Evaluating the effect of interannual variations of surface chlorophyll on upper ocean temperature

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[1] An important issue in modeling and predicting upper ocean variability is the nature of the interactions between ocean biology, ocean dynamics, and irradiance penetration. Numerous studies using in situ observations and model simulations to investigate the effects of biota on light penetration have demonstrated that this biological-physical feedback may be significant over a wide range of spatial and temporal scales. Using a general circulation model which takes into account interannual variations in surface chlorophyll for the period September 1997 to May 2003, we investigate the effect of varying chlorophyll concentration on surface temperature. We conclude that, by using climatological monthly mean chlorophyll values, we capture the first-order effect of chlorophyll on light penetration.

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1. Introduction

[2] An important issue in modeling and predicting upper ocean variability is the nature of interactions between ocean biology, ocean dynamics, and irradiance penetration. The bulk of the essential nutrients supplied to the sunlit surface comes from the deeper layers of the ocean, so ocean circulation and mixing processes exert a strong influence on ocean biological productivity [*Mann and Lazier*, 1996]. The biota, in turn, modulate the penetration of solar radiation in the upper ocean and control, to some extent, the temperature structure and local stratification of the surface ocean [*Sathyendranath et al.*, 1991]. Hence there is the capacity for two-way interactions, or feedback loops, between ocean biota and the physical state of the ocean [*Simonot et al.*, 1988; *Stramska and Dickey*, 1993; *Platt et al.*, 1994; *Sathyendranath et al.*, 1991].

[3] Most ocean general circulation models (GCMs) do not include biological processes, and usually neglect the effect of phytoplankton on light penetration and the consequent feedbacks. However, significant effects of ocean biota on sea surface temperature (SST) and on the dynamics have been found over a wide range of spatial and temporal scales and in both simple models and GCMs [*Murtugudde et al.*, 2002; *Edwards et al.*, 2001; *Timmermann and Jin*, 2002; *Gildor et al.*, 2003].

[4] *Murtugudde et al.* [2002] investigated this effect using ocean GCM and remotely sensed chlorophyll derived from the Coastal Zone Color Scanner (CZCS). In their study, Murtugudde et al. used annual mean chlorophyll and compared the result of an experiment in which this annual mean chlorophyll affects light penetration into the ocean to an experiment in which constant extinction profile of 17 m was used. They found significance variations in SST and, in particular, improvement of the model result in the tropical region, notably a warmer cold tongue in the tropical east Pacific. SST differences between the experiments amounted to 1.6°. Other GCM studies show a similar effect, i.e., SST differences between experiments which take into account the effect of chlorophyll on light penetration and those which do not can be more than 1° [*Rochford et al.*, 2001; *Nakamoto et al.*, 2000, 2001]. The sign of the differences between the above studies do not always agree in some areas, probably because of model differences. It is important to stress that the SST differences are not the result of the direct effect of ocean biota on light penetration. Rather, the minor direct differences stimulate a series of feedbacks which amplify the initial anomaly.

[5] The studies summarized above suggest that it is necessary to take into account the effect of ocean biota on light penetration in climate models. Ideally, one may use an ecological model as an integral part of the climate model, and calculate the in situ chlorophyll as a prognostic variable. In this way, the full coupling between ocean biota and dynamics will be resolved. This approach was taken recently by *Oschlies* [2004], *Manizza et al.* [2005], and *Marzeion et al.* [2005]. Unfortunately, current ecological models are not yet at a stage to give reliable prediction of chlorophyll, and the computational cost is high. A second option is to use empirical/statistical relations between chlorophyll and other model variables as per *Timmermann and Jin* [2002]. The third way is to specify spatially varying, annual or monthly mean chlorophyll data. The last option is certainly the

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simplest way to account for this effect in a climate model. Moreover, *Murtugudde et al.* [2002] have demonstrated that, by comparing the results of using annual mean chlorophyll values to the results of *Nakamoto et al.* [2000], who used seasonally varying chlorophyll, the first-order effects are captured.

