Reg Environ Change
DOI 10.1007/s10113-013-0430-x

ORIGINAL ARTICLE

An ensemble of models for identifying climate change scenarios in the Gulf of Gabes, Tunisia

Lara Lamon · Jonathan Rizzi · Antonio Bonaduce · Clotilde Dubois · Paolo Lazzari · Leila Ghenim · Slim Gana · Samuel Somot · Laurent Li · Donata Melaku Canu · Cosimo Solidoro · Nadia Pinardi · Antonio Marcomini

Received: 7 March 2012 / Accepted: 23 February 2013

Abstract Climate change is likely to increase the pressure on the environment and on human systems that are requiring new assessment tools aimed at supporting decision-makers and stakeholders towards a more sustainable and effective management of the coastal environment and its resources. This research appraises an ensemble of models that integrates complex interactions of climate and anthropogenic impacts on vulnerable Mediterranean coastal areas with application to the Gulf of Gabes, Tunisia. Starting from Global and Regional Circulation Models, the models' ensemble includes simulations of marine and atmospheric dynamics and biogeochemical processes in coastal waters under expected anthropogenic forcings, with a spatial domain ranging from subnational to local. In the case study area, the simulations showed that atmospheric temperature increase is likely to be around 4 °C in the summer months of 2100, relative to 1961–1990. In order to obtain the most reliable estimate of sea-level rate variations, satellite altimetry data have been processed over a period of 15 years (1993–2007) showing that sea-level changes on the Tunisian shelf were of the order of 2 mm/year. This value was considered as a reference for the sea-level change scenarios. As far as the water quality is concerned, the areas most impacted by pollution are located near major towns and human infrastructures, such as harbours. The set of results obtained by the proposed models' ensemble may be suitable for supporting a scientific dialogue with stakeholders and for the implementation of exposure scenarios supporting a regional risk assessment approach to the entire Gulf of Gabes area.

Keywords Models' ensemble · Model simulations · Gulf of Gabes · A1B climate change scenario · Present climate scenario

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Electronic supplementary material The online version of this article (doi:10.1007/s10113-013-0430-x) contains supplementary material, which is available to authorized users.

L. Lamon · J. Rizzi · A. Bonaduce · A. Marcomini
Centro Euro Mediterraneo sui Cambiamenti Climatici,
via Augusto Imperatore 16, Lecce 73100, Italy

L. Lamon · J. Rizzi · A. Marcomini (✉)
Department of Environmental Sciences,
Informatics and Statistics, University Ca' Foscari Venice,
Dorsoduro 2137, 30123 Venice, Italy
e-mail: marcom@unive.it

C. Dubois · S. Somot
Météo-France/Centre National de RecherchesMétéorologiques
(CNRM), 42 avenue Coriolis, 31057 Toulouse, France

P. Lazzari · D. M. Canu · C. Solidoro
Ecology and Computational Hydrodynamics in Oceanography
(ECHO), National Institute of Oceanography and Experimental
Geophysics (OGS), Borgo Grotta Gigante, Brisciki 42/c,
Sgonico-Zgonik, TS 34010, Italy

L. Ghenim · S. Gana
SAROST, SAROST Agency, Immeuble Saadi Tour EF,
El Menzah IV, Tunis 1082, Tunisia

L. Li
Laboratoire de Météorologie Dynamique, CNRS, UPMC,
Casier 99, 4 place Jussieu, 75005 Paris, France

N. Pinardi
Department of Physics and Astronomy, University of Bologna,
V. B. Pichat 6/2, Bologna 40127, Italy

Introduction

Coastal regions are extremely complex and vulnerable multifunction systems that are subject to a variety of pressures both of natural and anthropogenic origin.

Coasts are often densely populated (Collet 2010; EEA 2006) and consequently host a high concentration of human activities (urbanisation, tourism and recreational activities, industrial production, energy production, port activities, fishing and agriculture) that may impact well-preserved ecosystems or areas of great environmental value.

In order to manage the increasing pressures on coastal resources, the European Commission (EC 2002) adopted the Integrated Coastal Zone Management (ICZM) approach, aiming at a more collaborative and integrated approach to decision-making between end-users. The ICZM approach is oriented towards the principle of respect for natural processes and carrying capacity of ecosystems; it supports activities that are environmentally friendly and economically sound, and takes into account long-term social responsibility (EC 2002). ICZM procedures should also lead to better management of other ecosystems in Europe and beyond (EEA 2010).

