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3D ecological modelling of the Aveiro coast (Portugal)

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Abstract: Until now the most of studies concerning the dynamics of the Portuguese coastal ecosystem focused in estuarine, lagoon and rivers systems, whereas more knowledge about the spatial and the seasonal distribution of phytoplankton population at the coast is still needed. The present work is aimed to study some aspects of ecological modelling of the nearshore Aveiro coastal system, namely the influence of physical forcings in the distribution of phytoplankton biomass. In order to implement the ecological model, the validation of the model were assessed by comparing simulation to data to a vertical and horizontal distribution of temperature, nutrients and phytoplankton biomass, obtained from the several surveys performed along the Portuguese coast during the last decades (Moita, 2001). The results evidence, that the physical processes play an important role in the understanding the phytoplankton dynamics and the close relationship between the physical forcings and the temperature and the phytoplankton distributions.

Keywords: Aveiro coast; Modelling; Ecological; Upwelling; Nutrients: Chlorophyll-a.

1. INTRODUCTION

The Iberian Atlantic coast is characterized by the occurrence of important phytoplankton productivity, both in space and time. In fact, upwelling is the most important hydrodynamic process that occurs there, typically between April and October. The coastal upwelling change the general phytoplankton cycle due to additional energy input, associated to the nutrients upwelled into the euphotic zone.
The knowledge of rich variety of the dynamics along the Aveiro coastal waters is the primary key for the understanding of the evolution of this ecosystem. This region is characterized by intense mesoscale activity, with generation and evolution of complex meanders, eddies and filaments along the coast. The processes responsible for the underlying dynamics of many of these features are not yet well understood.

The ocean off the Iberian Peninsular is one of high seasonal variability and is a demanding area to model realistically (Stevens et al., 2000). Therefore the validation of an ecological model for the Aveiro coastal ecosystem will contribute to better understand its dynamic.
The model was setup for the study area in order to modelling the temperature, nutrients and chlorophyll-*a* distributions, in situations of upwelling favourable winds.

Scenarios representing, typical summer/winter conditions corresponding generally to upwelling/downwelling situations along the western Iberian coast and the influence of the Ria de Aveiro lagoon are presented. The results show that the model results, when compared to the data, reproduced correctly the vertical profiles of temperature (T), nutrients (NO_3) and chlorophyll-a (CHL-a), and that the physical forcings determine the ecosystem state of the water column. The model is now a valuable tool for assessing the ecosystem variability of the Aveiro coast.

2. NUMERICAL MODEL

2. 1 Introduction

The model used in this study is a three-dimensional coupled hydrodynamic and ecological model for coastal and shelf seas (Luyten, 1999, Proctor, 1997). It is constituted by four sub-models: the hydrodynamical/physical model, the biological model, the sediment model and the contaminant model. The physical model includes the main processes, namely, the advective and the diffusive transport of momentum, as well as the interaction with the atmosphere, through the momentum (wind stress at the surface) and the radiative exchanges. The biological sub-model is based on Tett conceptual model (Tett, 1998; Tett P. and Walne A., 1995) and has the following structure: a) internal non-conservative biological or chemical processes; b) photosynthesis by the absorption of PAR; c) physical transport by advection and diffusion; d) vertical sinking; e) deposition and erosion via a “fluff” layer; f) exchanges between the water column and the sediment layer. Its distinguishing features are: (1) the use of a microplankton compartment to include the biomasses and the microbial loop organisms activity, as well as those for the phytoplankton, and (2) the use of variations in the chemical composition (especially, the nitrogen: carbon ratio) and of the microplankton and the detrital components to control many of the biological processes.

2.2 The ecological model description

The ecological model is forced by a physical model which is represented by a set of equations including 3D hydrodynamic and transport models. The hydrodynamic model is very similar to the *Blumberg and Mellor* primitive equation models (1987), which use the sigma coordinates and an embedded turbulent closure scheme (Luyten, 1999, Proctor, 1997).

The biological sub-model is based on Tett conceptual model (Tett, 1998; Tett and Grenz, 1994; Tett and Walne, 1995) and has the following structure: a) internal non-conservative biological or chemical processes; b) photosynthesis by the absorption of PAR; c) physical transport by advection and diffusion; d) vertical sinking; e) deposition and erosion via a “fluff” layer; f) exchanges between the water column and the sediment layer.