[6] Interannual variability of chlorophyll can be quite large in certain regions (Figure 1), notably the North Atlantic [*Dutkiewicz et al.*, 2001; *Follows and Dutkiewicz*, 2002] and equatorial regions [*Halpern and Feldman*, 1994; *Christian and Murtugudde*, 2003; *Strutton and Chavez*, 2004]. With the few years of chlorophyll data now available, our goal here is to address whether it is sufficient to use "climatological" chlorophyll values or is it essential to have ecological model as integral part of climate models. In order to isolate the effect of the interannual variability of chlorophyll, we run two experiments using an ocean general circulation model in a region covering most of the Atlantic Ocean. The first experiment uses climatological monthly mean chlorophyll concentration derived from almost 6 years of SeaWiFS observations. We then conduct 6 years experiment with the same model, the only difference being the use of observed monthly chlorophyll during the 6 years. We demonstrate that the variations in SST are quite small compared with an experiment forced by monthly mean chlorophyll.

2. Chlorophyll Data

[7] SeaWiFS provides estimates of ocean chlorophyll from September 1997 and completes a global coverage approximately every 2 days. We use the monthly mean, Level 3 product for the period September 1997 until May 2003 regridded on $1^\circ \times 1^\circ$ cells. For the "climatology" experiment, we computed climatological monthly mean from this period, and for the "interannual" experiment, we use the observed monthly values.

3. Ocean Model

[8] The Lamont Ocean Atmosphere Model (LOAM) model is a primitive equation ocean GCM coupled to a simple model of the atmospheric boundary layer so there is no need of restoring boundary condition. In the present configuration it consists of 30 levels, five of them in the upper 100 m with a resolution of 20 m. The domain covers the Atlantic Ocean from 55°S to 72°N with zonal resolution of 1.5° and meridional resolution varying from approximately 0.3° around the equator to 1.8° in high latitudes. The model is coupled to the atmospheric advective mixed layer model of *Seager et al.* [1995] in which wind stress and fresh water flux are specified and vary from month to month but not from year to year. The model simulates the main feature of the Atlantic circulation quite realistically but we stress that our intention here is to investigate the sensitivity of the results to variations in surface chlorophyll and not to improve the model simulations.

[9] The treatment of the chlorophyll effect on light attenuation is as in the work of *Murtugudde et al.* [2002]. Of the radiation reaching the ocean surface, approximately half is absorbed within the upper first meter or so (with wavelengths $\geq$ 0.75 μm), while the rest is attenuated at different rates, depending on the wavelength and the amount of chlorophyll present [*Morel and Antoine*, 1994; *Ohlmann et al.*, 1996]. In our model, 47% of solar radiation is absorbed within the uppermost layer while the rest is attenuated with attenuation coefficient K_D. $K_D = 0.027 + 0.0518xCHL^{0.428}$ [*Morel*, 1988], where the pigment concentration, CHL, is derived from SeaWiFs data (unlike *Murtugudde et al.* [2002], who used CZCS data). Although in reality chlorophyll has a vertical structure and subsurface maximum is a common feature, the vertical profile of the chlorophyll is assumed to be constant, as there is no way to retrieve the vertical distribution.

4. Results

[10] In the "climatology" experiment the climatological monthly mean chlorophyll data are used when calculating light penetration into the ocean. The mean SST field and its standard deviations for February and August are shown in Figure 2 (other months are quite similar). Over most of the domain, the standard deviations are less than 0.1, demonstrating that the model is quite close to steady state, repeating the annual cycle.

[11] We next force the ocean model with observed monthly mean chlorophyll as derived from the SeaWiFS data starting from September 1997 to May 2003 ("interannual experiment"). In Figure 3 we compare the mean SST between the experiments for February, May, August, and November. The top panels show the SST from the "climatological" run, the middle panels show the differences between the "climatological" and "interannual" experiments, and the shaded regions in the bottom panels show regions where the difference in SST is statistically significant at the 95% confidence level using t-test (although, admittedly, the two series are somewhat too short for such statistical test). The effect on the mean SST is overall very small, less than 0.1° over most of the domain. Changes larger than that are not statistically significant (as they occur in regions with large variance). *Shell et al.* [2003] and *Gildor et al.* [2003] have shown that even small variation in SST may cause noticeable atmospheric response. Nevertheless, in the context of climate models, these differences are smaller than any expected error which may result from observational or model deficiencies.

