Can eddies make ocean deserts bloom?

Andreas Oschlies

Institut für Meereskunde an der Universität Kiel, Kiel, Germany

[1] An eddy-resolving coupled ecosystem-circulation model of the North Atlantic is used to investigate the impact of mesoscale variability on the nitrate supply to the light-lit euphotic zone. The focus is on the oligotrophic subtropical gyre where eddies have been suggested to reconcile apparently contradictory observational estimates of nutrient supply and export production. Comparison with observations indicates that the numerical model provides a realistic description of the subtropical eddy field and its interaction with biogeochemical tracers. The model results illustrate that the eddy-induced nitrate flux into the euphotic zone is largest near the margins of the oligotrophic gyre where both vertical and lateral nutrient supply by eddies are effective. Typical values of simulated eddy-induced nitrate supply are 0.05 mol m^{-2} yr^{-1}, which is much lower than has been suggested previously. This new estimate of eddy-induced nitrate supply is not sufficient to reconcile seemingly contradictory observational estimates of biological production in the subtropics. Alternative sources of fixed nitrogen, deviations from standard elemental stoichiometry, and possible effects of interannual variability will have to be considered in order to resolve apparent observational discrepancies in the oligotrophic subtropical gyres. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4806 Oceanography: Biological and Chemical: Carbon cycling; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 4842 Oceanography: Biological and Chemical: Modeling; *KEYWORDS:* eddy pumping, nutrient supply, eddy resolving, biogeochemical model, new production

1. Introduction

[2] A major problem in our present understanding of the oligotrophic subtropical ocean gyres is that indirect geochemical estimates of both nutrient supply to the light-lit surface layer [*Jenkins*, 1988] and export of photosynthetically fixed material sinking out of it [*Jenkins*, 1982] tend to be substantially higher than direct biological and physical measurements [e.g., *Lewis et al.*, 1986; *Lohrenz et al.*, 1992] could account for. One explanation that has been put forward to resolve this apparent discrepancy is that sporadic nutrient injections by mesoscale eddies may have been under-represented by the direct measurements, whereas they are automatically included in geochemical tracer budgets which integrate over longer time and space scales [*Jenkins*, 1988].

[3] Process-model studies have indicated that eddy-related upwelling of nutrient-replete density surfaces into otherwise nutrient-depleted surface waters can significantly enhance biological production [*Dadou et al.*, 1996; *McGillicuddy and Robinson*, 1997]. Although upward and downward excursions due to eddies will average out, the vertical asymmetry in the light field can result in a rectified nutrient

transport into the euphotic zone by allowing for enhanced consumption of nutrients by phytoplankton during upward displacements. So far, only a few direct observations of this process, often termed eddy-pumping, exist and interpretations regarding its long-term and basin-scale significance vary considerably [e.g., *Falkowski et al.*, 1991; *McNeil et al.*, 1999]. Note, that explaining the sparseness of direct observations of the eddy-pumping process by under-representation of eddies in the in situ observations is problematic: Statistically, there is no reason why in situ measurements should have undersampled (or oversampled) these events. The likelihood of systematic sampling errors should be particularly small for the long-term time-series sites in the subtropical oceans, the Bermuda Atlantic Time-series Study (BATS) and the Hawaii Ocean Time-series (HOT) with typical sampling intervals (monthly to fortnightly) similar to the lifetime of eddy signals [e.g., *McNeil et al.*, 1999].

[4] Previous estimates of eddy-induced nutrient supply have mostly concentrated on the uplift and uptake of nutrients, while recharging of isopycnals below the euphotic zone was parameterized by restoring to climatological nitrate concentrations [*McGillicuddy and Robinson*, 1997; *McGillicuddy et al.*, 1998; *Siegel et al.*, 1999]. A complete picture of eddy-enhanced new and export production, however, has to account not only for uplift and uptake of nutrients, but also for sinking and subsequent remineraliza-

tion of photosynthetically fixed organic matter. Because sinking is relative to the ambient water and thus constitutes a diapycnal transport, remineralization of organic matter occurs on denser (and locally deeper) isopycnals than its formation (Figure 1). Without recharging nutrient levels of the lighter isopycnals, the long-term effect of eddies would therefore be a net deepening of the nutricline to a level at which eddies cannot anymore raise nutrient-replete isopycnals into the euphotic zone, and eddy-pumping would cease. Irrespective of the level of eddy activity, the bottleneck of upper ocean nutrient supply still is the diapycnal flux that may either occur locally (i.e., vertically) or be associated with remote water mass transformation and subsequent isopycnal (i.e., lateral) transport.