The model is forced by seasonal cycles of vertical transport and mixing, light and zooplankton grazing pressure, and boundary conditions. The autotrophs (i.e. phytoplankton) growth rate is calculated from the cell quota threshold limitation (CQTL) theory (Droop et al., 1982), as the least growth rate predicted from light or nutrient controlled growth:

$$\mu_a = \min\left[\mu_{a1}(I_p), \mu_{a2}(Q)\right] \qquad (1)$$

where *Q=N/B* is the nitrogen quota defined as the ration of the organic nitrogen N (mmol N) and the nitrogen microplankton carbon(mmol C) and I_p is the photosynthetically active radiation (PAR).

The phytoplankton needs light for growth, and under some conditions (e.g. during winter) light, rather than nitrogen supply, limits the microplankton growth. The light intensity controlled growth are calculated as the sum of the photosynthetic production and respiration loss, by a formalism described by Droop et al. (1982) and Tett (1989), which takes into account the photosynthetical efficiency and the ratio of chlorophyll to autotrophic carbon:

$$\mu_1(I_p) = (\alpha \chi_a I_p - r_a)(1-\eta) - r_h \eta \qquad (2)$$

where $\alpha = k\, \varepsilon^X\, \Phi$ ((mmol C)(mg Chl)$^{-1}$(day^{-1} W^{-1} m^2)) is the photosynthetic efficiency, ε^X (m^2 mg^{-1} Chl^{-1}) the phytoplankton attenuation cross-section, Φ (nmol C μE^{-1}) the photosynthetic quantum yield, k a conversion factor, χ_a the ratio of chlorophyll to autotroph carbon and r_a the autotrophic respirations and r_h the heterotrophic respirations losses, respectively:

$$r_a = r_{0a} + b_a \mu_{a_1}(I_p) \qquad r_h = r_{0h} + b_h\, \mu_1(I_p) \qquad (3)$$

with r_{0a} and .r_{0h} corresponding to the basal respiration rate for autorothrops and heterothrops, respectively, and b_a and b_h the autotrophic and heterotrophic respiration-growth slopes, respectively. The heterotrophic fraction η is defined as:

$$\eta = \frac{B_h}{B_a + B_h} \tag{4}$$

with B_a and B_h , respectively, the autotrophs and the heterotrophs carbon biomass.

The nutrients controlled growth is calculated as a function of the nutrients cell quota and the respiration loss. The nutrient uptake is calculated by a Michaelis-Menten type kinetics function. Under nitrogen-limiting conditions, growth rate should, ideally, be calculated as a fraction of the maximum specific growth rate depending on the cell nutrient quota, less respiration:

$$\mu_2(Q) = \mu_{max_a} f(T)(1 - \frac{Q_{min_a}}{Q_a})(1-\eta) - r_h\eta \tag{5}$$

where Q_a is the (variable) autotrophic cell quota and f(T) the temperature growth.

The biological model cycles the concentrations of organic carbon and nitrogen through the microplankton and the detrital compartments with associated changes in dissolved concentrations of nitrate, ammonium and oxygen. The concentrations are updated in time by solving the transport equation for each state variable, whereby the biological interactions are included as source or sink terms and which takes account of vertical sinking and the physical transport by advection and diffusion.

3. STUDY AREA

The study area is located in the Atlantic upwelling system of the western coast of the Iberian Peninsula, characterised by meteorological conditions of strong north/northwest prevailing, during almost the year which favours the upwelling of nutrient enriched cold deep waters, the phytoplankton development and the primary production. The continental shelf of the Aveiro coast is relatively wide (~60km) and gently sloping with an edge defined by the 200-m isobath, where the Aveiro Canyon (40º42'N) is the most significant topographic feature due to the fact that the slope gets very steep in just a few kilometres (Peliz et. al., 2002).

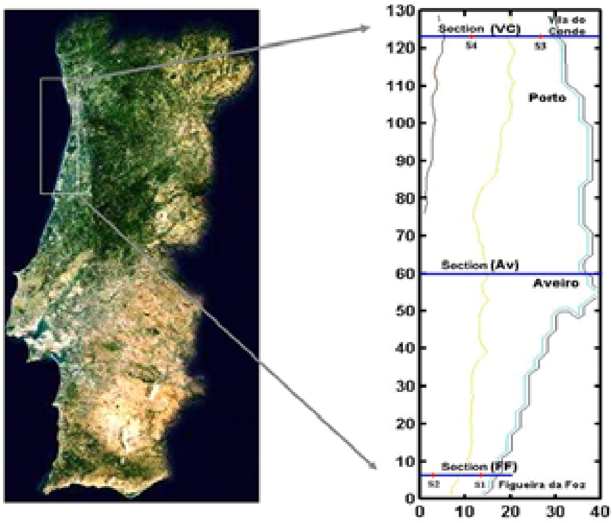

Figure 1: Study area. Costal area between Vila do Conde and Figueira da Foz, centred in Aveiro. Vertical sections W-E and offshore (S1 and S3) and inshore (S2 and S4) stations.

