1) As mentioned by the authors, the atmospheric deposition has a significant impact on the Mediterranean Sea. The first author quoted two of its own papers to support this. Even if no transient scenario for atmospheric deposition exists, did the model contain a present-day atmospheric deposition component? (As for example, the model analysis of Herrmann et al. (2014) and Macias et al. (2015) that used continued present–day discharge of nutrients)
If yes, the influence of the atmospheric depositions should be included in the discussion of the results. If not, I suggest use of continued present–day atmospheric depositions in the model.

The simulations presented in the article have no atmospheric deposition. However, we ran simulations containing the continued present-day atmospheric deposition of natural and anthropogenic nitrogen and phosphate from natural desert dust (the aerosol deposition fields used in Richon *et al* 2017). We initially chose to discard the results of these simulations from the article because we wanted to keep as much as possible a coherence in the scenarios for external biogeochemical forcings.
We include in the discussion section (4.1) a paragraph on these simulations (lines 587-601). These simulations show that in the beginning of the simulation period, the effects of nitrogen deposition are important in the northern and eastern part of the Mediterranean (15 to 20 % enhancement in average surface primary production). Phosphate deposition from natural dust has important impacts on the southern part of the Mediterranean (more than 20 % primary production enhancement in the South Ionian basin). These results are coherent with Richon *et al* (2017). By the end of the century, the results from these simulations indicate that the relative effects of nitrogen deposition have declined and the effects of phosphate deposition from dust are observed across the entire basin. These observations may be the result of the general phosphorus limitation in the Mediterranean. As a results of this limitation, the effects of extra nitrogen brought to the surface by deposition are negligible whereas the effects of phosphate are relatively important.

2) The present-day period (1966–81) cannot be older than the historical period (1980-99). Therefore, the CTRL simulations does not correspond to the present–day conditions, and because condition forcing between the periods 1966–81 and 1980-99 are different, results from the control simulation (CTRL) differed from those of the scenario simulation (HIS/A2) during the first simulated decades (from 1980 to now). Authors need to justify and clarify this choice.

This is an imprecision from us to call the CTRL period "present-day period". We change the phrasing to "*The control run CTRL is performed with forcing conditions corresponding to the period 1966–1981.*"
This control period was chosen in order to avoid years with too important warming such as the 80s and 90s.

In this section, the comparison of the model results with in situ data have been incorrectly conducted. The main issue is that no values to support the comparison between the model and the in situ data are provided (e.g., correlation coefficients, percentage of differences...). For example, the chlorophyll-a concentration in the Gulf of Lion seems two times lower in the model simulations than the estimates from satellite.

There is no information on the spatial variability of the nutricline depths (i.e., nitracline and phosphacline), and of the DCM.

The figure 1, associated with this section, compares data from the satellite and the model results during two different periods 1980-99 and 1997-2012.

The units are not coherent:

- ***"1 K colder than observations", temperature in Kelvin?***
- ***Figure A1 – "Chla 10^{-9} g m^{-3}", in the text: "227 ± 136 10^{-9} g L^{-1}", not consistent between them, and in the literature the most common unit is mg/m3 (or microg/L).***

Maybe, model values do not agree well with the in situ data, but spatial and temporal variabilities that exist between the different Mediterranean regions have to be simulated by the model. Unfortunately, quantitative information to support this hypothesis are not provided by the authors.

Reviewer is right, the evaluation of the model performances is mainly a visual comparison between the model outputs and the data.

In order to add some quantitative evaluation, we add a plot showing the average surface chlorophyll-a concentration over the Mediterranean basin from the satellite products of Bosc et al (2004) and from our HIS/A2 simulation for the years 1997 to 2005 (Figure 2). This figure shows the standardized average and standard deviation. We note that the model surface chlorophyll is underestimated (by a factor 2 on average) as shown on the maps. However, the satellites tend to yield overestimations of the surface chlorophyll-a concentrations, especially in the coastal and upwelling regions because of the high particulate matter concentrations in these areas, and also generally in the oligotrophic Mediterranean (see Claustre et al, 2002, D'Ortenzio et al, 2002, Bosc et al, 2004, Morel and Gentili 2009). The values show a good correlation between the model and the data over the 1997-2005 period. Therefore, the comparison of our modelled surface chlorophyll-a concentration with 2 independent data bases (namely SeaWIfs and MyOcean dataset) confirms that our model reproduces satisfyingly the surface chlorophyll-a in the Mediterranean.

We added some precisions on the nutricline variability (lines 233-240): "The vertical distribution of nitrate and phosphate over a section crossing the Mediterranean from East to West as well as chlorophyll and nutrient concentration profiles at the DYFAMED station are shown in appendix (Figures A1 and A3). These figures show that the model produces some seasonal and interannual variability of the nutricline depth and intensity. However, the nutricline depth and DCM depth are consistently overestimated by the model in comparison to the data. The nutricline intensities seem to be underestimated by about 50 % and the depth is overestimated. However, nutricline depth deepens from 100-120 m to 180-200 m between the western and the eastern basins (see Figure A3)."

- ***"1 K colder than observations", temperature in Kelvin?***

We changed the temperature difference units to degres C.

- ***Figure A1 – "Chla 10-9 g m-3", in the text: "227 ± 136 10−9 g L−1", not consistent between them, and in the literature the most common unit is mg/m3 (or microg/L).***

The units have been checked and corrected to ng/L. Figures A1 and A2 were changed to include the vertical profiles of chlorophyll at the DYFAMED station over several years.

Section 3.3.1 Evolution of phosphate and nitrate concentrations

Figure 3-4 – Adjust the y-axis, it is impossible to evaluate the results.

Figures 4, 5, 15 and 16 were readjusted. We rearranged the order, they are now figure 7, 8, 15 and 16. We also tried to accentuate the different lines and added average concentrations for the 1980-1999, 2030-2049 and 2080-2099 periods on the plots.

Line 259 – "A slight accumulation of phosphate is observed in the deep western basin" - For which simulations? Provide values.

We added the value (0.015 mmol m^{-3}) and precised this is for the HIS/A2 simulation.

Line 268 – "The evolution of nitrate concentration shows a marked accumulation over the century in all regions of the intermediate and deep Mediterranean waters" - For which simulations?

In the HIS/A2 simulation. We added the sentence "In particular, nitrate concentrations increase of about 0.5 mmol m^{-3} between 1980 and 2099 in the deep eastern basin."

Line 279-289 – Confusing, mixing general results (for both nitrate and phosphate) with results

specific to the nitrate that should have been present in previous paragraphs.
This sections need to be clearer. Stay with the same logic when you present your results. Compare CTRL with HIS/A2, western basin with eastern basin, depth by depth…

We rearranged this paragraph.

3.3.2 Exchange fluxes of nutrients at Gibraltar

Figure 5 – Keep the same x-axis as in the figures 3 and 4.
Figures 6, 7 and 8 were changed.

Line 293 – "We observe similar trends in phosphate and nitrate fluxes linked to the Redfieldian behavior of the primary production in PISCES." - What do you mean, where can we see this?
We modified this section to "Figure 6 shows the evolution of incoming and outgoing nitrate and phosphate fluxes at Gibraltar in the HIS/A2 and in the CTRL simulations. We observe similar trends in phosphate and nitrate fluxes in the model. This is linked to the Redfieldian behavior of the primary production in PISCES."

Line 295 – "the incoming fluxes decrease" - fluxes of what?
We added the precision "fluxes of nitrate and phosphate".

Line 295 - "According to the HIS/A2 simulation, the incoming fluxes decrease slightly until the middle of the century and then increase to reach values higher than the control in the last 25 years of simulations. Outgoing fluxes follow the same trends as incoming fluxes" – For the incoming fluxes, I see, a peak in the 90s, then stable incoming fluxes until a decrease in the 2030s, and then an increase in the last 25 years with a peak in the 2080s. For outgoing fluxes, I see, a slight increase in the first half of the 21st century and a decrease after. Not you?
The outgoing fluxes in figure 6c and 6d are negative, the lower absolute values indicate that the flux is weaker.
These sentences were changed to "According to the HIS/A2 simulation, the incoming fluxes of nitrate and phosphate decrease slightly (from 50 the 35 Gmol/month for nitrate and from 2.5 to 1.55 Gmol/month for phosphate) until the middle of the century (with a period of increased incoming fluxes of both phosphate and nitrate in the 1990s) and then increase to reach values higher than the control in the last 25 years of simulations (Figure 4). Outgoing fluxes follow the same trends as incoming fluxes: total outgoing nitrate and phosphate fluxes decrease from 1980 to 2040 (flux values getting closer to zero) and then increase until the end of the century."

Line 298 – "We observe a drift in the nitrate outgoing flux in the control." – Provide a value
We observe a decrease of about 15 % in nitrate outgoing flux between the beginning and the end of CTRL. (Lines 326-327: "We observe a decreasing trend in the nitrate outgoing flux in the control (from -129 to -110 Gmol/month representing about 18 %).")

Line 305 – "Figures 3a and 5b show that the evolution of phosphate concentration in the western basin is linked with Gibraltar inputs (Pearson's correlation coefficient is 0.63, p–value=10−14)" - Correlation between what and what, surface, intermediate or deep concentration of phosphate?

Correlation between surface phosphate concentrations and Gibraltar phosphate inputs. We added the precision in the sentence and corrected the value that was calculated for the entire water column.

Section 3.3.3 River fluxes of nutrients

Figure 6 – Keep the same x-axis as in the figures 3 and 4. Figure changed
All tables – In the result section you only wrote in percentages. Therefore, provide percentages values in tables.
We added percentage values in the Tables. Also, as suggested by another referee, we provide 2 schematics summarizing the phosphate and nitrate budgets and fluxes. We provide percentages in

these schematics (figure 18).

Line 311 – "River discharge is the main external source of nutrient for the eastern part of the basin." – Need references.

Sentence changed to "River discharge is the main external source of phosphate for the eastern part of the basin (Krom et al 2004, Christodoulaki et al 2013)".

Line 315 – "Nitrate discharge in the HIS/A2 simulation is significantly higher than in CTRL" – How much? Provide a value.

The difference is between 30 and 60 Gmol/month. Precision added.

Line 315 – "nitrate total discharge in the Mediterranean has continuously increased from the 1960s (see the CTRL values for the years 1966–1981)." - What was the value in the 1960s? The model simulations start in 1980.

The CTRL values are looping on the years 1966 to 1981. Therefore, the CTRL values represent the late 1960s.

Therefore, we can evaluate that nitrate total discharge increase from approximately 20 Gmol/month in 1966 to more than 55 Gmol/month in 1981.

I see that there is no internannual variability in the HIS/A2 simulations. You have to say something about it. Phosphate concentrations mainly decrease between 1980 and 2000. Why? Nitrate and Phosphate concentrations mainly increase between 2030 and 2050. Why?

In the Methods section (2.4), we stated "Yearly values are obtained by linear interpolation between 2000 and 2030 and between 2030 and 2050, after which they are held constant until the end of the simulation in 2100." There is no intrisic interannual variability accounted for in the nutrient riverine input scenario and this is the only transient scenario we found available. Moreover, the "Order from Strength" hypothesis appears the most consistent with the A2 climate change scenario.

Phosphate discharge decreased over the Mediterranean between 1980 and 2000 as a result of the European regulations on phosphate content in household products. After the 1980s, phosphate concentration in rivers decreased. No regulation on nitrate lead to the consistent increase in nitrate discharge observed in the forcings.

Section 4.4 Climate versus biogeochemical forcing effects

Line 559 – "They found a general decrease in plankton biomass that is lower than in our severe climate change scenario". – Provide a value.

We added some more precisions in our comparison with Lazzari et al.:

"Lazzari et al (2014) tested the effects of several land-use change scenarios on the A1B SRES climate change scenario over 10-years time slices. They found a general decrease in phytoplankton and zooplankton biomasses (about 5 %) that is lower than in our severe climate change scenario. In our simulations, average phytoplankton biomass decreases by about 2 to 30 % (see Figure 15 and average zooplankton biomass decreases by about 8 and 12 % (see Figure 16). However, our transient simulations revealed non linear trends in plankton biomass evolution. Lazarri et al (2014) also conclude that the river mouth regions are highly sensitive because the Mediterranean Sea is influenced by external nutrient inputs. Our results show the same sensitivity of the Mediterranean to external nutrient inputs."

Line 564 – "Results from Herrmann et al. (2014) indicate that chlorophyll production" – Chlorophyll production? Are you sure... I think you want to study Primary Production, or Net Primary Production. It is a major mistake…

Figure 3 and Table 1 from Herrmann et al (2014) show that chlorophyll is increasing by about 8 % between the present and future periods. See section 3.2.2 from their article "The annual total

chlorophyll biomass increases in average by 8 % between the present and future periods (Table 1). This increase is mainly associated with the winter mixing and spring bloom periods (February– May), whereas the total chlorophyll biomass does not change statistically significantly during the stratified summer-fall period (Figure 3). It can be attributed to the convection weakening and surface warming (Figure 2), which favors the photosynthesis in our model"
We changed the term to "Chlorophyll concentration".

Line 567 – "may lead to a decrease in chlorophyll and plankton biomass" - Provide values
We changed the sentence to "Our results indicate that the contrasting effects of vertical stratification and biogeochemical changes may lead to a decrease in chlorophyll-*a* concentration, phytoplankton and zooplankton biomass content of up to 50% locally and between 10 and 30 % at the basin scale as indicated by Figures 14, 15 and 16 "

Figure 14 & 15 – "nanophytoplankton and diatoms concentration (10^{-3} mol m^{-3})" "mesozooplankton concentrations (10^{-3} mol m^{-3})" – A mol of diatoms? A mol of mesozooplancton? Wrong units…
The model units are in moles of C. We added this precision in the figures.

Line 571 – "In particular, nutrient inputs at Gibraltar have substantial consequences on the western basin." – Provide an estimate.
"Results from Figures 4a and 5a and Table 4 indicate that the increase in nutrient inputs from Gibraltar at the end of the century are responsible for a 2.5 % increase in chlorophyll concentration in the western basin during the 2080-2099 period." lines 622-624

There are only four references in this crucial section (Lazzari et al., 2014; Herrmann et al., 2014; Macias et al., 2015). It is not enough…

We have added references to Luna et al 2012, Krom et al 2004, 2010, Pujo-Pay et al 2011 and Chust et al 2014.

List of corrections*:*

1) *Line 7 – "socio-economic", you used both socio-economic and socioeconomic in the text, choose the good one.*

We chose to use " socio-economic " in the text.

2) *Line 10 – "lead to changes in phytoplankton nutrient limitation factors.", which ones?*

We changed the sentence to " lead an expansion of phosphorus--limited regions across the Mediterranean. "

3) *Line 26 – "known as sapropels, have been recorded through the last 10 000 years", It is the most recent sapropel events that apparently lasted for 3000 years, other events occurred before. Please clarify.*

We changed the sentence to "In particular, high stratification events, characterized by the preservation of organic matter in the sediment, known as sapropels, have been recorded through several over geological times, the most recent was recorded 10 000 years ago and lasted about 3 000 years."

4) *Line 33 – "and had biogeochemical impacts", which ones? Where? Need references.*

Lascaratos *et al* (1999) showed that the interruption of the water exchanges between the Ionian and the Levantine basins triggered an increase in salinity in the Levantine basin.

***5)** Line 35 – “The modification of water transport led to modified nutrient distribution that can alter local productivity.”, Need references.*

Sentence changed to " Also, changes in the North Ionian Gyre circulation triggered the so-called Bimodal Oscillating System (BiOS) that influences phytoplankton bloom in the Ionian Sea through the modification of water transport that led to modified nutrient distribution and altered local productivity (Civitarese et al, 2010). "

***6)** Line 36 – “short residence time of water.” How long? Need references.*

We added the precision (about 100 years) and refered to Robinson et al 2001.

***7)** Line 38 – “that changes in these conditions can trigger important circulation changes, ultimately leading to changes in”, three times the word “change” in the same sentence.*

We thank the reviewer for this remark. We changed the sentence to " These events show that a semi-enclosed basin with short residence time of water (about 100 years) such as the Mediterranean is highly sensitive to climate conditions and that perturbations of these conditions can modify the circulation, ultimately leading to changes in the biogeochemistry. "

***8)** Line 40 – “The Mediterranean is connected to the global ocean by the narrow Strait of Gibraltar through which transport contributes substantially to its water and nutrient budgets.”, Transport of what? The link between the Strait of Gibraltar and the rest of the paragraph is unclear.*

We modified the sentence and moved it at the beginning of section 3.2.2. " The Mediterranean is connected to the global ocean by the narrow Strait of Gibraltar. Water masses transport through this strait contributes... "

***9)** Line 42 to 46 – “Future climate projections yield […] the western basin for greenhouse gases high-emission scenarios and…” Modify, “Future climate projections with greenhouse gases high-emission scenarios…”*

Changed

***10)** Line 47 – “In one of these MTHC weakening scenarios, Herrmann et al. (2014) show, in addition, a vertical stratification increase (Adloff et al., 2015).” Herrmann et al., 2014 or Adloff et al., 2015?*

Adloff et al, sentence changed

***11)** Line 52 – “mixing that bring together available nutrients and phytoplankton”, not clear.*

Phytoplankton cells can't swim against currents and therefore need current to encounter nutrients.

Sentence changed to ““mixing that brings nutrients to phytoplankton”

***12)** Line 65 – “as a result of density changes”, not clear, do you mean less stratify?*

Sentence changed to " density changes (increased stratification isolating the upper layer from the rest of the water column). "

***13)** Line 74 – “…chlorophyll–a concentrations, plankton biomass…”, Chlorophyll-a concentration is a proxy of phytoplankton biomass, please clarify.*

Chlorophyll concentration is linked to phytoplankton biomass through the chlorophyll-to-carbon ratio in the planktonic cells. In this version of PISCES, the Chlorophyll-to-carbon ratio is fixed. Therefore, chlorophyll concentration and phytoplankton biomass follow similar trends in response to nutrient and climate change. We chose to show the evolutions of both chlorophyll and plankton biomass in order to keep the results in this article as easily comparable as possible with other studies.

***14)** Line 83 – “In section 3.3, we expose the temporal evolution of the main nutrients, their budgets in present and future conditions and discuss their impact on the biogeochemistry of the Mediterranean Sea.”, You should discuss your result in the section 4 discussion.*

Sentence changed to “In section 3.3, we expose the temporal evolution of the main nutrients, their budgets in present and future conditions and discuss their impact on the biogeochemistry of the Mediterranean Sea in section 4.”

15) Line 117 – “by up to 3 K by”, temperature in Kelvin scale?
Temperatures in the model are in degrees Celcius. We kept the temperature difference in the international temperature unit: K

16) Line 121 – “0.5 (practical salinity scale)”, not in pratical salinity unit?

Changed to “practical salinity unit”

17) Line 127 – “reduced vertical mixing may also reduce nutrient supply to the surface waters. A reduction in deep convection may also tend to reduce the loss of P and N to the sediment.”, Is it not what you want to test? Why do you present this assumption here, in the section “2.2 The SRES–A2 scenario simulation”?

We thank the reviewer for this remark. We removed the sentence.

18) Line 178 – “the effects of climate and biogeochemical forcings”. You used the expressions “climate and biological forcings” and “climate and biological changes”, choose one of them.
We harmonized throughout the text by using " climate and biological changes "

19) Line 201 – “surface average chlorophyll concentrations in the top 10 meters of the CTRL and HIS simulations, and from satellites estimations”, it is chlorophyll-a concentration, source of data?
It is chlorphyll a concentration in both data and model. The data come from the MyOcean product (http://marine.copernicus.eu)

20) Line 225 – “analysis reveals much greater variability depending on the region”, for which regions? It is important for your results.
We added the sentence "For instance, the Balearic Sea is more sensitive to warming than the rest of the western basin, and the eastern basin has a more intense warming than the western basin (up to 3 K warming in the eastern basin and in the Balearic Sea). Also, the surface salinity in the Aegean Sea increases more than the other regions. "

21) Line 386 – “For instance, the P rich area between Crete and Cyprus is no longer observed in the 2080–2099 period (Figure 9). Moreover, Figure 10 shows that this area matches a productive zone observed in the 1980–1999 period.”, It is the only area in the Levantine basin with some phosphate, nitrate and production values different from zero simulated in 2080-99. Are you sure about your observation?
The color scale of the figure makes it difficult to see, but the phosphate concentration in the eastern Mediterranean is very close to 0. We changed the sentence to “around Crete and Cyrpus” to avoid confusion.

22) Line 388 – “The primary production integrated over the euphotic layer (0–200 m) is reduced in our simulation by 10 % on average between 1980–1999 and 2080–2099. However, Figure 10 shows a productivity decrease of more than 50 % in areas such as the Aegean Sea and the Levantine Sea.”, Provide time series, as in figure 3.
In order to make the argument clearer and since it has been suggested by other reviewers, we decided to include difference maps instead of the 2080-2099 maps.

23) Line 397 – “For instance, around Majorca Island, Corsica and Cyprus, changes in local concentrations of nutrients have substantial effects on primary productivity.”, Ok for Majorca, but I cannot see something with Corsica and Cyprus. There is also no values provided to evaluate these changes.
Sentence changes to " For instance, around Cyprus, changes in local concentrations of nutrients (decrease of about 50~\% in phosphate concentration) have substantial effects on primary

productivity (decrease from 40-50 gC m-2 year-1 to 20-30 gC m-2 year-1). "

24) Line 413 – "Sea, the northern Levantine basin and the South Adriatic.", In Fig 11, it is the South of the Levantine Basin and the North of the Adriactic which are P-limited.
As stated in the sentence before, these regions are N and P colimited (see figure 12).

25) Line 418 – "Figure 12 shows the average depth of the simulated DCM for the period 1980–1999 and for the period 2080–2099.", results for the CTRL not shown, why?
We chose not to show the CTRL values because we did not want to overload the article with figures. Plus, the DCM does not vary much between the simulations nor during the 21st century.

26) Line 429 – "At the DYFAMED station, the average DCM depth is unchanged but surface concentration is reduced." A change from 1.10-7 to 0.75.10-7 g m-3 = 1.10-4 to 0.75.10-4 mg m-3. Units are certainly wrong…
Units and figures have been corrected

27) Line 432 – "the subsurface maximum in the present and future periods is located at the same depth (100–120 m), but the average productivity is reduced by almost 50 %," Where can we see this? Chlorophyll-a concentration ≠ productivity.

We changed the sentence to "chlorophyll concentration is reduced"

28) Line 439 – "Table 4 reports total chlorophyll production in the 1980–1999, 2030–2049 and 2080–2099 periods of all the simulations in all Mediterranean subbasins Adloff et al. (Figure 2 2015)." Why did you quote this reference here?

Because the subbasins are descried in the Adlof et al article.

29) Line 496 – "and modification of the physical ocean (vertical mixing, horizontal advection, ...).." Modification of physical processes. Need references.
We added references to Ludwig et al 2009, Krom et al 2010 and Santinelli et al 2012.

30) Line 497 – "Nutrient fluxes from these sources." Which ones?
Sentence changed to " Nutrient fluxes external sources (rivers, aerosols and Gibraltar) may evolve separately "

31) Line 514 – "In these regions, the effects of nutrient runoff changes seem more important than climate change effects (see Table 4)." provide the percentages, and discuss these results.
Tables 2, 3 and 4 were corrected to add the percentage of concentration change for each period in comparison to the 1980-1999 period. In the Adriatic basin, table 3 shows that riverine nitrate discharge is responsible for 41 % increase in nitrate concentration over the simulation period. In the CTRL_RG simulation, nitrate concentrations are similar to the CTRL_R simulation showing no influence of Gibraltar inputs in this region. Finally, nitrate concentrations in the HIS/A2 simulation are close to the CTRL_R values showing that most of the nitrate evolution in this region is linked with riverine discharge.
32) Section 4.2 Climate change scenario. I do not see the point of this section. You decide to use the A2 scenario and already justified it in the introduction.
This section is provided as an encouragement to develop climate change scenarios over the Mediterranean in order to assess uncertainties in the current results.

33) Line 537 – "Nutrient concentrations in the intermediate and deep layers were shown to be slightly underestimated in comparison to measurements (see appendix)." Provide values.
" Nutrient concentrations can be underestimated by up to 50~\%, in particular in the deep eastern basin. "
34) Line 543 – "Model values were not corrected to match data, and we are therefore conscious that the uncertainties in the representation of present–day biogeochemistry by the PISCES model may be propagated in the future." This is an important decision that needs to

be justify.

In order to study the effect of climate and biogeochemical changes as perturbations we needed to start from a relatively stable initial state. This initial state has been obtained thanks to a long term spin-up simulation. The downside of this approach is the formation of a bias from the present day biogeochemical state. After quantifying the model bias against available observations, we could have corrected the model values (for instance multiplying nutrient concentrations by a factor to correct for the underestimated values in the deep layers). However, such a correction seems dangerous when modeling future evolution of the Mediterranean because threshold effects, and non linear processes are frequent in marine biogeochemical reactions. Therefore, artificially and arbitrarily correcting values may lead to masking some reactions.

35) Line 571 – "In particular, nutrient inputs at Gibraltar have substantial consequences" Provide the percentages, and discuss them.

"Results from Figures 4a and 5a and Table 4 indicate that the increase in nutrient inputs from Gibraltar at the end of the century are responsible for a 2.5 % increase in chlorophyll concentration in the western basin during the 2080-2099 period." lines 622-624

Responses to reviewer 2.

We thank the reviewer for their very constructive comments. We added Figures to summarize the nitrate and phosphate budgets and fluxes in the different periods we studied.

lines 160-165: Although I fully sympathize with authors regarding the difficulty to have fully consistent source for riverine water and nutrient discharge, and I am not against the choice the authors made, I would suggest authors to briefly discuss the potential impact associated to the incoherency between these, for instance showing how big this incoherence is.

Adloff et al (2015) evaluate the changes in runoff in the HIS/A2 simulation. Their Table 2 shows that the total freshwater runoff to the Mediterranean is lower than the Ludwig et al 2009 estimate (by about 30 %). They found approximately 27 % decrease in total runoff by the end of the 21st century. This trend is consistent with the deceasing trend found by Ludwig et al (2010). However, the 2050 estimates of freshwater runoff from Ludwig et al (2010) are only 13 % lower than the 1970 and 2000 estimates. Therefore, it seems that the freshwater runoff decrease in the physical model is more important than in the nutrient runoff model. This may result in higher nutrient concentrations at the river mouth. However, nutrients from river discharge are consumed rapidly at proximity of the river mouth and we believe this potential higher concentrations don't have a large impact of the results.

We added these details in Section 2.4 (lines 178-187)

Section 2: there is no mention of atmospheric deposition of nutrient in all the methods section. Only in the discussion (501 and 502) authors state that deposition was not considered because there are no future estimates of nutrient deposition up to 2100. Is deposition completely neglected or just kept constant at present day value?

In the simulations presented initially in the article, deposition is completely neglected. However, we performed extra simulations that are described in the discussion section. These new simulations include total nitrogen deposition from anthropogenic and natural sources modeled with the LMDz-INCA global atmospheric model (simulation labelled HIS/A2-N). Another simulation (HIS/A2-NALADIN) includes both nitrogen from LMDz-INCA and natural dust deposition modeled with the high resolution regional model ALADIN-Climat. These 2 atmospheric models are respectively available for the 1997-2012 and 1980-2012 periods which we repeat during the entire simulation period. Description of the results are included in the discussion section (lines 593-606).

Lines 205-210: given the errors at the mouth of the Nile, I suggest to add some more detail on the source of the data for this rivers and the uncertainty associated (e.g. see above).

The difference between model and satellite estimate of chlorophyll around coastal areas is likely linked with the uncertainty of satellite estimates in such areas. Satellite estimates are based on analysis of the water color. Therefore, in shallow, turbid areas, they often interpret the high concentrations of colored material as chlorophyll (see Morel and Gentili 2009). We added this reference. See lines 234-235: "Moreover, Morel and Gentili (2009) show that satellite estimates have a systematic positive bias in the coastal regions because of the high concentrations of colored dissolved organic matter."

Lines 210-220: while figure A2 immediately shows area where the model has higher or lower skills, I strongly recommend to add some numerical measures of the ability of the model to capture observed data. Furthermore, authors state that model correctly simulates a DCM, however figure A1 clearly shows how the DCM is much deeper than the data shows (roughly at twice the depth). Authors briefly mention this later in the paper, but I suggest to anticipate this here. It would be also interesting to see a comparison of T, S, nutrient profiles in the same

location, to understand the reasons of a deeper DCM

We added some precisions in section 3.1 (lines 201 to 216). We also added figures in appendix to show that the overestimation of the DCM depth is likely due to the overestimation of the nutricline depth as shown in figures A1 and A2.

lines 254-256: as authors state, phosphate start increasing in CTRL_RG only at the end of the century, therefore the "strong link" between phosphate and Gibraltar is "proofed" only at the end of the century, for most of the simulation surface phosphate seems to be close to CTRL and CTRL_R despite figure 5 shows quite different P influx around 1990 (positive) and 2040 (negative).

Reviewer is right. Figure 5 shows that Gibraltar fluxes are decreasing in the first half of the simulation period and increasing after 2040. The same trends are observed in the surface and intermediate western basin for phosphate concentrations in the HIS/A2 simulation but not in CTRL_RG. As shown by Table 2, the overall effects of Gibraltar exchanges of phosphate have limited effects on phosphate concentrations. The trend we observe in Figure 4a and 4b may be the sign that Gibraltar exchange effects are visible in the HIS/A2 simulation only after climate change has affected stratification. This paragraph has been rewritten to clarify.

Lines 263-265: the trend highlighted here is apparent only in the A2 forced simulation, raising the doubt that it could be linked to a spin-up issue (see below for other examples on this). Authors explained the initialisation procedure (lines 170-173) although this is not fully clear: all simulations started from the same restart (and in this case initial trend could be due to adjustment to new forcing, particularly in the climate case), or all scenarios have been run for more than 115 year since that initial common restart (and in this case why the trend is only in A2)?

All simulations start from the year 1980 from the same restart file after one long spin-up. Therefore, the trends observed in the A2 forced simulation are linked with climate change and/or biogeochemical changes only.

Lines 265-267: the interesting decennial cycle is not evident only in 3e (where is actually weak) and 3f, but also on the surface. Can authors suggest some mechanism for this? Is this a cycle in intensity of stratification? Is this associated to cycles in the atmospheric patterns?

