A Unified Approach to the Modelling of the Venice Lagoon–Adriatic Sea Ecosystem

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In this paper, a first attempt at analysing the macronutrients’ mass balance between the north Adriatic coastal sea and the lagoon of Venice by means of a nested and coupled model is presented. The hydrodynamic part of the model simulates the evolution of the sea-surface elevation and of the three-dimensional field of velocity, temperature, salinity and density. Tides, winds, river discharges, thermal and evaporative fluxes are included as forcings. Two models are nested in order to handle the correct spatial scales. The first one, with a resolution of about 10 km, is able to describe the basin and sub-basin scale hydrodynamical features; the second one, with a resolution of 1·2 km, describes the interactions between the open sea and the lagoon. This last circulation model has been coupled with a simple primary production submodel, in order to investigate the short-term dynamic of the ecosystem during spring time. Results show that, in some instances, the primary production can be sustained by macronutrients’ fluxes coming from the coastal area.

Keywords: transport models; primary production; northern Adriatic Sea; Venice Lagoon

Introduction

Some environmental problems of the Adriatic Sea, and in particular the coastal area near the lagoon of Venice, have received increasing attention from local and national authorities (Consorzio Venezia Nuova, University of Venice, National Research Council) and international associations (UNESCO) in the last decades. This interest has stimulated a scientific investigation of these ecosystems, which have been studied from the physical, chemical, biological and ecological point of view.

In all the models developed up to now, the Venice Lagoon and the Adriatic Sea have been considered as two independent systems, as they interact only through three narrow inlets. These were treated as boundaries in the lagoon models, while the lagoon area was completely neglected during simulations of the Adriatic Sea dynamics. This approach is certainly fully justified if one is interested only in describing the hydraulic circulation either of the lagoon or of the offshore area, but it might not be completely sufficient for studying the dispersion and fate of pollutants. In fact, although the Adriatic Sea general circulation is almost independent of the presence of the lagoon, the latter might become important for its loadings in macronutrients and chemicals.

A relevant fraction of the nutrient loads of the lagoon is carried along small rivers which flow into the basin, bringing nitrogen and phosphorous of agricultural, industrial and municipal origin. The central area is also affected by discharges coming from the industrial area of Porto Marghera and from the city of Venice. It has commonly been thought that the primary production in the lagoon is sustained only by these inputs, but recently some authors (Sfriso & Marcomini, 1993; Zago, 1995) have suggested that the Adriatic Sea might play a role as reservoir of nutrients for the lagoon during late spring–summer. According to these scientists, the sea could be the most important nutrients source in this period, when the fluxes from rivers are low because of their reduced flow. In fact, field studies have shown that inorganic nitrogen concentrations are sometimes higher offshore and at the inlets than inside the lagoon (Sfriso et al., 1994). These findings led the authors to quote that ‘the flow of eutrophic substances is not one-way from the mainland towards the northern Adriatic Sea’.

Transport models, based on hydrodynamic models, appear to be useful tools for investigating the above problems, but, due the different space-scales of the two systems, lagoons and seas have always been modelled separately. In this paper, a first attempt is presented of analysing the nutrients’ mass balance between the north Adriatic coastal sea and the lagoon of Venice by means of a nested and coupled model.
between sea and lagoon by means of a single model, which describes the circulation in the lagoon and in the coastal area. The nested transport model has been coupled with a very simple submodel of primary production, in order to understand whether fluxes of nutrients from the Adriatic Sea might become important for sustaining the primary production in the lagoon.

The circulation model

The first step of the work has been the development of two nested tri-dimensional circulation models, for carrying the information from the whole Adriatic basin (coarse resolution, with 9·6 km grid size, see Figure 1) to a smaller basin (medium resolution with 1·2 km grid size, see Figure 2) including the coastal region of the Venice Lagoon area.

The Adriatic Sea shows an elongated form, having the major axis of about 800 km and a width of 200 km; it is characterized by a maximum depth of 1200 m, but the north part of the basin, closed and shallower, has an average depth of 50 m. The Adriatic west coast, on which we focus in this study, shows a bottom depth gently deepening towards the offshore direction. On the other side, the lagoon covers an area of almost 450 km², 75% of which is not deeper than 2 m, while the main channels deeper than 6 m account for 5%; this reflects in the fact that most of the lagoon is generally well mixed.

