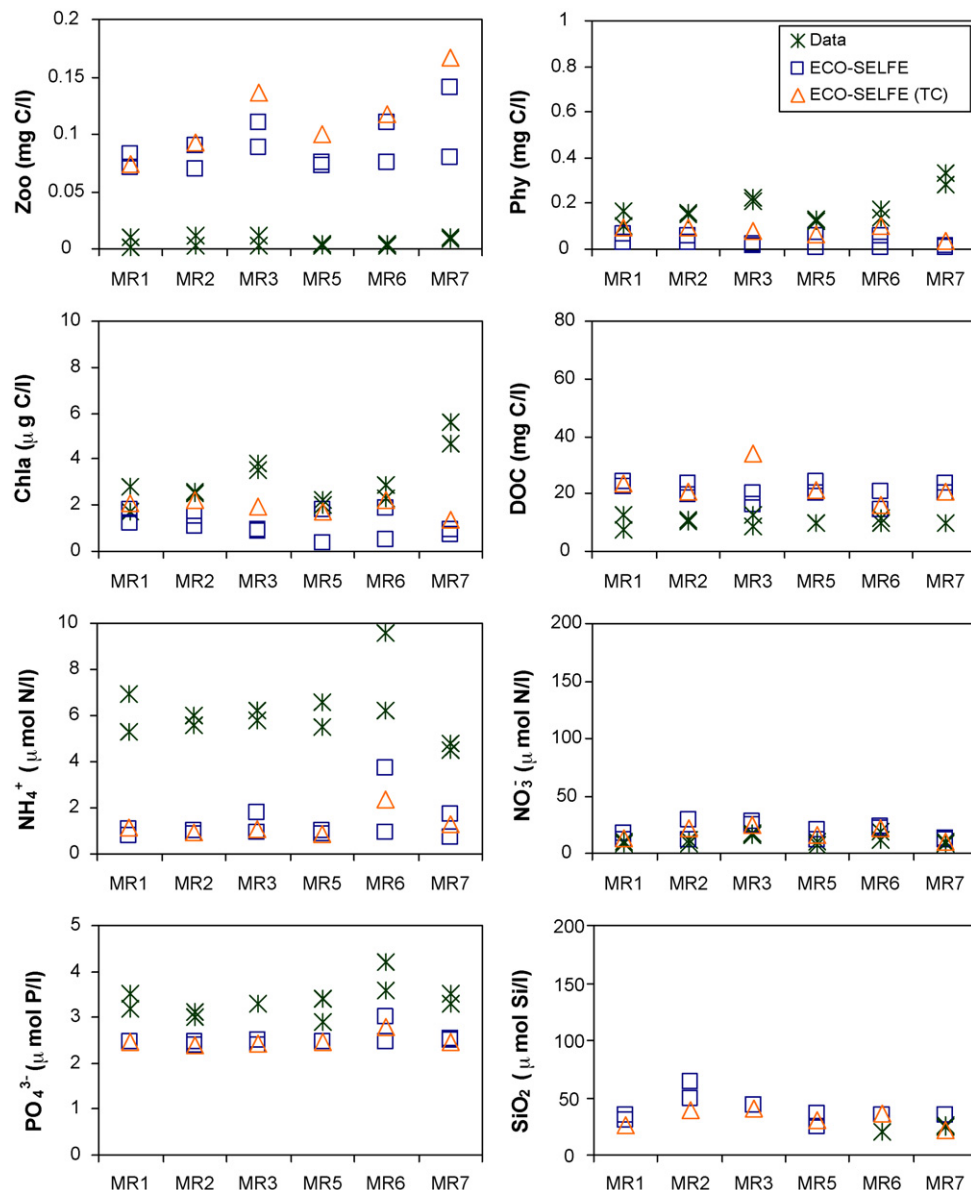


Fig. 12. Comparison between data and ECO-SELFE results for the ecological tracers in ModelRia stations (MR1, MR2, MR3, MR5, MR6 and MR7) for the period of Autumn 2000 (ECO-SELFE (TC)—model average values in a tidal cycle).

(neap tide/spring tide). The later approach reduces the uncertainty relative to the exact time of the measurements and some phase errors that derive from the hydrodynamic model.

A more detailed analysis shows that zooplankton is overestimated by the model in all ModelRia stations during the Autumn 2000 (Fig. 12). The differences between the model and the data are of 0.08–0.1 mg C/l, which corresponds to an overestimation by a factor of 10 when compared with the data. Although the error is significant, the agreement between model and data compares favorably with other published modeling studies in the Ria de Aveiro for the same period, where data were overestimated by a factor of 20–100 (Saraiva, 2005). In the Spring 2001 the model represents zooplankton concentrations in the lagoon with smaller differences of only 0.005 mg C/l, when considering the tidal cycle (Table 7). During this period the model is also able to reproduce the spatial variation of zooplankton, representing the larger concentrations observed in the Mira channel (MR7 station, Fig. 13). Although the model represents the mean concentrations of zooplankton, it fails to predict the amplitude of variation of zooplankton in

Mira channel, where the largest concentrations of zooplankton are observed during flood, which might be a punctual situation with a marine origin. This difference may derive from the lack of data at the marine boundary to impose adequate boundary conditions.