The Mediterranean Sea is prone to large decadal variability due to various internal mecanisms and external forcings (e.g. BiOS, EMT, WMT). We prefer not to call it "cycle" as this variability is probably not regular in time. The Mediterranean Sea model (NEMOMED) used to drive PISCES in this study is able to reproduce at least partly this variability (Beuvier et al. 2010, Herrmann et al. 2010, Somot et al. 2018) and it is expected to find its signature in the biogeochemistry variables. However, we would like to underline that the design of the historical and scenario simulations used here is not adequate to draw robust conclusions on the decadal scale. Indeed, some of the physical forcings (river, Near Atlantic) are only evolving every 10 years and the Ludwig et al. nutrient inputs do not represent interannual variability after 2000. Therefore, we prefer not to comment further on this decadal variability. Other modelling setting (hindcast, reanalysis) may be more suitable but are out of the scope of this study.

See for example:

Somot S., Houpert L., Sevault F., Testor P., Bosse A., Taupier-Letage I., Bouin M.N., Waldman R., Cassou C., Sanchez-Gomez E., Durrieu de Madron X., Adloff F., P. Nabat, Herrmann M. (2018) Characterizing, modelling and understanding the climate variability of the deep water formation in the North-Western Mediterranean Sea. *Climate Dynamics,* 51(3), 1179-1210, doi: 10.1007/s00382-016-3295-0

Herrmann M., Sevault F., Beuvier J., Somot S. (2010) What induced the exceptional 2005 convection event in the Northwestern Mediterranean basin ? Answers from a modeling study.
J. Geophys. Res. - Ocean, 115 (C12), doi:10.1029/2010JC006162

Beuvier J., Sevault F., Herrmann M., Kontoyiannis H., Ludwig W., Rixen M., Stanev E., Béranger K., Somot S. (2010) Modelling the Mediterranean Sea interannual variability over the last 40 years: focus on the EMT. *J. Geophys. Res. - Ocean*, *115*(C8), 1978-2012, doi:10.1029/2009JC005950.

Line 259 vs 269: authors claims that there is a "slight accumulation of phosphate in the deep Western basin" while "the evolution of nitrate concentration shows marked accumulation in all region". I could be wrong (this is simply a visual calculation), but focussing on A2 trend from 1980 to 2100 figure 3f shows an increase from approx .15 mmol/m3 to 17.5 mmol/m3 (+16%), figures 4e and 4f show a similar relative increase, while 4b and 4c a smaller relative increase. Even if we compare these with the CTRL simulation, the difference between the P accumulation in the deep Western basin and the N accumulation is not that big as the qualification "slight" and "marked" suggest.

Reviewer is right, we suppressed the adjectives "slight" and "marked" and gave percentage values.

Lines 274-277: Can authors explain why riverine discharge seem to have more impact on N than P? How much is simply due to the different evolution of the forcing, and how much is due to internal dynamics?

Ludwig et al (2010) show that even if the global river discharge of N and P over the Mediterranean increases according to their scenario, the N/P ratio of some of the largest rivers is changing. Overall, nitrate total discharge is increasing faster than phosphate total discharge, leading to an increase in the N/P ratio of river discharge over the 21st century (see Figure 1 below).

Moreover, our simulation shows that the Mediterranean is largely P limited. Therefore, phosphate entering the Mediterranean from external sources tend to be consumed faster than nitrate. The figures and tables included in the article are annual and inter-annual average concentrations. They represent the average biogeochemical state of the Mediterranean after nutrient consumption for biological production. Therefore, phosphate concentrations are always low in the P-limited Mediterranean.

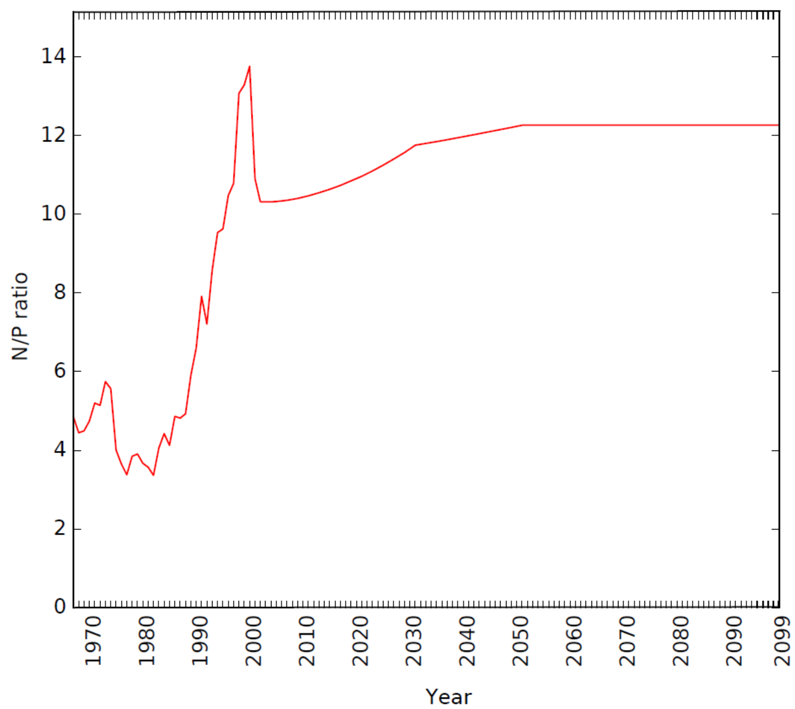

Figure 1: Average N/P ratio of the total riverine discharges of the Mediterranean. Data from Ludwig et al (2010).

Lines 283-285: I suggest authors to clarify what they means by “linked with nutrient exhaustion”. The link between stronger stratification and lower surface nutrient is well established in literature (due to lower winter mixing), what nutrient exhaustion add to this mechanism and do authors have supporting evidence for this?

Reviewer is right, stronger stratification and lower surface nutrients are linked by weakest winter mixing leading to less nutrient renewal in the surface layer. In a nutrient-limited system like the Mediterranean, nutrient consumption in surface is fast and the surface is quickly nutrient-poor during stratification periods because of biological production. We changed the sentence to “vertical stratification leads to a decrease in surface layer nitrate concentrations, probably linked both with lower winter mixing and nutrient exhaustion through consumption by phytoplankton.”

Line 301: in the absence of statistical measure of the trends, nutrient fluxes at Gibraltar seems characterised by a high interannual variability until about 2060 rather than a coupled decreasing-increasing trend.

We calculated a statistical linear regression between the incoming fluxes through the Strait of Gibraltar and time for the first and the second half of the simulation period (before and after 2040) using the Python tool SciPy Stat (www.scipy.org). Statistical indicators are summarized below. Slope indicates the slope of the linear regression, R is the correlation factor, standard error is the error of the slope estimate.

Period	Slope	R	P-value	Standard error
1980-2040	-26	-0.48	< 0.001	6.3
2041-2099	30	0.79	< 0.001	3.2
2030-2040	-9	-0.76	<0.01	2.8

Table 1 Statistical trends of phosphate incoming flux through the Strait of Gibraltar.

Period	Slope	R	P-value	Standard error
1980-2040	1.43	-0.48	< 0.001	0.3
2041-2099	1.74	0.80	< 0.001	0.2
2030-2040	-0.55	-0.77	< 0.01	0.2

Table 2 Statistical trends of nitrate incoming flux through the Strait of Gibraltar.

This table shows that both the decreasing and the increasing trends during the 2 simulations periods are statistically significant. However, the R value for the 1980-2040 period is low. Most of the decrease is actually observed during the 2030-2040 period (R=-0.76 and -0.77 for phosphate and nitrate respectively).

We changed this section to: “At the end of the 21st century, incoming fluxes of nutrient have increased in the scenario simulation by about 13 % (difference between the 2080-2099 and 1980-1999 periods). But this significant increase (linear regression reveals a positive slope with correlation coefficient greater than 0.75 and p-value < 0.001 for the second half of the simulation period) follows a decrease of over 20~\% in incoming nutrient fluxes between the 1980-1999 and the 2030-2049 periods. Most of the decrease is observed between 2030 and 2040 (decrease 15 and 1 Gmol/month for nitrate and phosphate respectively during this decade).”

Lines 300-304: authors correctly state that the relative increase in the influx is higher than the relative increasing of the outflux, but what’s the difference in absolute term? Is there a change in the net flux?

We thank the reviewer for this remark. If the relative changes in incoming and outgoing fluxes seem to indicate an increase in the net incoming flux, the absolute values seem to show a rather steady net flux between the beginning and the end of the century. Net flux at the beginning of the century is around -83 Gmol/month for nitrate and -3 Gmol/month for phosphate. At the end of the century, the fluxes are about -80 Gmol/month and -2.5 Gmol/month for nitrate and phosphate respectively. We added these details in the text. Net water, salt and heat fluxes through the Strait of Gibraltar are shown by Adloff et al (2015) to increase at the end of the 21st century in the A2 scenario simulation.

Line 326: similar to comment on 263-265, could the sudden drop be justified by the adjustment to the new forcing (spin-up)?

This is a good question. We do not believe that the trends observed are linked with adjustment to the new forcings because the trends observed in Figures 4 and 5 are longer than the 1980-1999 period. For instance in Figure 5c, the decrease in nitrate concentration lasts from 1980 to the 2020s. Similarly, the abrupt change in trend in Figure 5e happens before 1999. The changes in physical forcings in the A2 scenario are continuous over the simulation period. No abrupt change in the forcings is applied between the HIS and the A2 periods. Therefore, we do not believe that "spin-up like" drifts are observed in our results.

Lines 335-370: it is not clear if here authors are still discussing sedimentation fluxes, or rather the global nutrient budget. If the latter I recommend to separate this part with a different sub title (and develop this around the new suggested figure-table). Also, if the latter is true, I suggest to clarify the sentence "the sum of nitrogen fluxes in the Mediterranean": is this the total net flux in the Mediterranean?
Reviewer is right, this is a new section. We separated this section under the title: "Summary of the phosphate and nitrate evolution under climate and biogeochemical changes in the Mediterranean". We changed the first sentence to "In general, the sum of nitrogen net fluxes in the Mediterranean basin (Riverine, Gibraltar and sedimentary sources and sinks) increases by "

Line 354-356: authors seems to suggest that the accumulation of phosphate could be due by the decreased primary production, however this is in contrast with the fact that P is the more limiting nutrient in most of the domain (an accumulation in P should lead to an increase in primary production in a P limited environment). Authors should clarify the mechanisms behind the observed trends and the interaction among those mechanisms.
The P accumulation referred to in this paragraph is the one observed below the mixed layer in the least productive parts of the water column. We added the precision.

Section 3.4: from my understanding of the PISCES model, sedimentation of particulate nutrient is mostly driven by primary (sinking phytoplankton) and secondary (faecal pellet) productivity. If this is true, I would suggest authors to use the patterns observed in the biological productivity to discuss and interpret the sedimentation fluxes (an possibly anticipate 3.4 before sedimentation)
Reviewer is right, sedimentation in PISCES is largely influenced by biological productivity. We added a sentence on this matter in section 3.4. However, sedimentary fluxes are also influenced by vertical circulation. In Figure 8 of the article, sedimentary fluxes are highly variable. This may be linked with the sensitivity of the Mediterranean to extreme circulation events such as EMTs that disrupt the vertical circulation.

Section 3.4: authors discuss at length nutrient limitation presenting co-limitation as a widespread condition in most area of the Mediterranean. To my knowledge there is quite an extensive literature on P limitation in the Mediterranean, particularly in the Eastern basin (e.g. a long list of publications by Krom and co-authors), and authors do not refer to any of this. I strongly suggest to include these in the discussion, compare the results from the model with those findings and suggest potential reasons for the difference. (By the way, I want to emphasize that I have not contributed to any of those papers)
Reviewer is right. Although we are aware of this extensive literature, we failed to mention it in this section. We include the references in the section. Our study finds that most of the Mediterranean is N/P co-limited because of the way we calculated the limitations and co-limitations. Considering how low nutrient concentrations are in the Mediterranean and how low the nutrient limitation factors are, we consider that the small difference between the limitation factors indicate that the Mediterranean is both limited in P and N. The authors who previously studied the Mediterranean N/P ratio and nutrient limitations derived the limiting nutrient using the N/P ratio of the water (see Krom et al 2010). Therefore they identify the most limiting nutrient. We added the following lines in discussion section 4.3 (lines 695-704) "The modifications of chlorophyll production and plankton biomass are linked to changes in nutrient limitation (Figure 12). Our finding that most of the Mediterranean basin is N and P co-limited seems in contrast with previous literature on the matter (see Krom et al 2005, 2010 ; Pujo-Pay et al 2011 and references therein). These authors found from analyses of the N:P ratio of the waters a clear phosphorus limitation in the major part of the Mediterranean. The discrepancy between our results and literature estimates comes from the way we calculate nutrient limitations. Considering how low nutrient concentrations are in the Mediterranean and how low the nutrient limitation factors are, the small difference between the limitation factors indicate that the Mediterranean is both limited in P and N. Finding no clear definition of nutrient co-limitation, we propose that N and P are co-limiting when the difference in limitation factors is less than 1 %. This definition of nutrient co-limitation applies well to the Mediterranean case because of the very low nutrient concentrations."

line 409: the use of "thus" suggests that as a consequence of the increased P-limitation in the eastern basin, the surface P concentration will further decrease? Could authors clarify what is the positive feedback between P limitation and P reduction?
We thank the reviewer for this remark and removed this confusing sentence.

Lines 438-439: authors state that "The changes in DCM we observe combined with external nutrient input changes result in 17 % reduction in integrated chlorophyll production", however the DCM is a consequence of the chlorophyll production and not a cause. DCM is simply the location of the sub-surface maximum of chlorophyll, therefore, unless authors clarify the meaning of that sentence, is the reduction in the chlorophyll production that leads to the changes in the DCM

We changed this sentence to "changes in circulation combined with external nutrient input changes..."

line 468-470: as above, could these be a consequence of the A2 model still adjusting to new atmospheric forcing?

The apparent stabilization of plankton concentrations appears before 2000 (around 1998). This shows that this is not linked to the A2 forcings adjustment but rather to a response to nutrient conditions.

Line 512-514: the fact that coastal area (and in particular the Adriatic sea) is largely influenced by coastal nutrient inputs is not a new finding and authors should acknowledge the past literature

We added a reference to Spillman et al 2007.

Conclusions: the conclusions are too high level and therefore miss to emphasize the importance of the new findings. For instance the fact that the Western Med is more influenced by the Gibraltar influx than the Eastern Med (lines 590-596) is not that surprising. Furthermore, authors cite their work emphasizing that atmospheric deposition can bring up to 80% of phosphate in some region of the Mediterranean sea. As asked earlier, authors do not clarify if atmospheric deposition is completely neglected in this simulation or simply kept constant: is the former, a lot of the results and discussion are heavily biased by the simplifying assumption and authors should careful and rigorously discuss how this simplification affect all the results presented.

We modified the conclusion section and referred to the HIS/A2_N and HIS/A2_NALADIN simulations we mentioned in discussion.

Minor comments:

line 46: this sentence "the Mediterranean thermo- haline circulation (MTHC) may significantly change with a consistent weakening in the western basin for greenhouse gases high-emission scenarios..." needs clarification: does authors means that the MTHC weakens in the western basin in climate change scenario characterized by high emission scenario?

We clarified the sentence "As a result of these changes, the Mediterranean thermohaline circulation (MTHC) may significantly change with a consistent weakening in the western basin and a less certain response in the eastern basin **in climate change scenarios characterized by high greenhouse gases emission"**

Line 76: which daily 3D forcings are needed by the biogeochemical model? Do authors refer to boundary condition at Gibraltar?

These forcings are the physical drivers of the circulation such as wind, pressure and precipitation. We added the precision.

Line 112: "that" needs to be removed

Done

line 145: Although I understand that authors refer to original manuscript for details, I would suggest authors to briefly explain (or show within a map) the extent of the buffer zone

The dimensions of the buffer zone are explained line 94: "The Atlantic boundary is closed at 11°W and tracers are introduced in a buffer zone between 11°W and 6°W."

line 155: Authors state the four largest rivers of the Mediterranean and Black Sea are the Rhone, the Po, the Ebro and the Danube. Although I agree that these are 4 important rivers, these are surely not the 4 biggest one. Acording to Ludwig 2009 (cited by the authors) the Danube mean flow is 6573 m3/s, Rhone 1721m3/s, Po is 1569m³/s and Ebro is 416 m3/s. Clearly the Nile is the largest, and the Dniper is also bigger than the Ebro

We thank the reviewer for pointing out this mistake. We corrected the sentence to "4 of the largest".

lines 158-160: this sentence does not flow correctly in English, and is not clear, I suggest authors to revise it.

We changed the sentence to : "Ludwig et al. (2010) point out some substantial changes in the nutrient and water budget in specific regions. However, total riverine nutrient input is not drastically changed at the basin scale."

Line 315: nitrate needs to be capitalised after the full stop
Changed

line 540: If the authors want to suggest that the loss of nitrate in the CTRL run can be due by an underestimation of riverine fluxes in the CTRL riverine forcing, I recommend authors to rewrite the beginning of this sentence and explicitly state that, instead of simply referring to the discrepancy with A2 (since the latter can't influence CTRL)
We changed the sentence to "the low riverine discharge"

figures 3 and 4: it is very hard to distinguish between grey, blue and green line. Al- though I recognise that the quality of the picture in the PDF is not at the highest, I strongly suggest the authors to use more contrasting colours.

As suggested by other referees, we modified these figures. The scale was changed, colors and line width was improved and we included average concentration values for the different periods considered in the article. We hope this makes the figures more easily readable.

Figures 8-9-10: I suggest authors to consider to modify the 2080-2099 panels by show- ing a map of the difference with the 1980-2000 period to better highlight the evolution of N,P and primary production

We changed these figures to include the relative differences.

Reviewer 3.

This paper addresses the impact that climate change and future riverine nutrient inputs will have on the biogeochemistry of the Mediterranean Sea over the period 1980-2100 using a high resolution coupled NEMO/PISCES model. This paper is important for the scientific community as it is the first time a transient simulation on the response of the biogeochemistry of the Mediterranean Sea to climate change has been run. The authors separate the individual effects of the different scenarios to help determine the reasons for the future biogeochemical changes that the model predicts. In addition they looked at both the impact of each scenario to nutrients and the phytoplankton and zooplankton communities. This study concludes that nitrate concentrations in the Mediterranean are likely to increase in the future while there is no change in phosphate concentrations. They further predict a decrease in net primary productivity. In general, the use of English is good although there are some areas which need clarification which I have highlighted below. However I have some concerns regarding the initial conditions of the model and the analysis of model results which need addressing before this can be published. This review will start with more general comments before detailing more minor changes.

My main concern is regarding the initial nutrient conditions in the model. The authors state on line 212 that there is "some underestimation of nutrient concentrations" and again on lines 536-537 that "nutrient concentrations are slightly underestimated" but they do not quantify this. I was surprised when looking at Figure 4 to see deep water nitrate concentrations between 4 and 4.5 µM in the Western Mediterranean Sea. I was expecting to see nitrate concentrations on the order of 8-9µM and hence I do not call this a slight underestimation. Although there is a slight W-E gradient in nutrient concentrations within the model it is not anywhere near as strong as observations suggest. Together with the fact that nitrate in the DW is decreasing in the control scenario suggests to me that the model is not be capturing the biogeochemical cycling of nitrate correctly and raises the question of the validity of future model results. How does this underestimation of nitrate concentrations (and to a lesser extent phosphate concentrations) in the Western basin impact the results of changing circulation such as decreased deep water formation and increased stratification? Would this have a major difference on results? Can the model really predict future changes due to climate change if it can't predict present day conditions correctly?

This point was also outlined by another reviewer. We added in the appendix section vertical profiles of phosphate and nitrate at the DYFAMED station and along the BOUM section. These figures show that nutrient concentrations in the deep Mediterranean are underestimated by the model. However, the nutricline is represented for both nitrate and phosphate, although is it too weak. The model is indeed not representing the correct nutrient concentrations in the deep Mediterranean. However, the main biogeochemical characteristics are represented such as the position of the nutricline, a deep chlorophyll maximum and the west-to-east gradient of productivity. Moreover, we added in figure A1 of the article the chlorophyll profiles for different years at the DYFAMED station in February and in May. This figure shows that the model is able to reproduce a seasonal and an interannual variability in the biogeochemistry of the Mediterranean that generate a surface chlorophyll distribution that is supported by observations (figure 1 and 2).

The decrease of nitrate deep water concentrations in the CTRL may be linked with the unbalanced sources and sinks of nitrate in the Mediterranean. There may be sources of nitrate that we underestimate or fail to include due to a lack of observations (submarine groundwater discharge or sediment remobilization for instance). The same modelling approach, conducted with a higher resolution model (1/12°, Richon et al, 2017), lead also to underestimation of deep nutrients concentration, but with less amplitude. It suggests that changes obtained by increasing the dynamical model resolution improve the dynamics of the model (convections, eddy activities …), but also in consequences biogeochemical variables. Unfortunately, long climate change simulation performed for this study can not be conducted yet with higher resolution.

We believe that the discrepancy between modeled and measured nutrient concentrations are not

impacting qualitatively our conclusions. The results of this study should be looked at qualitatively and the trends should be remembered rather than the absolute numbers. The trends we observe (accumulation of nitrate, decrease of surface productivity) are the result of multiple factors and have the potential to modify nutrient limitation and surface primary and secondary production. Stratification is virtually isolating the surface layer from regenerated nutrients from the deep and the increase in riverine nitrate discharge (impacting the surface layer) will consequently increase surface nitrate concentration. The trends we observe are explained by the changes in sources and sinks of nutrients and by the circulation changes. Therefore, we believe the trends are robust, but we agree that the absolute values of present and future concentrations may be wrong.
Moreover, it is difficult to assess the robustness of future response of climate models. Models with important bias in the present conditions may not perform worse in future simulations than models with good performances in the present. This is mainly because physical mechanisms driving the response to climate change are not the same than the ones driving model bias in the present. Again, the model and scenario we use in this study are the only ones directly available to us at the moment.

My next concern is in regards to whether the authors include dissolved organic matter inputs though the Strait of Gibraltar and from rivers into the model? On line 291-293 the authors say that
"The Mediterranean is a remineralization basin that has net negative fluxes of inorganic nutrients (i.e. organic nutrients enter the basin through the Gibraltar Strait surface waters and inorganic nutrient leave the Mediterranean through the deep waters of the Gibraltar Strait"

However there is no mention of dissolved organic nutrients anywhere in this paper. Do the authors include them in the inputs through the Strait of Gibraltar (or in the riverine input)? If yes this needs to be explicitly stated and if no then they are missing a major source of phosphorus and nitrogen in their model (see Powley et al., 2017; 2018). In addition the paper tries to present a nutrient budget based solely on nitrate and phosphate and then use the imbalanced budget to explain the decrease in nitrate in the CTRL model (Line 540). However dissolved organic matter inputs need to be included in the budget so that total N and P inputs and therefore a complete budget can be calculated (see Powley et al., 2017; 2018) In addition I suggest creating a Table summarizing the budget as currently it is difficult to interpret from the graphs. Finally Lazzari et al. (2014) conclude that dissolved organic matter is increasing in their model in response to climate change. Do your results agree? (I know this is not a key result but a sentence regarding this could be added to the discussion)
Organic forms of phosphorus and nitrate are not included in the version of PISCES we used. They can only be calculated by multiplying the DOC by the Redfiled ratio. However, organic forms of nutrients are not available to phytoplankton. The only forms of organic matter are dissolved organic carbon (DOC) and particulate organic carbon. DOC from river and Gibraltar inputs is included. It can be remineralised to inorganic nutrients and therefore acts as an indirect source of nutrients. However, it is impossible to quantify this remineralization in our simulations. In the HIS/A2 simulation, the DOC riverine inputs are kept constant to the 2000 value over the 21st century. The evolution of DOC incoming and outgoing at Gibraltar is shown below. The three graphs represent respectively total incoming, outgoing and net DOC fluxes through the Strait of Gibraltar in the HIS/A2 simulation (Red) and in CTRL (blue). Numbers in the top right boxes represent respectively the total fluxes for the periods 1980-1999, 2080-2099 and 2040-2059. These figures show that the net DOC flux is increasing throughout the 21st century.

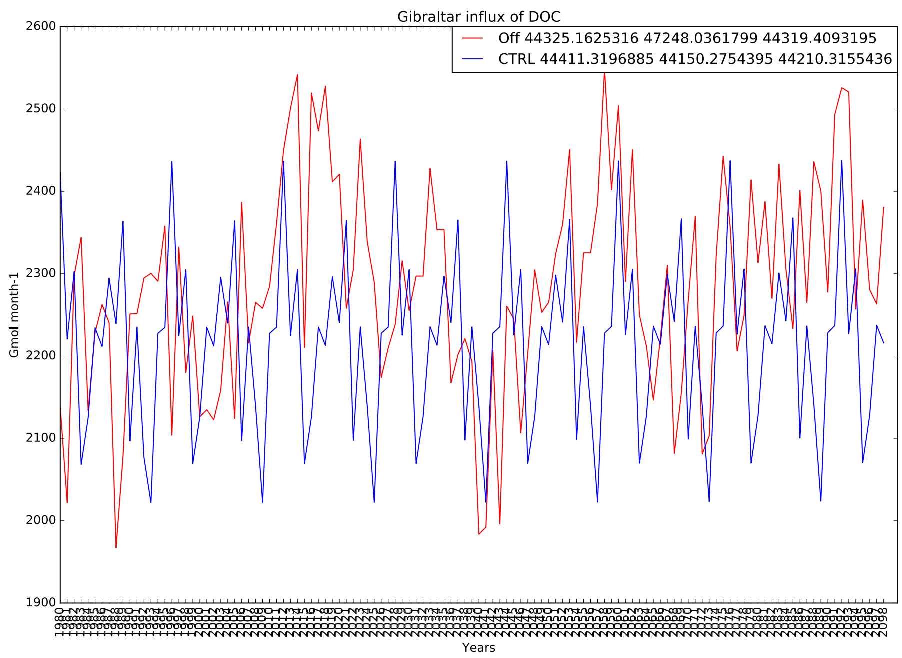

Figure 1 Influx of DOC through the Strait of Gibraltar

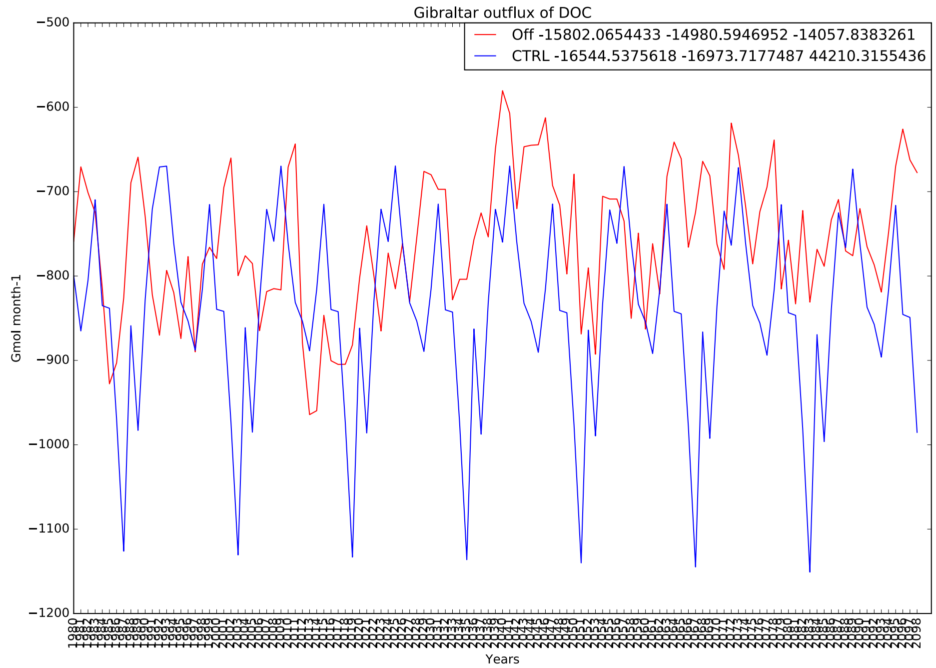

Figure 2 Outflux of DOC through the Strait of Gibraltar

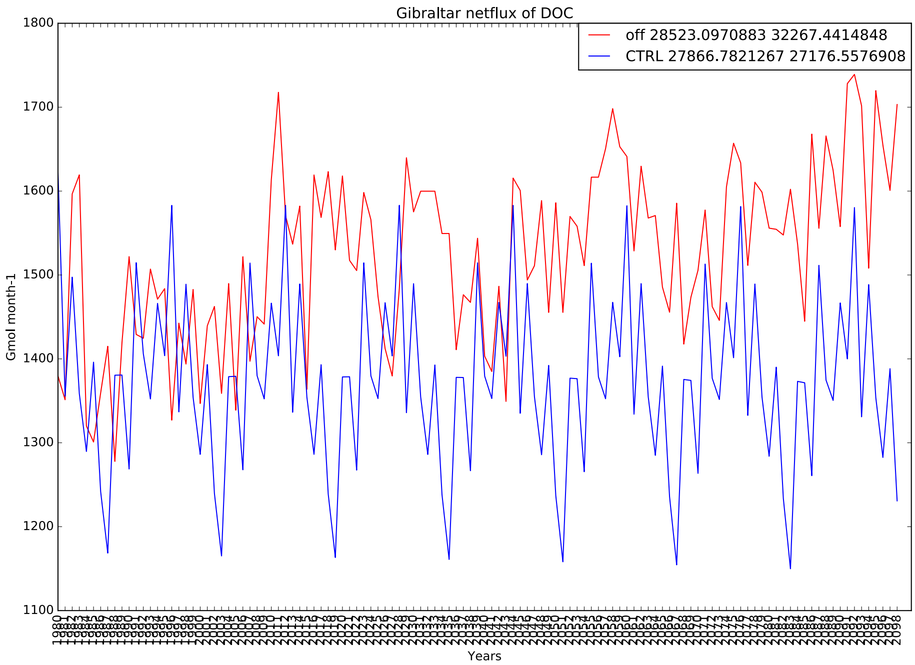

Figure 3 Net flux of DOC through the Strait of Gibraltar

In spite of this increase in DOC flux, the concentrations seems to be decreasing in the basin in our simulations (see the following figures). DOC concentrations in the surface layer are increasing in HIS/A2, but the important decrease in the intermediate and deep layers is probably linked with a decrease in vertical water flux.

