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The impacts of climate change and environmental management policies on the trophic regimes in the Mediterranean Sea: Scenario analyses

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ABSTRACT

The impacts of climate change and environmental management policies on the Mediterranean Sea were analyzed in multi-annual simulations of carbon cycling in a planktonic ecosystem model.

The modeling system is based on a high-resolution coupled physical–biogeochemical ocean model that is off-line and forced by medium-resolution global climate simulations and by estimates of continental and river inputs of freshwater and nutrients. The simulations span the periods 1990–2000 and 2090–2100, assuming the IPCC SRES A1B scenario of climatic change at the end of the century. The effects of three different options on land use, mediated through rivers, are also considered.

All scenarios indicate that the increase in temperature fuels an increase in metabolic rates. The gross primary production increases approximately 5% over the present-day figures, but the changes in productivity rates are compensated by augmented community respiration rates, so the net community production is stable with respect to present-day figures. The 21st century simulations are characterized by a reduction in the system biomass and by an enhanced accumulation of semi-labile dissolved organic matter. The largest changes in organic carbon production occur close to rivers, where the influence of changes in future nutrient is higher.

1. Introduction

Climate change can significantly affect the dynamics of marine ecosystems through the cumulative effects of the direct impact of the physical and chemical processes on individual organisms and a variety of indirect impacts that cascade on populations, communities and ecosystem structure (Harley et al., 2006). As an example, variations in seawater temperature can modify the water column density structure, thus altering the vertical fluxes of bio-limiting elements in open ocean systems (e.g., Vichi et al., 2003; Steinacher et al., 2010); variations in precipitation patterns can significantly modify the timing and volume of freshwater and nutrient delivery to coastal areas (Scavia et al., 2003; Cossarini et al., 2008); changes in physical and chemical properties alter plankton habitats and, consequently, plankton spatial distribution (Guisan and Thuiller, 2005); and changes in plankton phenology can interfere with the timing of species interactions, possibly triggering major changes in ecosystem structure and functioning (Yang and Rudolf, 2010). Clearly, all of these alterations can impact the ecosystem's capability to provide "goods and services" (Costanza et al., 1997).

The projection of the effects of climate change is often addressed by developing specific "scenarios," which are used to force a cascade of models of different complexity and resolution, usually nested via an off-line scheme (Najjar et al., 2000; Solidoro et al., 2010; Uncles, 2003). Typically, a socio-economic scenario defines properties, such as policy options, demographic changes and land use, which are used in combination with climate models to project the response of the physical climate system into the future (e.g., air temperature and atmospheric chemical composition), as shown in Fig. 1. Downscaling techniques then exploit global climate model outputs to assess the impact of global changes on selected components at the regional or local scales (von Storch et al., 1993).

The Mediterranean Sea region is characterized by strong variability in the (climate related) natural and anthropogenic pressures, making the area a climate change "hot spot" (Giorgi, 2006), which may lead to potentially important effects on ecosystems. In fact, the Mediterranean Sea is located in the sub-tropical climate belt and is characterized by large meridional and zonal climate gradients over a relatively limited area. The seasonal and inter-annual variability of the Mediterranean Sea general circulation is driven by atmospheric regimes (Tsimplis et al., 2006) that are linked to the physiographic characteristics of the Mediterranean as a whole and to its regional basins (such as the Liguro–Provencal or Levantine regions). Moreover,

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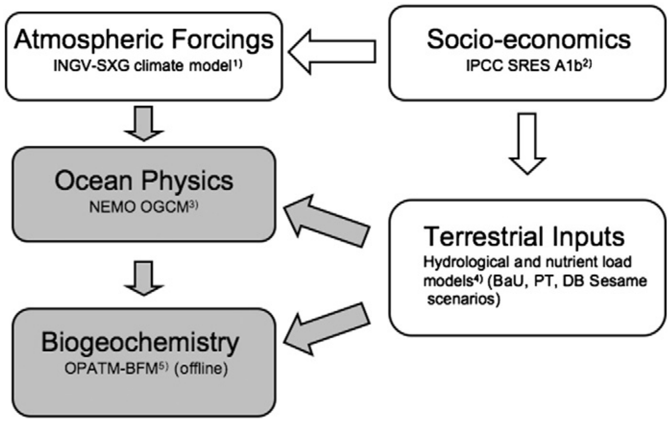

Fig. 1. A conceptual scheme of the model hierarchy. [1] Gualdi et al. (2008); [2] Nakicenovic and Swart (2000); [3] Oddo et al. (2009); [4] Ludwig et al. (2010); [5] Lazzari et al. (2012).

the mesoscale circulation of the Mediterranean Sea is characterized by eddies measuring less than 100 km, which impose the use of model grids with spatial steps of approximately 10 km or less. Human pressure and land–ocean interactions also play relevant roles in defining the Mediterranean mean state and variability. By 2025, the population located in the Mediterranean coastal region is projected to increase by 21% with respect to the value registered in 2000 (430 million people; Attané and Courbage, 2001), thus posing severe problems with respect to the related impacts on marine ecosystems, in particular, in terms of land-based nutrient discharges from rivers. This implies that climate change scenarios addressing the effect of climate on marine ecosystems cannot be limited to variations in the atmospheric features alone but that the hydrological cycle and associated river inputs of water and mass must also be considered.