[5] The present study aims at a consistent picture of nutrient uptake and replenishment by solving a unique set of prognostic equations for physical and biological variables both within and below the euphotic zone. With respect to earlier work using the same ecosystem model embedded into a circulation model of the North Atlantic [*Oschlies and Garçon*, 1998], the horizontal grid spacing of the coupled ecosystem-circulation model has been reduced from $(1/3)°$ (i.e., ~35 km) to $(1/9)°$ (i.e., ~12 km) which is now fine enough to realistically simulate the mesoscale eddy field in the subtropics and midlatitudes [*Oschlies*, 2002a]. As a result, the assimilation of satellite altimeter data (and hence a perturbation of the model dynamics) is not anymore necessary to achieve realistic levels of eddy kinetic energy. This will allow a more consistent analysis of eddy-related nitrate fluxes than was possible before.
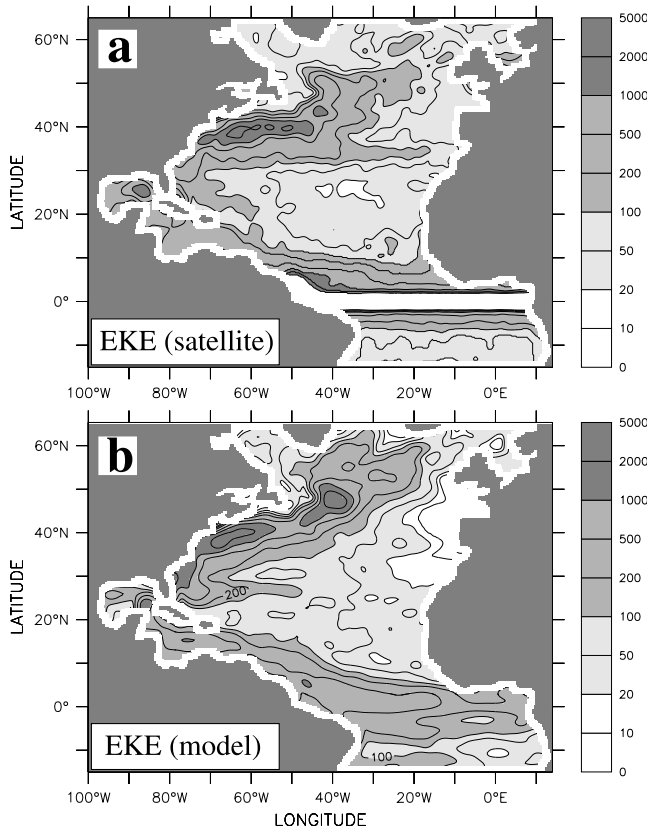
2. Model