[12] Overall, differences in mean mixed-layer depth (MLD) are also minor (Figure 4). Locations with differences more than 3 m are spurious and usually do not cover more than one grid cell. Within the mixed layer, the specific depth in which the radiation is absorbed is not that important; thus in regions and time when the mixed layer is deeper than a few tens of meters, we do not expect much difference. The spring bloom, where significant interannual variations occur, starts after the ocean begins to stratify, but the mixed layer can still be a few tens of meters deep and therefore the effect of changes in chlorophyll is not very large. Reduced sensitivity to the effect of chlorophyll on light penetration in the North Atlantic was found even by *Rochford et al.* [2001], who compared experiments with and without chlorophyll.

[13] Figure 5 presents mean SST (top panel) and standard deviation (bottom panel) for (from left to right) February, May, August, and November from the "interannual"

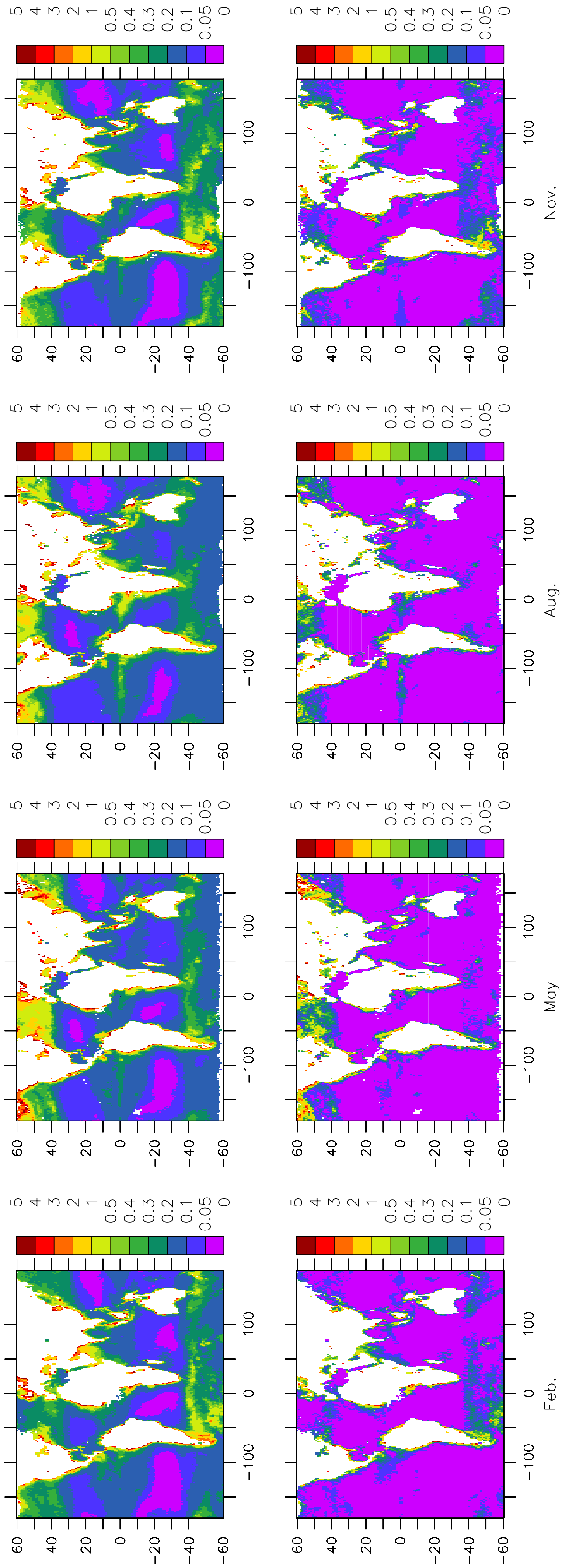

Figure 1. Mean (top) and standard deviation (bottom) of chlorophyll (in mg chl m^3) from monthly SeaWiFS data for the period September 1997 to May 2003 for (left to right) February, May, August, and November.