A correct simulation of the circulation in the coastal area, shallower than offshore, and nearby the inlets, where relatively high velocities are encountered, can be achieved only by taking into account the non-linearity of the advection terms in the numerical discretization of the Navier–Stokes equations. In addition, the need to follow changes in the bathymetric slopes from the Adriatic Sea to the lagoon area, demands a numerical model with a detailed vertical resolution. Last, as several small rivers flow in the lagoon, it is important to take into consideration the buoyancy effects due to freshwater mixing.

The Princeton Ocean Model POM (Blumberg & Mellor, 1987; Mellor, 1991) seemed to be a good tool for coping with the above problems, as it solves the primitive equations in their complete form, using a finite differences method. The model, therefore, takes into account the baroclinic terms and includes temperature and salinity as state variables.

Finite difference models with constant layer thickness often fail to reproduce physical and biological
processes because of the lack of resolution along the vertical axis, particularly where the bathymetry changes abruptly. In order to avoid these problems, the model uses a \( \sigma \)-coordinate reference system, obtained by the transformation \( \sigma = (z - z_c)/(H + z_c) \) where \( H \) is the water depth and \( z_c \) the sea-surface elevation, which allows one to properly follow the bathymetric profile.

In the simulations, a minimum basin depth of 1 m has been imposed; with the number of levels fixed at 10, this guaranteed a minimum level thickness of 0·1 m, which is quite reasonable. Even though this approximation slightly modifies the hydraulic behaviour of the tides propagation in the shallower part of the lagoon, it does not influence its general circulation.

With this vertical discretization the numerical stability is guaranteed for large timesteps, because implicit schemes can be used along the vertical. The parametrization of the vertical turbulent coefficients is carried out by means of a turbulence closure scheme of the second order (Mellor & Yamada, 1982). In this way, turbulent coefficients can be reproduced accurately even at small scales.

The momentum equations can be summarized by the following expression:

\[
\frac{\partial u}{\partial t} + u \cdot \nabla u = - \frac{1}{\rho} \nabla p + f(k \times u) + g + R
\]

where \( u \) stands for the velocity vector with components \((u, v, w)\) and \( t \) is time. The first term on the right hand side accounts both for barotropic and baroclinic pressure changes; \( \rho \) is water density, \( f \) the Coriolis parameter, \( k \) is the vertical unit vector, \( g \) is gravity acceleration and \( R \) represents the stress terms and the horizontal-vertical viscosities.

The circulation model allows the simulation of the tri-dimensional fields of velocity, temperature, salinity and density, and the evolution of the sea-surface elevation. It can take into account different forcings, such as astronomical and meteorological tides, winds, thermal and evaporative fluxes and river discharges, which can assume climatological values or be representative of selected transient situations. The numerical code has been modified and revised by the authors, making it suitable for the application to two nested models which describe the circulation in a complex coastal system; the whole Adriatic Sea and a coastal zone which includes the lagoon of Venice. The first system has been discretized using a 9·6 km size regular grid; its circulation drives the one of the smaller area, which is resolved with a grid size of 1·2 km. In Figure 2 a picture of the nested area is presented.

At this stage, the nesting has been applied one-way, that is the values at the boundary of the coastal area are given by an interpolation of those simulated by the basin-scale model. The interpolation accounts for the reduction of grid size. It must be remarked that a proper modelling of the circulation within the lagoon would certainly require a smaller grid-size; results are therefore to be considered with caution, especially as far as the transport is concerned. Nevertheless, preliminary results obtained with more detailed fully nested models confirm the results presented here.

The biochemical model

The primary production in the coastal area has been investigated using a simple three-dimensional biochemical model, which has been coupled with the transport one. In this first attempt, a minimum set of state variables has been chosen: a nutrient pool (total inorganic nitrogen), a phytoplanktonic pool and the concentration of dissolved oxygen. This choice is consistent with the aim of the present study, which is concerned with the analysis of the evolution of the primary production in the short term.