Climate change may cause additional pressure on coastal systems, thus increasing vulnerability on already highly susceptible areas; it generates new impacts, intensifies already occurring ones and promotes synergic and cascading effects (Douglas et al. 2012). Sea-level (SL) rise and changes in the frequency and intensity of extreme weather events (e.g. storms and associated surges, EEA 2008) are perceived as the largest climate change impacts on coastal areas; thus, highly urbanised and populated coastal areas are of particular concern within a climate change perspective as high-density population and urbanisation may limit and even impede natural adaptive processes such as landward migration or vertical accretion of wetland systems. Since population density is increasing on coastal areas (Collet 2010; Parry 2007), national and international governmental actions and policies need to be oriented towards the prevention of population exposure to coastal hazards.

Due to the threats global change may pose to coastal systems, climate issues continue to be a highly visible and contentious issue in public policy at the national and international level (King 2004; Richards and Nicholls 2009).

In order to better understand how climate change affects risks in coastal areas, the EC funded the DINAS-COAST project aimed both at providing a consistent source of data regarding SL rise at the global scale and at assessing the vulnerability of coastal systems to climate change (Vafeidis et al. 2008).

Furthermore, significant efforts have been made towards the definition of climate change scenarios that represent the scientific effort to predict the future climate as a result of the actions of past, present and future generations (Hulme and Dessai 2008).

Global Circulation Models (GCMs) are the primary tools for understanding how global climate may change in the future; however, it should be noted that results from available climate projections from GCMs do not provide reliable information on scales below 200 km (Meehl et al. 2007) up to now because of coarse numerical resolution. Considering the Mediterranean Sea, where the Rossby radius of deformation is 10 km (Pinardi and Masetti 2000), to resolve the mesoscale variability, the appropriate horizontal resolution would be greater than 1/8°.

As a consequence, to reliably assess hydrological impacts of climate change, higher-resolution scenarios are required for the most relevant meteorological and marine variables.

Previous studies addressed *ensemble of models* as the appropriate tool for the comparison of outputs coming from similar models. For instance, Eilola et al. (2011) applied three coupled physical–biogeochemical models to calculate changing nutrients' concentrations in the Baltic Sea for the present climate to address the reliability and uncertainties of the coupled models. Furthermore, other studies focused on the definition of climate change scenarios as a result of models' ensemble. For instance, Sanchez-Gomez et al. (2011) made a comparison of different RCMs for the evaluation of uncertainties in the future projections of water heat and freshwater inflow in the Mediterranean, and Johns et al. (2011) reported the results for the atmospheric variables under two climate change scenarios from a GCMs' ensemble. Baruffi et al. (2012) reported an integrated modelling approach aimed at addressing climate change impact assessment on groundwater resources. Although none of these studies defined a complete climate change scenario, they evidenced the need of integrating different models' results in assessing climate change impacts on environmental resources.

The activities reported in this research paper were developed within the Climate and local ANthropogenic drivers and impacts for the TunisIan COastal area (CANTICO) project, funded under the framework of Climate Impact Research and Response Coordination for a Larger Europe (CIRCLE ERA-Net). The project was aimed at applying an appropriate methodology, within ICZM standards, addressing both the disparity of natural systems and human actions (as required by EC 2002) and climate change impacts.

According to this, the main objective of this paper is to identify a set of climate change scenarios relevant to ICZM for the selected Mediterranean coastal area of the Gulf of Gabes (GoG), Tunisia. This work represents a first attempt in joining outputs from, essentially, different models (i.e.

biogeochemical models, circulation models) and time series analysis in order to consistently describe the climate change and anthropogenic impacts persisting on the GoG.

This objective is achieved by using an ensemble of different models that combine the overall records on climate change implications to characterise complex interactions of climate and anthropogenic impacts on the GoG—selected as a representative vulnerable Mediterranean coastal area.

From now on, by "ensemble" of models, we intend a set of models providing different outputs.

The first aspect of the presented methodology focuses on putting specific attention towards obtaining regional-scale scenarios, whenever possible. The second relevant aspect consists in the definition of climate scenarios based on both physical and chemical variables (atmospheric temperature, precipitation, wind speed, marine current, water temperature, nutrients' concentration and SL) and anthropogenic impacts (given by emissions of nutrients as nitrates and phosphates and the related net primary production, NPP), which are both taken into consideration to give a whole picture of climate change effects on the Tunisian coast and on the GoG. Outputs are presented within three different scenario families: (1) meteorological, (2) marine circulation and SL and (3) water quality.

The Gulf of Gabes

The GoG area within Tunisia was chosen as an appropriate case study area for a pilot application of the selected models' ensemble and shown in Fig. 1. The GoG is in fact a representative example of a coastal zone subject to a multitude of significant and rapidly evolving pressures from natural and anthropogenic drivers that are recurrent in the Mediterranean coastline.

More information on the case study area is placed in the electronic Supplementary Material (SM).