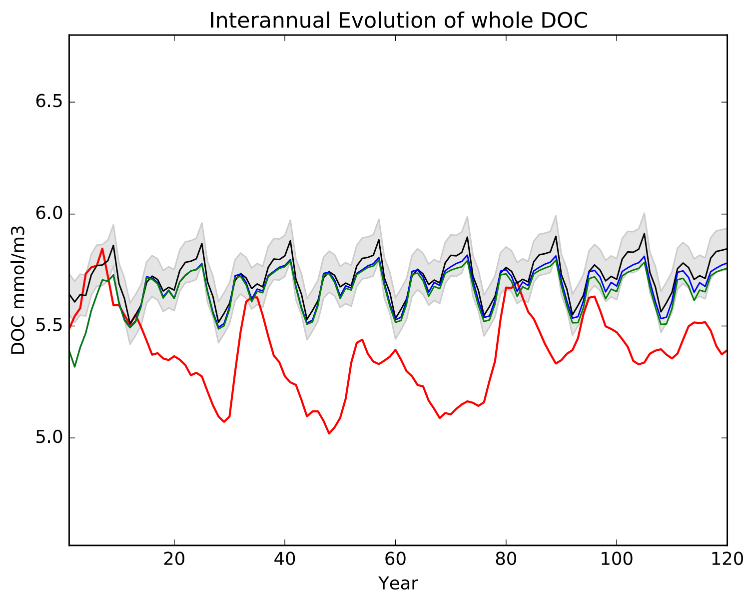

Figure 4 Interannual water column concentration of DOC in the eastern basin for all simulations (HIS/A2 in red, CTRL in black, CTRL_R in blue and CTRL_RG in green)

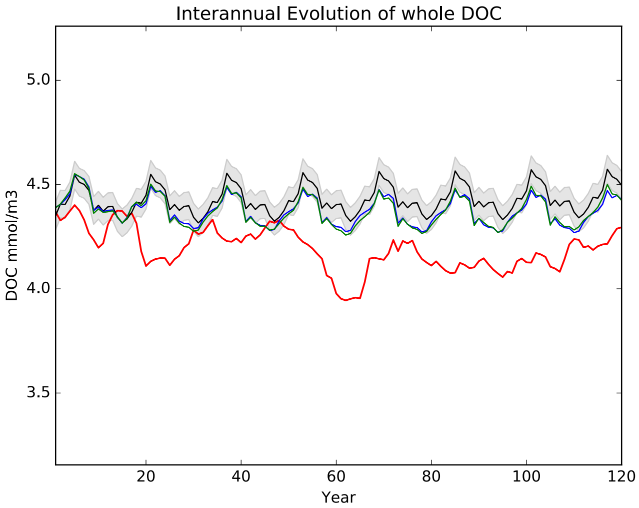

Figure 5 Interannual water column concentration of DOC in the western basin for all simulations (HIS/A2 in red, CTRL in black, CTRL_R in blue and CTRL_RG in green)

Reviewer is right to point out that in the absence of organic nutrient forms, our N and P budget is unbalanced. We add this point in the discussion (section 4.3).

The results section is very qualitative with little quantitative analysis. Phrases such as slightly increase and significantly increase are common with no data to back them up. In addition I feel that section 3 and especially section 3.3 can be condensed as there is a lot of repetition and is hard to follow in places. This would make the main conclusions and outputs of the paper clearer to the reader. I suggest re-organizing section 3.3 to start with the nutrient budget first, analysing the different inputs and outputs from rivers, Straits of Gibraltar and sediment before going on to look at the effect of the different scenarios to nutrient concentrations. This way you can bring in the analyse from the budgets to explain the concentration trends rather than having to repeat yourself analysing and explaining the trends in nutrient concentrations before you have analysed the causes. I would also in general try and keep the same structure within each section in regards to the analysis i.e compare phosphate first, then nitrate, etc.

We thank the reviewer for this suggestion. We followed the advice and reorganised the section. Also, as suggested by another reviewer as well, we tried to provide more quantitative analyses of the results.

General minor comments

While I appreciate that you are limited by both data and computational power in your model runs I suggest refraining from using 'external inputs' and instead be specific and use 'fluxes through the Straits of Gibraltar and riverine inputs'. As far as I understand you are not including atmospheric inputs, direct wastewater discharges or submarine groundwater discharges in your model which can all be considered external nutrient inputs.

Use Strait of Gibraltar or Gibraltar Strait throughout the paper rather than Gibraltar as Gibraltar is a body of land!

We thank the reviewer for these remarks and tried to correct the sentences wherever possible

Detailed minor comments

Line 8: Change "coastal nutrients" to riverine nutrients. Coastal nutrient inputs could mean coastal runoff, direct wastewater discharges submarine groundwater discharge.
Changed

Line 9: Do you just mean from riverine inputs rather than external sources.
Sentence changed to "These contrasted variations result from an unbalanced nitrogen--to--phosphorus input from fluxes through the Strait of Gibraltar and riverine discharge and lead an expansion of phosphorus--limited regions across the Mediterranean. "

Line 27: I thought the last deposited Sapropel was 10,000 years ago not that they have been deposited for the last 10,000 years
We added precisions in this sentence :"In particular, high stratification events, characterized by the preservation of organic matter in the sediment, known as sapropels, have been recorded through several over geological times, the most recent was recorded 10~000 years ago and lasted about 3~000 years."

Line 36: Please quantify the short residence time (i.e 100 year timescale) and add reference.
Precision added. The residence time is around 100 years (Robinson et al. 2001).
Robinson, A. R., Leslie, W. G., Theocharis, A., & Lascaratos, A. (2001). Mediterranean sea circulation. *Ocean currents: a derivative of the Encyclopedia of Ocean Sciences*, 1689-1705

Line 40-41: Please re-phrase. The word transport in this sentence doesn't make sense.
We removed this sentence that was out of the scope of the paragraph

Line 48: I am confused by the Adloff reference at the end. Do they also show this enhanced vertical stratification?
We rephrased : "In all A2 runs, Adloff et al (2015) show an increase in the stratification index at the end of the 21st century."

Line 49: remove "lead to"
Done

Line 70: Add Heurtas et al. (2012) to the Gibraltar references. Add more references for atmospheric deposition or say 'and references therein'. There have been a lot of studies on atmospheric deposition in the Mediterranean region. What about direct wastewater discharges (Powley et al., 2016) and submarine groundwater discharges (Rodellas et al. 2015). Note also Powley et al., (2017;2018) have calculated a complete nutrient budget for the Mediterranean and these should be referenced somewhere in this paper.
We thank the reviewer for these suggestions and added more references in this part.

Line 100: define the SST acronym rather than on line 222
Done

Line 111: define the SSS rather than on line 222 Done
Line 112: remove 'that'
Done

Section 2.3 Please add a bit more detail regarding the biogeochemical model and the compartments so the reader has an idea of what is included without having to go to the references (i.e Are there compartments for bacteria, DOM etc?).
There is no explicit bacterial compartment but bacterial biomass is calculated using zooplankton biomass (see Aumont et al (2006) for details). Organic matter is divided in 2 forms: dissolved organic carbon (DOC) and particulate organic carbon. Other organic nutrients such as phosphorus and nitrogen are not explicitly represented in this version of PISCES but can be derived from the Redfield ratio.

These precisions have been added to the section.

Section 2.3 Include a sentence regarding why you did not use atmospheric deposition, and other external inputs in this section.

We added the following sentence in section 2.4:

"We did not include atmospheric deposition as there is currently no scenario for its future evolution. Similarly, we did not include submarine groundwater discharge and direct wastewater discharge as there is to date no climatology for these sources." (lines 152-154).

Lines 150-155: Please be specific in which MEA scenario you use. None of the four scenarios are called business as usual. Also how did you combine values from the two Ludwig papers together as Ludwig et al. (2010) states that they are not directly compatible with one another.

The scenario we use is the Order from Strength (OS) from Ludwig et al 2010. PO4 and NO3 flux are from Ludwig et al. 2010 for both HIS and A2 only DIC and Si are based on Ludwig et al. 2009. There is no incompatibility issue.

Line 175: Why are 1966-1981 conditions used when the model results are from 1980 onwards? Please specify in the text.

The 1966-1981 period was chosen to avoid years with too much warming, which are observed as of 1980. During the CTRL, these years are looped over the simulation time (120 years). We present the results on the 1980-2099 time scale. Precisions are added in lines 187-190.

Line 184: Write minus rather than using the minus sign as it wasn't clear to me what you meant initially.

Changed

Line 203 satellite not satellites

Changed. Note that we added new figures and data in this section to evaluate the model performances.

Line 212-213: Quantify the error. Compare model results with measurements. (See my main concern)

We added a value of the underestimation (approximately 50%)

Line 224: When you say global I assume you mean across the entire Mediterranean. Please clarify

We changed the word "global" to "basin-wide" for more clarity.

Line 229-235: I suggest moving this section to where you discuss the budget as no results are given and it confuses the reader

This paragraph is intended as an introduction to the long section of results following. In these line we present the vocabulary we use afterwards. This is why we consider this paragraph important at this stage.

Line 230: Add references after "nutrient budgets are highly dependent on external sources".

References added to Ludwig et al 2009, 2010, Christodoulaki et al 2013, Huertas et al 2012

Line 244-246: State this later on when you are talking about limiting nutrients.

We removed the words 'limiting nutrients' from this sentence.

Line 252: How much does the phosphate concentration decrease by? From what to what?

Phosphate decreases by about 0.015 mmol/m3 in the surface layer and 0.017 mmol/m3 in the intermediate layer in the first half of the simulation period. It increases in the second half to reach concentrations close to the 1980 value in the surface layer and higher concentrations in the intermediate layer (by about 0.01 mmol/m3). These precisions were added.

Line 253: Only use significantly if it is statistically significant. If yes then the state the statistics.
We removed the word “significantly” from the sentence.

Line 254: Add “in the surface water in the Western Mediterranean Sea” after phosphate concentrations. The reader shouldn’t have to look at the figures to know which water body you are talking about.
Added

Line 254-255: What about the comparison between CTRL_RG and CTRL R?
We added the following sentences: “Figure 7a shows that the difference in phosphate concentrations in the surface layer of the western Mediterranean in the CTRL_RG and CTRL_R simulations is important only at the end of the 21st century (approximately from 2070). Therefore, the similar evolutions of phosphate concentration in HIS/A2 and of incoming fluxes of phosphate through the Strait of Gibraltar throughout the simulation period must be linked with changes in physical conditions. In this very dynamic part of the Mediterranean, changes in physical conditions linked with climate change are preconditioning the western basin to become more sensitive to nutrient fluxes thought the Strait of Gibraltar.”

Line 263: “The eastern part of the basin contains approximately 50 % less phosphate than the western part.” Where have you got this data from? Table 3 shows greater phosphate content in Western Mediterranean than Eastern Mediterranean. If you mean concentrations then I would still argue that your model is not showing 50% less.
Reviewer is right, this sentence is confusing. The eastern basin naturally contains more nutrients as its volume is greater. We mean that the concentrations are approximately 50% less in the eastern basin. We changed the sentence to “Nutrient concentrations in the eastern part of the basin are lower than in the western part (50 % lower phosphate concentration in the surface layer, about 30 % lower concentration in the intermediate layer and about 15 to 20 % lower concentration in the deep layer).”

Line 265-267: Give quantitative values.
We modified this paragraph to add quantitative values in the text:”In the surface layer, phosphate concentration decreases in the beginning of the simulation and remains low during the 21st century (from 0.022 mmol/m3 in 1980 to less that 0.015mmol/m3 in 2000, Figure 4d). There is, however, a large annual variability in surface phosphate concentration with peaks up to 0.025mmol/m3 in 2060. But the HIS/A2 simulation values are consistently below the CTRL concentrations showing an important effect of climate change on surface phosphate reduction. We observe in Figures 4e and 4f an accumulation of phosphate in the intermediate and deep layers (17 and 13 % respectively), with large decennial variability of phosphate concentration in the deep eastern basin. In both of these layers, HIS/A2 concentrations are higher than the CTRL concentrations. "

Line 268: State which scenario you are talking about.
We modified this paragraph to add precisions and quantitative values.

Line 272. Reference Figure 5 after Atlantic
The paragraph was modified and references to figures added

Line 278-281: Consider consolidating with previous paragraph as there is a lot of repetition (especially concerning impact of rivers of nitrate concentrations).
We thank the reviewer for the suggestion and merged the paragraph with the previous one.

Line 293: Reference needs brackets around it. Changed, reference to Gomez et al 2003 included as well.

Line 295-298: Put quantitative results.
This paragraph was modified to include more quantitative values.

Line 305-307: What about statistics for nitrate?
The Pearson correlation coefficient is 0.80 (p-value < 1%). We also recalculated the statistic for phosphate because we noticed the previous result was for the entire water column.

Line 308: I suggest adding a figure showing the net fluxes through the Strait of Gibraltar to show imbalance. Again, I also suggest the authors look at total nitrogen fluxes to be able to determine whether there is an imbalance at the Strait of Gibraltar not just nitrate.
In order to keep the number of figures, we did not include the net fluxes in the article. However, the Figures are shown below and we added discussion about the net fluxes in the paragraph (see lines 334 to 339).

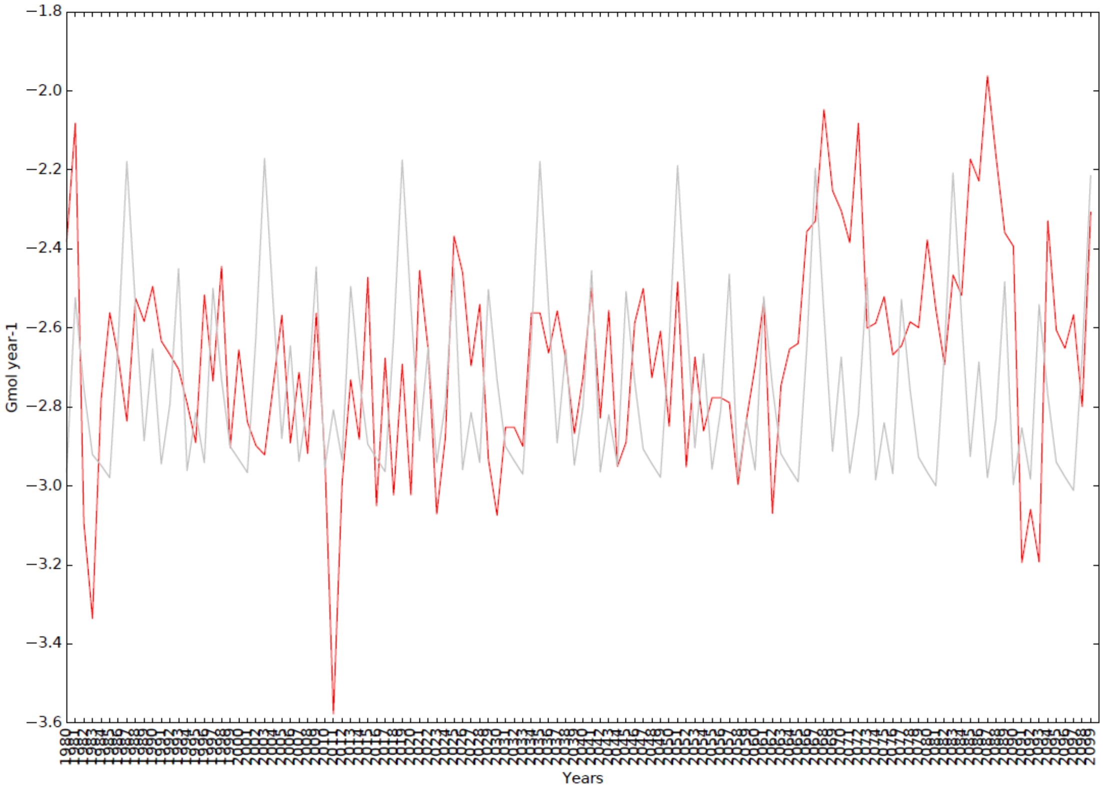

Figure 1: Net flux of phosphate throught the Strait of Gibraltar in HIS/A2 (red) and in CTRL (grey)

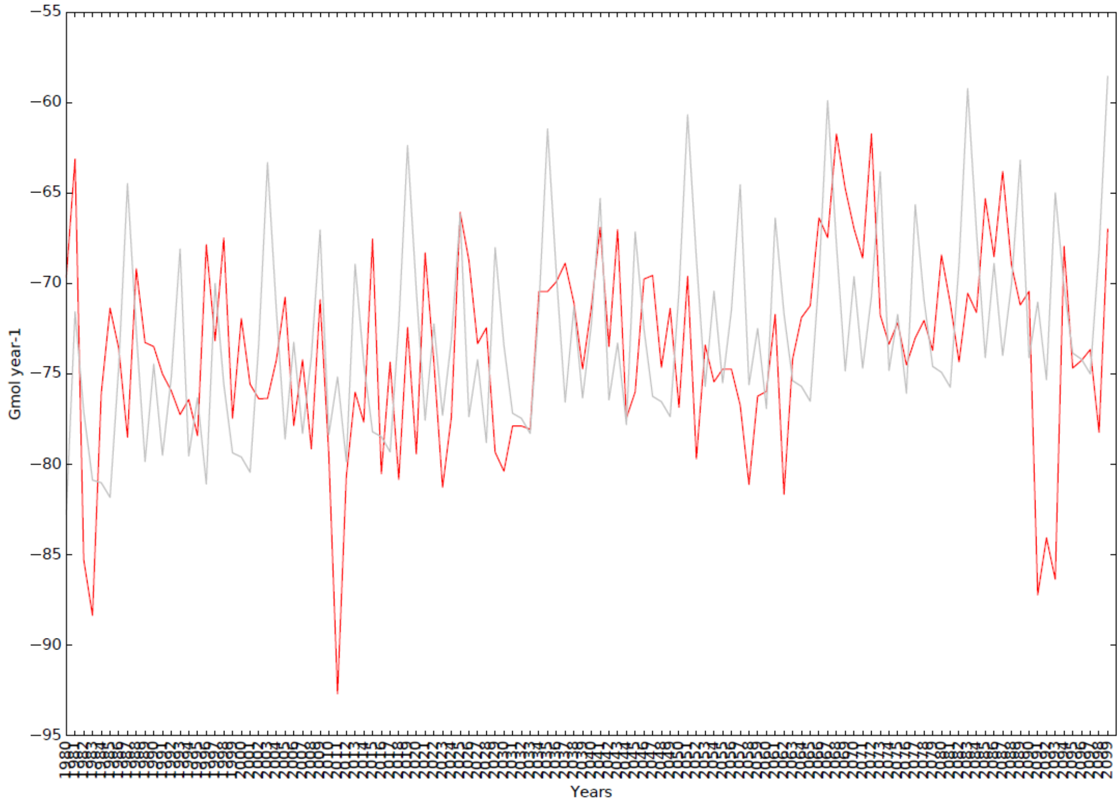

Figure 2: Net flux of nitrate through the Strait of Gibraltar in HIS/A2 (red) and CTRL (grey)

Line 315 Capitalise N in nitrate after full stop.
Done

Lines 315-320: Is there a difference in the evolution of riverine discharge of nutrients between Western and Eastern basins? Combining everything into one flux makes this impossible to see, but if it differs it would have a large impact on results and may explain the differences to the riverine scenario seen in the two basins.
We do not have a figure for the riverine discharge of the western and eastern basins separated. However, the figures below show nitrate and phosphate flux from 3 of the major rivers of the Mediterranean: the Po, the Nile and the Rhone. The nutrient outflow from these rivers have important impact on the local productivity.

Figure 3 below shows that the nutrient discharge from these important rivers evolves differently. In particular, phosphate flux from the Nile increases abruptly between 2000 and 2050 while nitrate flux remains low. This important phosphate source in the P-limited Levantine basin explains the high productivity observed at the end of the century in our HIS/A2 simulation.

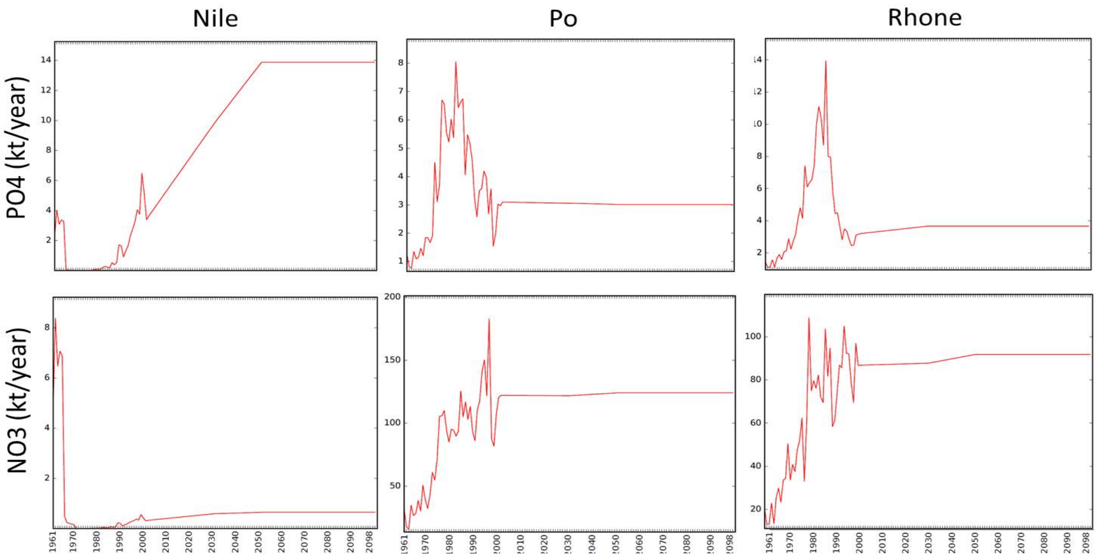

Figure 3: Phosphate (top) and nitrate (bottom) fluxes from the Nile (left), the Po (middle) and the Rhone (right) rivers during the simulation period. From Ludwig et al 2010.

Line 328: Replace "This" with "The"
This was corrected, but the sentence was moved to section 3.3.5, line 335.

Line 329-330: put comma after occurs and flux
Done, this sentence was also moved to section 3.3.5.

Lines 328-332: What happens to sedimentation in the CTRL-R and CTRLRG scenario? This

will make the argument stronger whether sedimentation is linked to decrease in vertical fluxes. Also please be more explicit about the process that would increase phosphate and nitrate in the deep water. A lower particulate matter flux to the deep water would lead to lower remineralisation fluxes and therefore lower phosphate and nitrate. Alternatively, higher water temperatures could lead to higher remineralisation and therefore a lower sedimentation flux despite the same flux of particulate matter exiting the surface water. How do the authors know it is not higher temperatures rather than changes in the water flux that alters the sedimentation flux?

We did not calculate the sedimentation fluxes in CTRL_R and CTRL_RG.
Temperature does not affect remineralization rates in the PISCES model. Therefore, the changes in export fluxes between CTRL and CTRL_R or CTRL and CTRL_RG are only linked with the changes in surface nutrient concentrations and vertical water fluxes.
We looked at the POC export fluxes at 1000m in the different simulations in order to explore the changes in sinking material. Our results show that POC export at 1000m in the HIS/A2 simulation is reduced more than twofold in the 2080-2099 period in comparison to the 1980-1999 period. In the CTRL_R and CTRL_RG simulations, the change in POC export is lower (up to -30%) and in the same order of magnitude than in the CTRL simulation. These observations are in favour of the hypothesis of lower vertical water fluxes explaining the decrease in sedimentation rates. Lower sedimentation coupled with a constant remineralization rate (because remineralization is invariant with temperature in PISCES) leads to the accumulation of nitrate and phosphate in the deep Mediterranean.
Line 334: A new section heading Is needed before line 334.
We moved this paragraph in the discussion section 4.4

Line 334: Into rather than in?
Changed

Line 334-335. Compared to when? The start of the model run? When you say the sum do you mean the balance between inputs through the Gibraltar Strait, riverine inputs and sedimentation? Be specific. Also, as mentioned before, I suggest including dissolved organic matter in your calculations and to produce a table to show the balance of the different inputs and outputs of phosphorus and nitrogen.
We mean in comparison to the beginning of the simulation (1980). “Sum” means indeed balance between inputs and outputs, we modified the sentence to be more specific.
We do not have organic nutrients explicitely represent in the model. However, we added Figure 18 in discussion section 4.4 to summarize the fluxes of nutrients to the basin and the evolution of nutrient budgets.

Line 350-351: The authors state “changes in Gibraltar exchange fluxes of phosphate seem to have limited effect on Mediterranean phosphate content” but on lines 305-306 they also state “evolution of phosphate concentration in the Western basin is linked with Gibraltar inputs”. Which one is it?
This sentence is confusing. We mean that the fluxes through the Strait of Gibraltar are having an important impact on the western basin, but do not seem to have large impact on the nutrient budget of the entire Mediterranean. We added “global” in the sentence to make it clearer.

Line 353-356: What about increase in temperature effecting results? Luna et al., (2012) hypothesise increasing deep water temperatures will increase prokaryotic metabolism, thus potentially increasing nitrate and phosphate concentrations. Lazzari et al., (2014) also predict that increasing temperatures increase metabolic rates.
We thank the reviewer for the reference to Luna et al that we were not aware of. Prokaryotes are not explicitly modeled in PISCES, and nutrient recycling is not a function of temperature in the model. Therefore, temperature increase in our simulations may have effects on planktonic production, but not on remineralization.

We added the following lines in the discussion : “Moreover, Luna et al 2012 hypothesise that the warm temperature of the deep Mediterranean may be a cause for important nutrient recycling via prokaryotic metabolism. In the version of PISCES used in this study, nutrient recycling is dependant on oxygen, depth, plankton biomass and bacterial activity. Therefore, we could not observe the effects of temperature on nutrient recycling."

Line 378: Replace "and shows" with "showing"
Done

Line 380: Delete as this is repeated and explained in the next paragraph.
Done

Line 384" surface phosphate what? Concentrations? Masses?
Concentration. This was added in the sentence

Line 386-387: The decrease does not look that clear to me and it certainly doesn't become entirely depleted in phosphate.
We removed the word 'largely', but phosphate concentration is reduced in all the eastern basin.

Line 409: Remove would
Done

Line 410-414: Why would the phosphate become the major limiting nutrient in areas where primary productivity is reduced?
Based on the results shown in Figure 11 and 12, the P-limited areas at the end of the simulation period match areas where the most important primary productivity decrease is observed. Our hypothesis is therefore that the imbalance in nitrate and phosphate budgets leading to decrease in the surface phosphate budget drives the surface eastern Mediterranean to a P-limitation. This hypothesis is confirmed by the nutrient budgets in Tables 2 and 3, even though we do not have the budgets of organic nutrients.

429-430: Reduced by how much?
We corrected the figure that was using the wrong units and find that the surface concentration in the 2080-2099 period is actually increased by about 25 ng/L in comparison to 1980-1999. This shows that local variability in circulation and biogeochemistry is an important feature of the Mediterranean biogeochemistry.

Line 433: Are we still talking about chlorophyll or primary productivity?
Chlorophyll, we changed this confusing term.

Line 434: What is "it"?
We replaced by "subsurface chlorophyll concentration"

Line 441: Remove Adloff reference?
This reference was formatted wrongly. ***It is "Figure 2 from Adloff et al"***

Line 452? Do you mean riverine nitrate inputs or total nitrate inputs?
Yes, we added the precision in the sentence.

Line 460-463: Which scenario are you talking about?
We rephrased this sentence: "In HIS/A2, we observe lower biomass for both phytoplankton classes across the Mediterranean Sea at the end of the century than at the beginning. "

Line 463: Add Western Mediterranean Sea after diatom concentrations.
Done

Line 465: Add diatoms after concentration
Done

Line 478: Add references if other studies have concluded this.
We are not aware of any studies focusing in zooplankton using NEMO/PISCES. This sentence is an hypothesis based on the authors' experience with the model.

Line 483: "After all" doesn't make sense in English. I suggest you use "Altogether".
We thank the reviewer for this suggestion and modified the sentence accordingly.

Lines 494-497: Add references to this sentence
References have been added to Ludwig et al (2009), Krom et al (2010) and Santinelli et al (2012).
Line 514 and 515: When talking about "coastal nutrient inputs" and "coastal runoff" are you only talking about riverine inputs? Be specific.
We refer to riverine inputs. We tried to harmonize this paragraph to make it more specific.

Line 518: 'developing' not 'developping' Corrected

Line 540: I don't think you can say there's an imbalance in sources and sinks without looking at the organic nitrogen aswell (unless you count nitrate sourced from DOM). There will always be an imbalance of nitrate in the Mediterranean if you only look at external sources as you mention yourself it is a remineralization basin.
We do not have organic nitrogen in the model. However, nitrate can be recycled from DOC in PISCES and is therefore included in the budget.
We added a sentence on this matter: "Organic forms of nutrients are not included in this version of PISCES. Powley et al (2017) show that organic forms of nutrient are an important part of the Mediterranean elemental budgets. Therefore, we may be missing a part of the N and P budgets in our calculations."

Line 591-592: Please re-phrase the sentence and be specific to what you are talking about. What inputs?
We rephrased: "Our results also illustrate how climate change and nutrient inputs from riverine sources and fluxes through the Strait of Gibraltar have contrasted influences on the Mediterranean Sea productivity."

Line 598: I disagree with this statement. There are lots of nutrients inputs that you haven't considered such as direct wastewater discharges, diffuse runoff, submarine groundwater discharge.
We changed this part to: "Finally, this study accounts for the changes in fluxes through the Strait of Gibraltar and riverine inputs, but some potentially important sources are missing such as direct wastewater discharge, submarine groundwater and atmospheric deposition. Measurements and models are still missing in order to include comprehensive datasets for past and future evolution of these nutrient sources."

Line620: Shown rather than showed
Corrected

Table 2: It would be more informative to present the numbers per m2 surface area and then comparisons between basins can happen as the Eastern Mediterranean is almost twice the size of the Western Mediterranean. The reader can still calculate the total mass if the surface area is given. Also taking the difference from the control rather than total values might make it easier to spot trends.
We added in the tables 2, 3 and 4 percentages. These correspond to the relative difference between each period and the 1980-1999 period and help see the trends. We also added on Figures 7,8, 14

and 15 the average concentrations of tracer for each simulation for the periods 1980-1999, 2030-2049 and 2080-2099.

Figures 3 and 4: Please create a greater contrast between the CTRL R and CTRL RG. These are difficult to see at present.
These figures were changed

Figure 5: it would be nice if the net flux of nitrate and phosphate across the Strait of Gibraltar could be added aswell.
For the sake of the number of figures, we chose not to include the net flux in the figures. However, we discuss it in the text.

