Supplementary information and figures for "Physical drivers of interannual chlorophyll variability in the eastern subtropical North Atlantic"

M. V. Pastor,1 J. B. Palter,2 J. L. Pelegrí,1 and J. P. Dunne3
1. Model Validation

This section offers a detailed assessment of the model’s ability to reproduce observed spatial and temporal patterns of chlorophyll (CHL), sea surface height (SSH), sea surface temperature (SST) and phosphate concentrations at 80 m (PO\textsubscript{4}). We use Level 3 SeaWiFS monthly chlorophyll downloaded from http://oceancolor.gsfc.nasa.gov at 9 km resolution. Satellite SSH is produced by Ssalto/Duacs and distributed by Aviso, with support from J. P. Dunne, NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA.

J. B. Palter, Atmospheric and Oceanic Sciences, McGill University, Montreal, Canada.

M. V. Pastor, Departament d’Ocenaografia Física, Institut de Ciències del Mar-CSIC, Barcelona, Spain. (mpastor@icm.csic.es)

J. L. Pelegrí, Departament d’Ocenaografia Física, Institut de Ciències del Mar-CSIC, Barcelona, Spain.

\(^1\)Departament d’Ocenaografia Física, Institut de Ciències del Mar-CSIC, Barcelona, Spain.

\(^2\)Atmospheric and Oceanic Sciences, McGill University, Montreal, Canada.

\(^3\)NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA.
CNES (downloaded from http://www.aviso.oceanobs.com/duacs). We averaged the original weekly data onto monthly. We use an optimally interpolated sea satellite surface temperature (SST) product at one-degree resolution provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from http://www.esrl.noaa.gov/psd. The variables CHL, SSH and SST data are compared with the model for the period November 1997 to December 2006, corresponding to the time period of model/SeaWiFS overlap. Climatological monthly phosphate concentrations from the World Ocean Atlas 2005 [Garcia et al., 2010] are also compared to the simulation-mean monthly phosphate concentrations. All data sets have been regridded into the model grid.

We evaluate the model’s skill in simulating spatial variability by comparing the annual means of the simulated variable to the observed variable. The model’s skill at reproducing temporal variability is evaluated with three metrics: 1) the correlation coefficient (R) between simulated and observed variables averaged over the study region is the statistic most widely used to determine the degree of similarity between two variables; 2) the standard deviation of the modeled variable, normalized to the standard deviation of the observed values (σ_M/σ_O), indicates the degree to which the two variables have the same amplitude of variation; 3) the centered root mean square difference (RMS_centered), or unbiased root mean square, quantifies how far the average error of the simulation is from zero [Taylor, 2001].

Simulated climatological mean chlorophyll concentrations generally compare well to SeaWiFS measurements, although there’s an important underestimation in the first pixel next to coast (Figure S1c). The model simulates an average chlorophyll concentration of 0.12 mg m^{-3} over the study region, while the satellite estimate provides an average of 0.21
mg m\(^{-3}\). Over the first pixel next to coast, the climatological model concentration is 0.42 mg m\(^{-3}\), while the observed value is 3.32 mg m\(^{-3}\). This is a common issue encountered when chlorophyll from biogeochemical models is compared to satellite chlorophyll [see for example *Doney et al.*, 2009; *Lachkar and Gruber*, 2011]. The difference could be caused by several factors. The model could be underestimating the coastal chlorophyll concentrations due to the coarse spatial resolution. On the other hand, SeaWiFS overestimation of the concentrations is well documented. For example, *Gregg and Casey* (2004) found that dust plumes spreading from the Saharan Desert represent about 15.3\% of positive bias in the Northeast Central Atlantic (10 to 40\(^\circ\)N). Nevertheless, the modeled and observed climatological location of the 0.2 mg m\(^{-3}\) isoline of chlorophyll shows a relative good agreement (Figure S1a and b).

The strong correlation between simulated and satellite-based monthly mean chlorophyll concentrations averaged over the study region (R=0.76, Table S1) indicates the model’s skill at reproducing temporal variability in the chlorophyll concentrations, when the seasonal cycle is included. The standard deviation of simulated chlorophyll is higher than in the satellite values. Correlations for the monthly anomalies are lower (R=0.46). However, their variance shows a good agreement.

As described in Section 2 of the main article, modeled SSH is zero for an ocean at rest and SSH at a given time step is given as the departure from this level. In our Boussinesq simulation, the SSH evolution is due only to non-steric effects. In contrast, remotely sensed Aviso SSH is obtained by adding the sea level anomaly to a mean dynamic topography calculated using a combination of altimetric and in-situ data and a modeled geoid. There is no condition that the global observed SSH average to zero, and its evolution includes
steric effects. Therefore, the mean simulated and observed values of SSH in our study area are not comparable and have been omitted from Table S1. Figure 2 of main article shows a map of the climatological SSH average from November 1997 to December 2006 for model and satellite. Even without including steric impacts on simulated SSH, the correlation between observed and modeled monthly SSH means averages 0.53 in the study region (Figure S2).