The bathymetry of the Portuguese coast for the study area has a 2 km resolution in both the latitude and the longitude directions (Cardoso, 2003). The computational domain, with the origin situated at 40º38'N and 8º27'W, corresponds to an area centred at the Aveiro station, extending 40 km offshore and 130 km alongshore (Fig. 1). It is represented by a uniform horizontal grid composed by 40x20 cells and a uniform 22 sigma levels distributed in vertical direction. The wind intensity and direction were taken from the WRF model (Weather Research and Forecast Model) a nesting mesoscale and assimilation forecast model.

4. MODEL VALIDATION

The model implementation included the calibration (Cardoso, 2005) and the validation. The last one may be defined as a procedure consisting in verifying if the model is able to reproduce data, independently of those involved in its calibration. Fig 2 shows vertical profiles for temperature, nitrates (NO_3) and chlorophyll-a (Chl-a) for two stations S_1 (near coast) and S_2 (offshore), both located at Figueira da Foz. It can be observed a good agreement between simulated temperature and data for S_1, whereas for S2 there is an overestimation by the model namely between 10 and 70m deep, corresponding to the intermediated layers (fig 2b). The simulated temperature profile presents a shallower thermocline, which in accordance to data should be between 30 and 70 m deep (fig 2b) and more smooth. Concerning the NO_3, (fig 2c), it can be observed that data and simulations are of the same order but the simulation shows a sharper profile than data. The model simulates well the near surface concentration (10 m) for the S_1 station but overestimates the concentration at deeper layers. For the offshore station (S_2) there is a good agreement for the near surface and bottom concentrations, but less for the intermediate layers. The Chl-*a*-simulated values for the S_1 station, (fig 2 (e)), are in the same range of data. The simulated profile presents a good agreement with data, although it overestimates it at 10 m deep (0.06 mg/m^3 instead of 0.09 mg/m^3 for data).

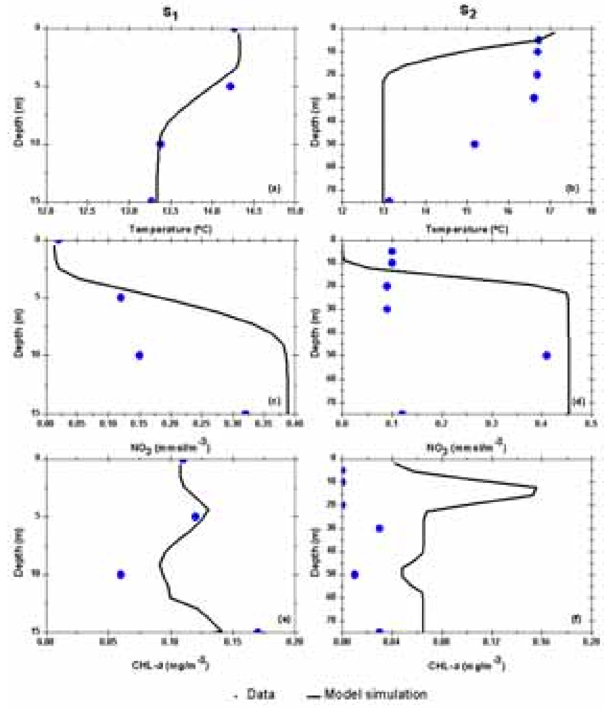

Figure 2: Vertical profiles of: (a)-(b) temperature; (c)-(d); NO_3 (mmol N. m^{-3}); (e)-(f) and Chl-*a* (mg Chl-*a*.m^{-3}), for two stations, S1 e S2, near Figueira da Foz, for the validation.

The results lead to conclude that, in general, the simulations values are of the same order of data. The model reproduces better data near the coast. Offshore station the simulation presents some deviations relatively to data, which may be attributed to the influence of boundary conditions.

5. MODEL APPLICATION IN THE STUDY OF SCENARIOS

The model was applied to study the following scenarios for the Aveiro coast: summer of 2005; winter of 2005; the influence of the Aveiro lagoon (Ria de Aveiro) input.