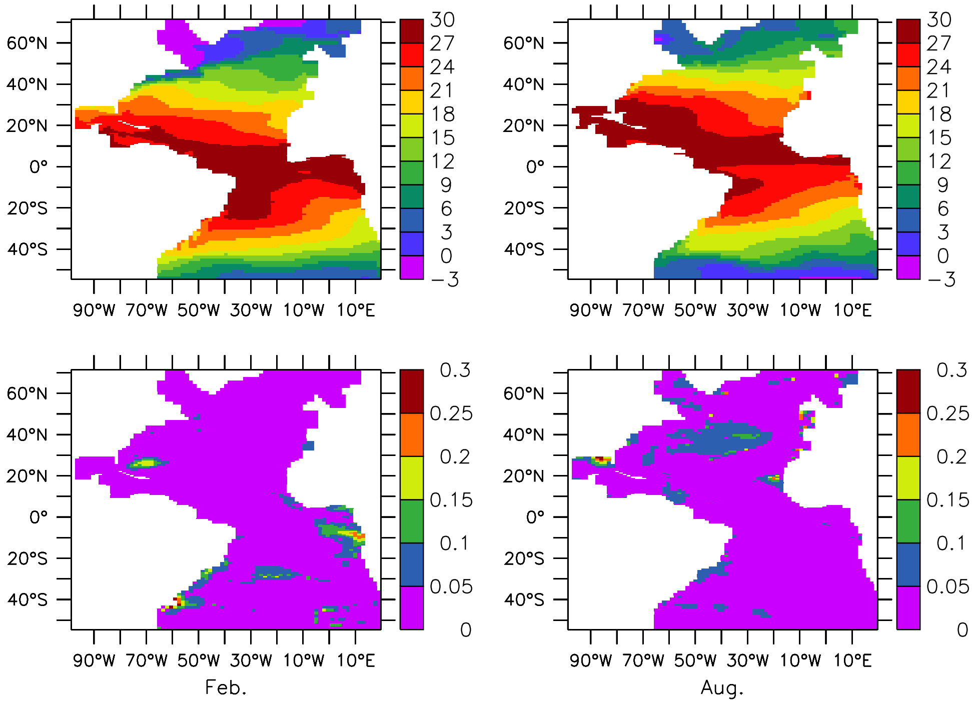

Figure 2. (top) Mean SST and (bottom) standard deviation for (left) February and (right) August in the "climatology" experiment. (The rest of the year is similar.)

experiment. Overall, although interannual variations in chlorophyll concentration can be quite large (Figure 1), the resulted variations in SST are a few tenths of a degree, at most. Compared to the "climatological" run, additional regions with SST variability are found at certain months, mainly in the east tropical Atlantic south of the equator (Figure 5, bottom left panel) or in coastal areas (Figure 5).

[14] Overall, the changes in the monthly mean values of SST, MLD, and currents (not shown) between the experiments are relatively minor, suggesting that the differences result from the direct heating effect and not from advection or stimulated feedbacks as those seen when comparing model with chlorophyll to model without chlorophyll at all. This can be seen from comparing specific months in which the differences were relatively large. As one example, in Figure 6 we compare August 2001 and August 1998. Differences in chlorophyll were quite large in the North Atlantic, in a narrow belt at the east equatorial Atlantic, and north to Brazil. Differences in SST are up to about 0.4°, with higher SST generally corresponding to higher chlorophyll concentration, demonstrating that the direct heating effect is the dominant one. Another indication of this is the temperature difference at 50 m depth which is almost a mirror image of the difference at the surface with opposite differences in the North Atlantic, west to Africa, and north to Brazil. The large difference at 50 m depth in the tropical Atlantic, which is larger than the surface anomaly, is the result of sporadic one-grid point convective events (such one-grid point anomalies of 20 m in mixed layer depth and up to 0.5° "jumps" between grid points in tropical and subtropical regions; see also bottom panels of Figure 4). Note that in the North Atlantic, the region with the highest SST difference is located somewhat southward of the region with largest difference in chlorophyll. There are two reasons. First, the relatively deep mixed layer (Figure 4) in the region with the highest difference in chlorophyll causes this region to be less sensitive. Second, the location of maximum chlorophyll difference in July was southward of its location in August, and the difference is the cumulative anomaly over the bloom period.