The equation governing the dynamics of a generic state variable can be written as:

\[
\frac{\partial c_i}{\partial t} + u \cdot \nabla c_i = \nabla (K \nabla c_i) + S_i(c, t)
\]

where \( c_i \) is the concentration or density of a stable variable and \( c \) is the state vector. \( K \) stands for the horizontal and vertical non-uniform diffusivities, while the last term accounts for the local rate of change due to interactions between the state variables (see Appendix, in which the first three terms are condensed in the total derivative expression, and \( S_i(c, t) \) are extensively presented).

The formulations which describe nutrient uptake and phytoplankton growth and decay are quite commonly used in such models; their parametrization has been taken from other modelling or sensitivity studies regarding the lagoon of Venice (Pastres et al., 1995). Formulations and parameters are presented in Appendix. The forcing functions of the primary production submodel are nutrient loads, which input points are shown in Figure 2, water temperature and light intensity. The circulation model succeeds in reproducing the dynamical evolution of nutrient concentration and temperature fields as passive tracers. Results will be seen in the next section. The hourly light intensity has been computed from climatological observations (Dejak et al., 1992); it varies according to
the season but does not depend on the position in the spatial grid.

Oxygen dynamics are mainly driven by the photosynthetic net production of phytoplankton. Biological decomposition has not been modelled in detail at this stage, by taking biological oxygen demand (BOD) concentration as a constant. The physical process of re-aeration is confined to the upper layer.

Results and discussion

In order to assess the capability of the model in simulating the major oceanographic features of the basin and sub-basin, a first run, without any biochemical reactions, was carried out forcing the whole Adriatic Sea with a Sirocco wind, blowing for 6 days at constant velocity (10 m s$^{-1}$, NW directed). Maximum vector 2.07.

![Figure 3. Total transports (m$^2$ s$^{-1}$) daily averaged during the 5th day of simulation, forcing the whole basin with Sirocco wind. (10 m s$^{-1}$, NW directed). Maximum vector 2.07.](Image)

Dispersion of nutrient and the short-term dynamics of the primary production have been investigated in two 60-day simulations. In both runs the circulation of the whole Adriatic basin has been forced by the M$_2$ tidal component, the principal component of the tide, applied along the open boundary at the Otranto strait, in the southern part of the region. The T-S initial configuration, in both cases, uses temperature and salinity fields obtained with standard objective analysis techniques (Bergamasco & Pierazzo, 1992) from in situ data collected monthly by CNR-ISDGM (Arcari & Bergamasco, 1995), as well as heat, precipitative and evaporative fluxes as forcing conditions (Picco, 1991).

The values of velocities, temperature and salinity computed by the coarse resolution model along the nesting area (9·6 km grid size) are used as boundary conditions of the fine resolution model (1·2 km grid size). The period simulated refers to the months of April and May, in which the light radiation and the temperature can enhance an appreciably phytoplanktonic growth.

In the first simulation, the biological non-conservative interactions have not been included, in order to test the consistency of the transport model and its capacity of generating a well-defined spatial pattern of nutrient concentration, starting from an idealized homogeneous initial condition, in presence of realistic loads from the mainland obtained from SILVIA database (Ministro dei Lavori Pubblici et al., 1994). The circulation reaches a quasi-steady state after about 30 days, as confirmed by the average kinetic energy plot in Figure 4; the plateau, clearly visible, indicates that there is a balance between tidal forcing and friction dissipation. A clear tendency towards a stationary state is also shown by the distribution of nutrient, which, in this run, behaves as a passive tracer. Therefore, the experiment shows that the model is able to disperse the nutrient without accumulation inside the lagoon, conserving its total amount; in fact the spatial pattern does not change appreciably after 2 weeks. In Figure 5 the surface nutrient distribution after 60 days in the first simulation shows relative maxima in the south and northwest area, where the loadings due to river discharges are greater.