Materials and methods

In order to characterise the main natural and anthropogenic pressures affecting the coastal area of the GoG, an ensemble of climate, circulation and biogeochemical models was identified. These models provide the information that is necessary to build meteorological, marine circulation and water quality scenarios comparing the present climate to the A1B climate change scenario, which was chosen as CANTICO reference scenario.

The A1B climate change scenario belongs to the A1 "World Market" family of scenarios, characterised by increasing globalisation and rapid economic growth; A1B is defined by a balanced use of all energy sources. The climate change forcing in the model simulations is driven by the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) A1B scenario (Nakicenovic et al. 2000) as the input for GCMs and RCMs as reported in Table SM1.

The 20CE scenario is a climatological reconstruction of the present conditions and is considered here as the reference scenario together with the ERA40 data set (Uppala et al. 2005).

Figure 2 represents the CANTICO models' ensemble aimed at obtaining the meteorological, marine circulation and SL, and water quality scenarios. Selected models include different types of numerical models simulating relevant climate, circulation and biogeochemical cycles that may influence climate change impacts on coastal areas at different spatial scales.

The meteorological scenario provides the evolution of atmospheric variables such as wind speeds, surface temperature and precipitation as outputs from ARPEGE-Climate.

The marine circulation and SL scenario aims at providing information on the evolution of marine variables as current velocity and SL. Such information is provided by LMDZ coupled with NEMOMED8 and together with MFS-Sys3 provides the information for this scenario.

The water quality scenario for the GoG is performed by coupling the three-dimensional biogeochemical OPATM-BFM model with forcing by the MFS-Sys3 in the framework of the SESAME-IP scenarios (Vichi 2009). Finally, a zero-dimensional water quality model was set up to investigate the system response to anthropogenic stressors and climate change.

In the following sections a comprehensive description of the three scenarios (meteorological, marine circulation and SL, and water quality) is presented.

Meteorological scenario

The meteorological scenario describes the evolution of the atmospheric conditions in the case study area in terms of wind speeds, air temperature and precipitation assuming the present and the A1B climate change scenario. Such atmospheric variables are derived from the global stretched-grid version of ARPEGE-Climate model (Déqué et al. 1994). Simulations were performed under a control period (1950–2000) and assuming the twenty-first century (2001–2100) following the A1B climate change scenario.

ARPEGE-Climate is a GCM which is stretched to resolution of around 50 km over the zone of interest. It has a vertical resolution of 31 vertical levels, and the time step is 22.5 min.

The first set of simulations covered the initial period and produced realistic hindcast over the 1958–2001 period driven by ERA-40 reanalysis; it is called an ARPERA data set.