Figures 8,9,10 and 12. I struggled to see the differences between the two time periods which were mentioned in the text. I suggest to produce a figure of the anomaly between 2080-2099 and 1980-1999 rather than having the 2080-2099 figure as it currently is. The changes with time will then be more evident to the reader.
We produced the anomaly maps and changed the figures

Figure 10. Units in caption do not match units in figure Changed
Figure 12: Why is the HIS/A2 scenario figures not presented aswell?
The CTRL is not presented. We chose not to show it as we are not discussing it and it is almost the same partition as in the HIS/A2 during the 1980-1999 period.

Figure 13: Units in caption are different than on figure Changed
Figures 14 and15: What are the units? mmol m-3 of what? Carbon? Yes, corrected
Figure A1: When were the data points collected? Would the HIS/A2 scenario be a better comparison than CTRL as it actually uses 1980-2000 data?
We changed the figure to include the comparison of HIS/A2 for the corresponding years
Figure A.2 Change P4 to PO4 in the label. Done

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Biogeochemical response of the Mediterranean Sea to the transient SRES–A2 climate change scenario

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Abstract. The Mediterranean region is a climate change hot-spot. Increasing greenhouse gas emissions are projected to lead to a significant warming of Mediterranean Sea waters, as well as major changes in its circulation, but the subsequent effects of such changes on marine biogeochemistry are still poorly understood. Our aim is to investigate the changes in nutrient concentrations and biological productivity in response to climate change in the Mediterranean region. To do so, we perform transient simulations with the coupled high resolution model NEMOMED8/PISCES using the ~~pessimistic~~ high–emission IPCC SRES-A2 socio-economic scenario and corresponding Atlantic, Black Sea, and ~~coastal~~ riverine nutrient inputs. Our results indicate that nitrate is accumulating in the Mediterranean Sea over the 21st century, whereas no tendency is found for phosphorus. These contrasted variations result from an unbalanced nitrogen–to–phosphorus input from ~~external sources and lead to changes in phytoplankton nutrient limitation factors~~fluxes through the Strait of Gibraltar and riverine discharge and lead to an expansion of phosphorus–limited regions across the Mediterranean. In addition, phytoplankton net primary productivity is reduced by 10 % in the 2090s in comparison to the present state, with reductions of up to 50 % in some regions such as the Aegean Sea as a result of nutrient limitation and vertical stratification. We also perform sensitivity tests in order to study separately the effects of climate and biogeochemical input changes on the Mediterranean future state. Our results show that changes in nutrient supply from the Strait of Gibraltar and from rivers and circulation changes linked to climate change may have opposing or synergistic effects on nutrient concentrations and surface primary productivity. In some regions such as the Adriatic Sea, half of the biogeochemical changes observed throughout the 21st century are linked with external nutrient input changes while the other half can be linked to climate change effects. This article is a first step in the study of transient climate change effects on the Mediterranean biogeochemistry, but

calls for presently missing atmospheric deposition scenario and coordinated multi-model efforts to explore the various uncertainty sources of such a future projection.

1 Introduction

The Mediterranean basin is enclosed by three continents, with mountains, deserts, rivers, and industrialized cities. This area is known as one of the most oligotrophic marine environment in the world (Béthoux et al., 1998). Because of its high anthropogenic pressure and low biological productivity, this region is predicted to be highly sensitive to future climate change impacts (Giorgi, 2006; Giorgi and Lionello, 2008).

Records of the past evolution of the Mediterranean circulation show that the Mediterranean has undergone abrupt changes in its circulation patterns over ancient times. In particular, high stratification events, characterized by the preservation of organic matter in the sediment, known as sapropels, have been recorded through the last several times through geological history. The most recent was recorded 10 000 years ago and lasted about 3 000 years. This accumulation of organic matter in the sediments is interpreted as the result of a strong stratification of the water column leading to suboxic deep layers (e.g. Rossignol-Strick et al., 1982; Rohling, 1991, 1994; Vadsaria et al., 2017). In more recent times, abnormal winter conditions have led to changes in deep water formation, such as the Eastern Mediterranean Transient (EMT) event that occurred during the early nineties (see Theocharis et al., 1999; Lascaratos et al., 1999; Nittis et al., 2003; Velaoras and Lascaratos, 2010; Roether et al., 2014) and had biogeochemical impacts and had chemical impacts such as an increase in the Levantine basin salinity (see Theocharis et al., 1999; Lascaratos et al., 1999; Nittis et al., 2003; Velaoras and Lascaratos, 2010; Roether et al., 2014). Also, changes in the North Ionian Gyre circulation triggered the so–called Bimodal Oscillating System (BiOS) that influences influenced phytoplankton bloom in the Ionian Sea (Civitarese et al., 2010). The through the modification of water transport that led to modified nutrient distribution that can alter local productivity and altered local productivity (Civitarese et al., 2010). These events show that a semi–enclosed basin with short residence time of water (around 100 years, see Robinson et al., 2001) such as the Mediterranean is highly sensitive to climate conditions and that changes in perturbations of these conditions can trigger important circulationchangesmodify the circulation, ultimately leading to changes in the biogeochemistry.

The Mediterranean is connected to the global ocean by the narrow Strait of Gibraltar through which transport contributes substantially to its water and nutrient budgets (e.g. Gómez, 2003; Huertas et al., 2012). Future climate projections with greenhouse gases high-emission scenarios yield an increase in temperature and a decrease in precipitation over the Mediterranean region (Giorgi, 2006; IPCC, 2012) leading to warmer and saltier seawater (Somot et al., 2006; Adloff et al., 2015). As a result of these changes, the Mediterranean thermohaline circulation (MTHC) may significantly change with a consistent weakening in the western basin for greenhouse gases high-emission scenarios and a less certain response in the eastern basin in climate change scenarios characterized by high greenhouse gases emission (Somot et al., 2006; Adloff et al., 2015). In ~~one of these MTHC weakening scenarios, Herrmann et al. (2014) show , in addition, a vertical stratification increase (Adloff et al., 2015)~~all A2 runs, Adloff et al. (2015) show an increase in the stratification index at the end of the 21st century. This will likely ~~lead to~~ weaken the vertical mixing ~~that finally~~ and may reduce nutrient supply in the upper layer of the Mediterranean that is essential for phytoplankton to bloom (d'Ortenzio and Ribera d'Alcalà, 2009; Herrmann et al., 2013; Auger et al., 2014).

Primary productivity in the ocean is influenced by water circulation and vertical mixing that ~~bring together available nutrients and~~ brings available nutrients to phytoplankton (Harley et al., 2006). Changes in oceanic physics such as modification of vertical mixing can have dramatic effects on plankton community dynamics and ultimately on the productivity of the entire oceanic food web (Klein et al., 2003; Civitarese et al., 2010). Few studies have investigated the sensitivity of the oligotrophic Mediterranean Sea to future climate change (e.g. Herrmann et al., 2014, for the northwestern Mediterranean). Lazzari et al. (2014) investigated the effects of the A1B SRES (Special Report on Emissions Scenarios) moderate climate change scenario on the Mediterranean biological productivity and plankton communities. They performed short (10–year) non–transient simulations at the beginning and the end of the 21st century and found a decreasing trend of phytoplankton biomass in response to this climate change scenario. Macias et al. (2015) simulated a "baseline" of expected consequences of climate change alone on the Mediterranean primary productivity. They found that according to the RCP 4.5 and RCP 8.5 scenarios, integrated primary productivity over the eastern Mediterranean basin may increase as a result of density changes (increased stratification isolating the upper layer from the rest of the water column). However, their results are based on non–transient simulations and present–day nutrient inputs~~and the~~ . The response of the Mediterranean biogeochemistry to transient climate and biogeochemical change scenarios has never been evaluated.

Being a semi–enclosed oligotrophic basin, the Mediterranean is highly sensitive to external nutrient inputs. Their origins are mainly from coastal runoff, river discharge (Ludwig et al., 2009), Atlantic inputs through ~~Gibraltar (Gómez, 2003)~~the Strait of Gibraltar (Gómez, 2003; Huertas et al., 2012), and atmospheric deposition ~~(Richon et al., 2017, 2018).~~ (see e.g. Dulac et al., 1989; Christodoulaki et al., 2013; Gallisai et al., 2014). Recent studies also showed that direct wastewater discharge (Powley et al., 2016) and submarine groundwater (Rodellas et al., 2015) may be important sources of nutrient for the Mediterranean. However, these sources are to date not well quantified. This study aims at understanding the biogeochemical response of the Mediterranean to a "business–as–usual" climate change scenario throughout the 21st century. For this purpose, we use the high resolution coupled physical–biogeochemical model NEMOMED8/PISCES. We model the evolution of biogeochemical tracers (nutrients, chlorophyll–a ~~concentrations~~concentration, plankton biomass and primary production) under the SRES A2 climate change scenario for the 21st century (IPCC and Working Group III, 2000). The choice of the A2 scenario was driven by the availability of daily 3–D forcings for the biogeochemical model

(Adloff et al., 2015)(physical forcings such as ocean currents, temperature and salinity, see Adloff et al., 2015). We are aware that using a single simulation will limit the robustness of our results. However the computer power required to perform large ensembles with PISCES and the unavailability of 3-D daily ocean transient scenario data currently prevent a more extensive assessment.

This article is organized as follows: the coupled model, forcings and the different simulations are first described. We briefly evaluate the biogeochemical model in Section 3.1 and present the evolution of the physical and biogeochemical forcings in Section 3.2. In section 3.3, we expose the temporal evolution of the main nutrients, their budgets in present and future conditions and discuss their impact on the biogeochemistry of the Mediterranean Sea . in section 4.

2 Methods

2.1 The ocean model

The oceanic general circulation model used in this study is NEMO (Madec, 2008) in its regional configuration for the Mediterranean Sea (NEMOMED8 Beuvier et al., 2010). The NEMOMED8 grid has a horizontal resolution of 1/8° stretched in latitude (i.e., with a resolution from 9 km in the North to 12 km in the South of the domain). The model has 43 vertical levels with varying thicknesses (from 6 m in the surface layer to 200 m in the deepest layer). The Atlantic boundary is closed at 11°W and tracers are introduced in a buffer zone between 11°W and 6°W.

Air–sea fluxes (momentum, heat, water) and river discharges used to force NEMOMED8 are prescribed by the atmospheric Regional Climate Model ARPEGE–Climate (Déqué et al., 1994; Gibelin and Déqué, 2003) using a global and stretched grid, which has a 50–km horizontal resolution over the area of interest.

2.2 The SRES–A2 scenario simulation

ARPEGE–Climate is itself driven by greenhouse gases (GHG) and aerosol forcings following the observations (up to year 2000) and the SRES–A2 scenario afterwards and by SST (Sea Surface Temperature) coming from a previously run CNRM–CM coupled GCM (General Circulation Model) simulation (Royer et al., 2002). In addition, the ocean component of CNRM–CM (a low resolution NEMO version) provides the near–Atlantic conditions (3–D potential temperature and salinity) for NEMOMED8. The various forcings and the modeling chain from the GCM to the ocean regional model are described in details in Somot et al. (2006) and Adloff et al. (2015).

The NEMOMED8 simulation (ocean physics and forcings) used here corresponds to one of the simulations used and studied in Adloff et al. (2015), and more specifically the simulations labeled HIS (historical period 1961 to 1999) and A2 (A2 scenario period 2000–2099) in their Table 1. This physical run has already been used to study climate change impacts on Mediterranean marine ecosystems (Jordà et al., 2012; Hattab et al., 2014; Albouy et al., 2015; Andrello et al., 2015).

The main changes on the Mediterranean Sea physics (SST, SSS -Sea Surface Salinity-, surface circulation, deep convection and thermohaline circulation, vertical stratification, sea level) ~~that~~ are detailed in Adloff et al. (2015). Briefly, changes in temperature and precipitation in the A2 scenario lead to increased evaporation in the basin at the end of the 21st century. Freshwater inputs from rivers and the Black Sea decrease along with total precipitation. This consequently leads to a significant increase in ~~Gibraltar net transport~~ net transport through the Strait of Gibraltar (+0.018 Sv by the end of the century). Temperature and salinity increase strongly, leading to a decrease in surface density and an overall increase in vertical stratification. Average sea surface temperature of the Mediterranean rises by up to 3~~K~~ °C by the end of the century. However, the temperature rise is not homogeneous in the basin, regions such as the Balearic, Aegean, Levantine and North Ionian undergo a more intense warming (over 3.4 ~~K~~°C) probably due to the addition of the atmosphere-originated quasi-homogeneous warming with the local effect of surface current changes. The salinity increases by 0.5 (practical salinity ~~scale~~units) on average across the basin.

In the A2 simulation, the entire Mediterranean basin is projected to become more stratified by 2100 and deep water formation is generally reduced. These variations in hydrological characteristics of the water masses generate important changes in the circulation and in particular in the vertical mixing intensity. The strong reduction in vertical mixing observed in all deep water formation areas of the basin is linked with the changes in salinity and temperature of the water masses. ~~Reduced vertical mixing may also reduce nutrient supply to the surface waters. A reduction in deep convection may also tend to reduce the loss of P and N to the sediment.~~

2.3 The biogeochemical model

Here, the physical model NEMOMED8 is coupled to the biogeochemical model PISCES (Aumont and Bopp, 2006), already used for investigations in the Mediterranean basin (Richon et al., 2017, 2018). This Monod–type model (Monod, 1958) has 24 biogeochemical compartments including 2 phytoplankton (nanophytoplankton and diatoms) and 2 zooplankton size classes (microzooplankton and mesozooplankton). Phytoplankton growth is limited by the external concentration of five different nutrients: nitrate, ammonium, phosphate, silicic acid and iron. In this version of PISCES, elemental ratios of C:N:P in the organic matter are fixed to 122:16:1 following Takahashi et al. (1985). There is no explicit bacterial compartment but bacterial biomass is calculated using zooplankton biomass (see Aumont and Bopp, 2006, for details). Organic matter is divided in 2 forms: dissolved organic carbon (DOC) and particulate organic carbon. The biogeochemical model is ran in offline mode (see e.g. Palmieri et al., 2015): biogeochemical quantities are passive tracers, they are transported following an advection–diffusion equation using dynamical fields (velocities, mixing coefficients...) calculated beforehand in a separate simulation with only the dynamical model NEMOMED8.

2.4 Boundary and initial physical and biogeochemical conditions

External nutrient supply for the biogeochemical model include inputs from the Atlantic Ocean and from Mediterranean rivers. We did not include atmospheric deposition as there is currently no scenario for its future evolution. Similarly, we did not include submarine groundwater discharge and direct wastewater discharge as there is to date no climatology for these sources. Atlantic input is prescribed from water exchange ~~at~~ through the Strait of Gibraltar in the NEMO circulation model along with the concentrations of biogeochemical tracers in the buffer zone. Nutrient concentrations in the buffer zone are prescribed from a global ocean climate projection using the A2 simulation values from IPSL–CM5–LR (Dufresne et al., 2013) performed within the framework of the CMIP5 project (Taylor et al., 2012). Nutrient concentrations in the buffer–zone are relaxed to these values with a time constant of one month.

Nutrients input from rivers are derived from ~~Ludwig et al. (2009) before 2000.~~ Ludwig et al. (2010) before 2000, Dissolved inorganic carbon (DIC) and Si are derived from Ludwig et al. (2009). For the 21st century, we use the estimations for nutrient discharge proposed by Ludwig et al. (2010) of the "~~Business As Usual~~Order from Strength" scenario from the Millenium Ecosystem Assessment (MEA) (Cork et al., 2005), which gives nitrate and phosphate discharge per sub–basin in 2030 and 2050. Yearly values are obtained by linear interpolation between 2000 and 2030 and between 2030 and 2050, after which they are held constant until the end of the simulation in 2100. Seasonal variability coming from ~~the four~~ four of the largest rivers for Mediterranean and Black Sea (Rhône, Po, Ebro and Danube) is also included. According to Ludwig et al. (2010), the future trends in nutrient discharge from the major rivers of the Mediterranean stay within the interannual variability over the past 40 years. ~~However, if the riverine nutrient input is not drastically changed at the basin scale,~~ This scenario is based on hypotheses of very little efforts made towards mitigation of climate change. Ludwig et al. (2010) point out some substantial changes in the nutrient and water budget in specific regions. However, total riverine nutrient input is not drastically changed at the basin scale. In particular, according to their scenario, the northern part of the Mediterranean has decreasing trends in nitrate discharge whereas it is increasing in the southeastern Levantine. Freshwater discharge from Ludwig et al. (2010) is based on the SESAME model reconstruction and differs from the ARPEGE–Climate model used here. This may lead to ~~incoherencies~~ incoherences between water and nutrient discharges, but the nutrient discharges from Ludwig et al. (2010) are the only available values, and the SESAME model is not coupled with NEMO/PISCES. Adloff et al. (2015) evaluate the changes in total freshwater runoff in the HIS/A2 simulation. Their Table 2 shows that the total freshwater runoff to the Mediterranean is lower than the Ludwig et al. (2009) estimate (by about 30 %). They found approximately 27 % decrease in total runoff by the end of the 21st century. This trend is consistent with the deceasing trend found by Ludwig et al. (2010). However, the 2050 estimates of freshwater runoff from Ludwig et al. (2010) are only 13 % lower than the 1970 and 2000 estimates. The freshwater runoff decrease in the physical model is more important than in the nutrient runoff model. This may result in higher nutrient concentrations at the river mouth. We are also aware that the future evolution of river discharges into the Mediterranean Sea is highly uncertain and depends at least on the scenario choice and on the model and modelling strategy choice (Sanchez-Gomez et al., 2009; Dubois et al., 2012; Adloff et al., 2015). However, nutrients from river discharge are consumed rapidly at proximity of the river mouth and we believe these potential higher concentrations don't have a large impact of the results.

Initial nutrient concentrations in the Mediterranean come from the SeaDataNet database (Schaap and Lowry, 2010) and initial nutrient concentrations in the buffer zone are prescribed from the World Ocean Atlas (WOA) (Locarnini et al., 2006). Salinity and temperature are initialized from the MEDATLAS II climatology of Fichaut et al. (2003).

All simulations begin from a restart of a historical run starting in January 1965 following a spin–up of more than 115 years done with a loop of the period 1966 to 1981 for the physical forcings and the river nutrient discharge.

2.5 Simulation set–up

All simulations are performed for 120 years(from 1980 to 2100). The control run CTRL is performed with present–day conditions forcing (forcing conditions corresponding to the 1966–1981). period looped over the simulation period. This period was chosen in order to avoid including in the CTRL years with too important warming such as the 1980s and 1990s. The scenario simulation is referred to as HIS/A2 as in Adloff et al. (2015). HIS is the name of the historical period (in our case between 1980 and 1999), and A2 is the name of the 2000–2099 scenario simulation.

In order to quantify separately the effects of climate and biogeochemical forcingschanges, we performed 2 additional control simulations: CTRL_R with climatic and Atlantic conditions corresponding to present–day conditions and river nutrient discharge following the scenario evolution, and CTRL_RG with climatic conditions corresponding to present–day conditions, and river nutrient discharge and Atlantic buffer–zone concentrations following the scenario conditions. Table 1 describes the different simulations. The effects of external nutrient inputs nutrient inputs from exchanges through the Strait of Gibraltar and riverine discharge independent of climate effect are derived by CTRL_R-CTRL R minus CTRL and CTRL_RG-CTRLRG minus CTRL_R. Similarly, to derive the effects of climate change and nutrient input change on nutrient budgets, we use the difference between HIS/A2 and CTRL. To derive the effects of climate change only, we calculate the difference between HIS/A2 and CTRL_RG.

3 Results

3.1 Evaluation of the NEMOMED8/PISCES model

NEMOMED8 has already been used in a number of regional Mediterranean Sea modeling studies either in hindcast mode (Beuvier et al., 2010; Herrmann et al., 2010; Sevault et al., 2014; Soto-Navarro et al., 2015; Dunić et al., 2016) or scenario mode (Adloff et al., 2015). It produces the main characteristics of the Mediterranean Sea circulation. Evaluation of the HIS simulation provided in Adloff et al. (2015) shows that the main physical characteristics of the Mediterranean are produced, in spite of a too cold upper layer (1 K °C colder than observations) and too little stratification in comparison to observations. In particular, the HIS simulation matches closely the observed thermohaline circulation in the Adriatic and Ionian basins (see Adloff et al., 2015).
The regional NEMOMED physical model has already been coupled to the biogeochemical model PISCES on a 1/12° grid horizontal resolution (Palmieri et al., 2015; Richon et al., 2017, 2018), but no future climate simulation has yet been performed. As a first study coupling NEMOMED8 with PISCES, we compared the main biogeochemical features of our control simulation simulations with available data. Figure 1 shows the surface average chlorophyll concentrations in the top 10 meters of the CTRL and HIS/A2 simulations, and from satellites estimations satellite estimations from MyOcean Dataset (http://marine.copernicus.eu). All chlorophyll values in the article and the data are chlorophyll–a. The model correctly reproduces the main high–chlorophyll regions such as the Gulf of Lions and coastal areas. However, Figure 1 shows an underestimation of about 50 % of the surface chlorophyll concentrations by the model in these productive areas. The west–to–east gradient of productivity is also reproduced by the model with values that agree with satellite estimates. Moreover, this Figure shows that chlorophyll produced by the CTRL is stable over time. The model fails, however, to reproduce the observed chlorophyll–rich areas in the Gulf of Gabes and at the mouth of the Nile. Even though the satellite estimates are uncertain in the coastal areas, the model seems to underestimate chlorophyll concentrations in those regions. This discrepancy is probably linked with insufficient simulated nutrient discharge from coastal runoff in these regions. Moreover, several studies (see e.g. Claustre et al., 2002; Morel and Gentili, 2009) show that satellite estimates have a systematic positive bias in the coastal regions because of the high concentrations of colored dissolved organic matter and the presence of dust particles in seawater back scattering light. Figure 2 provides an evaluation of the average chlorophyll surface concentration evolution over the entire basin for the period 1997–2005. This Figure shows that the normalized chlorophyll surface concentration in the model is close to the estimates provided by the SeaWiFs satellite data (Bosc et al., 2004). Even though the interannual variability of the model is 50 % smaller than in the satellite product, the model captures the increase in chlorophyll concentration between 2002 and 2005 (approximately 15 % of increase in the model and 30 % in the satellite data). The evaluation of the model against 2 independent datasets shows that the model yields satisfying estimates of surface

chlorophyll.

The vertical distribution of nitrate and phosphate over a section crossing the Mediterranean from East to West as well as chlorophyll and nutrient concentration profiles at the DYFAMED station are shown in appendix (Figures A1 and A3). These figures show that the model produces some seasonal and interanuual variability of the nutricline depth and intensity. However, the nutricline depth and DCM depth are consistently overestimated by the model in comparison to the data. The nutricline intensities seem to be underestimated by about 50 % and the depth is overestimated. However, nutricline depth deepens from 100–120 m to 180–200 m between the western and the eastern basins (see Figure A3).

In spite of some underestimation of nutrient concentrations that are probably linked with the features of the simulated intermediate and deep waters characteristics, the PISCES model reproduces the main characteristics of the Mediterranean biogeochemistry, including a salient west–to–east gradient in nutrient concentrations, low surface nutrient concentrations and a deep chlorophyll maximum (DCM). The average chlorophyll concentration observed at the DYFAMED station in the top 200 m is ~~227~~ 233 ± ~~136~~146 10^{-9}g L^{-1} (average over the 1991–2005 period), while the model value for the HIS~~period is 173~~/A2 simulation over the same period is 159 ± ~~150~~87 10^{-9}g L^{-1}. These performances lend credence to our efforts to investigate the evolution of the Mediterranean biogeochemistry under the A2 climate change scenario with the same modeling platform.

3.2 Evolution of temperature and salinity

Average surface temperature and salinity (SST and SSS) evolution in the entire basin during the CTRL and HIS/A2 simulations are shown in Figure 3, which confirms results from Adloff et al. (2015) and shows that the CTRL simulation is stable over time. Beyond this ~~global~~ basin–wide average variation in SST and SSS, a more detailed analysis reveals much greater variability depending on the region (Somot et al., 2006; Adloff et al., 2015). For instance, the Balearic Sea is more sensitive to warming than the rest of the western basin, and the eastern basin has a more intense warming than the western basin (up to 3°C warming in the eastern basin and in the Balearic Sea). Also, the surface salinity in the Aegean Sea increases more than the other regions.

3.3 Evolution of the nutrient budgets in the Mediterranean Sea

The nutrient budgets of the semi–enclosed Mediterranean basin are highly dependent on external sources (e.g. Ludwig et al., 2009, 2010; Huertas et al., 2012; Christodoulaki et al., 2013). In order to map the effects of climate change on the Mediterranean nutrient balance, we calculated mass budgets of inorganic nitrate and phosphate during the simulated period. These budgets take into account changes in Atlantic input, river discharge and sedimentation. Nitrate can also accumulate in the Mediterranean waters through N_2 fixation by cyanobacteria, but this process accounts for less than 1 % of the total nitrate budget (Ibello et al., 2010; Bonnet et al., 2011; Yogev et al., 2011), and is neglected here.

In this Section, we refer to the period 1980-1999 as the beginning of the century, to the period 2030–2049 as the middle of the century and to the period 2080–2099 as the end of the century. Also, we derive the effects of river input changes as the difference of nutrient concentrations between CTRL_R and CTRL over these time periods. Similarly, the effects of changes in ~~Gibraltar exchange~~ nutrient fluxes through the Strait of Gibraltar are derived by the differences between CTRL_RG and CTRL_R, and the effects of climate change by the difference between HIS/A2 and CTRL_RG.

3.3.1 ~~Evolution of phosphate~~ Phosphate and nitrate ~~concentrations~~budgets under climate and biogeochemical changes in the Mediterranean

~~In order to observe the general evolution of tracer concentrations over the 21st century, we plotted the evolution of the main limiting nutrients (~~Tables 2 and 3 summarize the average phosphate and nitrate ~~) concentrations for the entire simulation period in the western and eastern basins. The separation between western and eastern basin is the Sicily Strait. Therefore, the eastern basin includes the Ionian, Levantine, Adriatic and Aegean basins. Figure 7 shows the evolution of average phosphate concentrations in the western and eastern basin, respectively, for the surface (0–200 m), intermediate (200–600 m) and bottom (> 600 m) layers of the water column.~~ content in all simulations for the 3 time periods described earlier.

~~We observe that phosphate concentration in~~ Phosphate content in the entire Mediterranean has increased in our simulation by 6 % over the 21st century, as determined by the difference between CTRL and HIS/A2 ~~decreases in the surface and intermediate layers of~~ simulations between 1980-1999 and 2080–2099. The increase is more important in the eastern basin than in the ~~western basin until the middle~~ western basin. In particular, we observe an 8 % increase in phosphate content in the Ionian–Levantine sub–basin in 2080–2099 compared to 1980–1999. The effects of phosphate river input changes are substantial over the first half of the century~~and then increases again until the end of the century. Figure 7a shows that phosphate concentrations in the CTRL_RG simulation differ significantly from those in CTRL at the end of the 21st century. This is a sign that phosphate concentration in the western basin is strongly linked to Gibraltar inputs. However, the concentrations in the CTRL_RG simulation do not differ significantly from the CTRLsimulation in the intermediate layer (Figure 7b). Nutrients enter the Mediterranean at Gibraltar through the surface layer and leave through intermediate and deep waters. A slight accumulation of~~ . We observe 3 % decrease in phosphate ~~is observed in the deep western basin. The significant difference between the HIS/A2 simulation and the control runs shows that the evolution of the Mediterranean physics linked with climate change is primarily responsible for the changes in phosphate concentration in the intermediate~~

~~and deep western basin~~content in the entire Mediterranean between 1980–1999 and 2030–2049 due to river input changes (difference between CTRL_R and CTRL). Changes in phosphate fluxes thought the Strait of Gibraltar seem to have limited effect on the global Mediterranean phosphate content. However, climate change effects lead to a global enhancement of 10 % in phosphate content in 2080–2099 in comparison to 1980–1999. This result shows contrasted effects of physical and biogeochemical conditions on the evolution of nutrient concentrations.

~~The eastern part of the basin contains approximately 50 % less phosphate than the western part. In the surface layer, phosphate concentration decreases in the beginning of the simulation and remain low during~~

Table 3 shows that in the model, the combined effects of climate, riverine and Atlantic nutrients input changes over the 21st century ~~(Figure 7d). We observe in Figures 7e and 7f a slight accumulation of phosphate in the intermediate and deep layers and large decennial variability of phosphate concentration in the deep eastern basin. The evolution of nitrate concentration shows a marked accumulation over the century in all regions of the intermediate and deep Mediterranean waters (Figures 8b, 8c, 8e and 8f). In the surface waters of the western basin, nitrate concentrations are stable until the middle of the 21st century , and then sharply increase until the end~~ lead to a 17 % increase in nitrate content over the Mediterranean in the 2080–2099 period compared to 1980–1999 (derived from the calculation of HIS/A2–CTRL). Changes in river discharge in the Mediterranean over the century lead to 9 % enhancement of nitrate content by the end of the century (2080–2099) compared to the beginning of the simulation period ~~. This evolution follows nitrate inputs from the Atlantic. Nutrient dynamics in the surface western basin seem mainly dependent on Gibraltar exchanges. In the eastern basin, the impacts of river discharges of nitrate seem to have large influence on the nitrate accumulation as shown by the similar evolution of HIS/A2 and CTRL_R simulations.~~ (1980–1999). The most important effects of river input changes are observed in the Adriatic basin (over 50 % nitrate accumulation by the end of the century). Over the entire Mediterranean, the effects of changes in the fluxes though the Strait of Gibraltar on nitrate content are weak ($<$ 1 %). However, the ~~evolution of physical conditions seems to have similarly large impacts on the nitrate concentrations in the eastern basin as shown by the difference between CTRL_R and HIS/A2. The large differences between the CTRL simulations and the HIS/A2 shows that modification of circulation resulting from climate change have substantial impacts on the deep and intermediate nutrient concentrations. Figure 8d shows the contrasted effects of climate and biogeochemical changes. The strong difference between CTRL_R and CTRL concentrations at the beginning of the simulation indicates that riverine nutrient discharge has a strong influence on surface nitrate concentrations in the eastern basin. But the strong difference between~~ comparison of nitrate content in CTRL_R and CTRL_RG in the western basin shows a 3 % decrease in nitrate content in the western basin during the 2030–2049 period followed by an increase resulting in +1 % nitrate by 2080–2099 compared to the 1980–1999 period. Finally, climate change effects lead to 7 % increase in nitrate content over the Mediterranean basin in the 2080–2099 period compared to 1980–1999 (computed by HIS/~~A2 at the end of the century indicates that vertical stratification leads to a decrease in surface layer nitrate concentrations, probably linked with nutrient exhaustion. In the intermediate and deep layers of the eastern basin (Figures 8e and 8f), nitrate concentrations increase as a result of the effects of both climate and river discharge changes. In contrast, the difference between HIS/A2 and CTRL_RGphosphate concentrations (Figure 7)indicates that the variations of phosphate concentrations during the~~ A2–CTRL_RG). These results indicate that river inputs and climate change are the main drivers of nitrate content changes in the Mediterranean basin over the 21st century~~are primarily linked with climate change~~.

