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Remarks on the redefinition of system boundaries and model parameterization for downscaling experiments

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Abstract:

The paper discusses problems encountered while implementing a downscaling experiment for testing the potential impacts of changes in temporal precipitation patterns on the biogeochemical properties of the lagoon of Venice. The paper shows how coupling different models implies redefining the boundaries, as well as space and time scales of the systems to be modelled, carefully revising model assumptions and parameterization, and possibly integrating new elements in the model. The paper also details how, in order to account for changes and adaptation in planktonic pools, a structural dynamic model was implemented by linking the kinetic parameters of a pre-existing calibrated functional response to the recent evolution of environmental conditions. Parameterizations of the boundary conditions of rescaled models and of links among models are also discussed.

1. Introduction

Analyses of the potential impacts of climate changes are complex studies as they necessarily involve considering processes acting on different spatial and temporal scales. Indeed, the crux of so-called downscaling experiments is to consider the consequences of global processes on local scales (von Storch et al. 1993). This entails integrating and reconciling local and global models, which are designed to operate at different scales and for different purposes and therefore adopt different levels of process resolution and approximations. In the literature, this is often attempted by nesting - usually via an off line scheme - a cascade of models of different complexity and resolution (Najjar et al. 2000, Uncles 2003).

Although this approach is viewed as zooming in towards a finer and finer resolution of space, time and physical processes, it is often implicitly a combination of local model upscaling and global model downscaling. More generally, the integration of models operating at different scales can be more clearly analysed by recognizing that it includes three conceptually distinct steps: a) choosing the space and time scale of the system to be modelled (system definition), b) rescaling both local and global models to cope with the newly defined scales, c) coupling the rescaled models. This might require adopting new parameterization of specific processes and introducing new definitions for boundary conditions that are seldom explicitly described and discussed.

We focus on the potential impacts of changes in temporal precipitation patterns on the biogeochemical properties of a coastal lagoon (Venice, Italy). The idea is that climatic changes can induce variations in precipitation patterns and substantially modify the timing and volume of freshwater and nutrient delivery to coastal wetlands. The implementation of this approach, seldom studied because of difficulties in describing these cascading effects (Scavia et al. 2002, Howarth et al. 2000), requires assembling different models in a hierarchy that is used to explore the effects of alternative scenarios. The results of the scenario analysis are reported elsewhere (Cossarini et al. 2008, Salon et al. 2008). The aim of this brief note is to offer some general remarks on methodological problems encountered in downscaling experiments and to exemplify how some of these problems have been tackled in a real application.

The section which follows gives details on the definition of the system and on the hierarchy of models employed, section 3 deals with the re-parameterization of temperature functional response for multi-decadal time scale while section 4 describes how the boundary conditions have been defined in order to account for the models' coupling.

2. Definition of the system and set-up of model hierarchy

The hierarchy of models used in our numerical experiments is built from 2 starting components, the regional climate model RegCM (Giorgi et al., 2004a, Gao et al. 2006), and the biogeochemical three-dimensional model TDM (Solidoro et al. 2005).

RegCM provides multi-decadal evolution of high-resolution atmospheric variables for the Euro-Mediterranean region, including rain, irradiance, wind, humidity and air temperature. It solves processes on spatial scales from 10^1 to 10^3 km and on time scales from days to multi-decade. A subset of data referring to the drainage basin of the lagoon of Venice is used to force the bio-optical and heat flux modules of the biogeochemical model of the lagoon, thereby enabling the levels of water temperature and surface irradiance to be computed.

TDM is a validated model for the lagoon of Venice which simulates cycles of nitrogen, phosphorus and carbon through dissolved inorganic phases, phytoplankton, zooplankton, detritus and upper sediment compartments on spatial scales from 10^{-1} to 10^{2} km and on time scales from seasonal to multi-year. This model is able to reproduce the seasonal evolution of major biogeochemical compartments in different scenarios of meteorological forcing, nutrient loads, and water quality of the adjacent Adriatic Sea (Solidoro et al. 2005).

The specific application entails simulating climatic conditions and biogeochemical processes on the lagoon and its drainage basin (10^{-1} to 10^{2} km) over a multi-decadal time scale. The best way to proceed is to first upscale the local model, since it provides the proper resolution of the processes of interest, then to downscale the regional climate model considering boundary conditions, forcing and resolution of the upscaled local model.

The upscaling of TDM to multi-decadal simulation requires redefining the parameterization of temperature influence (see section 3). Furthermore, in order to consider the effects of rivers and exchanges with the sea, the redefinition of TDM model boundaries and their parameterization (loads of nutrients from tributaries and open boundaries condition at the inlets) is appropriate too. These inputs for TDM are not directly provided as RegCM output, and have to be computed by two purposely identified statistical models, which use RegCM output as input data (see section 4). The downscaling of RegCM to local scale is performed considering a subset of the original domain centered over the area of the lagoon drainage basin. The averaged atmospheric fields over this area have been considered as a spatially constant forcing for all TDM grid points and for the two statistical models.