Figure 6 evidences a small increase in the positive nutrient net flux from the Venice Lagoon to the sea, resulting from an incoming flux along Lido inlet, (negative values) which does not compensate the two positive contributions along Chioggia and

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Malamocco. This trend can find an explanation in the local circulation gyre, which is mainly anti-cyclonic in the coastal area, while the general circulation of the northern Adriatic Sea is cyclonic. The local gyre moves northward the nutrient outcoming from Malamocco and Chioggia inlets, and pushes it back into the lagoon area through Lido inlet. This dynamic is suggested also by Figure 7, where the total daily mean transport field averaged during day 30 is presented. It could be interesting compare this field with the one already presented by Figure 3; differences emerging are due to the different forcing applied (Sirocco wind in the former, only $M_2$ tide in the latter).

In the second numerical experiment, biological interactions have been considered. The initial
distribution of nitrogen has been taken from the previous simulation (see again Figure 5) while phytoplankton density has been set initially constant.

The surface fields of nutrient, phytoplankton, temperature and oxygen at day 20 are shown in Figure 8(a–d). Phytoplanktonic bloom is at its maximum, as can be seen in Figure 9, which shows the evolution in the lagoon of the total mass of nitrogen and phytoplankton, expressed in organic carbon units. Maximum values of phytoplankton density are located in the central-west area [Figure 8(b)], where the temperature is higher than in the...
southern area [Figure 8(c)]. Water temperature can be considered a limiting factor at the beginning of the bloom, as the concentration of nutrients is above the half saturation constant ($K_N$ in the appendix) in the whole basin at the end of the winter. Therefore, phytoplankton starts blooming in the northern area, where the morphology and the shallow basin cause a faster increase of the temperature. As a consequence, in this area, nutrient is depleted at a higher rate and is not promptly restored by inputs from the mainland. On the contrary, the central-west area is enriched by relevant nutrient loads from the mainland which sustain the primary production. In fact, as can be seen in Figure 8(a), nitrogen is higher in the central-west area, even though phytoplankton is more abundant in this area. Oxygen concentration clearly depends on phytoplankton density, as shown in Figure 8(d), in which the spatial pattern closely resembles that of Figure 8(b).

After the bloom, the southern part of the basin sustains relatively high phytoplankton values for a longer period than the north area, as can be seen in Figure 10. This seems to be caused by recirculation processes around Chioggia inlet and localized river discharges. In the picture, nutrient and phytoplankton concentrations are presented for the length of the simulation in two areas, representative of the north lagoon (thick line) and of the south lagoon.

The plot of total nitrogen fluxes, solid line in Figure 11, shows again a net export from the lagoon to the sea until about day 15. Fluxes are sea directed at Chioggia and Malamocco, while at Lido, inlet nutrient flow is opposite. After that the lagoon imports nutrient, due to small inflows at Chioggia and Malamocco inlets.

Conclusions

Results presented in the previous section show that the general circulation model, nested to resolve high scales and coupled to simulate biological processes, can be successfully applied, after being purposely modified, to the modelling of complex coastal behaviour. The high flexibility achieved allows one to deal with different spatial scales which characterize a basin and its sub-basins. These features make it possible to correctly model the circulation and the dispersion of pollutants in a real system like the lagoon of Venice.
and the Adriatic Sea, previously treated as two separate systems. This approach is particularly useful for modelling energy and mass transport phenomena and their effects on primary production, as one can estimate the flux of nutrients between the two systems. Even if in this paper, short-term simulations of the evolution of a spring algal bloom are presented, and the results show that the net flux of nutrients is not always directed one-way from the mainland to the open sea. Such counterintuitive theoretical finding is in agreement with the opinion of some field researchers and suggests once more that ecological models of complex systems need to be supported by detailed descriptions of transport processes. Nevertheless, this first evidence should be confirmed by more detailed field analysis and theoretical studies. In particular, the study could gain useful improvements from a more detailed discretization of the lagoon area, which would increase the channels resolution, and from an improvement of the biochemical submodel, e.g. including remineralization and grazing.