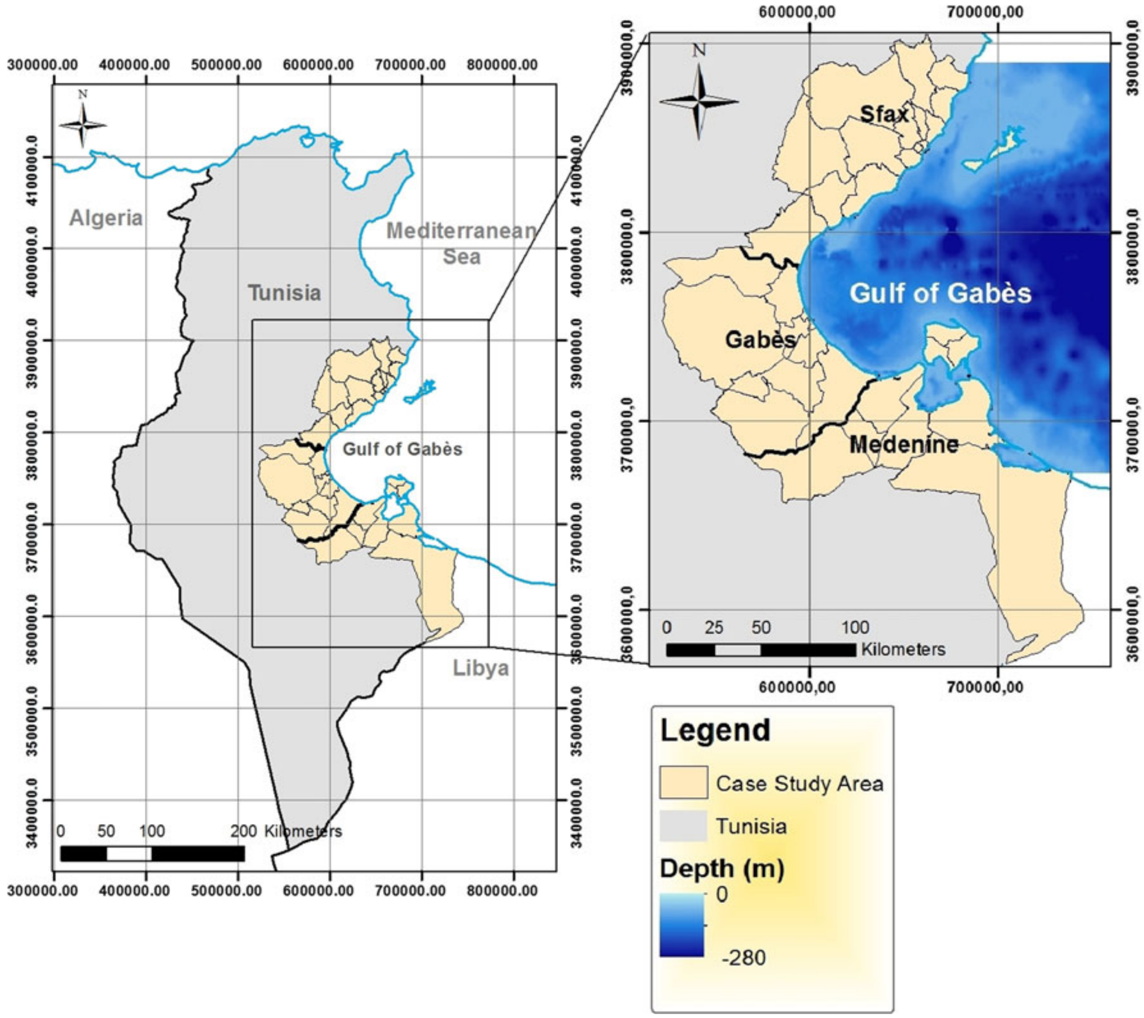

Fig. 1 Case study area. The Tunisian coastline and the Gulf of Gabes

The second set of simulations consisted in one scenario simulation for the period 1950–2100; it was forced by sea-surface temperature (SST) anomalies and followed by observations of greenhouse gas emissions and aerosol concentration for the year 1950–2000. The SRES-A1B scenario emissions of GHG and aerosol concentration were from the year 2001 to 2100. For the climate change scenario, ARPEGE-Climate was forced by solar constant, SST, greenhouse gas concentration and aerosol concentration (Somot et al. 2006).

Marine circulation and SL scenario

As it is shown in Fig. 2, this scenario provides information on marine temperature and salinity, on sea circulation and on SL.

First, the regional coupled model consists of an atmospheric component, LMDZ-med, and an oceanic (from now on it will be referred to as *marine*) component, NEMO-MED8, applied for Mediterranean Sea simulations (Sevault et al. 2009). LMDZ-med provides heat fluxes, freshwater fluxes and wind stress at the marine–atmosphere interface to NEMO-MED8. NEMO-MED8 provides in return the SST to LMDZ-med and has 1/8° (~ 12 km) resolution. The coupling frequency was set at the daily rate, which implies neglecting the diurnal cycle in the marine–atmosphere interaction. The regional coupled model was driven by the ERA40 data from 1958 to 2001 (44 years) and by ERA-Interim from 1989 to 2009. The regional coupled model was then applied for future climate projections assuming the A1B scenario, covering the period 2001–2050.

Moreover, a Mediterranean Sea reanalysis was used as the best estimate of the marine circulation for the period 1985–2007 (Adani et al. 2011). The reanalysis is based on the NEMO modelling system (Oddo et al. 2009; Tonani et al. 2008) at 1/16° (~ 6.5 km) horizontal resolution and 72 vertical levels, modified by Adani et al. (2011) to have realistic free surface and salinity boundary conditions. Ocean reanalysis is a