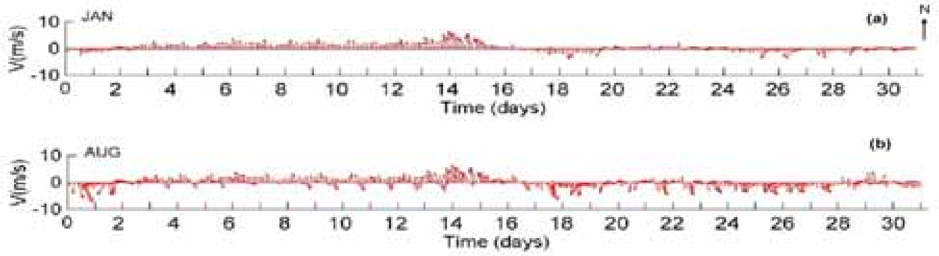

Figure 3: Wind Intensity and direction for: (a) January (winter) and (b) August (Summer) of 2005 year, given by WRF model (Weather Research and Forecast Model).

The wind intensity and direction (fig 3), air temperature, pressure and humidity were taken from the WRF model (Weather Research and Forecast Model), a nesting mesoscale and assimilation forecast model (Skamarock et al., 2007; Michalakes et al., 2005), which allows a mesh refinement, enabling a high resolution output focused over the Aveiro region.

5.1. The 2005 Summer Scenario

This scenario has been performed considering a situation for which winds are predominantly northerly along the Aveiro coast (fig 3(b)), which are typical situation of the upwelling at the western Iberian coast. It was chosen due to the fact that the wind intensity for this summer was relatively higher for this season, when compared with typical situation.

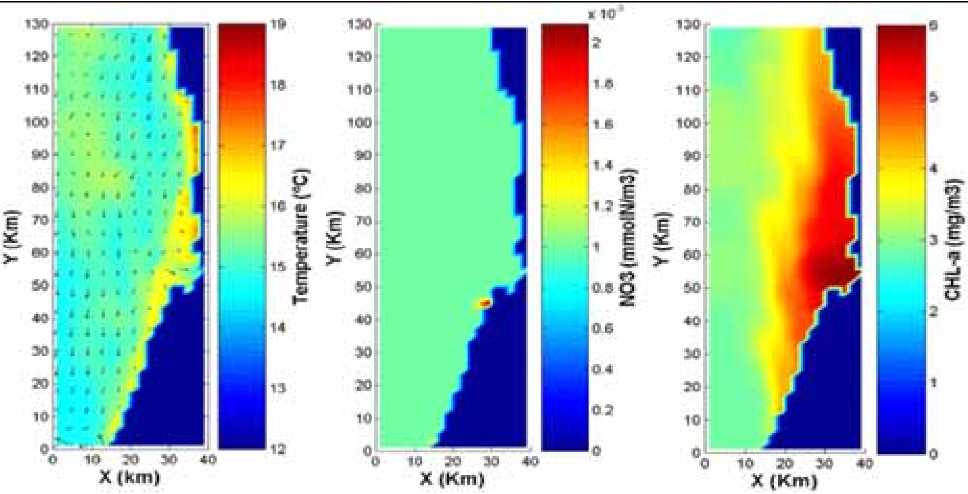

Figure 4: Simulated maps of surface: temperature, NO_3 concentration (mmol N. m^{-3}) and Chl-*a* concentration (mg Chl-*a*.m^{-3}), for 2005 summer. The arrows presented at the temperature map represent the current vectors.

The surface temperature distribution is almost homogeneous (14.5-15ºC). This uniform surface temperature distribution differs from a typical summer situation observed in August 1985 by Moita (2001), which may be attributed by the stronger upwelling, which brings more cold water to the surface, induced by the strong northeasterly wind. Indeed, the temperature vertical sections (Fig. 5(a-c)) shows a cold thin superficial layer (5-10m), with temperatures of about 14.5ºC-16ºC, which was established in the east-wet direction, evidencing the influence of the strong upwelling. It can be observed, as well, the presence of a layer cold water and the changes of declivity of the isotherms close to the coast, which are signatures of the upwelling. Very close to coastal line it can be observed some spot of relatively high surface temperature (16ºC), due the shallowness of the area (fig 4a).