The cascade of models therefore consists of four components (Fig.1). RegCM (component 1) provides the input for heat fluxes and bio-optical modules of TDM (component 2) and for the statistical models which -in turn- compute nutrient loads (component 3) and boundary conditions at the lagoon inlets (component 4). Further details are given in Cossarini et al. (2008), Salon et al. (2008).

3. New parameterization of temperature influence

When using a model to project future scenarios, it is implicitly assumed that the simulated system and the environmental conditions do not greatly differ from the setup used when identifying and calibrating the model structure. In reality, when considering the impacts of climatic changes, it is necessary to acknowledge a systematic variation in background temperature and the fact that biological systems may change in response to this (Najjar et al. 2000).

A full description of this process would require incorporating an evolutionary model capable of reproducing adaptation and changes in functional response of the simulated organisms. A model for possible invasions of alloctonous species would also be appropriate. Unfortunately, this would increase the complexity of the analysis probably beyond our present level of knowledge. Indeed, a number of downscaling experiments, including even highly sophisticated approaches (Vichi et al. 2003), simply do not consider this point.

Alternatively, we could recognize that evolution/adaptation takes place, and that the response to environmental conditions of the pool of species observed at any given time is the result of evolutionary processes coded in DNA and captured by kinetic parameters. Then it is possible to use a structurally dynamic model, i.e. a model having parameters that are continuously varied in

time, in order to account for adaptations and shifts in species composition (Jørgensen, 1986). In literature, parameters of structurally dynamic models are changed in agreement with expert or empirical knowledge, or by optimization of so-called goal functions.
A simpler way to incorporate the results of evolutionary drift could be to link kinetic parameters to recent history of environmental conditions. We considered that when there is a change in average temperature (T), a species either adapts its response to new conditions, or it is replaced by another species which fits better in the new environment. If the change is almost monotonic and slow enough to allow adaptation by recombination of the genetic pool (and subsequent selection), as in our case, one can then assume that the shape of functional response to changing variables does not overly vary, but is simply shifted toward higher (or lower) values of that variable. In other words, kinetic parameters change, whereas kinetic laws, considered to be an expression of physiological and thermodynamic constraints, do not. This assumption, besides being coherent with niche theory, appears to be supported, to some extent, by experimental observations (Suzuki and Takahashi, 1995).

In practice, given a functional response to a forcing, *Env*, f(*Env*, *par*), where *par* represents the vector of kinetic parameters, it is possible to rewrite it as a function of the anomaly of the forcing, *EnvAn*, as f(*EnvAn*, *par'*), where $EnvAn = Env\text{-}Env_{avg}$, Env_{avg} is the average of *Env* over a suitable period, and *par'* is the vector of re-calibrated kinetic parameters.

In our case, the original formulation used in TDM for modelling the dependence of phytoplankton growth on water temperature was an empirical function proposed by Lassiter and Kearns (1974), calibrated to reproduce seasonal evolution in a scenario of present environmental conditions. This function is characterized by an exponential increase up to an optimal temperature T_o and a decline above it until vanishing at a cut-off temperature, T_a:

$$f(T,\alpha) = \left[(T_a - T)/(T_a - T_o) \right]^{b(T_a - T_o)} \exp\left[b(T - T_o) \right].$$

This function can be rewritten as a function of temperature anomaly $t = T - T_{avg}$, by replacing the parameters T_a and T_o with $t_a = T_a - T_{avg}$ and $t_o = T_o - T_{avg}$:

$$f(t,\alpha') = \left[(t_a - t)/(t_a - t_o) \right]^{b(t_a - t_o)} \exp\left[b(t - t_o) \right].$$

The last point to be defined is the choice of the time interval over which one should compute T_{avg}, and the frequency of updating of the formulation (T_o , T_a and *b* are calibrated once only against present situation, but T_{avg} changes). Since evolution is a continuous process in which stochastic events play an important role, this choice cannot be objective. Following the approach of Giorgi et al. (2004b), we consider an update frequency of 10 years. This temporal interval was used to update the concentrations of greenhouse gases in forcing RegCM future scenario simulations. Other functional responses to temperature are treated in a similar way.

4. Parameterization of the missing processes

The boundary conditions required by a local model are often not readily available as direct output of larger scale models, nor is a model available for them. Hence integration of the regional and local models requires some attention to the definition of proper models and/or transfer functions for the missing links.