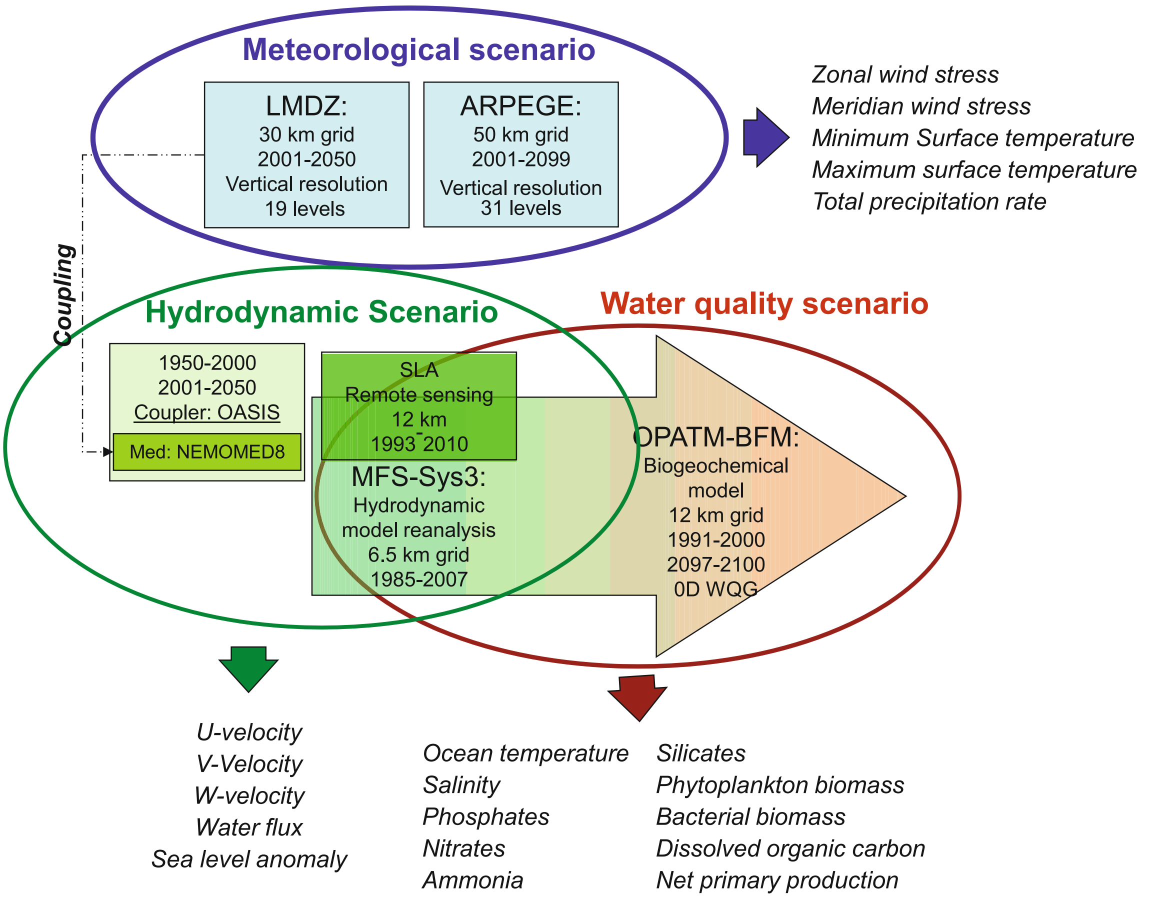

Fig. 2 Scheme showing the models' ensemble applied in the case study area and the corresponding outputs. Existing links between the different models are evidenced by *arrows*: LMDZ was coupled with NEMOMED8; OPATM-BFM was coupled with forcing by MFS-Sys3. SLA stands for SL reanalysis

novel but consolidated technique in oceanography allowing the production of consistent, three-dimensional estimates of marine circulation variables from both observations and model simulations. Among other opportunities, the reanalysis data sets offer the possibility to study derived fields from different observational data sources, considering their specific errors. Specifically, the reanalysis is here analysed for the SL. For the Mediterranean reanalysis, the quality was assessed in Adani et al. (2011) and root mean square errors associated with SL were shown to be of the order of 3 cm average over the whole Mediterranean Sea.

In order to provide a forecast for the SL, a reconstruction based on the past 100 years was carried out using statistical techniques and combined information of satellite and tide gauge data. Such reconstruction was performed with statistical methods applied for the first time at the global ocean scale and then within the Mediterranean Sea (Bonaduce 2012; Church et al. 2004). The method consists in decomposing the satellite data into spatial orthogonal functions (empirical orthogonal functions—EOFs), containing different fractions of the satellite altimetry field variance and temporal amplitudes. To perform the reconstruction, the first 20 leading EOFs from the SL anomaly altimetry data (Pujol and Larnicol 2005) were considered, assuming all available tide gauges from the year 1885 to 2010. The longest available time series correspond to the stations in Alicante, Marseille, Genoa, Trieste and Venice.

Finally, another model (Sevault et al. 2009), similar to the one used in the reanalysis was run also during the period 1970–2000 following the realistic twentieth-century greenhouse gas scenario and during 2070–2100 following the A1B climate change scenario forcing. The results of this simulation were considered as an input for the water quality scenario, described in the next section.

Water quality scenario

The ensemble of simulations for the biogeochemistry of the GoG consists in a hindcast simulation spanning within the period 1990–2000, assuming the 20CE scenario and an A1B climate change scenario simulation spanning the period 2090–2100. The parameterisation of the three-dimensional numerical transport and reaction model OPATM-BFM was set constant in all the performed tests except for the forcing field, consisting in marine current, water temperature, salinity, wind speed and short-wave radiation (Lazzari et al. 2010) and in riverine input data (Ludwig et al. 2009); these tests are based on the IMAGE model (Bouwman et al. 2006) and were defined for the two considered climate scenarios. The OPATM-BFM model was then validated for the spatio-temporal variability of primary producers' dynamics at the Mediterranean scale (Lazzari et al. 2012).