As observed for zooplankton, phytoplankton is better represented by the model in the Spring 2001 than in the Autumn 2000 (Table 7). Considering the tidal cycle, these differences are of about 0.06 mg C/l (30%) in Spring 2001 and 0.1 mg C/l (60%) in Autumn 2000 when phytoplankton is underestimated by the model. The larger differences are observed in the MR3 station in both periods (Figs. 12 and 13) and in MR7 in Autumn 2000 (Fig. 12). The results observed for phytoplankton are similar to those achieved for chlorophyll *a*, which is predicted by the model with average deviations of about 1.5 $\mu\text{g C/l}$ (Table 7, Figs. 12 and 13).

For DOC the model tends to overestimate the data by about 10–12 mg C/l in the Autumn period (Table 7). The larger differences being observed in the station located near the Antuã river (MR3 station, Fig. 12). In Spring 2001 the deviations are smaller, about 40% relative to the average data (Table 7). In this period the largest

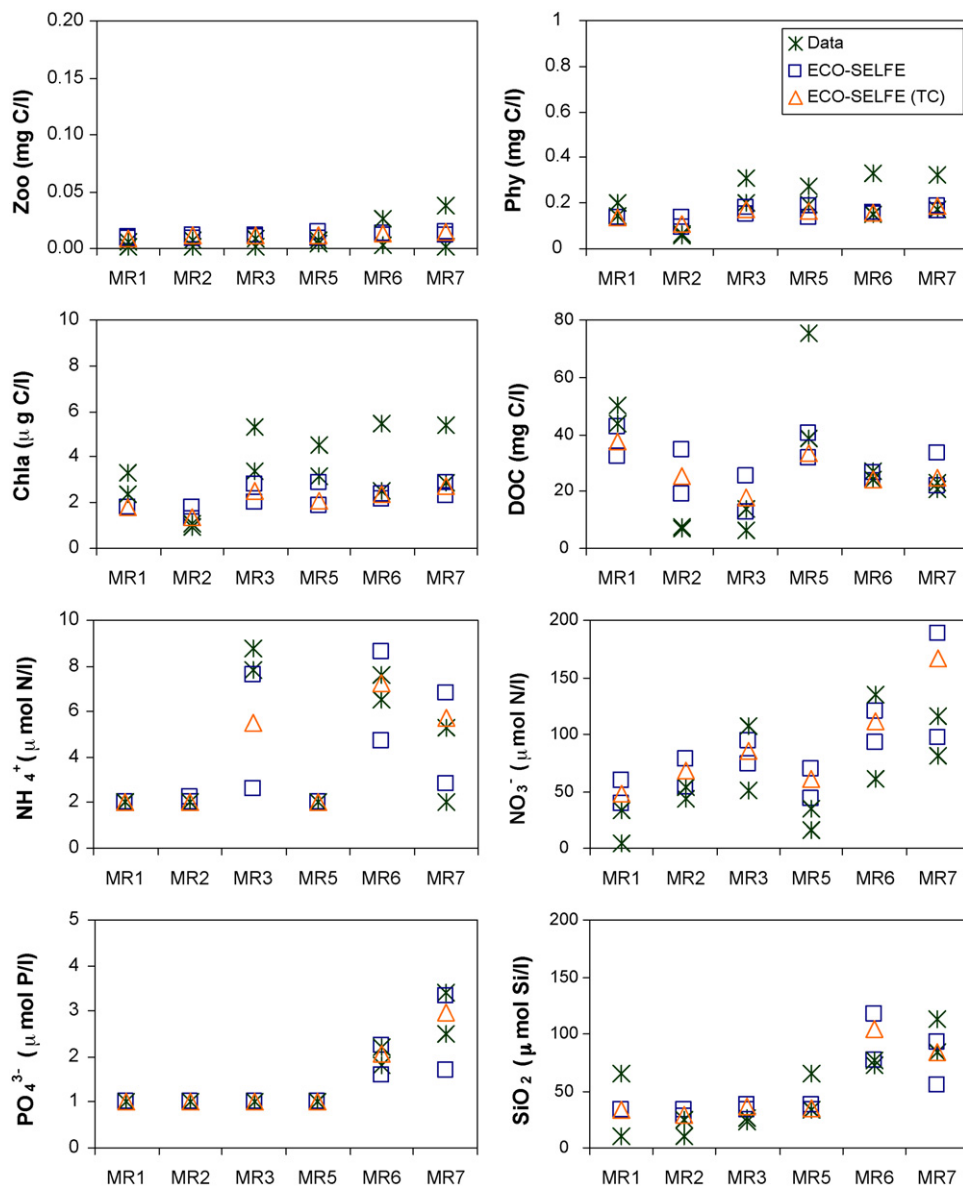


Fig. 13. Comparison between data and ECO-SELFE results for the ecological tracers in ModelRia stations (MR1, MR2, MR3, MR5, MR6 and MR7) for the period of Autumn 2000 (ECO-SELFE (TC)—model average values in a tidal cycle).

Table 7

Relative deviation (ΔR) between data and model results for ecological tracers during Autumn 2000 and Spring 2001. Data variation range and mean value (in parentheses) are presented. Relative deviations are calculated considering the MR1, MR2, MR3, MR5, MR6 and MR7 stations. ΔR (TC) refers to the relative deviations calculated with the model average values in a tidal cycle.

Ecological tracer	Data	ΔR	ΔR (TC)
<i>Autumn 2000</i>			
Zooplankton (mg C/l)	0.01–0.12 (0.006)	0.08	0.10
Phytoplankton (mg C/l)	0.10–0.34 (0.18)	0.15	0.10
Chlorophyll <i>a</i> ($\mu\text{g C/l}$)	1.7–5.6 (3.1)	1.9	1.1
DOC (mg C/l)	7.6–12.7 (10.3)	10.5	12.5
NH_4^+ ($\mu\text{mol N/l}$)	4.5–9.6 (6.1)	4.8	4.8
NO_3^- ($\mu\text{mol N/l}$)	7.4–18.5 (11.6)	6.8	6.4
PO_4^{3-} ($\mu\text{mol P/l}$)	2.9–4.2 (3.5)	0.8	0.8
SiO_2 ($\mu\text{mol Si/l}$)	–	–	–
<i>Spring 2001</i>			