The NO_3 responses of the model are presented in the horizontal maps and vertical sections (Figs. 4b and 5(d-f), respectively). Fig. 4 shows that NO_3 surface concentrations are practically null (1.0×10^{-3} mmolN/m^3).These values are quite similar to those observed by Moita (2001) in August 1985, for both the offshore and the inshore surface waters. The NO_3 vertical section, fig 5 (d-f), shows a depleted layer, within the first 20 m depth, and the NO_3 concentration rapidly increase toward the bottom. Near the coast the NO_3 concentration is practically null through the entire water column, which reflects a depletion by phytoplankton, as, illustrated in Chl-*a* vertical distribution of fig 5(g-i) .

Fig 4c (surface concentration) and Fig. 5g (vertical section) show that Chl-*a* surface concentration is extremely high for the season, reaching a maximum value of 6.0 mg Chl-*a*.m^{-3}, near the coast (Av), and 2.5-3.0 mg Chl-*a*.m^{-3} offshore. Inshore, the Av and the VC sections show that the maximum Chl-*a* concentration is located near the bottom. A plume of a thin layer of maximum Chl-*a* concentration emerges from the coast, stretches and deepens offshore, between 20m and 40 m depth. At the section FF the plume of maximum Chl-*a* concentration is shallower and sinks offshore between 15 and 20 m depth. The maximum Chl-*a* concentration is located within the euphotic zone, around 10 m bellow the surface, deepening offshore to values close to 40 m, at VC and Av stations, and 20m at FF station. Furthermore, the zone of maximum Chl-*a* concentration nearly follows the bottom profile. A rough estimation shows that the euphotic zone is, therefore, of the order of 5-10 m, near the coast, and 20-40 m offshore.

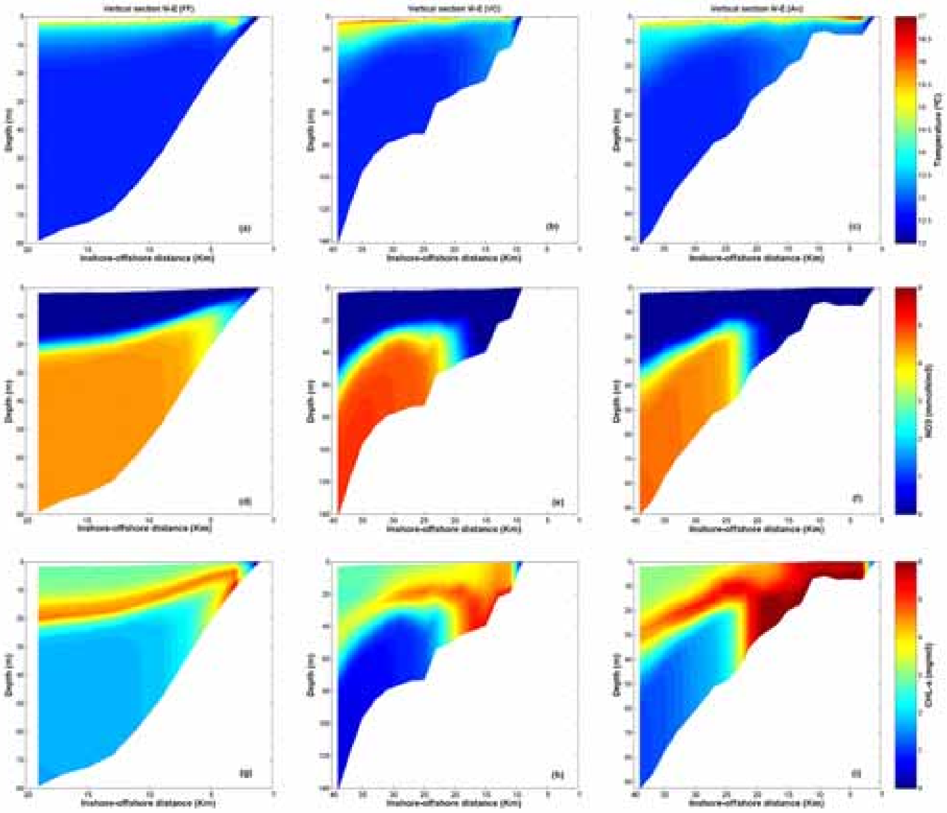

Figure 5: Vertical sections of (a-c) temperature (ºC); (d-f) NO_3 concentration (mmol N. m^{-3}); and (g-i) Chl-*a* concentration (mg Chl-*a*.m^{-3}), at Figueira da Foz (FF), Aveiro (Av) and Vila do Conde (VC) respectively, to the 2005 summer.