After the first work by Thorpe and Bigg (2000), the anticipated climate impacts on the physical structure and dynamics of the Mediterranean Sea have been mostly investigated with global climate models that embedded a low resolution of the Mediterranean (e.g., Marcos and Tsimplis, 2008). To increase the detail of the oceanic features, Somot et al. (2006) used a higher resolution ocean model (1/8°) that is off-line driven by regionally downscaled climate simulation results based on the SRES A2 emission scenario, which allowed them to infer more details on the impacts of tropospheric warming. With respect to the upper part of the water column, which is the most relevant for biological production, both Thorpe and Bigg (2000) and Somot et al. (2006) found an overall increase in sea surface temperature and salinity, which resulted in a decrease of surface density and enhanced vertical stratification.

Only recently results from fully coupled regional climate models have been published (Gualdi et al., 2012; Planton et al., 2012; Somot et al., 2008), most of which were developed in the framework of the CIRCE project, funded by the European Commission (Climate Change and Impact Research: the Mediterranean Environment). CIRCE regional models have been used to project changes in the oceanography of the Mediterranean Sea until the year 2050, following the SRES A1B scenario (Dubois et al., 2012; Gualdi et al., 2012). These simulations have significantly improved the representation of climate variability over the region, and the ensemble mean shows a significant warming of the sea surface temperature (SST) of approximately 1.5–2 °C in 2050 (Gualdi et al., 2012; their Fig. 4). However, even these state-of-the-art models appear to suffer from significant systematic errors. For example, a comparison of the CIRCE experiments with an updated reanalysis (Adani et al., 2011) indicates a cold bias in the SST for present-day conditions of approximately 2.5 °C (Dell'Aquila et al., 2012). Therefore, due to the intrinsic nonlinearity of climatic systems, it is not possible to predict how such errors will propagate over time within scenario simulations. The projections of climate change impacts on marine biogeochemical properties are a recent development in this field, and consequently, many additional assumptions must be made. The results are even more uncertain and must still be considered only first-order estimates.

Here, we present the results of a first attempt to estimate the effects of climate change on the biogeochemical properties of the Mediterranean Sea using a model hierarchy that integrates atmospheric and ocean circulation models with a biogeochemical model. The strategy followed in this study is to use the results from medium-resolution global climate simulations to force a high-resolution physical ocean model, which is ultimately coupled to a model of marine biogeochemistry. The main aim is to provide an assessment of the major changes in the dynamics of the primary biogeochemical properties of the Mediterranean Sea in the 21st century, assuming a reference scenario of climatic change (the IPCC SRES A1B, Nakicenovic and Swart, 2000) and different scenarios of environmental management policies.

This work was conceived in the framework of the SESAME project (Southern European Seas: Assessing and Modelling Ecosystem changes) that started at the same time as the CIRCE project.

The paper is organized as follows. The next section describes the layout of the simulations and includes the model hierarchy, the initial and boundary conditions and the characteristics of the scenarios, including the reference, the present climate simulation and three future climate simulations, based on three environmental management policies. Section 3 presents the main results, from both the physical and biogeochemistry models, which are then discussed in Section 4.

2. Material and methods

The layout of the conceptual scheme underpinning our experimental set-up is shown in Fig. 1. Socio-economic scenarios determine both the emission and the river load scenarios. The former influence the atmospheric and ocean circulation models, which in turn drive the biogeochemistry model. The latter influence the ocean circulation and biogeochemistry models. Our model hierarchy explicitly describes the processes depicted in the shaded box in Fig. 1, i.e., the marine physical and biogeochemical properties, considering river loads and atmospheric forcings to be boundary conditions. The atmospheric forcings are derived from the climate model outputs given by Gualdi et al. (2008). The river loads are computed from hydrological and land use model studies (Ludwig et al., 2010). The details concerning each module of the model hierarchy follow in next sections.

2.1. The ocean general circulation and transport models

The ocean general circulation model (OGCM) is based on the NEMO modeling system (Nucleus for European Models of the Ocean; Madec, 2008, see also http://www.nemo-ocean.eu, version 2.3). The domain configuration and physical set-up are derived from the Mediterranean Ocean Forecasting System (MFS, Oddo et al., 2009). The OGCM domain (Fig. 2) covers the whole Mediterranean Sea and extends to the Atlantic Ocean with a spatial resolution of 1/16° and three open boundaries in the Atlantic, located at the western, northern, and southern boundaries.

The horizontal scale factors are approximately 6 km in longitude and approximately 7 km in latitude. There are 72 levels in the vertical scale, with uneven grid spacing ranging from 3 m at the surface to 337 m at the bottom. The OGCM computes the air–sea fluxes of water, momentum and heat using specific bulk formulae tuned for the Mediterranean Sea (Castellari et al., 1998).

The OGCM results were used to drive the biogeochemical model off-line using the OPA transport model (Aumont et al., 1998; Foujols et al., 2000). This coupling was originally developed for an operational tool that has been routinely used to produce short-term forecasts of the biogeochemistry of the Mediterranean Sea since 2007 (Lazzari