5. Summary

[15] Numerous studies using in situ observations and model simulations which investigated the effects of biological-physical interaction by biota on light penetration demonstrated that this feedback may be significant [*Sathyendranath et al.*, 1991; *Murtugudde et al.*, 2002; *Timmermann and Jin*, 2002]. In the present study we do not compare the differences between experiments including and excluding chlorophyll effect on light penetration; rather, we isolate the net effect of interannual variation in surface chlorophyll on upper ocean SST using a general circulation model. (Our model also shows significant variations in SST when comparing experiments with and without the effect of chlorophyll on light penetration). We concentrate on SST because this is what the atmosphere "feels." We compare an experiment which takes into account interannual variations in surface chlorophyll for the period September 1997 to May 2003 to an experiment which uses climatological monthly mean concentrations with all else being equal. Interannual variations in SST stimulated by interannual variations in chlorophyll are relatively small, a few tenths of a degree in limited regions. Our results therefore suggest that by using climatological monthly mean chlorophyll values we capture the first-order effect of chlorophyll on

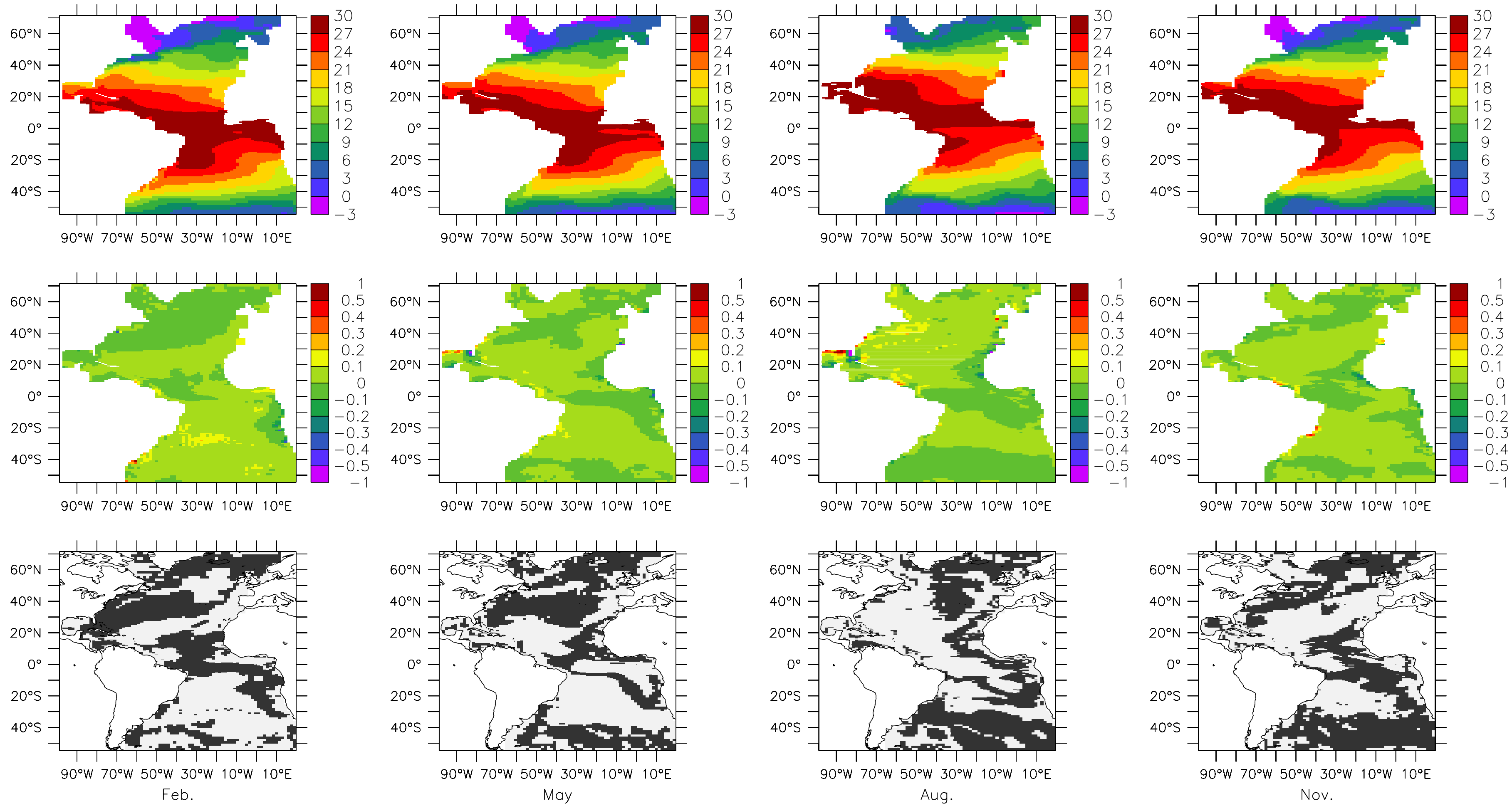

Figure 3. Differences in mean SST. (top) Mean SST from the "climatological" experiment and (middle) difference between the "climatological" and the "interannual" experiments for (from left to right) February, May, August, and November. Shaded regions in the bottom panels show regions where the difference in SST is statistically significant at the 95% confidence level using t-test. Differences larger than 0.1° are not statistically significant (as they occur in regions with large variance).

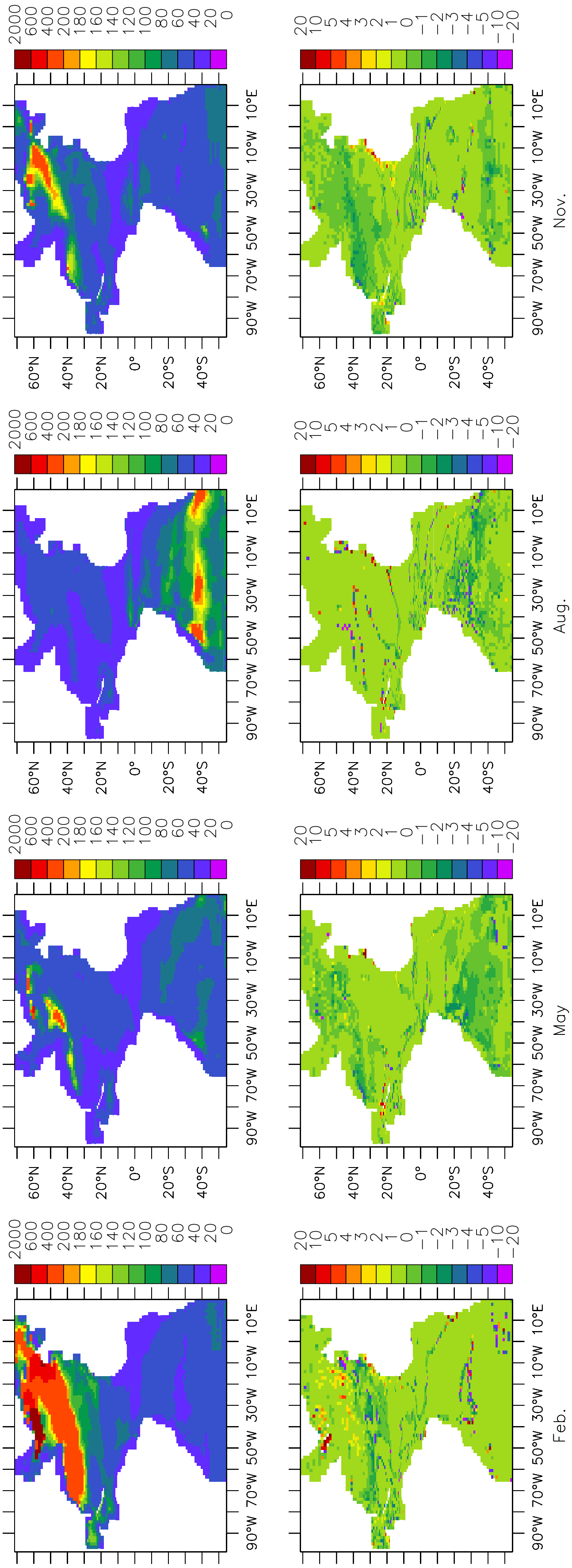

Figure 4. Differences in mixed layer depth (MLD). (top) Mean MLD from the "climatological" experiment and (bottom) difference between the "climatological" and the "interannual" experiments for (from left to right) February, May, August, and November.