4.1. Nutrient loads from rivers

We followed a two step procedure. First, a logarithmic regression between observed annual precipitation and nutrient loads is used to predict annual nutrient loads from RegCM projection of precipitation (left side of Fig. 1). Historical data used in the regression were collected during a 3 year monitoring program of the water quality of the lagoon of Venice (Solidoro et al. 2004). The choice of a logarithmic regression takes into account saturation effects, as well as the fact that nutrients accumulate in soils and underground waters during dry periods, and are flushed into rivers during wet periods (Justić et al., 2005). Secondly, daily precipitation load is computed by partitioning the annual load on the basis of simulated daily rain intensity, $rain_d$. In particular, monthly loads L_m are assumed to be proportional to monthly precipitations $rain_m$, and daily loads L_d are estimated as a weighted sum of a 'normal flow' and a 'flood event' related components. The first is a linear interpolation, computed by assuming that each monthly load, normalized by the number of days of each month's day_m, is assigned at the 15th day of the month. The second is proportional to the daily amount of precipitation over the monthly amount of rain, with no delay coefficient since the response time to a storm event is of order one day for this basin (Zuliani et al., 2005). Daily loads are:

$$L_d = \alpha \left[\frac{L_{m+1}/day_{m+1} - L_m/day_m}{(day_{m+1} + day_m)/2} \right] \tau_d + (1-\alpha) \frac{rain_d}{rain_m} L_m \text{ and } L_m = \frac{rain_m}{rain_y} L_y$$

where τ_d is the number of days after the 15th day of the month. The parameter α represents the quota of the monthly load that is due to normal flow. In agreement with suggestions given in Rinaldo et al (2006) we chose a value of 0.6. Finally, the daily loads were divided by 24 to obtain the hourly loads, and partitioned among the 12 tributaries proportionally to annual outflows recorded in a monitoring program of the catchment basin (Zonta et al. 2005).

This parameterization of nutrient loads is very simple but allowed us to consider the effect of river inputs. Furthermore, considering that the implementation of sophisticated methodologies (Neff et al. 2000, Tappin et al. 2002) requires a huge amount of information which was not (and seldom is) available. The final aim of our work is to derive a seasonal climatology by averaging over multi-decadal simulations, which we believe to be acceptable.

4.2. Boundaries conditions at the inlets

The boundary conditions at the lagoon inlets, C_d , are also given by a two step procedure. In this case, specifically identified linear regressions predict seasonally averaged values of concentrations of variables of interest, C_s, according to RegCM simulated seasonal precipitation $rain_s$. Then, a somewhat arbitrarily defined operator returns a smooth modulation in time for each parameter, using observed daily evolution as a template. The linear regressions are based on seasonally grouped data collected within a water quality monitoring program of the coastal area adjacent to the lagoon for the period 1991-2004, and on daily precipitation data from the same time interval. We chose to work on a seasonal base because in this case the data set was rich enough to allow this choice, and accordingly the results of the regressions were more significant. The daily evolution used as a template in the definition of the modulating operator, M_d, is computed by cubic spline interpolation of monthly data collected close to the inlets (Solidoro et al. 2004). Daily evolution M_d is then multiplied by daily weights arising from linear interpolation of the ratios between the seasonal concentrations predicted by the statistical regression, C_s and the seasonally averaged concentrations of the daily values referring to the same period, $\langle M_d \rangle_s$.

Finally, an error noise of normal distribution, zero mean and standard deviation equal to the standard deviation of the observations, is added to the regression model when the p-value of statistical regression exceeds the limit 0.2. The boundary conditions read as:

$$C_d = \left[\frac{C_{s+1}/\langle M_d \rangle_{s+1} - C_s/\langle M_d \rangle_s}{90} \right] \tau_d * M_d \text{ and } C_s = \beta_0 + \beta_1\, rain_s \left[+ \eta(0, std(C))\, if\ p > 0.2 \right].$$

Again, we recognize that this parameterization is very simple. However, the definition of open boundary conditions in climatic simulations is a difficult issue, and there is no consensus on how to solve it. Indeed, although the issue is critical it is seldom addressed in literature. For example Uncles (2003) states that there are significant approximations in his approach, whereas the point is not discussed explicitly in Justic et al. (2005) and Vichi et al. (2003) avoided the problem by using a closed 1D system. The parameterization here proposed is a contribution towards resolving an issue which still appears to be open.

5. Conclusion

The goal of this paper is to highlight, by providing a working example, that the coupling of different models working at different scales is never a trivial operation, nor a merely technical one. Indeed this integration implies redefining the boundaries and the space and time scales of the systems to be modelled. In turn, this implies careful revision of model assumptions and parameterization, and possibly including new elements in the model.