3.3.2 ~~Exchange fluxes~~ Fluxes of nutrients ~~at~~ through the Strait of Gibraltar

The Mediterranean is connected to the global ocean by the narrow Strait of Gibraltar. Water masses transport through this strait contributes substantially to its water and nutrient budgets (e.g. Gómez, 2003; Huertas et al., 2012) . The Mediterranean is a remineralization basin that has net negative fluxes of inorganic nutrients (i.e. organic nutrients enter the basin through the Gibraltar Strait surface waters and inorganic nutrient leave the Mediterranean through the deep waters of the Gibraltar Strait Huertas et al., 2012). Figure 4 shows the evolution of incoming and outgoing nitrate and phosphate fluxes through the Strait of Gibraltar in the HIS/A2 and in the CTRL simulations. We observe similar trends in phosphate and nitrate fluxes in the model. This is linked to the Redfieldian behavior of the primary production in PISCES. According to the HIS/A2 simulation, the incoming fluxes ~~decrease slightly~~ of nitrate and phosphate decrease slightly (from 50 the 35 Gmol month^{-1} for nitrate and from 2.5 to 1.55 Gmol month^{-1} for phosphate) until the middle of the century ~~and~~ (with a period of increased incoming fluxes of both phosphate and nitrate in the 1990s) and then increase to reach values higher than the control in the last 25 years of simulations (Figure 4). Outgoing fluxes follow the same trends as incoming fluxes: total outgoing nitrate and phosphate fluxes decrease from 1980 to 2040 (flux values getting closer to zero) and then increase until the end of the century. We observe a ~~drift~~ decreasing trend in the nitrate outgoing flux in the control (from -129 to -110 Gmol month^{-1} representing about 18 %). At the end of the 21st century, incoming fluxes of ~~nutrient~~ nutrients have increased in the scenario simulation by about 13 % (difference between the 2080–2099 and 1980–1999 periods). But this significant increase (linear regression reveals a positive slope with correlation coefficient greater than 0.75 and p–value < 0.001 for the second half of the simulation period for both nitrate and phosphate) follows a decrease of over 20 % in incoming nutrient fluxes between the 1980–1999 and the 2030–2049 periods. Most of the decrease is observed between 2030 and 2040 (decrease of 15 and 1 Gmol month^{-1} for nitrate and phosphate respectively during this decade). Outgoing fluxes increase less between the beginning and the end of the century (3.5 and 3.9 % for phosphate and nitrate respectively, Figure 4). If the relative changes in incoming and outgoing fluxes seem to indicate an increase in the net incoming flux, the absolute values seem to show a rather steady net flux between the beginning and the end of the century. Net flux at the beginning

of the century is around -83 Gmol month^{-1} for nitrate and -3 Gmol month^{-1} for phosphate. At the end of the century, the fluxes are about -80 Gmol month^{-1} and -2.5 Gmol month^{-1} for nitrate and phosphate respectively. Also, these net fluxes are close to the CTRL net fluxes. These trends result from the evolution of water fluxes through the Strait of Gibraltar computed by NEMOMED8 and the A2 scenario of nutrient concentrations in the buffer zone taken from Dufresne et al. (2013). Figures 7a and 4b show that the evolution of phosphate concentration in the western basin is linked with Gibraltar inputs (Pearson's correlation coefficient is 0.63, p–value=10^{-14}).
The imbalance between incoming and outgoing nutrient flux anomalies may be a cause for the observed accumulation of inorganic nutrients (in particular of nitrate) in the basin.

3.3.3 River fluxes of nutrients

River discharge is the main external source of nutrient phosphate for the eastern part of the basin (Krom et al., 2004; Christodoulaki et al., 2013). Figure 5 shows the total river discharges discharge of phosphate and nitrate from rivers to the Mediterranean Seain nitrate and phosphate during the .

Phosphate discharge decreases by 25 % between the beginning and the end of the simulation period. As suggested by Ludwig et al. (2010), phosphate discharge in the A2 period stays lower than in the HIS period, in spite of a small discharge enhancement between 2030 and 2049.
Nitrate discharge in the HIS/A2 simulation is significantly higher than in CTRL . nitrate (between 30 and 60 Gmol month^{-1} difference). Nitrate total discharge in the Mediterranean has continuously increased from the 1960s (see the CTRL values for the years 1966–1981). According to the HIS/A2 simulation, total river nitrate discharge is 24 % larger during 2080-2099 than during 1980-1999. Simultaneously, phosphate discharge decreases by 25 %. As suggested by Ludwig et al. (2010), phosphate discharge in the A2 period stays lower than in the HIS period, in spite of a small discharge enhancement between 2030 and 2049.

3.3.4 Sedimentation

Sedimentation removes nutrients from the Mediterranean Sea. In this version of PISCES, the loss of nitrogen and phosphorus to the sediment is calculated from the sinking of organic carbon particles to the sediment (linked through the Redfield ratio). Sediment fluxes of phosphorus and nitrogen during the simulations are shown in Figure 6.

The loss to the sediment decreases rapidly during the HIS simulation (1980–1999). By the end of the 21st century, sedimentation of P and N are almost 50 % lower relative to the 1980 fluxes. This strong decrease in sedimentation that occurs despite an enhancement in nutrient flux coming from the Atlantic and an enhanced nitrate river flux may be linked to the decrease in vertical water fluxes, which would explain the accumulation

3.3.5 Evolution of phosphate and nitrate concentrations

In order to observe the general evolution of nutrient concentrations over the 21st century, we plotted the evolution of phosphate and nitrate in concentrations for the entire simulation period in the western and eastern basins. The separation between western and eastern basin is the Sicily Strait. Therefore, the eastern basin includes the Ionian, Levantine, Adriatic and Aegean basins. Figure 7 shows the evolution of average phosphate concentrations in the western and eastern basin, respectively, for the surface (0–200 m), intermediate (200–600 m) and bottom (> 600 m) layers of the deep layers of the Mediterranean Sea (Figures 7c, 7f, 8c and 8f). water column.

In general, the sum of nitrogen fluxes in the Mediterranean basinincreases by 39 % at the end of the century in the scenario (Figures 7a and 4b show that the evolution of surface phosphate concentration in the western basin is linked with phosphate inputs through the Strait of Gibraltar (Pearson's correlation coefficient is 0.85, p–value < 1 %). We observe that phosphate concentration in HIS/A2)whereas it is increased by 23 % in the control (CTRL) . The sum of phosphorus fluxes increases by 9 % in the scenario andby 11 % in the control. These results suggest a significant accumulation of nitrogen in the Mediterranean basin over the century when phosphorus fluxes can be considered roughly stable. Tables 2 and 3 summarize the average phosphate and nitrate content in all simulations for 3 periods of time: the beginning of the century (1980–1999), A2 decreases in the surface and intermediate layers of the western basin until the middle of the century (2030–2049) and concentration decreases by about 0.015 mmol m^{-3} in the surface layer and by 0.017 mmol m^{-3} in the intermediate layer) and then increases again until the end of the century (2080-2099). Phosphate content in to reach similar concentration than in 1980 in the surface layer and higher concentrations than in 1980 in the intermediate layer (about 0.01 mmol m^{-3} higher). This evolution is different than the controls. Figure 7a shows that the difference in phosphate concentrations in the surface layer of the western Mediterranean in the entire Mediterranean has increased in our simulation by 6 % over the CTRL_RG and CTRL_R simulations is important only at the end of the 21st century, as determined by the difference between CTRLand century (approximately from 2070). Therefore, we hypothesize that the similar evolutions of phosphate concentration in HIS/A2 simulations between 1980-1999 and 2080–2099. The increase is more important in the eastern basin than in the western basin. In particular, we observe an 8 % increase in phosphate content in A2 and of incoming fluxes of phosphate through the Strait of Gibraltar throughout the simulation period are linked with changes in physical conditions. In this very dynamic part of the Mediterranean, changes in physical conditions linked with climate change are preconditioning the western basin to become more sensitive to nutrient fluxes thought the Strait of Gibraltar. A slight accumulation of about 0.015 mmol m^{-3} of phosphate is observed in the HIS/A2 simulation in the deep western basin. The significant difference between the HIS/A2 simulation and the control runs shows that the evolution of the ~~Ionian–Levantine sub–basin in 2080–2099 compared to 1980–1999. The effects of phosphate river input changes are substantial over the first half of the century. We observe 3 % decrease in phosphate content in the entire Mediterranean between 1980–1999 and 2030–2049 due to river input changes (difference between CTRL_R and CTRL). Changes in Gibraltar exchange fluxes of phosphate seem to have limited effect on the Mediterranean phosphate content. However, climate change effects lead to a global enhancement of 10 % in phosphate content in 2080–2099 in comparison to 1980–1999. This result shows contrasted effects of physical and biogeochemical conditions on the evolution of nutrient concentrations~~Mediterranean physics linked with climate change is primarily responsible for the changes in phosphate concentration in the intermediate and deep western basin. Climate change effects lead to an accumulation of phosphate in the intermediate and deep layer that is probably linked to a decrease in surface primary productivity (hence, in nutrient consumption and export), decreased sediment fluxes (see Figure 6), and increased stratification, thus isolating most of the phosphate pool from the surface.

~~Table 3 shows that in the model,~~ Nutrient concentrations in the eastern part of the basin are lower than in the western part (50 % lower phosphate concentration in the surface layer, about 30 % lower concentration in the intermediate layer and about 15 to 20 % lower concentration in the ~~combined effects of climate, riverine and Atlantic nutrients input changes over the~~ deep layer). In the surface layer, phosphate concentration decreases in the beginning of the simulation and remains low during the 21st ~~century lead to a 17 % increase in nitrate content over the Mediterranean in the 2080–2099 period compared to 1980–1999 (derived from the calculation of HIS~~century (from 0.022 mmol m^{-3} in 1980 to less that 0.015 mmol m^{-3} in 2000, Figure 7d). There is, however, a large annual variability in surface phosphate concentration with peaks up to 0.025 mmol m^{-3} in 2060. But the HIS/~~A2–CTRL). Changes in river discharge in the Mediterranean over the century lead to 9 % enhancement of nitrate content by the end of the century (2080–2099)compared to the beginning of the simulation period (1980–1999). The most important effects of river input changes are observed in the Adriatic basin (over 50 %nitrate accumulation by the end of the century). Over the entire Mediterranean, the effects of Gibraltar input changes on nitrate content are weak ($<$ 1 %). However, the comparison of nitrate content in CTRL_R and CTRL_RG in the western basin shows a 3 %~~ A2 simulation values are consistently below the CTRL concentrations showing an important effect of climate change on surface phosphate reduction. We observe in Figures 7e and 7f an accumulation of phosphate in the intermediate and deep layers (17 and 13 % respectively), with large decennial variability of phosphate concentration in the deep eastern basin. In both of these layers, HIS/A2 concentrations are higher than the CTRL concentrations.

The evolution of nitrate concentration shows an accumulation over the century in all regions of the intermediate and deep Mediterranean waters (between 9 and 20 %) in the HIS/A2 simulation

(Figures 8b, 8c, 8e and 8f). In the surface western basin, the evolutions of the HIS/A2 and CTRL_RG simulations are similar, showing the regulating effects of fluxes through the Strait of Gibraltar (Figure 8d). In the intermediate layer, nitrate concentration in the HIS/A2 simulation is decreasing from 4.05 to 3.6 mmol m^{-3} between 1980 and 2030. After 2030, the concentration increases again up to 4.3 mmol m^{-3}. In the deep western basin, we observe a slight decrease in nitrate content in the western basin during the 2030–2049 period followed by an increase resulting in +1 % nitrate by 2080–2099 compared to the 1980–1999 period. Finally, climate change effects lead to 7 % increase in nitrate content over the Mediterranean basin in the 2080–2099 period compared to 1980–1999 (computed by concentration in the controls from 4.4 to about 4.15 mmol m^{-3} whereas there is a slight accumulation from 4.5 to 4.75 mmol m^{-3} in the HIS/A2–CTRL_RG). These results indicate that river inputs and climate change are the main drivers of nitrate content changesin the Mediterranean basin over the 21st century .

A2 over the simulation period.

In the eastern basin, the impacts of river discharges of nitrate seem to have large influence on the nitrate accumulation as shown by the similar evolution of HIS/A2 and CTRL_R simulations (Figures 8e and 8f). However, the evolution of physical conditions seems to have similarly large impacts on the nitrate concentrations in the eastern basin as shown by the difference between CTRL_R and HIS/A2 (see also Table 3). In particular, nitrate concentrations increase by about 0.5 mmol m^{-3} between 1980 and 2099 in the deep eastern basin. Approximately 50 % of this accumulation is due to river discharge. The large differences between the CTRL simulations and the HIS/A2 show that modification of circulation resulting from climate change have substantial impacts on the deep and intermediate nutrient concentrations. Figure 8d shows the contrasted effects of climate and biogeochemical changes. The strong difference between CTRL_R and CTRL concentrations at the beginning of the simulation (almost 0.4 mmol m^{-3}) indicates that riverine nutrient discharge has a strong influence on surface nitrate concentrations in the eastern basin and is responsible for an important part of the eastern Mediterranean nitrate budget (see also Table 3). But the strong difference between CTRL_R and HIS/A2 at the end of the century indicates that vertical stratification leads to a decrease in surface layer nitrate concentrations, probably linked both with lower winter mixing and nutrient consumption by phytoplankton.

3.4 Present and future biological surface nutrient concentrations, primary productivity and nutrient limitations in the surface Mediterranean

Figures 9 and 10 show the average surface concentrations of nitrate and phosphate in the beginning of the century (1980–1999) and the relative concentration differences with the end of the century (2080–2099) in the HIS/A2 and CTRL simulations. In the Mediterranean Sea, biological primary productivity is mainly limited by these 2 nutrients and their evolution in the future may ~~determine~~ impact the productivity of the basin. Figure 9 confirms the previous results ~~and shows~~ showing an accumulation of nitrate in large zones of the basin, except for the southwestern part of the western basin (Alboran Sea) and a small area in the southeastern Levantine~~that appears to be the result of Nile discharge influence.~~.

On the contrary, Figure 10 shows that phosphate surface concentration is decreasing everywhere in the basin except near the mouth of the Nile and in the Alboran Sea. The specific concentrations observed next to the Nile mouth are linked with an inversion of the N:P ratio (i.e. increase in P discharge and decrease in N discharge) in this river in our scenario. The distribution of surface phosphate concentration at the end of the century (2080–2099) shows that all P–rich areas of the eastern basin at the beginning of our simulations are ~~largely~~ depleted by the end of the simulation. For instance, the P rich ~~area between~~ areas around Crete and Cyprus ~~is~~ are no longer observed in the 2080–2099 period (Figure 10). Moreover, Figure 11 shows that ~~this area matches a productive zone observed in the 1980–1999 period~~these areas match productive zones. All the most productive zones of the beginning of the century are reduced in size and intensity by the end of the century. The primary production integrated over the euphotic layer (0–200 m) is reduced in our simulation by 10 % on average between 1980–1999 and 2080–2099. However, Figure 11 shows a productivity decrease of more than 50 % in areas such as the Aegean Sea and the Levantine Sea. In general, the differences in surface biogeochemistry between the 1980–1999 and 2080–2099 periods are weaker in the western basin because of the strong regulating impact of ~~Gibraltar nutrient exchange .~~ nutrient exchange through the Strait of Gibraltar. The large scale reduction of surface primary productivity may be a cause for the observed reduction in sedimentation (see Figure 6).

We also observe local changes in nutrient concentrations and primary production. For instance, around ~~Majorca Island, Corsica and~~ Cyprus, changes in local concentrations of nutrients (decrease of about 50 % in phosphate concentration) have substantial effects on primary productivity (decrease from 40-50 gC m^{-2} $year^{-1}$ to 20-30 gC m^{-2} $year^{-1}$). These mesoscale changes may be linked with local circulation changes (such as mesoscale eddies). These observations show that the evolution of the Mediterranean biogeochemistry is influenced by both meso and large scale circulations patterns.

Figure 12 presents the limiting nutrient calculated using PISCES half–saturation coefficients (see Aumont and Bopp, 2006). The limiting nutrient is derived from the minimal value of limitation factors. In the Monod–type model PISCES, nutrient–based growth rates follow a Michaëlis–Menten evolution with nutrient concentrations. In the present period, most of the productive areas are N and P colimited in the simulation (Figure 12). This includes regions such as the Gulf of Lions, the South Adriatic, the Aegean Sea and the northern Levantine. Future accumulation of nitrogen in the basin ~~would modify~~ modifies the nutrient balance causing most eastern Mediterranean surface waters to become P–limited. ~~Thus, future phosphate surface concentrations in the Mediterranean would tend to decrease.~~ The total balance of phosphate is more negative in the future than in the present period whereas we observe an inverse situation for nitrate. Therefore, phosphate would become the major limiting nutrient in most of the regions where productivity is reduced such as the Aegean Sea, the northern Levantine basin and the South Adriatic.

3.5 Modifications of the Mediterranean deep chlorophyll maximum

One specificity of Mediterranean biology is that most planktonic productivity occurs below the surface at a depth called the deep chlorophyll maximum (DCM). Hence, most of the chlorophyll concentration is not visible by satellites (Moutin et al., 2012). Figure 13 shows the average depth of the simulated DCM for the period 1980–1999 and for the period 2080–2099.

We observe that the DCM depth changes little during the simulation, even though the physical characteristics of the water masses do change (salinity and temperature). The DCM tends to deepen slightly in some regions such as the South Ionian and the Tyrrhenian basin. These results suggest that the DCM depth is not significantly altered in the future but the intensity of subsurface productivity seems reduced (see Figure 11).

Figure 14 shows the average vertical profiles of chlorophyll at the DYFAMED station (43.25° N, 7.52° E) and the average profiles for the western and eastern basins for the 1980–1999 and 2080–2099 periods. The results show that the subsurface chlorophyll maximum is still modeled at the end of the century. At the DYFAMED station, the average DCM depth is unchanged but surface concentration is ~~reduced.~~ enhanced by about 25 10^{-9} g L^{-1}. This shows that local variability in the Mediterranean circulation and biogeochemistry is important. However, we simulated seasonal variability in the chlorophyll concentration profiles at the station with intensity and depth of DCM reduced by about 40 % for some month (not shown). In the western basin, the subsurface maximum in the present and future periods is located at the same depth (100–120 m), but the average ~~productivity~~ chlorophyll concentration is reduced by almost 50 %, which confirms the results from Figure 13. In the eastern basin, ~~it~~ subsurface chlorophyll concentration is reduced and the subsurface ~~productivity~~ chlorophyll maximum deepens from 100–120 m to below 150 m.

In the oligotrophic Mediterranean, the majority of the chlorophyll is produced within the DCM. The changes ~~in DCM we observe combined with external nutrient input changes~~ circulation combined with changes in fluxes through the Strait of Gibraltar and riverine inputs result in 17 % reduction in integrated chlorophyll production between the 1980–1999 and 2080–2099 periods. Table 4 reports total chlorophyll production in the 1980–1999, 2030–2049 and 2080–2099 periods of all the simulations in all Mediterranean subbasins ~~Adloff et al. (Figure 2 2015)~~(Figure 2 from Adloff et al., 2015) . Table 4 shows that chlorophyll production is stable over the CTRL simulation but decreases in all Mediterranean subbasins over the HIS/A2 simulation. The decrease in chlorophyll production is more important in the eastern regions, in particular in the Adriatic and Aegean Seas (-29 and -15 % respectively). In the western basin, the loss of chlorophyll is smaller (-13 %). The chlorophyll production is probably maintained by the enhancement of ~~Gibraltar nutrient fluxes~~ nutrient fluxes through the Strait of Gibraltar (chlorophyll production in CTRL_RG does not significantly decrease in the western basin).

The results indicate that 85 % of the reduction in chlorophyll production in the future period modeled in the HIS/A2 simulation is explained by climate effects (difference between HIS/A2 and CTRL_RG). However, the effects of increased ~~Gibraltar inputs~~ nutrient inputs through the Strait of Gibraltar, decreased riverine phosphate inputs and increased ~~nitrate inputs~~ riverine inputs of nitrate seem to have opposing effects to climate and circulation changes on chlorophyll production. In particular, in the western basin, changes in riverine discharge of nutrients seem to reduce chlorophyll production (see CTRL_R values), whereas changes in ~~Gibraltar inputs~~ fluxes through the Strait of Gibraltar seem to enhance chlorophyll production (see CTRL_RG).

3.6 Plankton biomass evolution

Most of the biological activity in the marine environment is confined to the euphotic layer which is confined to the upper 200 m. Figure 15 shows the evolution of nanophytoplankton and diatom concentrations in the top 200 m for the entire simulation period in all simulations in the western and eastern basins. ~~We observe~~ In HIS/A2, we observe lower biomass for both phytoplankton classes ~~their biomass~~ across the Mediterranean Sea ~~are lower~~ at the end of the century than ~~in the present conditions~~at the beginning. In general, diatoms seem more sensitive to climate change and their biomass decreases more sharply than nanophytoplankton. Moreover, Figure 15c shows that diatom concentrations in the western basin seem to be sensitive to changes in nutrient input across the Strait of Gibraltar as indicated by the large difference between CTRL_RG and CTRL_R. However, the low diatom concentration observed in HIS/A2 indicates that the evolution of the diatom concentration over the 21st century is primarily influenced by climatic drivers.

Figure 16 shows the evolution of zooplankton biomass in the top 200 m during the simulation. The same general evolution is found than for the simulated phytoplankton: a decrease in microzooplankton during 1980–2000 (from 0.165 to approximately 0.114 mmol m^{-3}), after which it remains stable and consistently below the CTRL values until the end of the simulation in ~~2100.~~ 2100 in all basins~~; a~~ . A large drawdown in mesozooplankton levels is simulated in the eastern basin. The average mesozooplankton concentration in the eastern part of the Mediterranean declines by almost

60 % in 2099 in comparison to 1980. However, the average mesozooplankton concentration over the 2080–2099 period is only slightly lower than the average concentration over the 1980–1999 period (0.10 and 0.11 mmol m^{-3} respectively) because the decline in concentration occurs within the first years of the HIS/A2 simulation. In the western basin, we observe a marked decrease of mesozooplankton concentrations between 1980 and ~~2040.~~ 2040 (a decrease of 0.05 mmol m^{-3} is observed between these 2 periods). After 2040, ~~surface concentrations of mesozooplankton~~ mesozooplankton surface concentration increases regularly to similar values than at the beginning of the simulation. This evolution is similar to those ~~for~~ of nutrient concentrations in surface waters of the western basin (Figure 7). In the PISCES model, zooplankton, and in particular mesozooplankton is highly sensitive to the variations of external climatic and biogeochemical conditions because that is the highest trophic level represented. Owing to their bottom–up control, zooplankton canalize all changes at the basin scale and ultimately displays the largest response. This behavior is similar to the trophic amplification observed by Chust et al. (2014) and Lefort et al. (2015).

~~After all~~Altogether, the analysis of plankton biomass evolution during the simulation period suggests that primary and secondary production in the eastern basin are more sensitive to climate change than the western basin in this simulation. The eastern part of the basin is more isolated from the open Atlantic Ocean than is the western part and it receives less nutrients from the Atlantic and from coastal inputs. The eastern basin is also deeper and less productive than the western basin (Crispi et al., 2001). The eastern basin exhibits a decline in the phytoplankton biomass that is similar to the decline in the phosphate concentration. Biological production is mainly P–limited in this basin (see also Figure 12). Therefore, the constant low concentrations of phosphate observed throughout this century limit biological production and keep plankton biomass at low levels.

4 Discussion

4.1 Biogeochemical forcings

Climate change may impact all drivers of biogeochemical cycles in the ocean. In the case of semi–enclosed seas like the Mediterranean, the biogeochemistry is primarily influenced by external sources of nutrients ~~(namely rivers, Atlantic and atmospheric inputs) and~~ (namely rivers, Atlantic and atmospheric inputs, see Ludwig et al., [and modification of the physical ocean ~~(vertical mixing, horizontal advection, . . .).~~ (vertical mixing, horizontal advection, ..., see Sant . Nutrient fluxes from ~~these sources~~ external sources (rivers, aerosols and fluxes through the Strait of Gibraltar) may evolve separately and differently depending on ~~socioeconomic~~ socio-economic decisions and climate feedbacks. In this study, different scenarios were used for river inputs ~~("Business as Usual" from Ludwig et al., 201~~ ("Order from Strength" from Ludwig et al., 2010, based on the Millenium Ecosystem Assessment report) and for Atlantic nutrient concentrations (SRES/A2 from Dufresne et al., 2013). ~~No atmospheric deposition was considered in this study because there is, to our knowledge, no transient scenario~~

for atmospheric deposition evolution over the Mediterranean Sea. Scenarios from the MEA report are based on different assumptions from the IPCC SRES scenarios used to compute freshwater runoff in the HIS/A2 simulation. Moreover, the Ludwig et al. (2010) nutrient discharge transient scenario does not represent the interannual variability of nutrient runoff from rivers. Other studies by Herrmann et al. (2014) and Macias et al. (2015) used continued present–day discharge of nutrients. As there is no consensus nor validated scenario for nutrient fluxes from coastal riverine runoff in the Mediterranean, we chose to use one scenario from Ludwig et al. (2010). This scenario has the advantage of being derived from a coherent modeling framework. However, according to these authors, the socio–economic decisions made in the 21st century will influence nitrate and phosphate discharge over the Mediterranean. It is difficult to forecast these decisions and the resulting changes in nutrient discharges fluxes are uncertain. Moreover, our results emphasize that the biogeochemistry in many coastal regions of the Mediterranean Sea such as the Adriatic Sea are highly influenced by coastal nutrient inputsriverine nutrient inputs, which is in accordance with previous work (e.g. Spillman et al., 2007, and references therein). In these regions, the effects of nutrient runoff changes from rivers seem more important than climate change effects (see Table 4). In the Adriatic basin, table 3 shows that riverine nitrate discharge is responsible for 41 % increase in nitrate concentration over the simulation period (difference between the 1980–1999 and the 2080–2099 periods). In the CTRL_RG simulation, nitrate concentrations are similar to the CTRL_R simulation showing no influence of fluxes through the Strait of Gibraltar in this region. Finally, nitrate concentrations in the HIS/A2 simulation are close to the CTRL_R values showing that most of the nitrate evolution in this region is linked with riverine discharge. Therefore, the choice of coastal river runoff scenario will greatly influence the results in these regions. Associated discrepancies and the uncertainties linked with the use of inconsistent scenarios in our simulation should be addressed by developping developing a more integrated modeling modelling framework to study the impacts of climate change on the Mediterranean Sea biogeochemistry.

No transient atmospheric deposition was considered in this study because there is, to our knowledge, no transient scenario for atmospheric deposition evolution over the Mediterranean Sea. However, in order to evaluate the potential effects of aerosol deposition on the future Mediterranean Sea, we performed 2 simulations with respectively total nitrogen ($NH_4 + NO_3$) deposition (labeled HIS/A2_N) and total nitrogen and natural dust deposition (labeled HIS/A2_NALADIN). The deposition fields are derived from the global model LMDz–INCA and the regional model ALADIN–Climat respectively (see Richon et al., 2017, and references therein for description and evaluation of the atmospheric models) . The atmospheric deposition fields represent present–day aerosol deposition fluxes (1997–2012 and 1980–2012 for total nitrogen and dust deposition respectively) that are repeated over the 1980–2099 simulation period. The following figure (Figure 17) shows the relative effects of total nitrogen and natural dust deposition on surface primary production in the 1980–1999 and 2080–2099 periods. As shown in Richon et al. (2017), dust deposition is a source of phosphate for the surface Mediterranean.

As our HIS/A2 simulation shows a decrease in surface PO_4 concentrations, thus accentuating phosphate limitation over the Mediterranean basin by the end of the 21st century, the relative effects of phosphate deposition from dust are increased in the 2080–2099 period in comparison to the 1980–1999 period. Conversely, nitrogen atmospheric deposition has very little effect on Mediterranean primary production at the end of the simulation period because most of the basin is not N–limited.

4.2 Climate change scenario

Although the physical model adequately represents the MHTC (Adloff et al., 2015), there are many uncertainties linked with climate change projections. Some are discussed in Somot et al. (2006), in particular, the need to using different IPCC scenarios for climate change projections and THC MTHC changes. Adloff et al. (2015) apply an ensemble of SRES scenarios and boundary conditions to the Mediterranean Sea and discuss their effects on MTHC. In particular, their results suggests that the choice of atmospheric and Atlantic conditions has a strong influence on the MTHC. The A2 scenario that we used was the only available with 3–D daily forcings for coupling with the PISCES biogeochemical model. However, Adloff et al. (2015) showed that other SRES scenarios such as the A1B or B1 may lead to a future decrease in the vertical stratification with probably different consequences on the Mediterranean Sea biogeochemistry. Our study should be considered as a first step for transient modeling of the Mediterranean Sea biogeochemistry but should be complemented by new simulations that explore the various sources of uncertainty (model choice, internal variability, scenario choice) once appropriate forcings become available for multiple models as expected from the Med–CORDEX initiative (Ruti et al., 2015)(Ruti et al., 2016).

4.3 Uncertainties from the PISCES model

The evaluation of the CTRL simulation showed that NEMOMED8/PISCES is stable over time in spite of a slight drift in nitrate concentrations (see Figure 8). Nutrient concentrations in the intermediate and deep layers were shown to be slightly underestimated in comparison to measurements (see appendix). Nutrient concentrations can be underestimated by up to 50 %, in particular in the deep eastern basin. Moreover, nitrate fluxes from coastal discharge in CTRL are lower than in HIS/A2. This discrepancy The low riverine discharge and the imbalance in sources and sinks explains the loss of nitrate in the CTRL (see Figures 8 and 9). Organic forms of nutrients are not directly available to phytoplankton in this version of PISCES, and are not included in our nutrient budgets. Powley et al. (2017) show that organic forms of nutrient are an important part of the Mediterranean elemental budgets. Therefore, we may be missing a part of the N and P budgets in our calculations. The simulated chlorophyll–a vertical profiles at the DYFAMED station show a correct representation of the subsurface productivity maximum of the Mediterranean in spite of a mismatch in the subsurface chlorophyll maximum depth between model and measurements. Model values were not corrected to match data, and we are therefore conscious that the uncertainties in the representation of present–day biogeochemistry by the PISCES model may be propagated in the future.