Zooplankton (mg C/l)	0.001–0.04 (0.009)	0.009	0.005
Phytoplankton (mg C/l)	0.06–0.33 (0.20)	0.07	0.06
Chlorophyll <i>a</i> ($\mu\text{g C/l}$)	0.9–5.5 (3.7)	1.4	1.4
DOC (mg C/l)	6.4–75.3 (28.1)	11.3	10.4
NH_4^+ ($\mu\text{mol N/l}$)	<2–8.8 (4.2)	1.2	0.8
NO_3^- ($\mu\text{mol N/l}$)	5.0–135.5 (61.3)	27.7	29.1
PO_4^{3-} ($\mu\text{mol P/l}$)	<1.0–3.4 (1.5)	0.2	0.01
SiO_2 ($\mu\text{mol Si/l}$)	10.0–113.5 (50.4)	19.0	14.6

differences are observed in the MR5 station, where the model is unable to reproduce the amplitude of variation of the data (Fig. 13). Since there is a lack of data to establish the boundaries concentrations during the periods simulated, this uncertainty may contribute to the observed errors.

Regarding nutrients, the model is also able to represent these tracers with smaller differences in Spring 2001 than in Autumn 2000. NH_4^+ tends to be underestimated by the model throughout the lagoon during Autumn 2000. The errors are of about $4.8 \mu\text{mol N/l}$, which correspond to a difference of about 80% to the data (Table 7). The underestimation of NH_4^+ as been observed in another model application to the lagoon in the same period (Lopes et al., 2008). In the Spring 2001, the differences between model and data are smaller, of about 20% (Table 7). PO_4^{3-} is represented by the model with deviations smaller than $0.85 \mu\text{mol P/l}$ (25%) in the Autumn 2000 and than $0.02 \mu\text{mol P/l}$ (15%) in the Spring 2001. During the Spring 2001 these differences are very low, of about 1%, when considering the results for the tidal cycle. The model also represents well the seasonal variation of some variables, like NO_3^- , which is larger in the Spring 2001 than in the Autumn 2000, and PO_4^{3-} , which is larger in the Autumn 2000 (Figs. 12 and 13). SiO_2 is represented in the Spring 2001 with differences of about 30%, which corresponds to an error of about $15\text{--}19 \mu\text{mol Si/l}$. The observed differences may be due to several factors, including the uncertainty associated with the boundary conditions, as mentioned above.