In addition, three different future riverine input scenarios were defined, considering terrestrial nutrients' load predictions assuming possible future socio-economic scenarios (Ludwig 2009). One baseline scenario (Business As Usual, BAU) and two alternative scenarios, Policy Target (PT) and Deep Blue (DB), were considered. The BAU scenario is defined by projecting future trends and policy responses in different sectors, namely agriculture, fisheries, tourism, household consumption, transport and urbanisation and coastal activities. In the PT and DB scenarios, different degrees of social and environmental concern are hypothesised and their impacts on nutrients' loads in the marine environment with respect to the BAU are taken into account.

PT scenario shows the same demographic increase in the baseline scenario BAU, but with an increasing concern (with respect to BAU) towards environmental problems. PT scenario, therefore, assumes a more environmentally aware transnational governance action. In the DB scenario, the resource management is based on communitarian policies; compared to BAU, the population growth is lower and the economy is slower.

Nitrate load reduction is projected for the PT and DB scenarios. More information on these scenarios is reported in the SM.

The model simulates fluxes of carbon, nitrogen, phosphorus and silica in their inorganic and organic form in the lower trophic levels (i.e. in the plankton).

In this work the water quality scenario was set up by taking into account only a subset of the OPATM-BFM model's variables selected in the CANTICO Project's risk assessment tool, that is, inorganic nutrients, phytoplankton, bacteria biomass and NPP.

Results and discussion

In the following paragraphs, the results on the trends of the variables identified in the three scenarios are presented and described. First, results from the meteorological scenario are presented, followed by the Marine circulation and SL scenario and the water quality scenario. These scenarios represent the GoG environmental situation under the A1B climate change scenario, compared with the current one.

Meteorological scenario

ARPEGE-Climate predicts an average summer atmospheric temperature of up to 30 °C inland for the present scenario (1961–1990). Atmospheric temperatures on the coastal areas and on the open sea are lower with mean estimated summer temperatures of around 20 °C. From the simulations, in winter the highest expected temperatures are forecasted on the open sea, with values reaching about 15 °C. Compared with the observational onset, the simulated temperatures are slightly underestimated (Brohan et al. 2006; Jones et al. 1999; Rayner et al. 2003, 2006).

The precipitations simulated by ARPEGE-Climate are slightly overestimated over Tunisia in the summer and winter months.

The projected wind fields are mainly in the north to south direction on the north of Tunisia, whilst they are directed predominantly from west to east in the GoG summer. During winter months, model simulations show that the wind velocity is lower and winds follow the direction east to west.

For the meteorological scenario, evolutions of temperature and precipitation under the A1B climate change scenario are simulated over the GoG region considering two time periods: near future (2021–2050) and distant future (2071–2100).

By 2021–2050, the temperature increase is estimated to vary between 1.6 and 2.1 °C in the summer months and in the range 0.9–1.4 °C in the winter months (as shown in Fig. SM1). By 2071–2100, the temperature increase is even more pronounced with an increase of about 3.1–4.0 °C in the summer months and 1.7–2.8 °C in the winter months. In retrospect, the internal regions are getting warmer than the open sea areas.

Under the A1B climate change scenario, precipitation is increasing in the summer months, and such increase is stronger over land than over sea (as it is evident from the observation of Fig. SM2). Fig. SM2 shows that during winter months a decrease in precipitation is calculated over the north of Tunisia and over Sicily, whereas an increase is estimated in the GoG and in the south of Tunisia.

Finally, wind speeds are increasing during the summer months following the ARPEGE-Climate simulations, as it is shown in Fig. SM3; such increase is stronger over land than over the sea for the period 2021–2050. This trend is reversed over the period 2071–2100, also illustrated in Fig. SM3. During the winter months, a decrease in wind speed over the coast of Tunisia and the GoG is expected under the A1B climate change scenario.

Marine circulation and SL scenario

Regarding the marine circulation and SL scenario, simulations were performed in order to identify trends for the GoG in marine current, marine temperature, salinity and SL.

Figure SM4 shows the evolution of the Mediterranean thermal and saline contents for different layers (as illustrated by different colours) from 1958 to 2009. Results from three simulations are reported here: two from the IPSL regional coupled model driven by ERA40 (1958–2001) and ERA-Interim (1989–2009), and one from the Mediterranean Sea reanalysis (1985–2007; Adani et al. 2011). The reanalysis should be taken only as a reference, as it infers as much as possible available observations. Even though reanalysis and model simulations have been performed using in both cases the NEMO modelling system, the differences in resolution, forcings and the data assimilation performed in the reanalysis allow to consider the two data sets as independent.