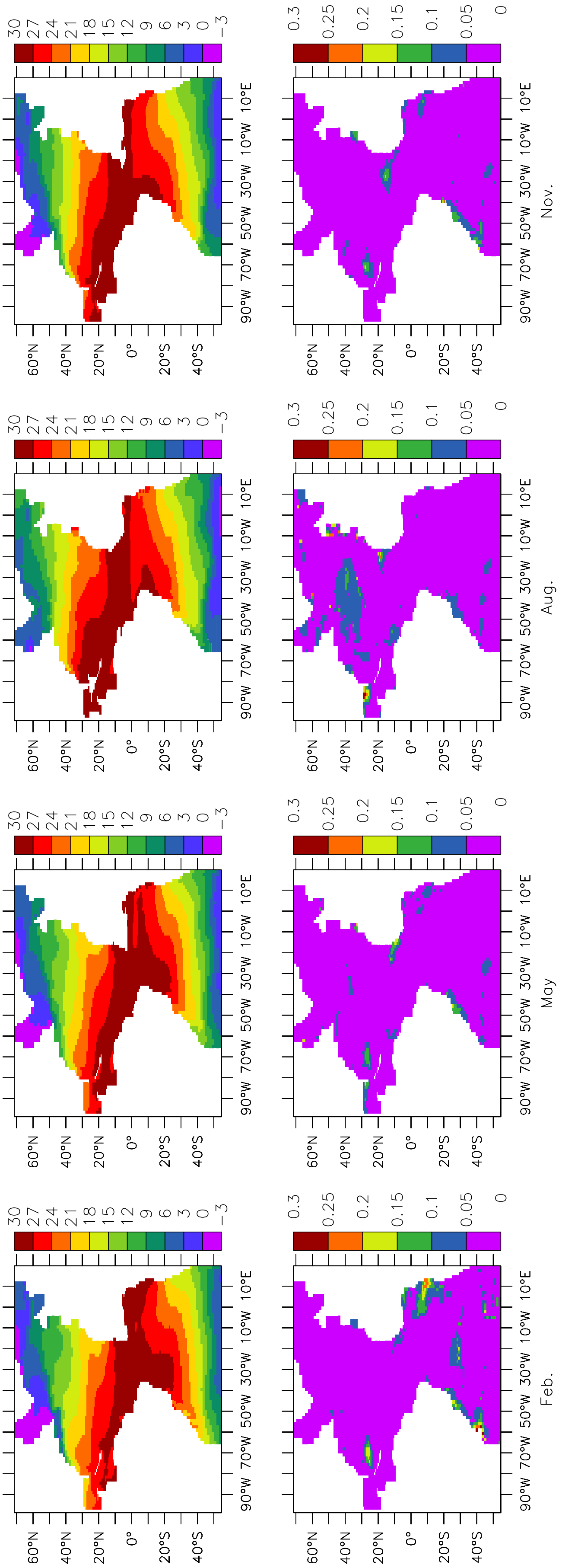

Figure 5. (top) Mean SST and (bottom) standard deviation for (from left to right) February, May, August, and November in the "interannual" experiment.