The results show the reinforcement of the summer upwelling induced by the strong northerly winds conditions, which mobilise more nutrients to the shallow layers. This condition associated to condition of high temperature and no light limitation, favour the phytoplankton development and high Chl -*a* concentrations. The near depletion of the NO_3 at the surface denotes the intense phytoplankton activity.

5.2. The 2005 Winter Scenario

This scenario corresponds to a situation for which winds are predominantly southerly along the Aveiro coast (fig 3(a)), which is a typical situation of downwelling.

The analysis of fig 6 shows that the surface temperature varies between 14 ºC (offshore) and (12ºC inshore). At southern part of the domain the temperature distribution is more uniform, about 14ºC. It can be observed for the surface, near the coast, the establishment of a warmer water layer, which extending offshore along the bottom. This warm water results from the convergence associated to the Ekman transport due to southerly winds. The vertical distribution of temperature presented in fig 7(a-c) shows as well that temperature is nearly homogeneous within the water column and it is, as well, of the order of 14ºC. It can be observed that the termocline is almost inexistent.

The surface NO_3 concentration is homogeneous with values of 3.5-4 mmolN/m^3 (fig 6), however the concentrations of the northern section (VC) are smaller than that of the southern section (FF), where a maximum concentration of 4 mmolN/m^3, is observed at 40m depth.

At the Av section the NO_3 concentration is smaller (3.5 mmolN/m^3) than that for the remaining stations. Contrarily to the previous scenario (Summer situation) where the surface concentration is almost null, the winter scenario show high NO_3 surface concentrations , since the nutrients consumption by phytoplankton is lower due to its low concentration (fig 6). This result is in agreement with Moita observations (2001). In general, near the coast the nitrate concentrations are lower than offshore, which reflects a downwelling situation.

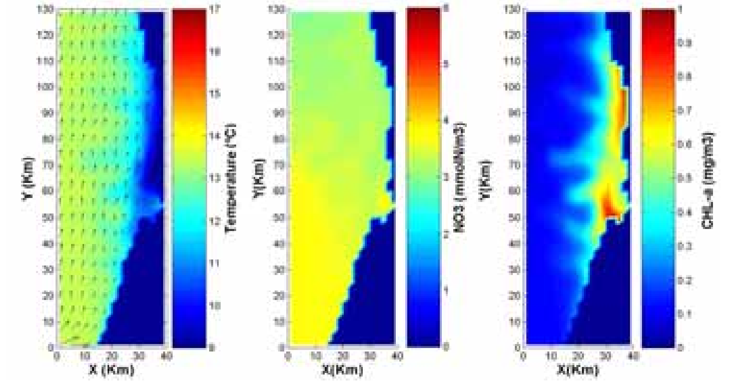

Figure 6: Simulated maps of surface temperature, NO_3 concentration (mmol N. m^{-3}); and Chl-*a* concentration (mg Chl-*a*.m^{-3}), for 2005 winter. The arrows presented at the temperature map represent the current vectors.

The surface Chl-*a* concentrations stretches in a band along the coast mainly between Av and VC sections, where the maximum concentrations of about 1mg/m^3 is observed (very low values when compared to the summer situation) (fig 6). The maximum Chl-*a* concentration deepens following a typical downwelling path as the phytoplankton must be supplied in nutrients (fig 7(g-i). Offshore the Chl-*a* concentrations are low and, therefore, the nutrients availability increases (fig 7 (e-f). In general, the maximum Chl-*a* concentration appears inshore, near the surface (fig 7 (h-i)).