In general, the model has a good level of performance in reproducing the evolution represented by the reanalysis, especially the first-layer heat content. We can see a general cooling simulated by the model from 1960s to 1980s, which is in agreement with observations (L'Hévéder et al. 2012). A warming trend is evident during the recent period for both model simulation and reanalysis. In deep layers, the simulation forecasts a warmer temperature (around 0.5 °C) compared to the reanalysis result. For the saline content, a general bias in the model simulation is observed, as predictions show a higher level of salinity if compared with the reanalysis of about 0.1–0.2 PSU. The increase in saline content during the recent period is well replicated.

Fig. SM5 shows the temporal evolution of the Mediterranean temperature profile and saline content for the scenario run from 1951 to 2050 (historical emission of greenhouse gases before 2000 and A1B scenario after 2000). The driving forcing comes from the global ocean–atmosphere coupled simulation by IPSL regional coupled model. In comparison with Fig. SM4, the surface water has a much colder temperature, but a lower salinity in terms of present-day climate. This discrepancy is due to biases in the global model. Fig. SM5 also revealed a small initial drift in terms of temperature, which is due to model biases and a too short spin-up (20 years) before starting the simulation. Regarding salinity, a continuous drift is observed in Fig. SM5, especially in the surface layer. The estimated temperature trend consists in an increase in temperature by about 2 °C at the end of the period, compared to the beginning. The salinity shows a weak decreasing trend, although evaporation increases and precipitation decreases in the same region.

The analysis of the SL variability, starting from the reanalysis data set, shows seasonal variability associated with a steric component will result in an amplitude of approximately 14 cm; in winter this will result in having minimum values and in summer maximum.

Concerning the spatial variability, the reanalysis reproduces the satellite signal all along the Tunisian coast, as it is shown in Fig. SM6; the comparison between the reanalysis and rough data is reported with correlation coefficients between the two data sets ranging between 0.9 and 0.2. Throughout the GoG only correlations of the order of 0.4 are reached: this is explained by the fact that the reanalysis and the satellite data have different approaches to reconstructing the SL in shallow waters; unfortunately, both are affected by large errors.

In order to analyse the satellite Mean SL Anomaly trend (1992–2007), the steric effect was removed from the initial data. The trend indicated a high spatial variability whilst results show that the Tunisian coast consistently has a positive trend of about 2 mm/year. In all, the average trend over the entire Mediterranean basin is 1.7 mm/year in the same period. Satellite data show that SL trends along the Tunisian coastline are higher if compared to the basin average SL during the same period.

It is also interesting to note that the variations for the period 1992–2007 show a positive trend in the study area ranging between 1.2 and 2.2 mm/year according to the length of the period considered (Liebmann et al. 2010), and stable positive patterns are observed when the data time series lasts over 13 years.

Water quality scenario

A subdivision of the GoG into four boxes was made in order to redefine four subsystems characterised by different geographical and physical properties (as shown in Fig. SM7, panel b); Box 1, Box 2 and Box 3 have an average depth lower than 20 m, and they are divided according to the specifications of the three administrative districts. Box 4 is characterised by a depth varying between 20 and 40 m. This subdivision is useful in order to compare simulated versus observed data, and also for the definition of anthropogenic inputs defined for each district.

Fig. SM7 panel a shows the anomalies of the selected variables between the future scenarios and the present one.

The anomalies obtained consider the difference between three future scenarios (A1B-BAU, A1B-PT and A1B-DB) and the present scenario shown; on average, a negative trend for nitrates and ammonia and positive trends for phosphates (as it is reported in Fig. SM7, panel a) were found. The positive anomaly for phosphates' concentration (averaged for each box in Fig. SM7) lays within the range 0–26 % as a direct consequence of the change in nutrient terrestrial inputs under the A1B climate change scenario that indicates a strong increase in the pressures on the south eastern Mediterranean coasts in terms of phosphate loads and reduction in nitrate terrestrial inputs. The anomalies in phytoplankton and bacteria biomass are lower than the simulated inorganic nutrients; in fact, the averaged values fall within the range −5 to 8 %. The carbon fixation rate anomaly is positive (4–16 %) for all scenarios compared to the present scenario due to the temperature increase affecting the plankton metabolic activity. In all, it can be stated that the spatial variability of the anomalies is relevant (as observed in Fig. SM7, panel a, values in parentheses), due to the anomalies all being statistically significant (*t* test, *p* value <0.05).