[6] The numerical model consists of a simple four-component nitrate-phytoplankton-zooplankton-detritus (NPZD) ecosystem model [*Oschlies and Garçon*, 1999] embedded into an eddy-resolving $2/15° \times 1/9°$ resolution circulation model based on the Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model (MOM [*Pacanowski et al.*, 1991]). There are 37 levels in the vertical, with 11 levels being situated in the upper 150 m. Vertical mixing is modeled by a turbulence closure scheme [*Gaspar et al.*, 1990] tuned to closely match observational estimates of diapycnal diffusion derived from a tracer-release experiment in the main thermocline of the eastern subtropical North Atlantic [*Ledwell et al.*, 1993, 1998]. The atmospheric forcing consists of ''climatological'' monthly mean wind stress and heat flux fields derived from the years 1989 to 1993 of the reanalysis project carried out at the European Centre for Medium-Range Weather Forecasts (ECMWF) [*Gibson et al.*, 1997]. The chosen period corresponds to a positive phase of the North Atlantic Oscillation (NAO) and is distinct from the forcing used in the earlier $(1/3)°$ model study by *Oschlies and Garçon* [1998] representing a more negative phase of the NAO. This results in simulated winter mixed layers near Bermuda being shallower and associated convective nitrate supply being smaller in the present model compared to the earlier version (see discussion by *Oschlies* [2001, 2002b]). Freshwater fluxes are parameterized by restoring surface salinity to observed monthly means taken
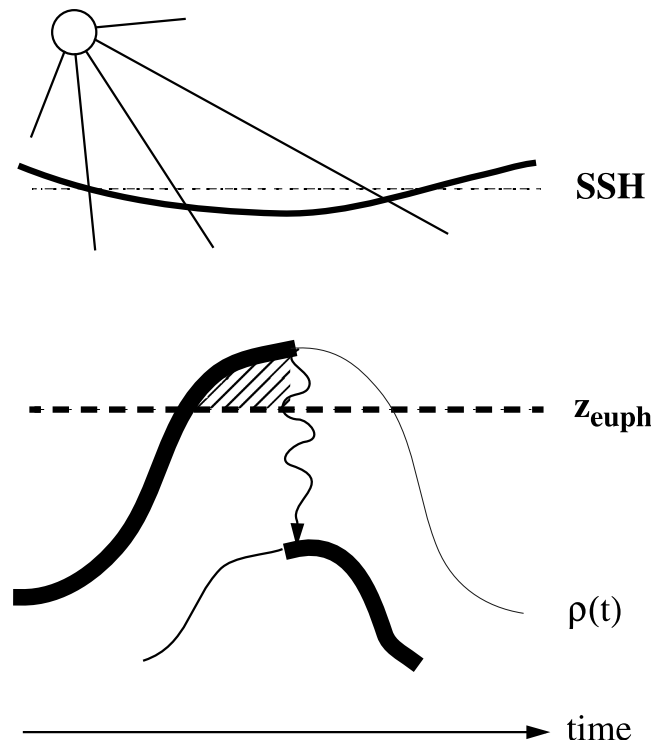
Figure 1. Schematic representation of the eddy upwelling mechanism as a function of time, representing formation and decay of a cyclonic eddy. The thick solid lines indicate nutrients that, on formation of the eddy, are lifted into the euphotic zone. Because sinking of particulate organic matter is a diapycnal transport, subsequent remineralization will eventually deposit these nutrients on denser and locally deeper isopycnal surfaces, resulting in a net deepening of the nutricline. To reestablish the initial conditions, nutrients have to be fluxed back onto the lighter isopycnal either by local diapycnal mixing or by lateral isopycnal transport.

from the *Levitus et al.* [1994] atlas. To account for water mass transformation outside the limited model domain, temperature, salinity, and nitrate are restored to climatological data in buffer zones (15 grid points wide) at the closed northern and southern walls and in the Mediterranean outflow.

[7] With respect to the earlier $(1/3)°$ version, the $(1/9)°$ simulation requires a 9-fold increase in storage space and a 27-fold increase in the number of computer operations. The $(1/9)°$ configuration is run on 4 processors of a Cray SV-1 vector machine, using about 400 MWords core memory and 130 CPU days per simulated year. After starting from a spun-up state of a $(1/3)°$ simulation, the $(1/9)°$ model is integrated for one year before biology is inserted, and the coupled model is run for five more years. Although the relatively short integration period does not allow the $(1/9)°$ model to reach dynamic (or even thermodynamic) equilibrium, an investigation of eddy effects on upper ocean physics and biogeochemistry seems already sensible at this stage. Encouraging in this respect are an almost stationary kinetic energy level reached after about 2 years [*Oschlies,*, 2002a] of the high-resolution run and the short (approx-

Figure 2. (a) Eddy kinetic energy computed from a blended data set of the TOPEX/Poseidon and ERS-1 satellite altimeter data for the year 1993 [*Le Traon et al.*, 1998]. (b) Eddy kinetic energy computed from the $(1/9)°$ model, accounting for all deviations from the 3-year mean velocities at a depth of 53 m. Units are $cm^2 s^{-2}$.

imately annual) adjustment time of the pelagic ecosystem model [*Oschlies and Garçon*, 1999]. For the present study, results will be shown for the third to fifth year of the coupled $(1/9)°$ run. During this 3-year period, simulated winter mixed-layer depths and upper-ocean biogeochemical properties are found to be remarkably stable. With the exception of a 10% decline in the simulated vertical advective nitrate input by eddies in the Gulf Stream region (see Figure 7e below), none of the properties analyzed in this study was found to display a significant drift over this period.