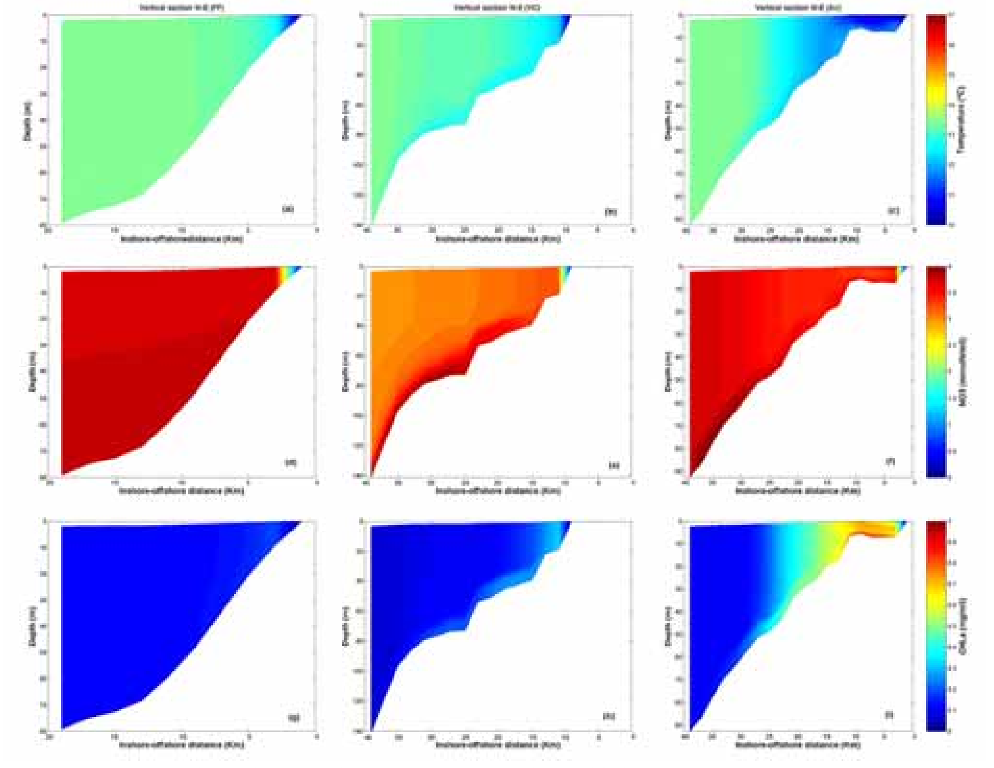

Figure 7: Vertical sections of (a-c) temperature (ºC); (d-f) NO_3 concentration (mmol N. m^{-3}); and (g-i) Chl-*a* concentration (mg Chl-*a*.m^{-3}); at Figueira da Foz (FF), Aveiro (Av) and Vila do Conde (VC) respectively, to the 2005 winter.

This result is, as well, in agreement with Moita observations (2001), and lead to conclude that in southerly wind conditions a downwelling situation is setup forcing, the nutrients to be concentrated near the bottom and offshore. In overall the surface phytoplankton concentration is low, as the phytoplankton tends to sinks in order to reduce the limitation by light and nutrients.

5.3. The influence of the lagoon outflow

To assess the influence of the Ria de Aveiro lagoon (situated at the center of the eastern boundary), a scenario identical to the 2005 summer scenario was considered, where it has been imposed a constant outflow from the lagoon. All the other conditions were maintained equal.

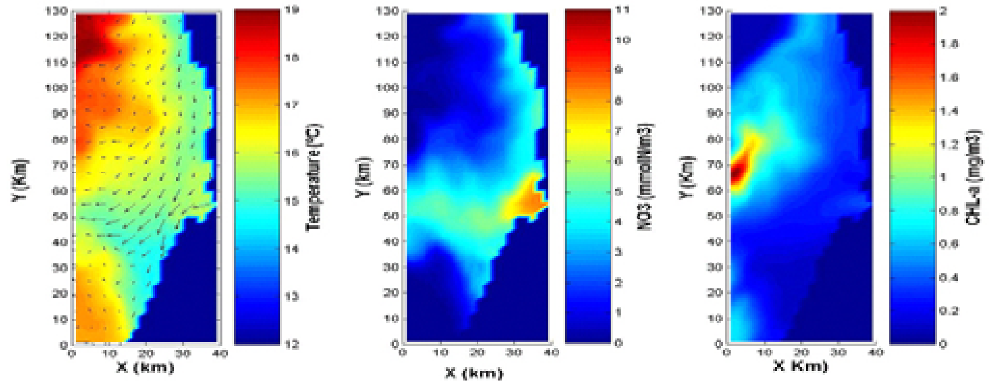

Figure 8: Simulated surface maps of: temperature, NO_3 concentration (mmol N. m^{-3})and chlorophyll-a and Chl-*a* concentration (mg Chl-*a*.m^{-3}). The arrows presented at the temperature map represent currents vector.

Fig 8 shows the influence of the lagoon input. Comparing to fig 4(a) it can be observed that the lagoon induces an intensification of currents near the eastern boundary of the study area.