The resolution of the biogeochemical model is 1/8°; this implies that local geographical features (i.e. the coastline) cannot be resolved, as it is evident in the Fig. SM7 Box 3 where a portion of the box is not covered by model grid points. The model takes into account spatial variability (1/4°) of loadings along the coast, calculated by Ludwig (2009), which is too coarse to resolve specific point sources that are definitively relevant to the coastal biogeochemistry. Furthermore, the industrial inputs of phosphates in the area of Sfax (Barhoumi et al. 2009) and data on phosphorous inputs due to leakage of phosphogypsum deposition currently practiced on land and the sea in coastal zone of Sfax are currently missing. Moreover, future scenario simulations do not take into account trends on the local socio-economic activities.

Compared to loading estimation given in Artebjerg et al. (2001), nitrogen and phosphorous loadings are lower, respectively, 23 % for nitrogen and 30 % for phosphorous. The published nitrogen data for the GoG (Bel Hassen et al. 2009) report values in the range 0.5–0.7 mmol N m^{-3}, comparable with model results (i.e. 0.35 mmol N m^{-3}). On the contrary, measured phosphate values are one order of magnitude higher than what commonly found in Ionian waters and with modelled phosphorus values (<0.02 mmol P m^{-3}). As inferred by Bel Hassen et al. (2009), coastal inputs could be responsible for the high phosphate values measured in the GoG. Model nutrient underestimates are consequences of lower coastal inputs.

Given these considerations, we focused our analysis on anomaly results assuming that possible errors arising from the lack of local parameterisations were filtered out because it affects both the hindcast and future scenario.

Summary

In summary, the model outputs presented in the Results and Discussion section show that, regarding the atmospheric conditions, wind speeds are in general increasing under the A1B climate scenario and that atmospheric temperature is expected to increase up to 4 °C in summer months in the GoG in the period 2071–2100.

Regarding the marine circulation and SL, results have shown that water temperature is increasing by about 2 °C, whereas salinity tends to be constant under both the A1B climate change scenario and the present. As underlined by Tsimplis and Rixen (2002) and Cazenave et al. (2001) in the Mediterranean Sea and Cazenave and Llovel (2010) for the global ocean, the increase in water temperature and heat content is one of the leading factors for SL rise. In agreement with the SL rates obtained in Cazenave et al. (2001) and Calafat and Gomis (2009) using satellite altimetry data, SL is expected to be higher in the GoG area than in the Mediterranean (2 vs. 1.7 mm/year) as shown from the reanalysis presented in the former section.

Finally, regarding the water quality scenario, in general a decrease in nitrates and ammonia and an increase in phosphates were predicted. These findings are considered as a direct consequence of the variation in nutrients' terrestrial inputs under the A1B climate scenario. It should be noted that the results regarding the biogeochemical variables are based on a pelagic model and are extrapolated for a coastal zone. More precise estimates could be produced by higher-resolution models in which interaction with coastal dynamics is amplified.

Conclusions

The most significant novelty of this research consists in the definition of climate scenarios taking into account both physical environmental variables (atmospheric temperature, precipitation, wind speed, marine current, water temperature, nutrients' concentration and SL) and a class of anthropogenic emissions (given by emissions of nutrients as nitrates and phosphates and the related NPP). This is a first attempt towards the definition of a complete climate change scenario for the selected case study area considering all diverse outputs that were presented in three scenario families: meteorological, marine circulation and SL, and water quality scenarios, giving a detailed description on the trends of physical and chemical variables under the A1B climate change scenario.

The outputs provide climate change trends for the identified relevant variables and may be useful in decision-making and communication of climate change effects on meteorology, water quality and circulation in the case study area. This considerable effort of creating an ensemble of models for the definition of climate change scenarios in the GoG represents the first scientific contribution in constructing a reliable understanding of coastal and climatic processes to characterise the impacts of the defined climate change scenarios. To assure that coasts and communities prepare, mitigate and adapt adequately to the impacts of climate change, this information should ideally move from scientists to stakeholders, as they require it most (Sarewitz and Pielke 2007). Next, it would prudent to implement the defined GoG climate change scenarios into a regional risk assessment approach (Torresan et al. 2010), in order to assess and prioritise risks for both climate change and anthropogenic impacts on coastal areas, thus supporting the definition of adaptation strategies and ICZM options (Marcomini 2011).

Further developments may consist in the improvement of the proposed models, including downscaling, thorough effort in resolving models' design, and in models' integration. Moreover, retrieving new historical data could support a better calibration of each model in order to obtain more robust results based on the same reference scenario and for the same temporal time frame. Finally, the integration of other information (i.e. from fisheries models) could be useful in order to produce new scenarios for the analysis of different coastal impacts related to climate change.

Acknowledgments The activities described in this paper were developed in the frame of the CANTICO project, funded under the CIRCLE-MED programme.

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