The larger errors observed in the Autumn 2000 may also derive from the phytoplankton–zooplankton dynamics. During this period, the phytoplankton biomass increases in the beginning of the simulations, which leads to a growth of zooplankton, and then to reduction in phytoplankton. Since the zooplankton's growth is fueled by food availability, the overestimation of phytoplankton may contribute to the increase of zooplankton and to the reduction of NH_4^+ predicted by the model. The following zooplankton overestimation leads to the model phytoplankton underestimation when compared with data. The phytoplankton overestimation in the beginning of the simulations may derive from the modeled structure of the ecosystem, since only one primary producer group is considered (phytoplankton). Indeed, another important primary producer (macroalgae) may compete for the available resources, thereby reducing the growth of the phytoplankton and, consequently, the available food for zooplankton. However, increasing the complexity of the ecosystem representation would also increase

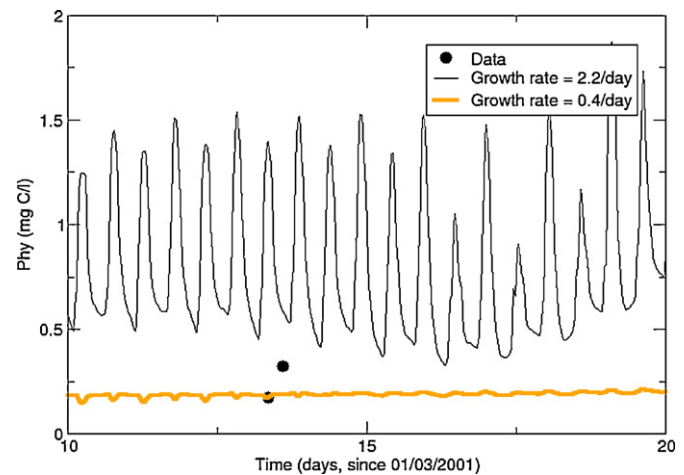


Fig. 14. Influence of the phytoplankton temperature-dependent maximum growth rate in the phytoplankton concentration at the MR7 station (Spring 2001).

the uncertainty associated with the parameterization. Additionally, data are unavailable for other primary producers. Several parameters considered in the establishment of the ecological model are also sources of errors and uncertainty, since site-specific information for their establishment is unavailable in the Ria de Aveiro. Sensitivity analysis performed on the ecological model parameters (Rodrigues et al., 2008, 2009) showed the relative influence of these parameters in the final results of the model. Among these parameters, the phytoplankton temperature-dependent growth rate was one of the most relevant. Since the zooplankton growth depends on the quantity of food available, this parameter will also affect zooplankton concentration. The parameters related to food ingestion by zooplankton and its excretion and mortality rates also affect the results significantly. Several tests in the Ria de Aveiro showed the influence of these parameters in a real system (Fig. 14) and the need to obtain more site-specific data.

4. Conclusions

The reliability of a new fully coupled three-dimensional, unstructured grid, hydrodynamic and ecological model (ECO-SELFE) was demonstrated in an application to the Ria de Aveiro, using a site-specific formulation for zooplankton. The application of the coupled model was its first application in a real system and allowed the model validation with a reasonably adequate set of field data. The application also allowed the evaluation of the different environmental conditions in the dynamics of the lagoon.

First, simulations using the hydrodynamic model (SELFE) alone were done, for efficiency. These simulations showed the good performance of the model in the reproduction of the water levels, velocities and salinities in the Ria de Aveiro. In particular, the velocity field, which is fundamental for the correct simulation of the transport processes, is represented by the model with errors smaller than 5 cm/s . These simulations also showed the importance of using accurate boundary conditions, namely for the freshwater inputs in the lagoon. Although Ria de Aveiro is a very important estuarine system, with ecological and economical values, river flows data are scarce. This question needs to be addressed in future studies in order to establish adequate methodologies to determine or estimate the boundary conditions for freshwater inputs when there is a lack of data.

The simulations performed with ECO-SELFE for the Autumn 2000 and Spring 2001 periods showed that globally the model reproduces the ecological dynamics along the branches of the Ria during the Spring, fitting the model results inside the range of

data variation. In the Autumn period, the model tends to overestimate the zooplankton concentrations by a factor of 10. In this period, phytoplankton and ammonium concentrations are underestimated. Although some differences between the model and the data remain, the results achieved here compare similarly or favorably with other studies in the same periods (Saraiva, 2005), in particular for zooplankton.

Possible explanations for these differences include the boundary conditions used and the parameterizations considered. The simplification of the ecosystem structure, namely in terms of the primary producers, may also lead to the observed differences. The availability of more ecological data, namely with longer temporal coverage, will also be useful to perform more specific validations of the model. Additional exploitation of the model for different scenarios will allow a more detailed study of the environmental factors affecting the zooplankton dynamics, contributing for the lagoon management.

Due to the complexity of the model and the spatial resolution used, CPU times are a limiting factor. Therefore, for complex simulations and longer simulation periods the use of the parallel version of the model, which was recently developed, is essential to achieve acceptable computational times.

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