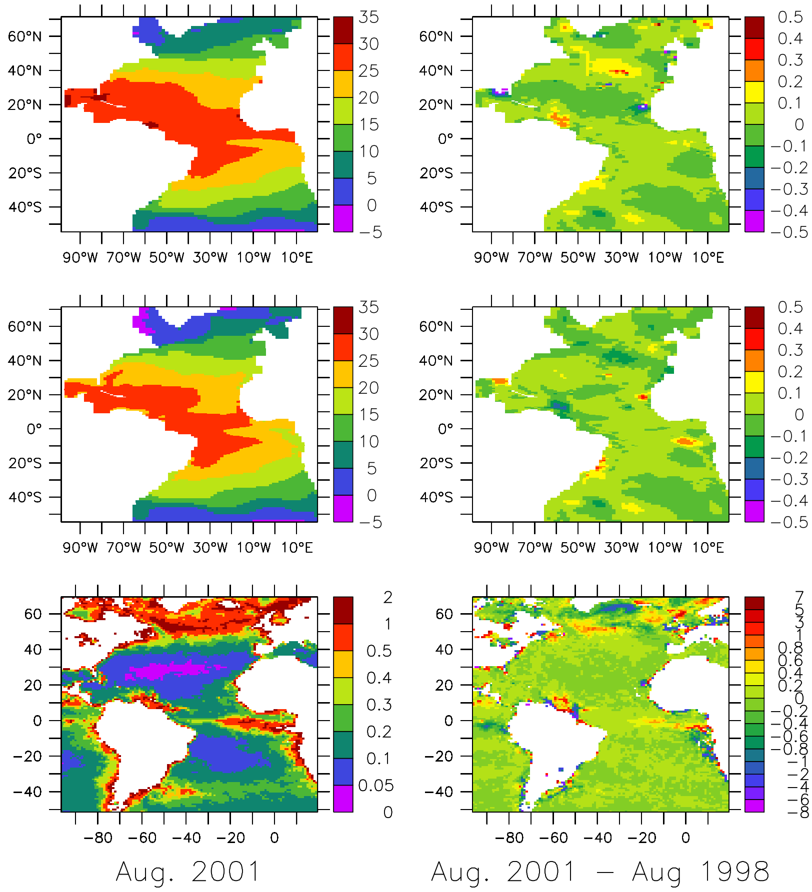

Figure 6. Differences in mean SST and chlorophyll for August 2001 and August 1998 of the interannual experiment. (top left) SST from August 2001 and (top right) difference in SST between August 2001 and August 1998. (middle left) Temperature from August 2001 at depth of 50 m and (middle right) difference in 50 m temperature between August 2001 and August 1998. (bottom left) Chlorophyll from August 2001 and (bottom right) difference in chlorophyll between August 2001 and August 1998.

SST. We note that *Murtugudde et al.* [2002] suggest that it might be enough to use spatially varying but annual mean values. *Frouin and Iacobellis* [2002] suggest that on global and annual average, the radiative forcing of phytoplankton is 0.25 $\frac{W}{m^2}$ (compared to clear water). However, because of the nonlinear relation between chlorophyll concentration and the radiative forcing of phytoplankton (through the albedo effect), even large variations from present-day concentration are expected to result in relatively small changes in the radiative forcing. Our model result suggest similar conclusions regarding the effect chlorophyll on the light absorption within the ocean. It is important to consider climatological values in model simulations; variations from these values have relatively small effect. Other deficiencies in present-day climate models and uncertainties in their parameters are expected to result in larger errors than those introduced by neglecting interannual variability in chlorophyll.

[16] However, a few caveats should be kept in mind. First, we have used observed data for a period spanning less than 6 years. This period is too short to derive "climatological" chlorophyll values, and interannual variation might be small compared to other periods. (However, even within this short period, we experienced significant interannual variations in surface chlorophyll. If the effect of these variations was very strong, we would have expected to see it in our model.) Second, the effect of chlorophyll on SST is expected to be more significant where and when mixed layer depth is shallower [*Kara et al.*, 2004; *Murtugudde et al.*, 2002; *Nakamoto et al.*, 2001; *Rochford et al.*, 2001]. The thickness of the upper layer in our model is 20 m, as is common in climate models, and this reduces the model sensitivity to the investigated effect. Last, there are indications that interdecadal variability might exert a strong influence on the marine ecological system [*Oschlies*, 2001; *Barton et al.*, 2003] although there is no conclusive evidence for a trend in phytoplankton concentration [*Frouin and Iacobellis*, 2002]. A similar study should be repeated as more years of observations become available.

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