Simulated sea surface temperature shows excellent agreement with observed values (Figure S3). The model has a slight cold bias, as modeled and observed climatological SST averaged over the study region are 24.3°C and 25°C, respectively. Correlation coefficients for both monthly mean SST averaged over the study region and monthly anomalies are high (0.99 and 0.88, respectively), and the variance of the model SST is almost identical to that of observations (Table S1).

No observations of interannual variability of PO$_4$ are available; therefore we compare the climatological modeled PO$_4$ concentrations at 80 m with the corresponding observed climatological values. PO$_4$ concentrations compare generally well, with both modeled and observed climatological mean concentrations averaged over the study region being 0.5 mmol m$^{-3}$ (Figure S4a and b). The latitudinal variation of zonally integrated concentrations is remarkably good (Figure S4d). North of 18°N, the model overestimates the PO$_4$ concentrations by 1.8 mmol m$^{-3}$, and south of 18°N the model underestimates the observations by 1.5 mmol m$^{-3}$ (Figure S4d). The spatial correlation between the two climatologies is 0.95 (Table S1).

In order to further assess the level of interannual variability captured by the model, we also compare 12-month smoothed anomalies in the modeled
SST with the Extended Reconstructed Sea Surface Temperature (ERSST.v3b, http://www.ncdc.noaa.gov/oa/climate/research/sst/sst.php), the Kaplan Extended SST V2 (http://www.esrl.noaa.gov/psd/data/gridded/data.kaplan_sst.html) and the Hadley Centre SST data set (HadSST2, http://www.metoffice.gov.uk/hadobs/hadsst2/) over the entire model period for the region of interest (40°W to coast, 10 to 24°N), and the zonal SST gradient across this region (Figure S5). Comparison of the SST anomalies demonstrates that the amount of interannual variability from the early part of the record during which there is relatively sparse data assimilated in the atmospheric reanalysis is similar in scope to the variability from the later part of the record for which there is an ever increasing set of observational constraints. The model’s ability to capture features in the observations does not show any clear evidence of a secular trend. The mismatches between model and observations are highlighted when focusing in on the SST gradient which is nearly always underestimated by the coarse resolution model in not representing the full scope of coastal cold-water-upwelling (Figure S5b). Nevertheless, this mode of analysis too demonstrates the general pattern correspondence between modeled and observational inter-annual variability.

References


Figure S 1. Mean surface chlorophyll concentrations (mg m\(^{-3}\)) from (a) model and (b) SeaWiFS satellite for the period November 1997 to December 2006. The residual (c) shows model minus satellite values. The black line is the 0.2 mg m\(^{-3}\) chlorophyll isoline.

Figure S 2. Map of correlation coefficients between observed and modeled monthly SSH values for the period November 1997 to December 2006.
**Figure S 3.** Mean sea surface temperature (°C) from (a) model and (b) NOAA Optimum Interpolation V2 satellite data for the period November 1997 to December 2006. The residual (c) shows model minus satellite values.

**Figure S 4.** Mean phosphate concentrations at 80 m (mmol m\(^{-3}\)) from (a) model and (b) World Ocean Atlas 2005 for the period November 1997 to December 2006. The residual (c) shows model minus observed values. Panel (d) shows the meridional distribution of phosphate concentrations integrated zonally across the study region.
Figure S 5. Time series of SST averaged over the study region from model output (red line), the Extended Reconstructed Sea Surface Temperature (ERSST.v3b, solid line), the Kaplan Extended SST V2 (dotted line) and the Hadley Centre SST data set (HadSST2, dashed line). Panel (a) shows the anomalies averaged over the study region. Panel (b) shows the zonal SST gradient across the region (Kaplan is not shown as it is only available as an anomaly). All time series have been smoothed with a 12-month filter.
**Table S 1.** Model-observation skill metrics for monthly values and monthly anomalies (noted as a primed quantity) of chlorophyll (CHL, mg m\(^{-3}\)), sea surface height (SSH, cm), and sea surface temperature (SST, °C), and skill metrics of spatial patterns for phosphate concentration at 80 m (PO\(_4\), mmol m\(^{-3}\)). The metrics calculated are the correlation coefficient (R), centered root mean square difference (\(\text{RMS}_{\text{centered}}\)), observation (O) and model (M) mean and standard deviations (\(\sigma\)).

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<th>(\sigma)_M</th>
<th>mean(_O)</th>
<th>(\sigma)_O</th>
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*Statistics of spatial patterns