Acknowledgements

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References


Appendix

The equation set, the parameters and functional expressions used for the biochemical model are hereby presented; note that the left sides represent the total derivative, which therefore accounts for both advective and diffusive processes.

\[
\begin{align*}
\frac{dP}{dt} &= \left[ p_{\text{max}} f_1(L) f_2(T) f_3(N) - K_{\text{resp}} - K_{\text{ml}} \right] P \\
\frac{dN}{dt} &= \left[ -R\text{NC}_{\mu_{\text{max}}} f_1(L) f_2(T) f_3(N) \right] P + \text{Input} \\
\frac{dO}{dt} &= K_{\text{sat}} (O_{\text{sat}} - O) + \text{ROC}_{p_{\text{max}}} f_1(L) f_2(T) f_3(N) - K_{\text{resp}} \right] P - K_{\text{dec}} \text{BOD}
\end{align*}
\]

where BOD is not modelled as a state variable, but as an oxygen demand constant in time and changing in space.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Unit</th>
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<tbody>
<tr>
<td>P</td>
<td>Phytoplankton concentration</td>
<td>mg C l(^{-1})</td>
</tr>
<tr>
<td>O</td>
<td>Dissolved oxygen concentration</td>
<td>mg O(_2) l(^{-1})</td>
</tr>
<tr>
<td>O_{sat}</td>
<td>Saturation oxygen concentration</td>
<td>mg O(_2) l(^{-1})</td>
</tr>
<tr>
<td>BOD</td>
<td>Biological oxygen demand</td>
<td>mg O(_2) l(^{-1})</td>
</tr>
<tr>
<td>K_{resp}</td>
<td>Phytoplankton respiration coefficient</td>
<td>0·004 day(^{-1})</td>
</tr>
<tr>
<td>K_{mf}</td>
<td>Phytoplankton mortality coefficient</td>
<td>0·007 day(^{-1})</td>
</tr>
<tr>
<td>K_{dec}</td>
<td>BOD decayment coefficient</td>
<td>0·0048 day(^{-1})</td>
</tr>
<tr>
<td>K_{rear}</td>
<td>Reaeration coefficient</td>
<td>0·04585 day(^{-1})</td>
</tr>
<tr>
<td>(\mu_{\text{max}})</td>
<td>Phytoplankton maximum growth rate</td>
<td>0·1 h(^{-1})</td>
</tr>
<tr>
<td>ROC</td>
<td>Conversion ratio oxygen/carbon</td>
<td>2·66 adimensional</td>
</tr>
<tr>
<td>RNC</td>
<td>Conversion ratio nitrogen/carbon</td>
<td>0·15 adimensional</td>
</tr>
</tbody>
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\[
f_1(L) = \frac{I_0 e^{-K_{\text{ext}} L}}{I_0 e^{-K_{\text{ext}} L} + K_{\text{light}}} \quad \text{(Steele, 1962)}
\]

\[
f_2(T) = \left( \frac{T_{\text{MAX}} - T}{T_{\text{MAX}} - T_{\text{opt}}} \right)^{\beta(T_{\text{MAX}} - T_{\text{opt}})} e^{\beta(T - T_{\text{opt}})} \quad \text{(Lassiter & Kearns, 1974)}
\]

<table>
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<th>Parameter</th>
<th>Explanation</th>
<th>Unit</th>
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<tr>
<td>(\beta)</td>
<td>Thermal coefficient</td>
<td>0·1157 °C</td>
</tr>
<tr>
<td>T_{MAX}</td>
<td>Phytoplankton growth max. temperature</td>
<td>30 °C</td>
</tr>
<tr>
<td>T_{opt}</td>
<td>Phytoplankton growth opt. temperature</td>
<td>20 °C</td>
</tr>
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</table>
\[ f_3(N) = \frac{N}{N + K_n} \]  

(Monod, 1942)

\[ O_{sat} = a - bT + cT^2 + dTS + eS^2 \]  

(Gromiec, 1983)

<table>
<thead>
<tr>
<th>N</th>
<th>Nitrogen concentration</th>
<th>mg N l(^{-1})</th>
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<tbody>
<tr>
<td>K_n</td>
<td>Nitrogen half saturation constant</td>
<td>0.05 mg N l(^{-1})</td>
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N = 14.6244
b = 0.367134
c = 0.0044972
d = 0.00005
e = 0.0002739

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<tr>
<th>T</th>
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<td>Salinity</td>
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