The case discussed here illustrates these points well, by clarifying that this integration is a three step process: system definition, model rescaling, and model coupling. Our example also illustrates how we addressed some of the difficulties encountered in the definition of boundaries conditions, missing processes and links among rescaled models in a real application. These details are often considered technicalities and are not fully described in scientific literature, even if they might well be important, indeed sometimes critical.

Finally, the study provides an example of how structural dynamic models can be used for first parameterizations of changes in structure and functioning of biological communities, also as a consequence of adaptation and evolution.

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Figures

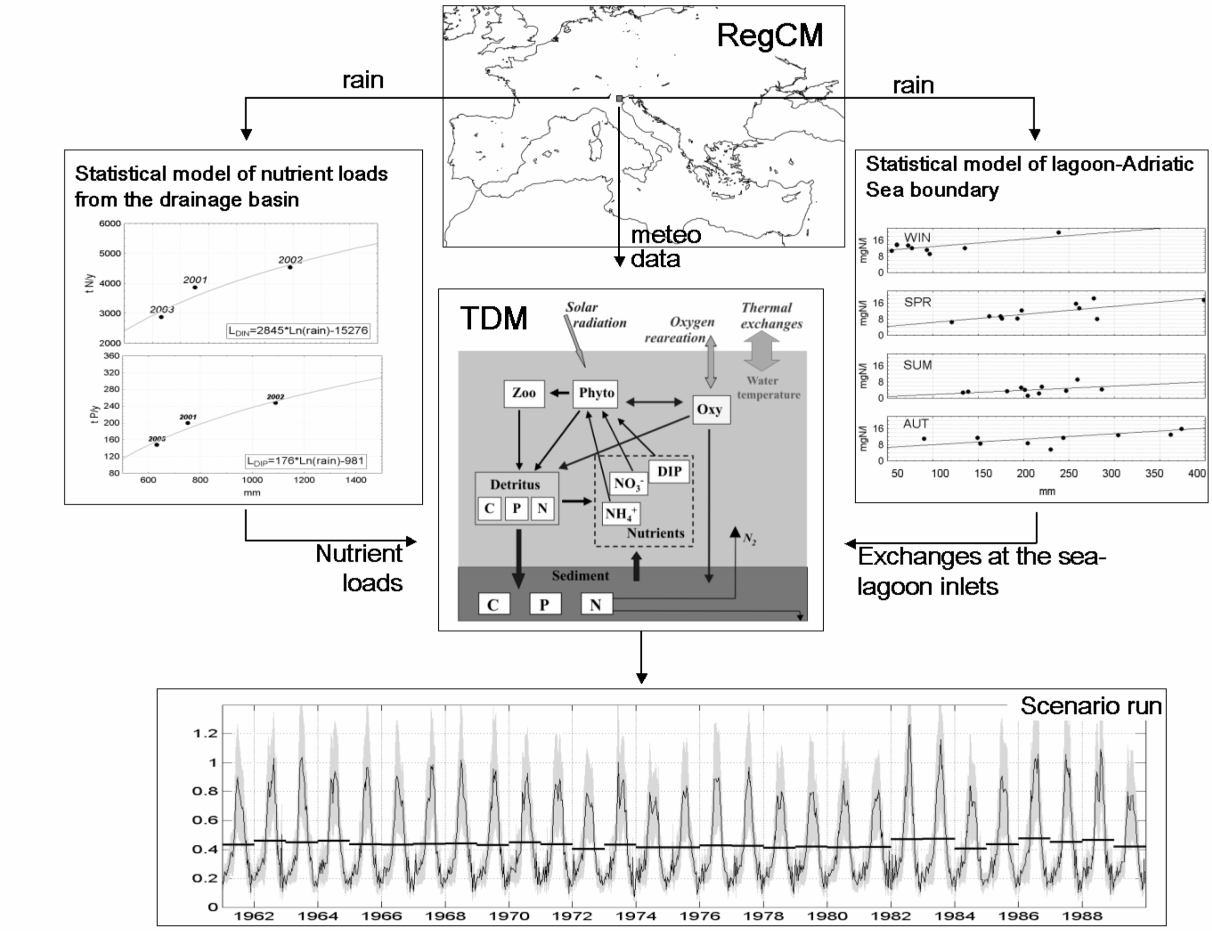

Figure 1. Layout of the downscaling approach. The scheme depicts relationships among the RegCM (component 1, the upper panel shows the domain), statistical models (component 3 and 4, left and right boxes), TDM (component 2, the central panel illustrates main biogeochemical processes considered; modified from Solidoro et al. (2005) with permission from Elsevier). The lower plot gives an example of the multi-decadal output (spatial average and dispersion of concentrations of chlorophyll). The box in the upper map indicates the area of interest.