In the PISCES version used in this study, nitrate and phosphate concentration variations are linked by the Redfield ratio (Redfield et al., 1963). The Redfield hypothesis of a fixed nutrient ratio used for plankton growth and excretion holds true for most parts of the global ocean, but may not be true for oligotrophic regions such as the Mediterranean Sea (e.g. Béthoux and Copin-Montégut, 1986). Moreover, changes in nutrient balance influence the nutrient limitations as shown by Figure 12. The results simulated with the Redfieldian hypothesis are coherent with the observed variations of nutrient supply to the Mediterranean Sea and yield realistic biological productivity. But results concerning nutrient limitations might change in a non Redfieldian biogeochemistry model.

4.4 Climate versus biogeochemical ~~forcing~~ changes effects

Figure 18 summarizes the fluxes of phosphate and nitrate in and out of the Mediterranean considered in this study.

In general, the sum of nitrogen net fluxes into the Mediterranean basin (Riverine, Gibraltar Strait and sedimentary sources and sinks) increases by 39 % at the end of the century in the scenario (HIS/A2) whereas it is increased by 23 % in the control (CTRL) in comparison to the beginning of the simulation (1980). The balance between inputs and outputs of phosphorus increases by 9 % in the scenario and by 11 % in the control (net gain of phosphorus in the basin). These results suggest a significant accumulation of nitrogen in the Mediterranean basin over the century when phosphorus fluxes can be considered roughly stable. The strong decrease in sedimentation (Figure 6) occurring in spite of an enhancement in nutrient flux, coming from the Atlantic and an enhanced nitrate river flux may be linked to the decrease in vertical water fluxes. This would explain the accumulation of phosphate and nitrate in the deep layers of the Mediterranean Sea (Figures 7c, 7f,8c and 8f). The difference between HIS/A2 and CTRL_RG phosphate concentrations (Figure 7) indicates that the variations of phosphate concentrations during the 21st century are primarily linked with climate change whereas nitrate concentration seems equally sensitive to changes in biogeochemical forcings.

To our knowledge, this is the first attempt to study the basin–scale biogeochemical evolution using a transient business–as–usual (A2) climate change scenario. Lazzari et al. (2014) tested the effects of several land–use change scenarios on the A1B SRES climate change scenario over 10–years ~~tie~~ time slices. They found a general decrease in ~~plankton biomass~~ phytoplankton and zooplankton biomasses (about 5 %) that is lower than in our severe climate change scenario. ~~They~~ In our simulations, average phytoplankton biomass decreases by about 2 to 30 % (see Figure 15 and average zooplankton biomass decreases by about 8 and 12 % (see Figure 16. However, our transient simulations revealed non linear trends in plankton biomass evolution. Lazzari et al. (2014) also conclude that the river mouth regions are highly sensitive because the Mediterranean Sea is influenced by external nutrient inputs. Our results show the same sensitivity of the Mediterranean to external nutrient inputs. Herrmann et al. (2014) studied the transient biogeochemical evolution of the northwestern Mediterranean Sea under the A2 and A1B scenarios with the coupled ECO3M–S/SYMPHONIE model. But they used present–day conditions for biogeochemical forcings, as did Macias et al. (2015). Results from Herrmann et al. (2014) indicate that chlorophyll ~~production~~ concentration and plankton biomass in the northwestern Mediterranean increase slightly as a result of vertical stratification. Our results indicate that the contrasting effects of vertical stratification ~~and changes in biogeochemical forcings~~ biogeochemical changes may lead to a decrease in chlorophyll concentration, phytoplankton and zooplankton biomass content of up to 50 % locally and between 2 and ~~plankton biomass production~~ 30 % at the basin scale ~~.~~ as indicated by Figures 14, 15 and 16. The modifications of chlorophyll production and plankton biomass are linked to changes in nutrient limitation (Figure 12). Our finding that most of the Mediterranean basin is N and P co–limited seems in contrast with previous literature on the matter (see Krom et al., 2004, 2010; Pujo-Pay et al., 2011, and references therein) . These authors found from analyses of the N:P ratio of the waters a clear phosphorus limitation in the major part of the Mediterranean. The discrepancy between our results and literature estimates comes from the way we calculate nutrient limitations. Considering how low nutrient concentrations are in the Mediterranean and how low the nutrient limitation factors are, the small difference between the limitation factors indicate that the Mediterranean is both limited in P and N. Finding no clear definition of nutrient co–limitation, we propose to consider that N and P are co-limiting when the difference in limitation factors is less than 1 %. This definition of nutrient co–limitation applies well to the Mediterranean case because of the very low nutrient concentrations. Chust et al. (2014) have shown that regional seas and in particular the Aegean and Adriatic were sensitive to trophic amplification. Our results seem to agree with these conclusions by showing sign of trophic amplification (see Figures 15 and 16). Finally, Luna et al. (2012) hypothesise that the warm temperature of the deep Mediterranean may be a cause for important nutrient recycling via prokaryotic metabolism. In the version of PISCES used in this study, nutrient recycling is dependant on oxygen, depth, plankton biomass and bacterial activity. Therefore, we could not observe the effects of temperature on nutrient recycling.

Results from our different control simulations indicates the extent to which the choice of the biogeochemical forcing scenario may influence the future evolution of the Mediterranean Sea biogeochemistry. In particular, nutrient inputs ~~at~~ through the Strait of Gibraltar have substantial consequences on the western basin. Results from Figures 7a and 8a and Table 4 indicate that the increase in nutrient inputs through the Strait of Gibraltar at the end of the century is responsible for a 2.5 % increase in chlorophyll concentration in the western basin during the 2080–2099 period. Moreover, climate and nutrient forcing changes may have contrasting influences on the Mediterranean Sea biogeochemistry. Stratification may lead to increased productivity in the surface because of the nutrient concentration increase (see also Macias et al., 2015), while decreasing coastal discharges of phosphate may decrease the productivity in the basin.

Conclusion

This study aims at assessing the transient effects on of climate and biogeochemical changes on the Mediterranean Sea biogeogeochemistry from climate and biogeochemical forcings under the under the high–emission IPCC A2 climate change scenario. The NEMOMED8/PISCES model adequately reproduces the main characteristics of the Mediterranean Sea: the west–to–east gradient of productivity, the main productive zones and the presence of a DCM, in spite of certai shortcomings. Hence. Hence, it appears reasonable to use it to study the future evolution of the biogeochemistry of the Mediterranean basin in response to increasing atmospheric CO_2 and resulting climate change. For the first time, we performed a continuous simulation over the entire period of the future IPCC scenario (A2), between 1980 and 2099.

This study illustrates how future changes in physical and biogeochemical conditions, including warming, increased stratification, and changes in Atlantic and river inputs, can lead to a significant accumulation of nitrate and a decrease in biological productivity in the surface, thus affecting the entire Mediterranean ecosystem.

Our results also illustrate how variations of the Mediterranean Sea biogeochemistry can be influenced by external nutrient inputs and that climate change and nutrient discharges inputs from riverine sources and fluxes through the Strait of Gibraltar have contrasted influences on the Mediterranean Sea productivity. In particular, the biogeochemistry in the western basin displays similar nutrient trends as does its input across the Strait of Gibraltar. Therefore, it appears critical to correctly represent the future variations of external biogeochemical forcings of the Mediterranean Sea as they may have equally important influence on biogeochemical cycles as climate. The eastern basin receives less nutrients from the Atlantic. As a consequence, its biogeochemistry biogeochemistry of the eastern basin is more sensitive to vertical mixing and river inputs than the western basin (that receives regulating effects from exchanges through the Strait of Gibraltar) and the stratification observed in the future leads to a steep reduction in surface productivity.

Finally, this study accounts for the changes in all external biogeochemical forcings except fluxes through the Strait of Gibraltar and riverine inputs, but some potentially important sources are missing such as direct wastewater discharge, submarine groundwater and atmospheric deposition. However, Richon et al. (2017, 2018) showed that atmospheric deposition can account for up to 80 % of phosphate supply in some Mediterranean Sea regions and has significant impacts on surface productivity. We did not include atmospheric deposition in this study because Measurements and models are still missing in order to include comprehensive datasets for past and future evolution of these nutrient sources. The HIS/A2_N and HIS/A2_NALADIN simulations presented in the discussion section include continued present–day nitrogen and phosphate deposition. Although these atmospheric fluxes have been evaluated previously and were shown to represent correctly the deposition fluxes, there is no guarantee that these fluxes are going to remain constant over the next century. Results showed that the future sensitivity of the Mediterranean to atmospheric deposition depends on the surface nutrient limitations. However, there is to our knowledge no available transient scenario for the 21st century evolution of atmospheric deposition . But this nutrient source may be subject to important changes in the future and no ensemble simulations to assess the future evolution of the Mediterranean Sea under different climate change scenarios. A new generation of fully coupled regional models have been developed and used to study aerosols climatic impacts (Nabat et al., 2015). These models include a representation of the ocean, atmosphere, aerosols and rivers and should be used to perform consistent future climate projections consistent at the Mediterranean regional scale.

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Appendix A: Evaluation of the NEMOMED8/PISCES model

The comparison of modeled surface chlorophyll–*a* concentration with satellite estimates has revealed that the model correctly simulates the main characteristics observed in the Mediterranean Sea (Figure 1 Figures 1 and 2). Comparison with in situ observation provides more refined estimates.

Figure A1 presents the average chlorophyll–a profiles at the DYFAMED station (43.25°N, 7.52°E) compared with measured concentrations for the month of February (low stratification, high productivity) and June (high stratification, low productivityMay (end of spring bloom, beginning of stratification and DCM appearance). There are few data points below 200 m. The model produces the characteristic of the deep chlorophyll maximum generated in JuneMay, even if its depth is too important. The colors show that the model represents some interannual variability in chlorophyll production in spite of the consistent bias.

The vertical overestimation of the DCM depth may be due to the overestimation of nitracline and phosphacline as shown by figure A2. This Figure shows the vertical profiles of nitrate and phosphate at the DYFAMED station in May, colors represent the different years in the model and in the observation.

The vertical distribution of nitrate and phosphate concentrations along a West–to–East transect is showed shown in Figure A3. The model produces the salient West–to–East gradient of nutrient concentrations. Concentrations in the surface layer seem correctalthough the nutricline . The nutricline is located 100 to 150 m deep in the western basin and deepens around 180 to 200 m in the eastern basin. Although the model represents the spatial variability of the nutricline, it is too smooth, leading to the underestimated underestimation of deep water concentrations . (by about 30 to 50 %).

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Name	Dynamics (NEMO years)	Buffer zone concentrations	River inputs
CTRL	1966–1981	1966–1981	1966–1981
CTRL_R	1966–1981	1966–1981	1980–2099
CTRL_RG	1966–1981	1980–2099	1980–2099
HIS/A2	1980–2099	1980–2099	1980–2099

Table 1. Description of the simulations. The years indicate the forcing years throughout the 120 years of simulation. The cycles are repeated in the CTRL simulations.

Simulation	Period	Whole Med.	Western	Eastern	Ionian-Levantine	Adriatic	Aegean	Atlantic buffer zor
	1980–1999	551	241	310	305	1.5	4.0	535
HIS/A2	2030–2049	570 (+3.4)	240 (0)	329 (+6.1)	324 (+6.2)	1.4 (0)	3.6 (-10)	543 (+1.5)
	2080–2099	598 (+8.5)	251 (+4.1)	346 (+11.6)	341 (+11.8)	1.5 (0)	3.5 (-12.5)	562 (+5.0)
	1980–1999	545	238	307	302	1.6	4.0	532
CTRL	2030–2049	553 (+1.5)	238 (0)	314 (+2.3)	309 (+2.3)	1.6 (0)	4.2 (+5.0)	532 (0)
	2080-2099	560 (+2.6)	241 (+1.3)	319 (+3.9)	313 (+3.6)	1.7 (+6.3)	4.2 (+5.0)	532 (0)
	1980–1999	547	239	309	303	1.5	4.2	534
CTRL_R	2030-2049	536 (-2.0)	232 (-2.9)	304 (-1.6)	299 (-1.3)	1.4 (-6.7)	3.5 (-17)	534 (0)
	2080-2099	538 (-1.6)	230 (-3.8)	309 (0)	303 (0)	1.5 (0)	3.7 (-12)	534 (0)
	1980–1999	548	239	309	303	1.5	4.2	535
CTRL_RG	2030–2049	536 (-2.2)	233 (-2.5)	303 (-1.9)	298 (-1.7)	1.4 (-6.7)	3.5 (-17)	544 (+1.7)
	2080–2099	540 (-1.5)	235 (-1.7)	306 (-1.0)	301 (-0.7)	1.4 (-6.7)	3.6 (-14)	562 (+5.0)

Table 2. Simulated integrated phosphate content (10^9 mol) over 20 years periods in the Mediterranean sub–basins in the different simulations. Basins are the same as defined in Fig.2 of Adloff et al. (2015), with the eastern basin including the Ionian, Levantine, Adriatic and Aegean subbasins. Values in parenthesis indicate the percentage difference from the 1980–1999 period.

1240

Simulation	Period	Whole Med.	Western	Eastern	Ionian-Levantine	Adriatic	Aegean	Atlantic buffer z
	1980–1999	13400	5520	7890	7690	66.9	132	8091
HIS/A2	2030–2049	13800 (+3.0)	5450 (-1.3)	8350 (+5.8)	8100 (+5.3)	88.5 (+32)	163 (+23)	8230 (+1.7)
	2080–2099	14700 (+9.7)	5750 (+4.2)	8920 (+13)	8650 (+12)	98.3 (+47)	164 (+24)	8510 (+5.2)
	1980–1999	13500	5530	7970	7760	66.2	144	8050
CTRL	2030–2049	12900 (-4.4)	5320 (-3.8)	7610 (-4.5)	7420 (-4.4)	61.7 (-6.8)	131 (-9.0)	8050 (0)
	2080-2099	12500 (-7.4)	5170 (-6.5)	7330 (-8.0)	7150 (-7.9)	58.7 (-11)	123 (-15)	8050 (0)
	1980–1999	13300	5470	7870	7760	66.8	138	8070
CTRL_R	2030-2049	13300 (0)	5250 (-4.0)	8020 (+1.9)	7770 (+0.1)	88.0 (+32)	162 (+17)	8070 (0)
	2080-2099	13700 (+3.0)	5300 (-3.1)	8440 (+7.2)	8170 (+5.3)	94.2 (+41)	177 (+28)	8080 (+0.1)
	1980–1999	13300	5480	7870	7760	66.8	138	8090
CTRL_RG	2030–2049	13300 (0)	5270 (-3.8)	8010 (+1.8)	7760 (0)	88.0 (+32)	162 (+17)	8080 (-0.1)
	2080–2099	13800 (+3.8)	5390 (-1.6)	8430 (+7.1)	8160 (+5.2)	94.3 (+41)	177 (+28)	8080 (-0.1)

Table 3. Simulated integrated nitrate content (10^9 mol) over 20 years periods in the Mediterranean sub–basins in the different simulations. Basins are the same as defined in Fig.2 of Adloff et al. (2015), with the eastern basin including the Ionian, Levantine, Adriatic and Aegean subbasins. Values in parenthesis indicate the percentage difference from the 1980–1999 period.

Simulation	Period	Whole Med.	Western	Eastern	Ionian-Levantine	Adriatic	Aegean	Atlantic buffer
	1980–1999	25700	9680	16000	13500	830	1720	3210
HIS/A2	2030–2049	23800 (-7.4)	8980 (-7.2)	14800 (-7.5)	12700 (-5.9)	720 (-13)	1440 (-16)	3280 (+2.2)
	2080–2099	23400 (-8.9)	9180 (-5.1)	14300 (-11)	12200 (-9.6)	690 (-17)	1390 (-19)	3570 (+11)
	1980–1999	27000	10200	16700	14200	880	1670	3180
CTRL	2030–2049	27000 (0)	10200 (0)	16900 (+1.2)	14300 (+0.7)	890 (+1.1)	1710 (+2.4)	3180 (0)
	2080–2099	26600 (-1.5)	9980 (-2.2)	16600 (-0.1)	14000 (-1.4)	880 (0)	1690 (+1.2)	3180 (0)
	1980–1999	27000	10300	16700	14100	875	1720	3210
CTRL_R	2030–2049	26800 (-0.7)	10100 (-1.9)	16700 (0)	14300 (+1.4)	780 (-12)	1610 (-6.4)	3210 (0)
	2080-2099	26400 (-2.2)	9940 (-3.5)	16500 (-1.2)	14100 (0)	760 (-13)	1600 (-7.0)	3220 (0.3)
	1980–1999	27000	10300	16700	14100	875	1720	3230
CTRL_RG	2030–2049	26900 (-0.4)	10200 (-1.0)	16700 (0)	14300 (+1.4)	780 (-12)	1600 (-7.0)	3260 (+0.9)
	2080–2099	26700 (-1.1)	10200 (-1.0)	16500 (-1.2)	14100 (0)	750 (-14)	1600 (-7.0)	3420 (+5.9)

Table 4. Simulated integrated chlorophyll production (10^9 mol) over 20 years periods in the Mediterranean sub–basins in the different simulations. Basins are the same as defined in Fig.2 of Adloff et al. (2015), with the eastern basin including the Ionian, Levantine, Adriatic and Aegean subbasins. Values in parenthesis indicate the percentage difference from the 1980–1999 period.

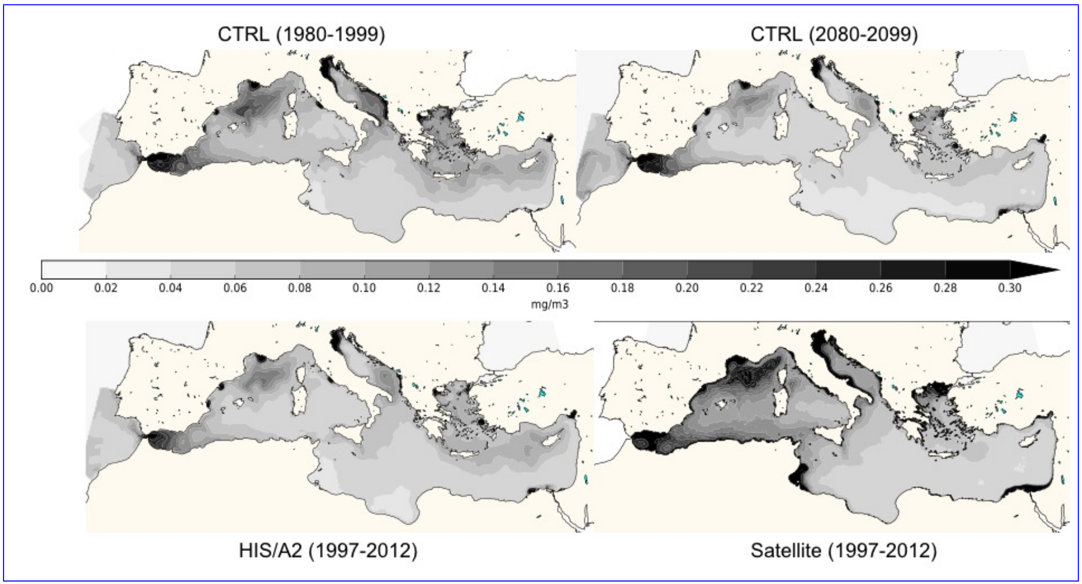


Figure 1. Average surface chlorophyll concentration from the CTRL (top, left: 1980–1999 right: 2080–2099) and HIS/A2 (bottom left) simulations, and from satellite estimations (MyOcean Dataset 1997–2012, bottom right).

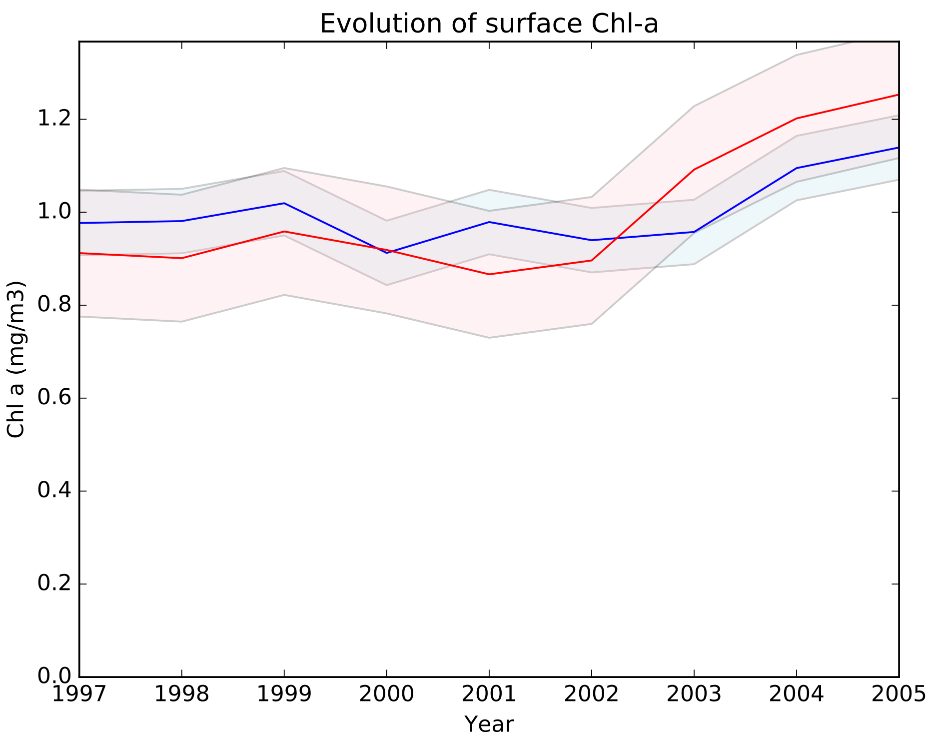
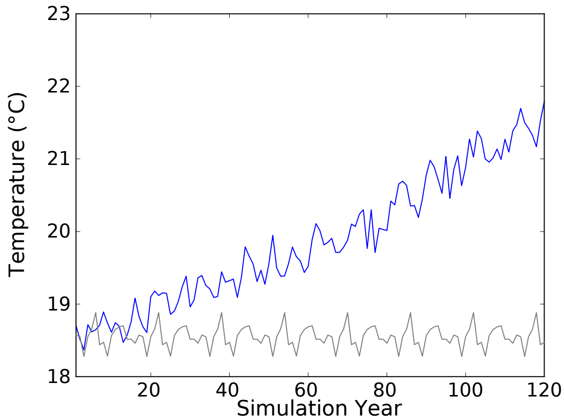
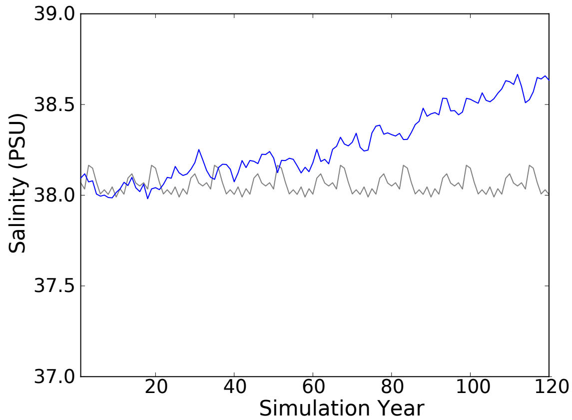


Figure 2. Average surface chlorophyll concentration from the HIS/A2 simulation in blue and from the SeaWiFs satellite data (Bosc et al., 2004) in red over the period 1997–2005. Shaded colors represent the standard deviations. Values are normalized by dividing by the average cholorphyll concentration over the period.

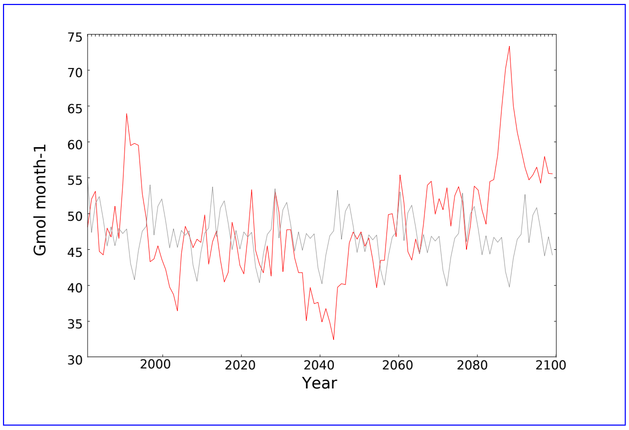


(a) Average Mediterranean SST

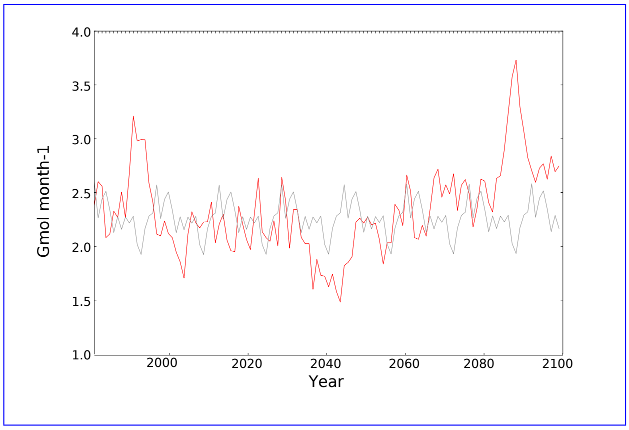


(b) Average Mediterranean SSS

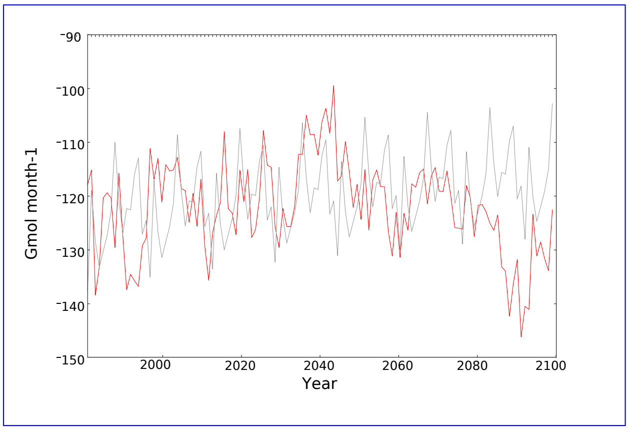
Figure 3. Evolution of average Mediterranean SST (left) and SSS (right) in CTRL (grey line) and HIS/A2 (blue line) simulations.



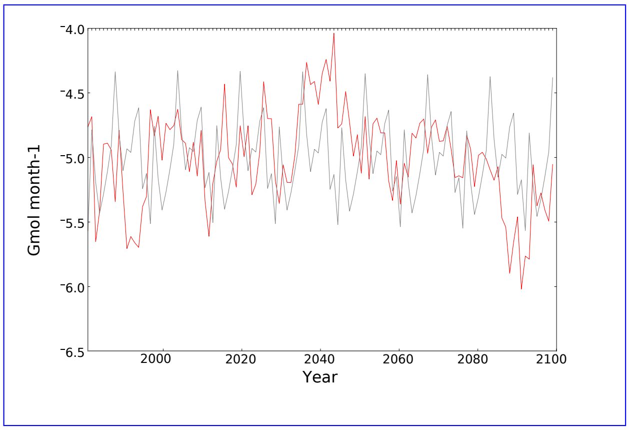
(a) Total incoming nitrate



(b) Total incoming phosphate

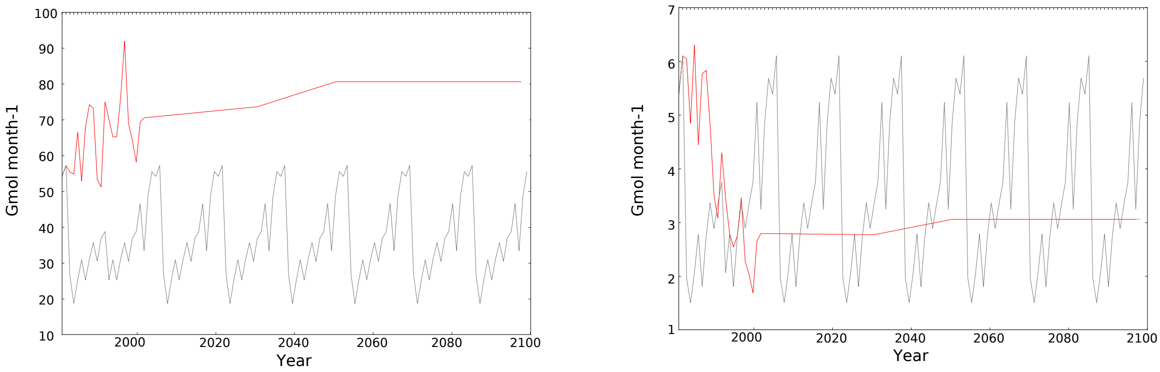


(c) Total outgoing nitrate



(d) Total outgoing phosphate

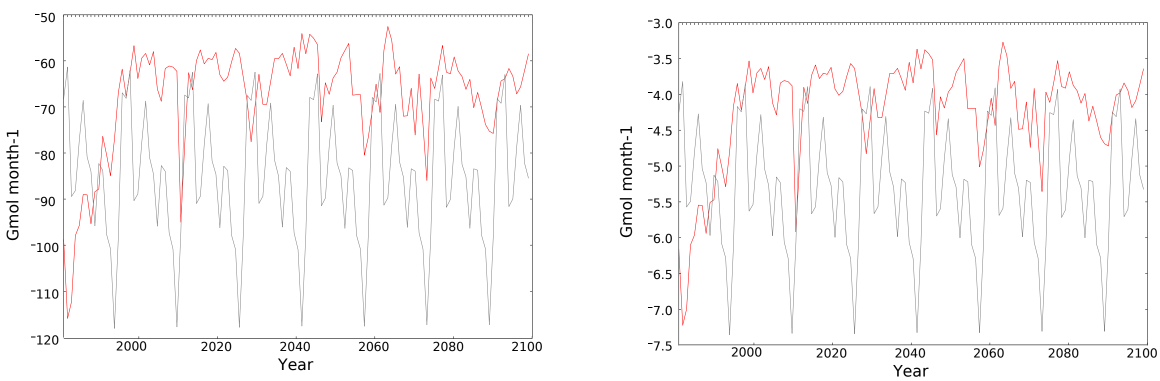
Figure 4. Evolution of total incoming (top) and outgoing (bottom) fluxes of nitrate and phosphate (10^9mol month^{-1}) through the Strait of Gibraltar in CTRL (grey line) and HIS/A2 (red line). Negative values indicate outgoing fluxes of nutrients.