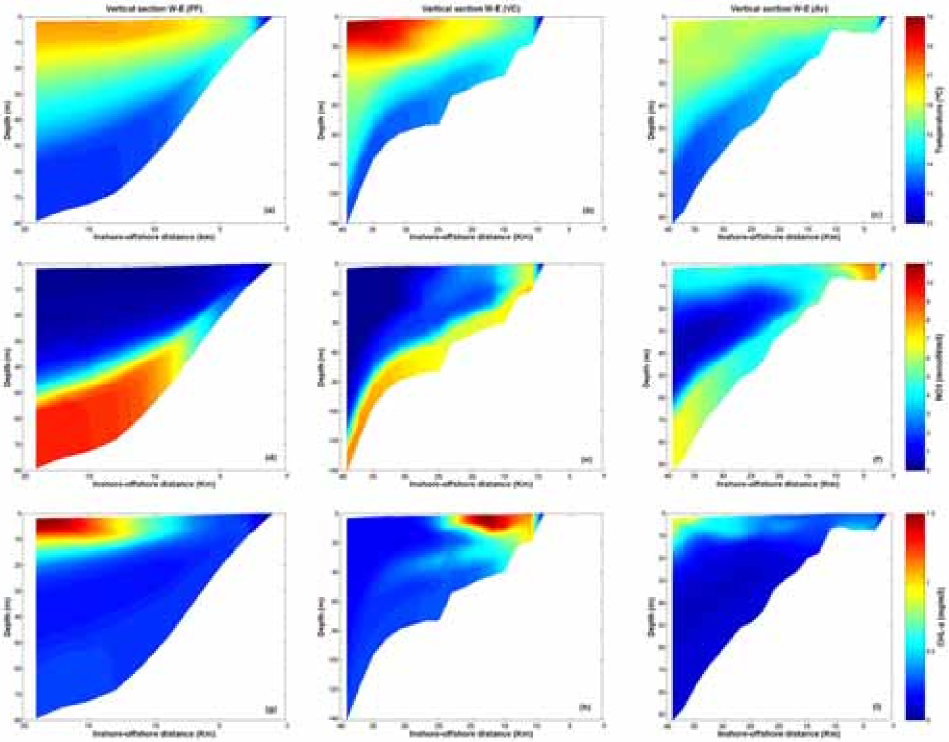

Figure 9: Vertical sections of (a-c) temperature (ºC); (d-f) NO_3 concentration (mmol N. m^{-3}); and (g-i) Chl-*a* concentration (mg Chl-a.m^{-3}); (j-l), at Figueira da Foz (FF), Aveiro (Av) and Vila do Conde (VC) respectively (Ria de Aveiro input).

The surface temperature at the northern area are higher (17-19ºC) than that of the central and the southern areas, which are about to 17-19ºC. The vertical sections shows that a cool water band (15-16ºC) has developed at the eastern boundary, while offshore a warm water layer of about 20m thickness has formed at FF (fig 9 (a)), reaching a value close to 40 m at Av and VC sections (fig 9(b-c). This warm water, located offshore, is due to the intensification of the divergence associated to the Ekman transport.

At the eastern boundary, close to the lagoon mouth, the NO_3 surface concentration is higher relatively to the summer scenario, with concentrations of about 8 mmolN/m^3, and stretches offshore suggesting an enhancing of the nutrients upwelling due to the currents intensification (fig 8 e 9(f)). On the other hand, at Av and VC sections, the maxima concentrations are located near bottom (fig 9 (d-e).

The surface Chl-*a* maximum concentration is occurs offshore, indicating that Chl-*a* distribution reflects this time the influence of the lagoon outflow (Fig 8 and fig 9 (g and i).

At Vila do Conde the surface Chl-*a* maximum concentration is located close to the coast. A secondary Chl-*a* concentration appears stretching offshore at about 40m depth (fig 9 (h)).

This scenario leads to conclude that the lagoon outflow influences the coastal circulation, as well as the intensity of the upwelling. As a consequence, the transport of nutrients and phytoplankton biomass distributions are affected.

6. CONCLUSIONS

The model reproduced correctly the vertical profiles of temperature (T), nutrients (NO_3) and chlorophyll-a (Chl-*a*) at the Aveiro coastal system. The scenario results evidence the influence of the northerly winds in the upwelling intensity, as well as in the availability of nutrients and the phytoplankton development, whereas the southerly winds induce a downwelling situation and lower surface phytoplankton concentration. On the other hand, we has evidenced that the lagoon outflow influences the upwelling intensity and, therefore, phytoplankton biomass distributions. In overall, the results confirm that the model is a valuable tool for assessing the ecosystem variability of the Aveiro coast and confirm the crucial role played by the physical processes in the phytoplankton in this system.

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