(a) Total river discharge of nitrate

(b) Total river discharge of phosphate

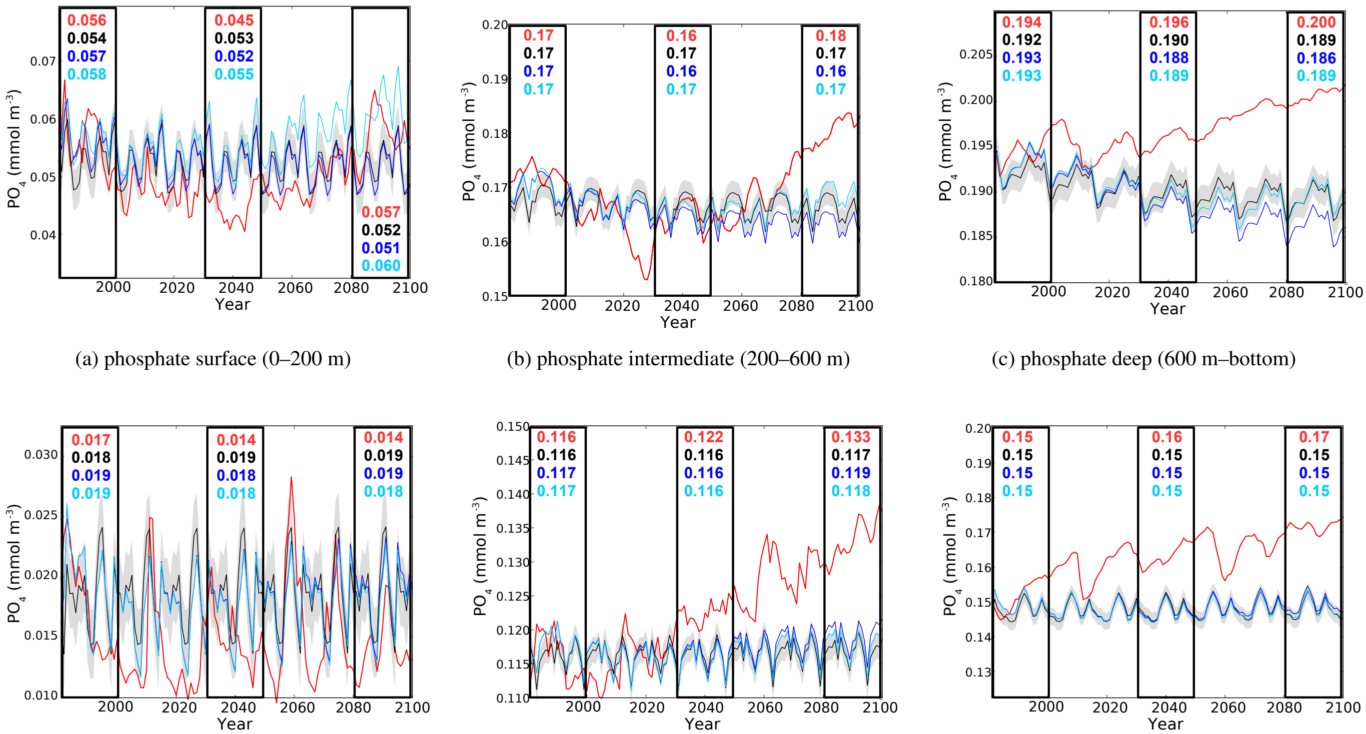
Figure 5. Evolution of total river discharge fluxes of nitrate and phosphate (10^9mol month^{-1}) to the Mediterranean Sea in CTRL (grey line) and HIS/A2 (red line).



(a) Total nitrogen sedimentation

(b) Total phosphorus sedimentation

Figure 6. Evolution of total sedimentation fluxes of N and P (10^9mol month^{-1}) in the Mediterranean Sea in CTRL (grey line) and HIS/A2 (red line). Negative fluxes indicate that the nutrients are exiting the Mediterranean waters.



(a) phosphate surface (0–200 m)

(b) phosphate intermediate (200–600 m)

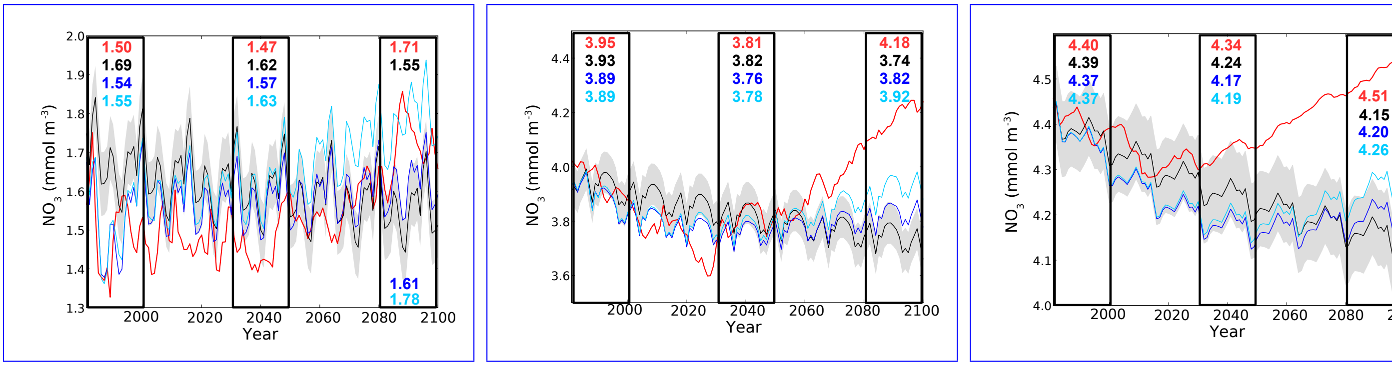
(c) phosphate deep (600 m–bottom)

(d) phosphate surface (0–200 m)

(e) phosphate intermediate (200–600 m)

(f) phosphate deep (600 m–bottom)

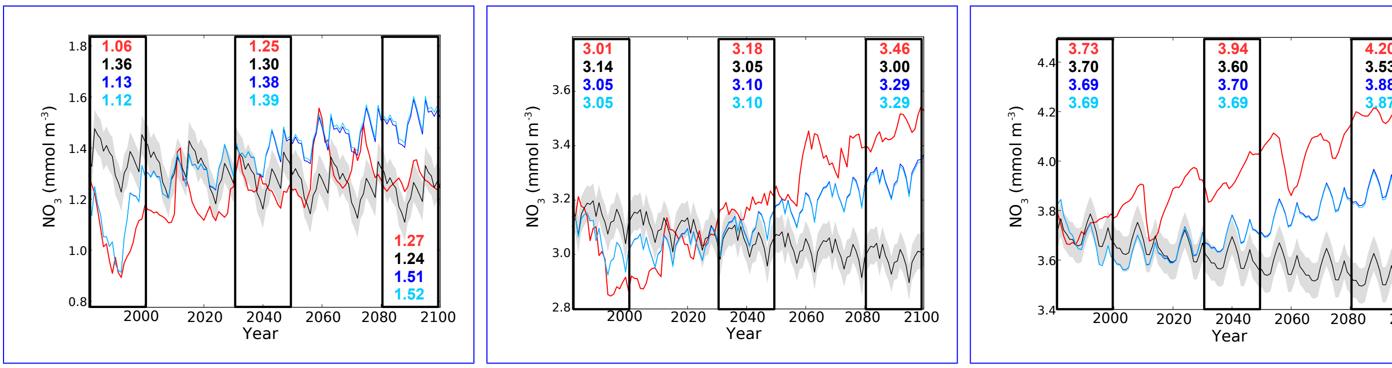
Figure 7. Evolution of yearly average phosphate concentration (10^{-3}mol m^{-3}) in the surface (left), intermediate (middle) and bottom (right) layers in the western (top) and eastern (bottom) basin. ~~Black line~~ Red lines represent the HIS/A2 simulation, ~~grey dashed line~~ black lines represent the CTRL (with standard deviation), ~~dashed~~ blue and ~~green~~ light blue lines represent the CTRL_R and CTRL_RG simulations respectively. Colored numbers in the highlighted areas represent the average concentrations in the corresponding simulations for the highlighted time periods.



(a) nitrate surface (0–200 m)

(b) nitrate intermediate (200–600 m)

(c) nitrate deep (600 m–bottom)

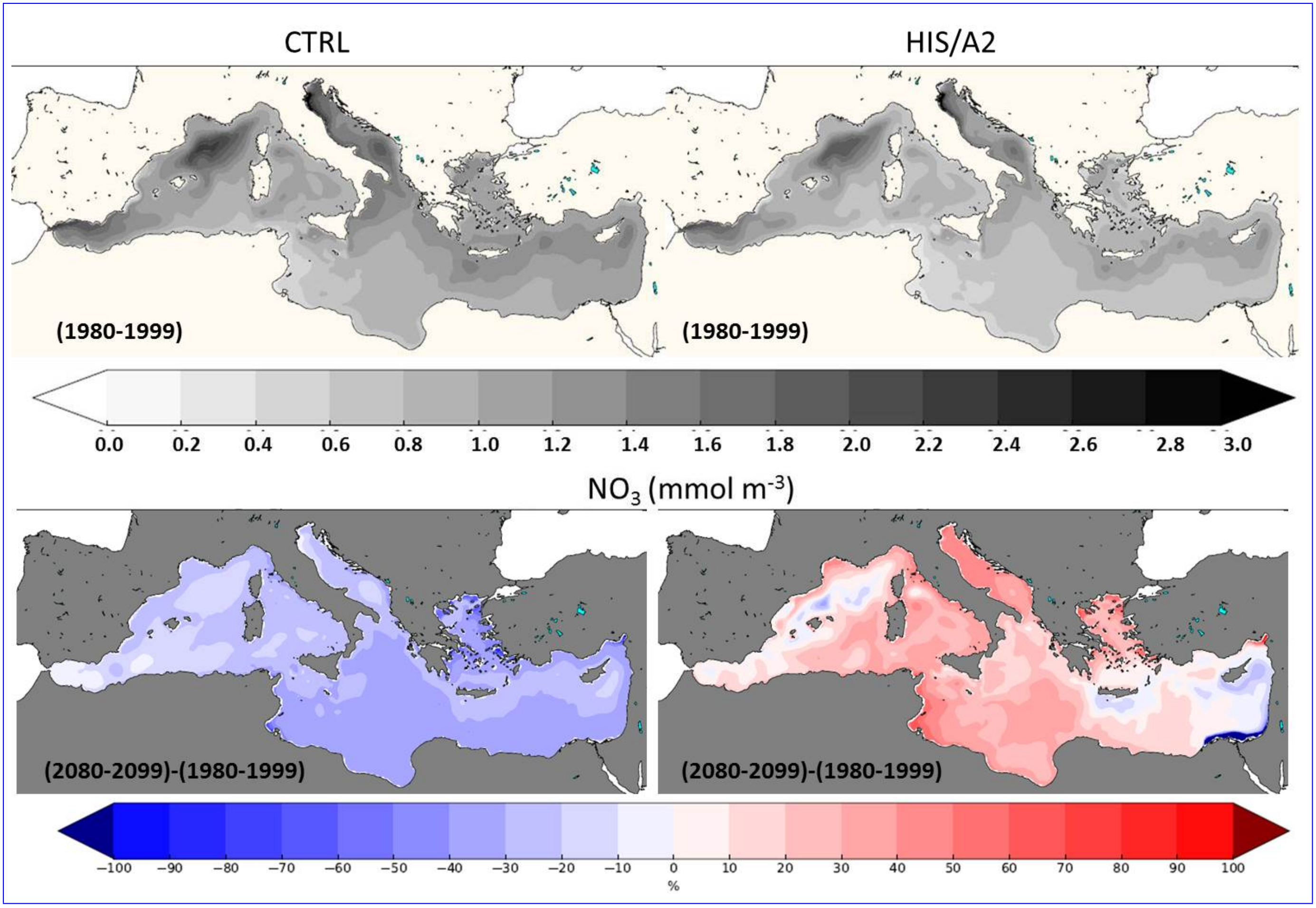


(d) nitrate surface (0–200 m)

(e) nitrate intermediate (200–600 m)

(f) nitrate deep (600 m–bottom)

Figure 8. Evolution of yearly average nitrate concentration (10^{-3}mol m^{-3}) in the surface (left), intermediate (middle) and bottom (right) layers in the western (top) and eastern (bottom) basins. ~~Black line~~ Red lines represent the HIS/A2 simulation, ~~grey dashed line~~ black lines represent the CTRL (with standard deviation), ~~dashed~~ blue and ~~green~~ light blue lines represent the CTRL_R and CTRL_RG simulations respectively. Colored numbers in the highlighted areas represent the average concentrations in the corresponding simulations for the highlighted time periods.



Evolution of total river discharge fluxes of nitrate and phosphate (10^9mol month^{-1}) to The bottom maps show the Mediterranean Sea in CTRL relative difference (grey linein %) between the 2080–2099 and HIS/A2 (red line).

Evolution of total sedimentation fluxes of N and P (10^9mol month^{-1}) in the Mediterranean Sea 1980–1999 periods in CTRL (grey lineleft) and HIS/A2 (red lineright).

Evolution of total river discharge fluxes of nitrate and phosphate (10^9mol month^{-1}) to The bottom maps show the Mediterranean Sea in CTRL relative difference (grey linein %) between the 2080–2099 and HIS/A2 (red line).

Evolution of total sedimentation fluxes of N and P (10^9mol month^{-1}) in the Mediterranean Sea 1980–1999 periods in CTRL (grey lineleft) and HIS/A2 (red lineright).

Figure 9. Evolution of total Gibraltar incoming Present (1980–1999, top) and outgoing interannual average surface (bottom0–200 m) fluxes concentrations of nitrate and phosphate (10^{9-3}mol month^{-1}m^{-3}) in the CTRL (grey lineleft) and HIS/A2 (red lineright) simulations. Negative values indicate outgoing fluxes of nutrients. Evolution of total river discharge fluxes of nitrate and phosphate (10^9mol month^{-1}) to The bottom maps show the Mediterranean Sea in CTRL relative difference (grey linein %) between the 2080–2099 and HIS/A2 (red line).
Evolution of total sedimentation fluxes of N and P (10^9mol month^{-1}) in the Mediterranean Sea 1980–1999 periods in CTRL (grey lineleft) and HIS/A2 (red lineright).

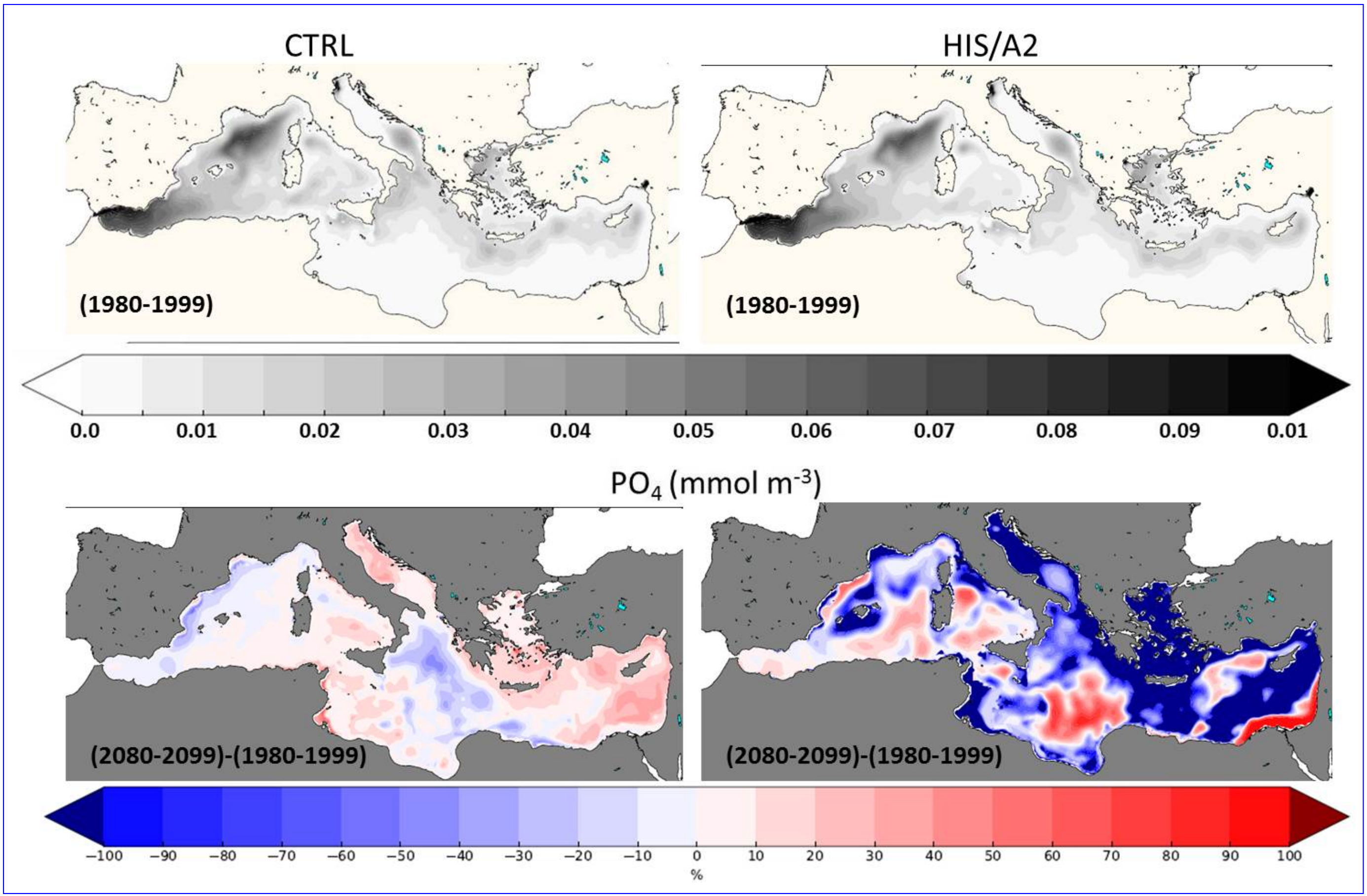


Figure 10. Present (1980–1999, ~~left~~top) ~~and future (2080-2099, right)~~ interannual average surface (~~0–200 m~~0–200m) concentrations of ~~nitrate~~ phosphate (10^{-3}mol m^{-3}) in the CTRL (~~top~~left) and HIS/A2 (~~bottom~~right) simulations. ~~Present~~ The bottom maps show the relative difference (~~1980–1999, left~~in %) ~~and future (2080-2099, right) interannual average surface (0–200m) concentrations of phosphate (10^{-3}mol m^{-3})~~ in primary production between the 2080–2099 and the 1980–1999 periods in CTRL (~~top~~left) and HIS/A2 (right)~~simulations~~.

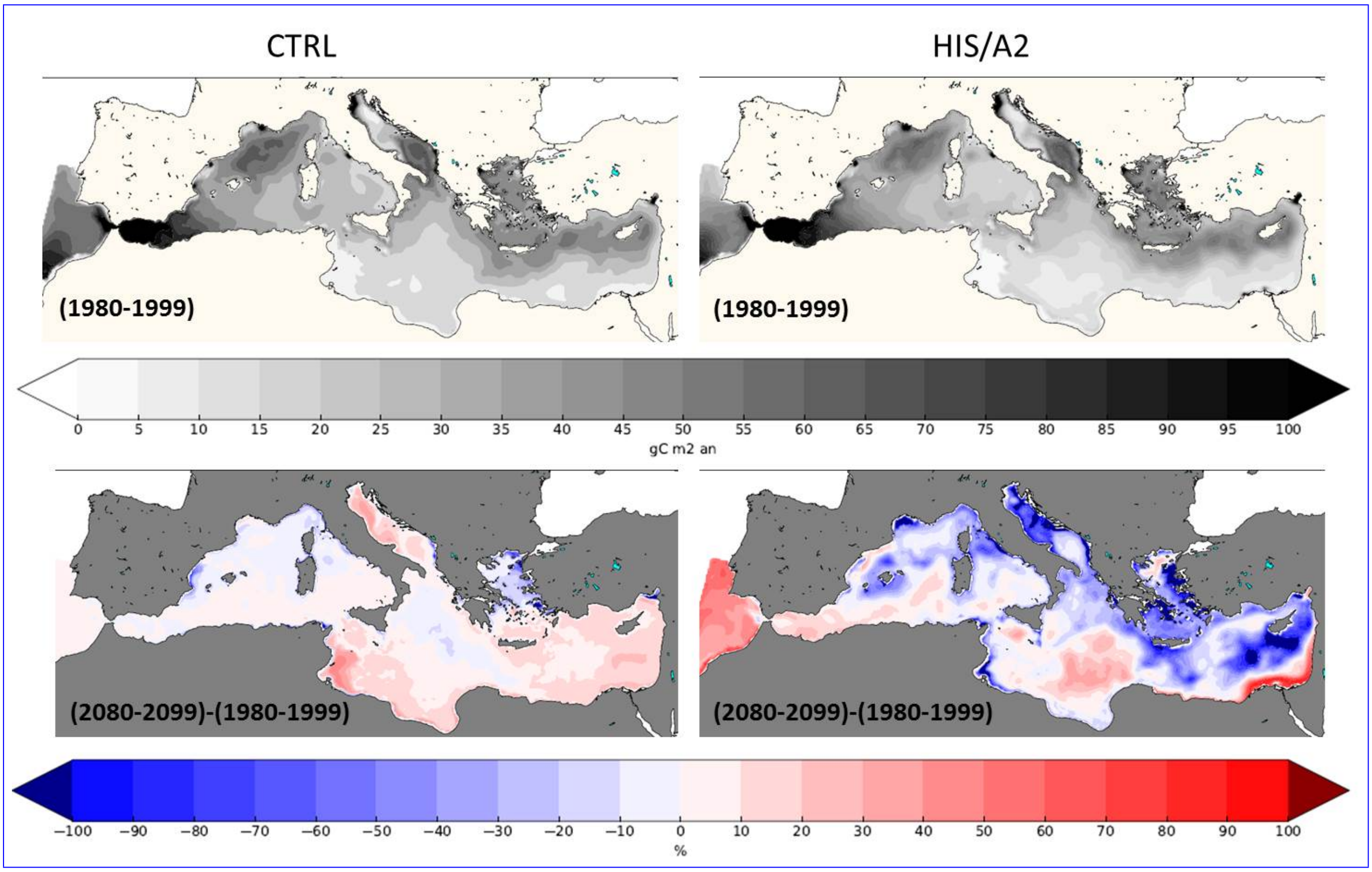


Figure 11. Present (1980–1999, ~~left~~top) ~~and future (2080-2099, right)~~ interannual average surface (0–200 m) integrated primary production (gC m^{-2}) in the CTRL (~~top~~left) and HIS/A2 (~~bottom~~right) simulations. The bottom maps show the relative difference (in %) between the 2080–2099 and the 1980–1999 periods in CTRL (left) and HIS/A2 (right).

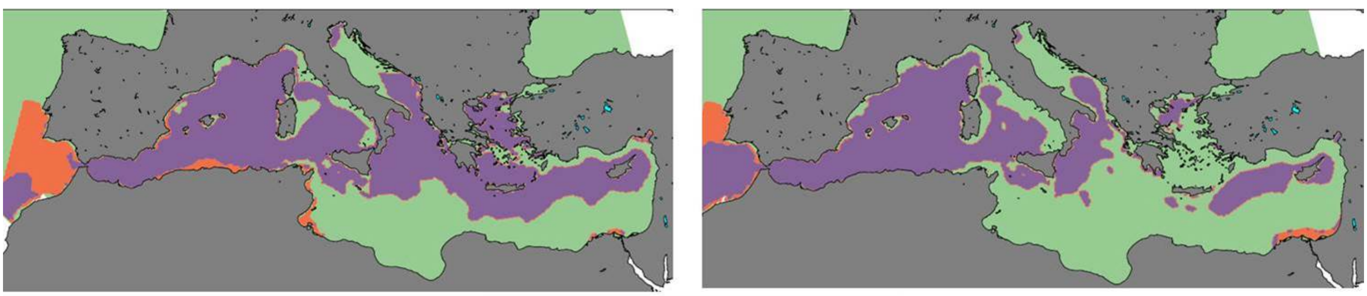


Figure 12. Present (1980–1999) and future (2080-2099) interannual average surface (0–200 m) limiting nutrient in the HIS/A2 simulation. N and P colimitation is considered when limitation factors for N and P differ by less than 1 %. Green zones are P–limited, Orange zones are N–Limited and purple zones are N and P co–limited.

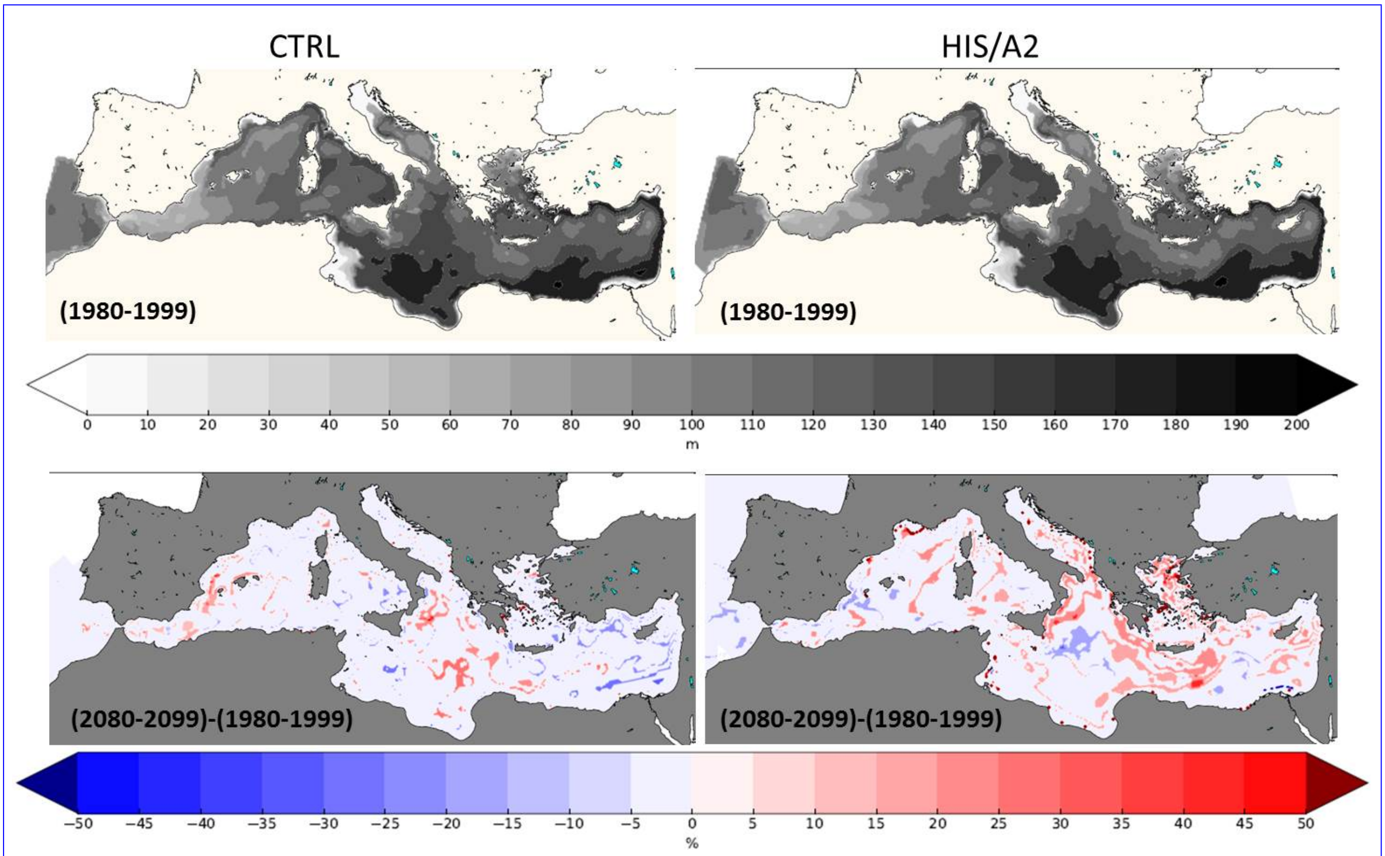
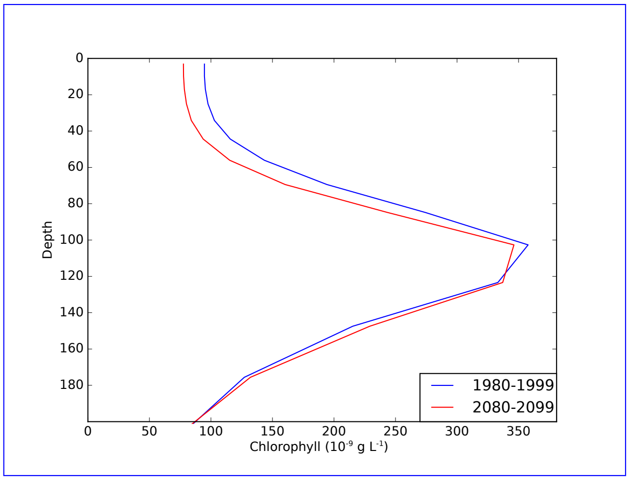
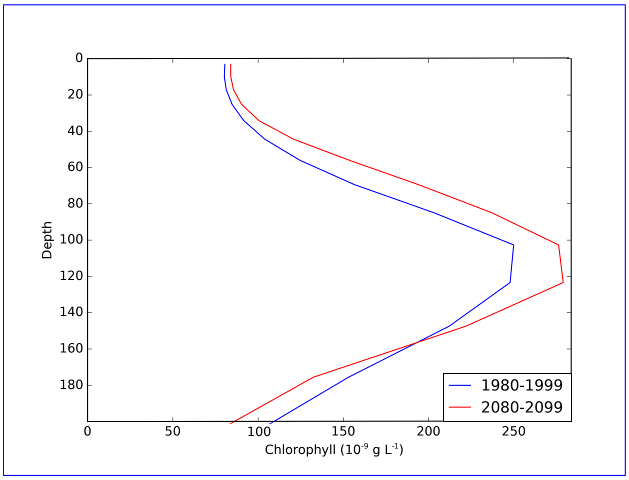


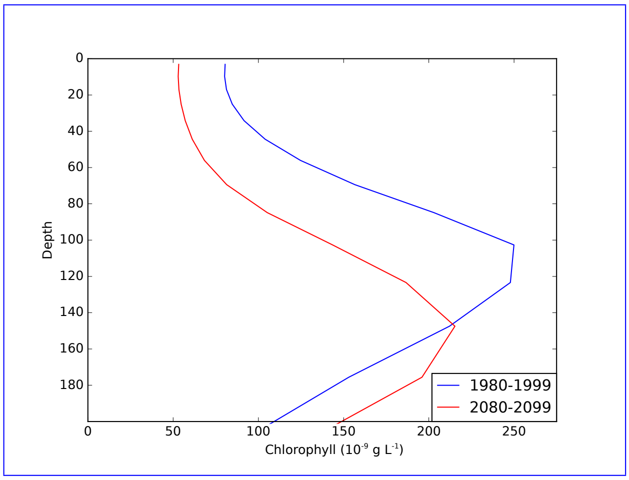
Figure 13. Present (~~left, ~~1980–1999~~) and future (right~~, ~~2080-2099~~top) interannual average ~~surface ~~DCM (~~0–200 ~~m) ~~DCM depth ~~in the ~~scenario simulation~~CTRL (left) and HIS/A2 (right) simulations. The bottom maps show the relative difference (in %) in DCM between the 2080–2099 and the 1980–1999 periods in CTRL (left) and HIS/A2 (right).



(a) DYFAMED

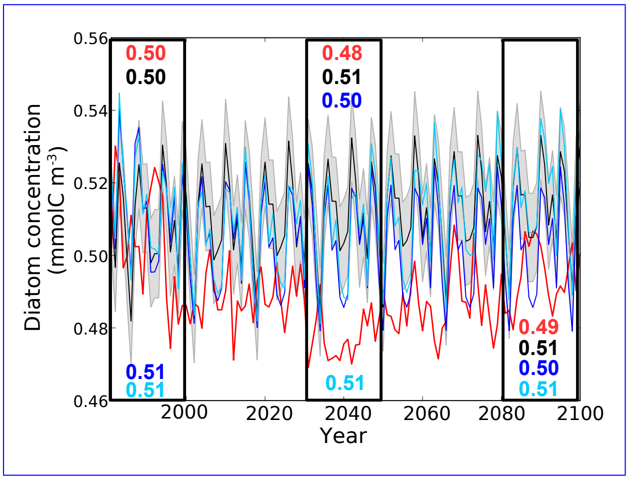


(b) Western basin

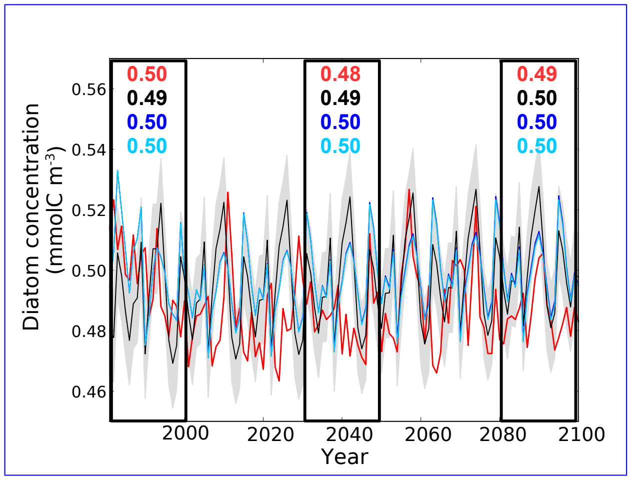


(c) Eastern basin

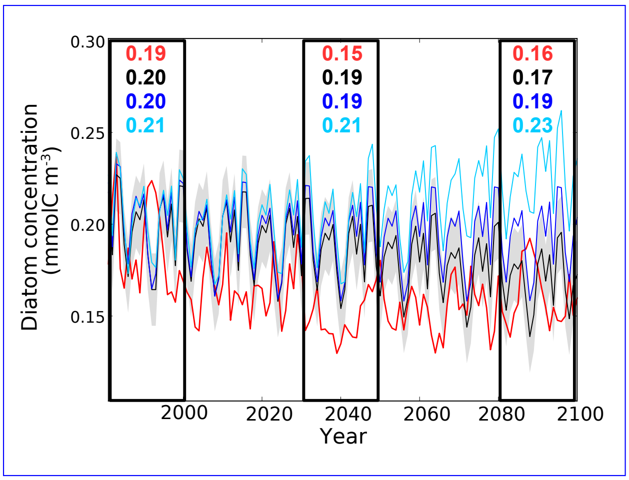
Figure 14. Present (1980–1999) and future (2080–2099) interannual average vertical profiles of total chlorophyll *a* (10e^{-3-9}g m^{-3}L^{-1}) at the DYFAMED station and averaged profiles over the western and eastern (including Aegean and Adriatic) basins.



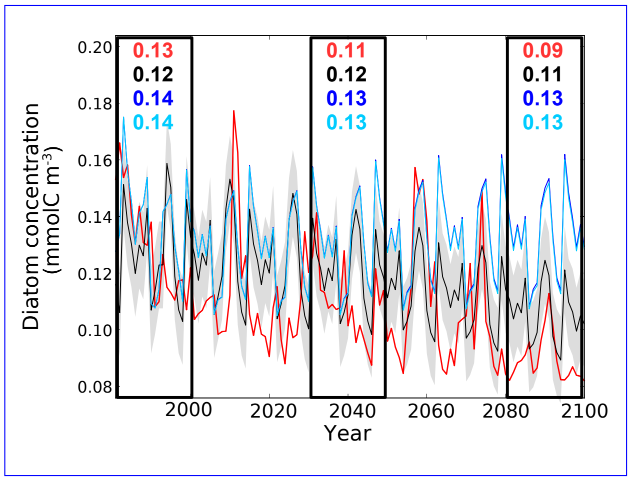
(a) Nanophytoplankton western basin



(b) Nanophytoplankton eastern basin

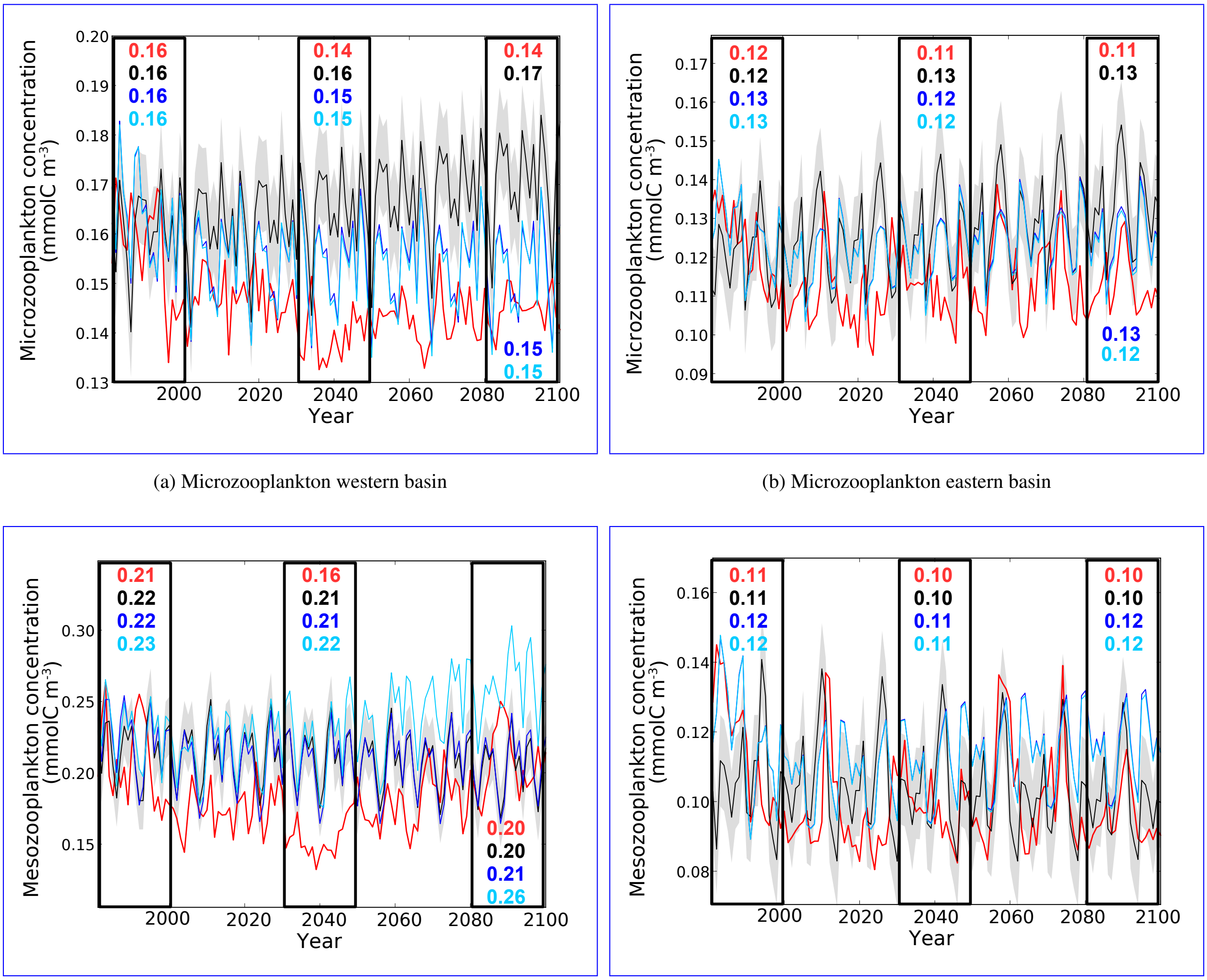


(c) Diatoms western basin



(d) Diatoms eastern basin

Figure 15. Evolution of yearly average nanophytoplankton and diatoms concentration (10^{-3}mol m^{-3}) in the surface layer of the western and eastern basin. ~~Black~~ Red line represent the HIS/A2 simulation, ~~grey dashed line~~ black lines represent the CTRL (with standard deviation), ~~dashed~~ blue and ~~green~~ light blue lines represent the CTRL_R and CTRL_RG simulations respectively. Colored numbers in the highlighted areas represent the average concentrations in the corresponding simulations for the highlighted time periods.



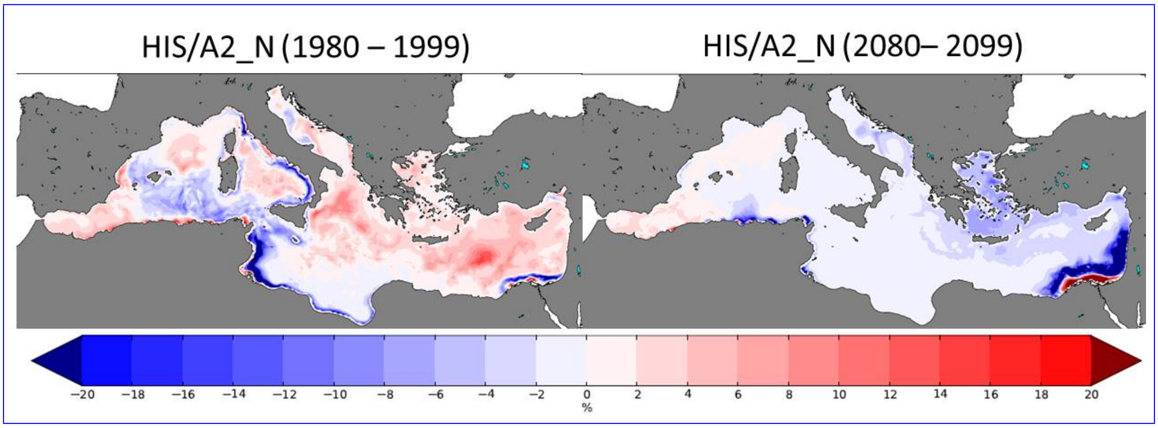
(a) Microzooplankton western basin

(b) Microzooplankton eastern basin

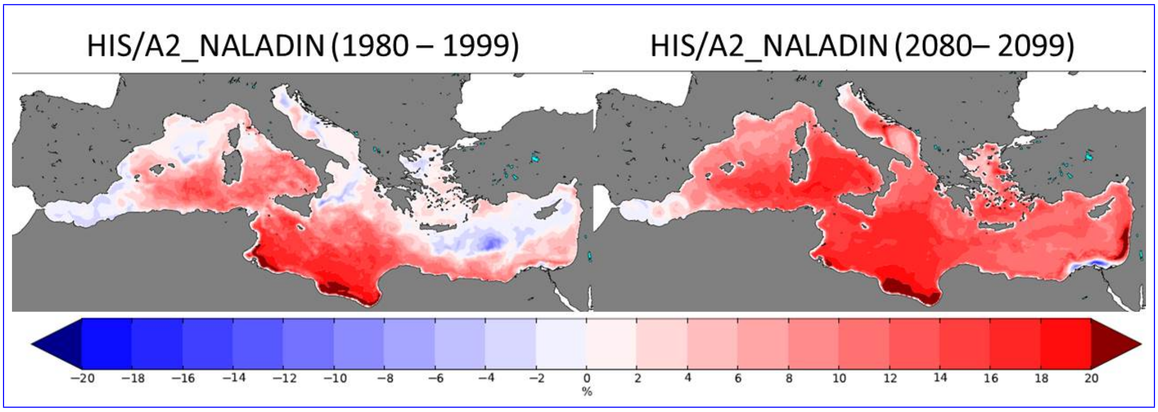
(c) Mesozooplankton western basin

(d) Mesozooplankton eastern basin

Figure 16. Evolution of yearly average microzooplankton and mesozooplankton concentrations (10^{-3}mol m^{-3}) in the surface layer of the western and eastern basins. ~~Black line~~ Red lines represent the HIS/A2 simulation, ~~grey dashed line~~ black lines represent the CTRL (with standard deviation), ~~dashed~~ blue and ~~green~~ light blue lines represent the CTRL_R and CTRL_RG simulations respectively. Colored numbers in the highlighted areas represent the average concentrations in the corresponding simulations for the corresponding time periods.

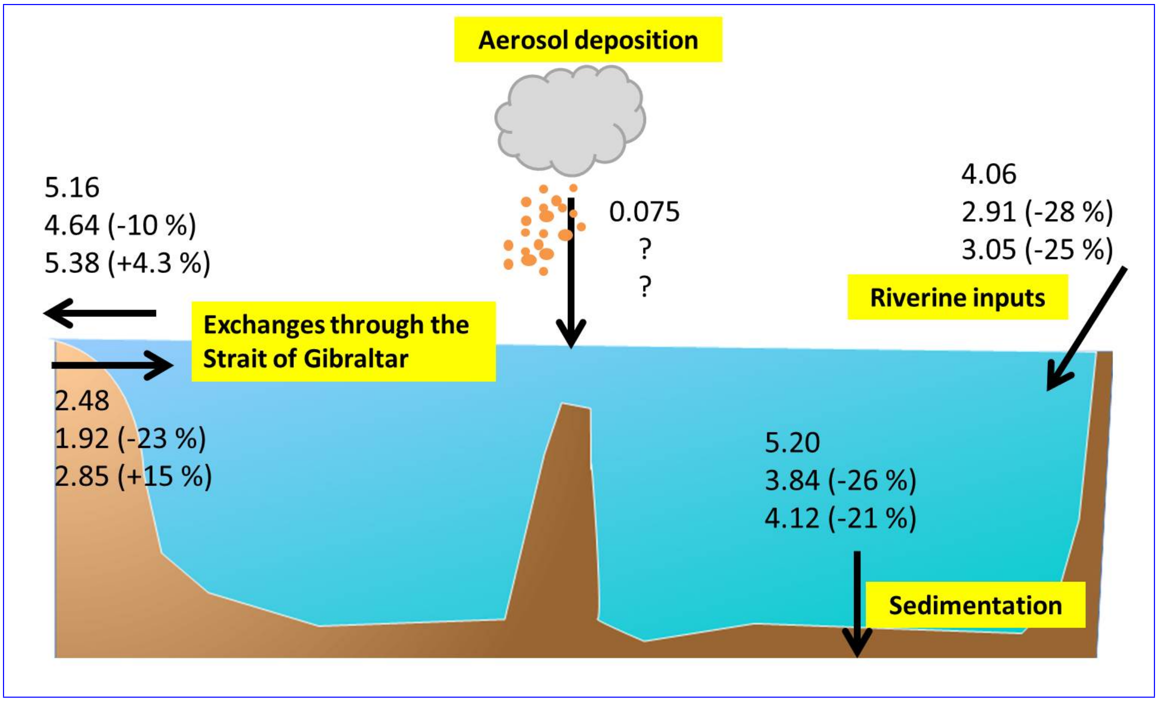


(a) Relative effects of total nitrogen deposition

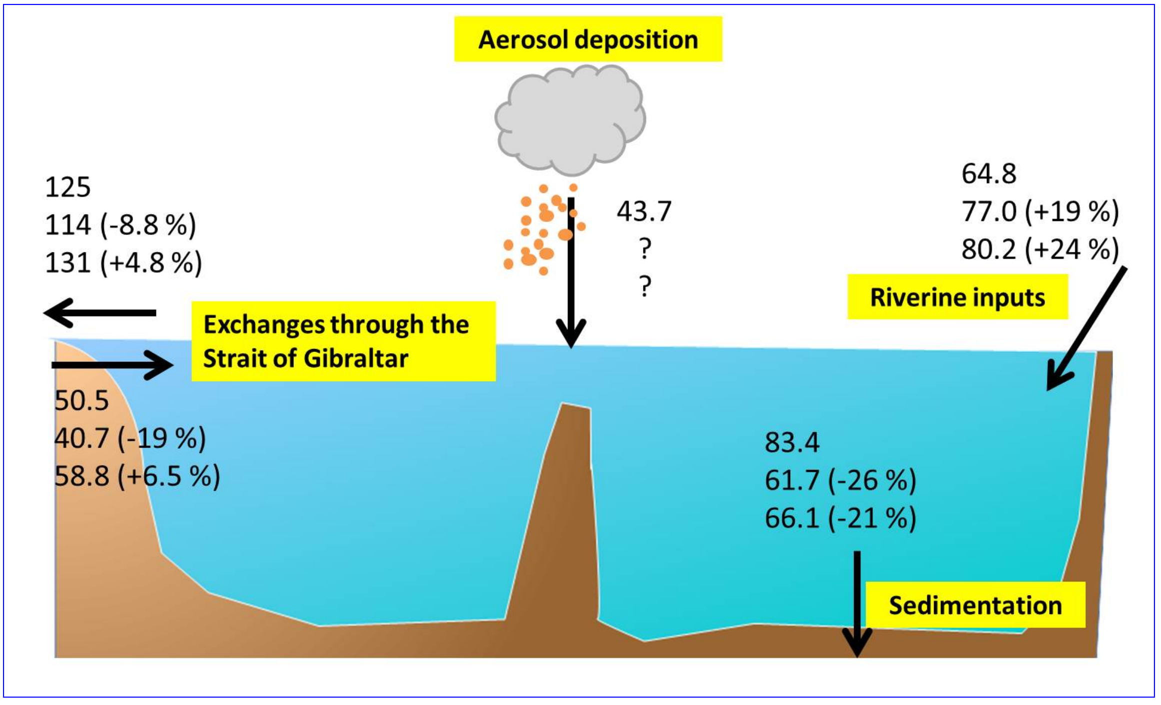


(b) Relative effects of natural dust deposition

Figure 17. Present (1980–1999) and future (2080–2099) relative effects of total nitrogen (top) and natural dust (bottom) deposition on surface (0–10 m) total primary production.

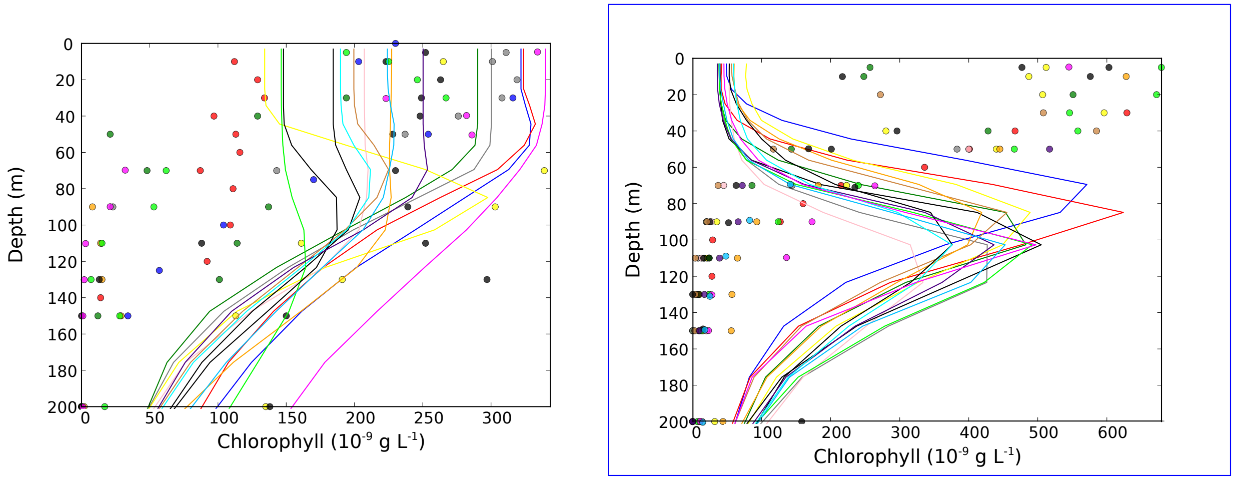


(a) Phosphate fluxes



(b) Nitrate fluxes

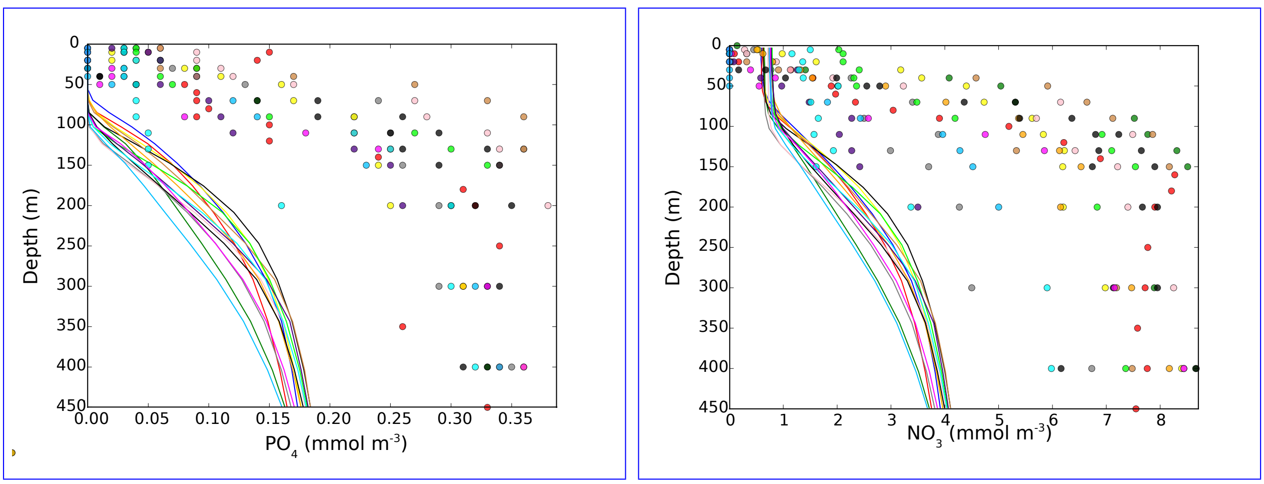
Figure 18. Schematic diagrams illustrating the Mediterranean budgets of phosphate and nitrate. For each component, the 3 lines represent the average fluxes (in Gmol year^{-1}) over the periods 1980–1999, 2030-2049 and 2080-2099, numbers in parenthesis indicate the percentage difference from the 1980–1999 values.



(a) February

(b) May

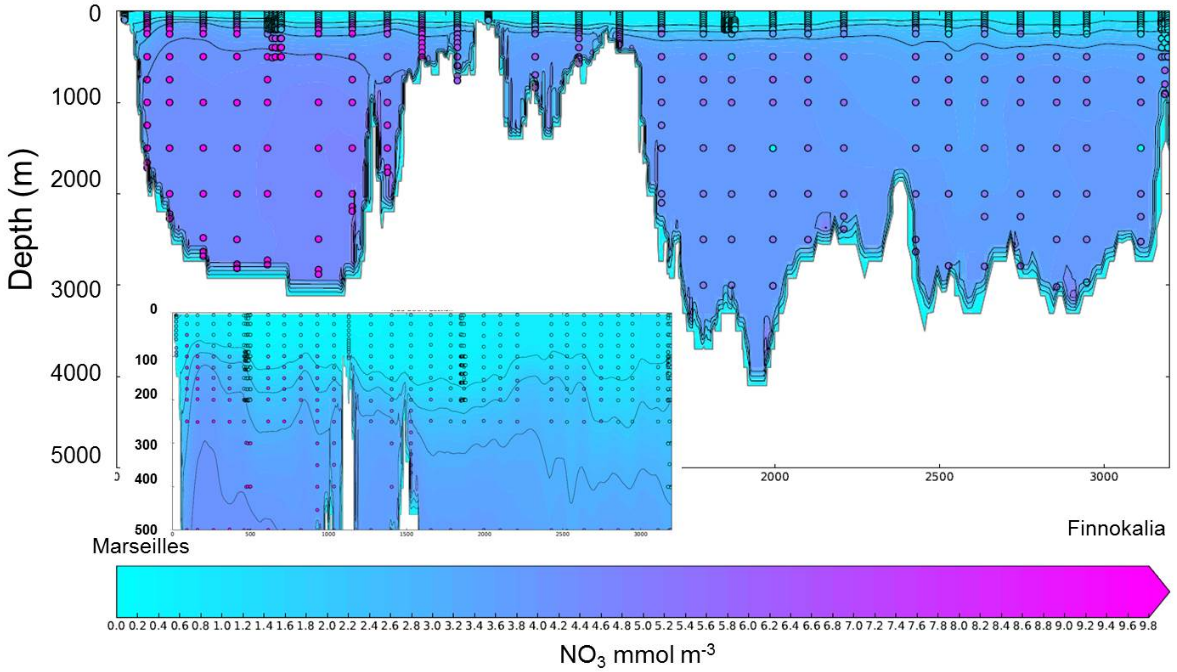
Figure A1. Average chlorophyll–a profiles in February (left) and ~~June~~ May (right) for the ~~first 20~~ years ~~of the CTRL simulation~~ 1991 to 2005 at the DYFAMED station in the Ligurian Sea Sea (43.4277°N, 7.2522°E). Dots represent data points (Marty et al., 2002; Faugeras et al., 2003). Lines represent the HIS/A2 simulation. Colors represent individual years.



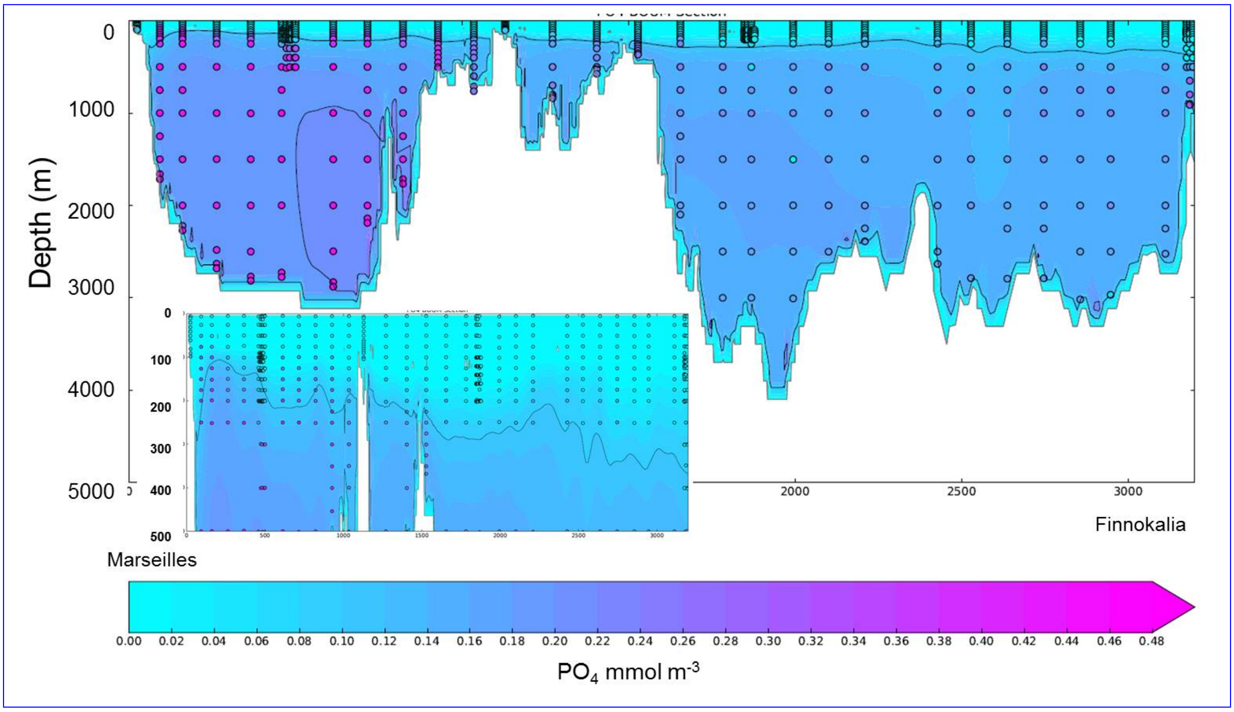
(a) Phosphate

(b) Nitrate

Figure A2. Average phosphate (left) and nitrate (right) profiles in May for the years 1991 to 2005 at the DYFAMED station in the Ligurian Sea Sea (43.4277°N, 7.2522°E). Dots represent data points (Marty et al., 2002; Faugeras et al., 2003). Lines represent the HIS/A2 simulation. Colors represent individual years.



(a) nitrate concentration



(b) PO_4 concentration

Figure A3. Average concentrations of nitrate (top) and phosphate (bottom) for the 20 first years of the control simulation (CTRL). The dots represent data along a transect from Marseille to Finokalia from the BOUM campaign (distances in km Moutin et al., 2012). The framed areas represent a vertical zoom of the top 500 m along the whole transect.