3. Results

[8] Major improvements in physical properties simulated by the eddy-resolving $(1/9)°$ model with respect to the earlier $(1/3)°$ version are described by *Oschlies* [2002a] and include a more realistic simulation of sea surface height (SSH) variability and eddy kinetic energy (EKE), although detailed spatial patterns are affected by the model's failure to reproduce the Azores Current and to correctly position the North Atlantic Current (Figure 2). Also improved are the simulated surface heat budget and the depth of the winter mixed layer which is systematically shallower over the

subpolar North Atlantic in the $(1/9)°$ model. This is related to a better resolution of small-scale ageostrophic processes that can draw on potential energy stored in lateral density gradients within the mixed layer [*Nurser and Zhang*, 2000]. Most relevant for the present study that focuses on the oligotrophic ocean deserts is, however, that the model can generate realistic EKE levels and mixed layer depths in the subtropics.

[9] To illustrate the new model's capability to resolve the eddy field and its impact on upper ocean biology, two snapshots of the simulated surface chlorophyll concentrations are displayed in Figure 3. The top panel shows the situation in mid-April. The onset of the North Atlantic spring bloom is visible as an east-northeastward sloping band of elevated surface chlorophyll concentrations. For the situation 6 months later, the bottom panel shows similarly high concentrations mainly in the subpolar North Atlantic and along the equator. Over the subtropical gyre, the area of low chlorophyll concentrations (<0.01 mg m^{-3}) is much larger in autumn than in spring. An ubiquitous phenomenon is the pronounced variability of the simulated surface-chlorophyll field at the mesoscale, i.e., in the range of about 50 to 200 km. A detailed analysis of spatial and temporal scales of the simulated surface chlorophyll field in relation to sea surface height and surface temperature will be presented elsewhere. Here, the focus is on the eddy-induced nutrient supply to the euphotic zone, which need not always be linked to the surface chlorophyll field [*Kawamiya and Oschlies*, 2001].

3.1. Test Case Bermuda

[10] A pivotal test of the new model's ability to realistically simulate eddy-induced nutrient transport is made possible by the extensive data set available from the Bermuda Atlantic Time-series Study [*Michaels and Knap*, 1996] (BATS, 32°N, 64°W). At this location, simulated SSH variance (8.9 cm) and EKE (113 $cm^2 s^{-2}$) agree well with those derived from satellite altimetry ($\sim$9 cm, and 115 $cm^2 s^{-2}$, respectively [*Siegel et al.*, 1999]). *Oschlies* [2002a] further shows that the model can accurately reproduce observed spatial SSH spectra in this region. A comparison with BATS data demonstrates relatively good agreement between simulated and observed mean nitrate profiles as well as of the variance of vertical displacements of nitrate surfaces, their correlation with surface height anomalies, and the correlation between nitrate and density (Figure 4). For example, right below the euphotic zone, typical vertical displacements amount to 35 m both in the model and in the observations. The model fails to reproduce the local maximum of 50 m root-mean-square (rms) vertical displacement of nitrate isosurfaces at depths between 300 and 400 m, which may indicate a slight underestimation of the eddy-pumping mechanism during periods of deep mixed layers. Similarly, the fact that simulated correlations between nitrate and density in the depth range between 120 and 270 m are slightly smaller than in the BATS data may also point to some underestimation of eddy-induced upwelling of nitrate in the model. On the other hand, the model's small overestimation of mean nitrate concentrations below 200 m may generate slightly too high estimates of eddy-induced nitrate supply. Errors in the simulated mean
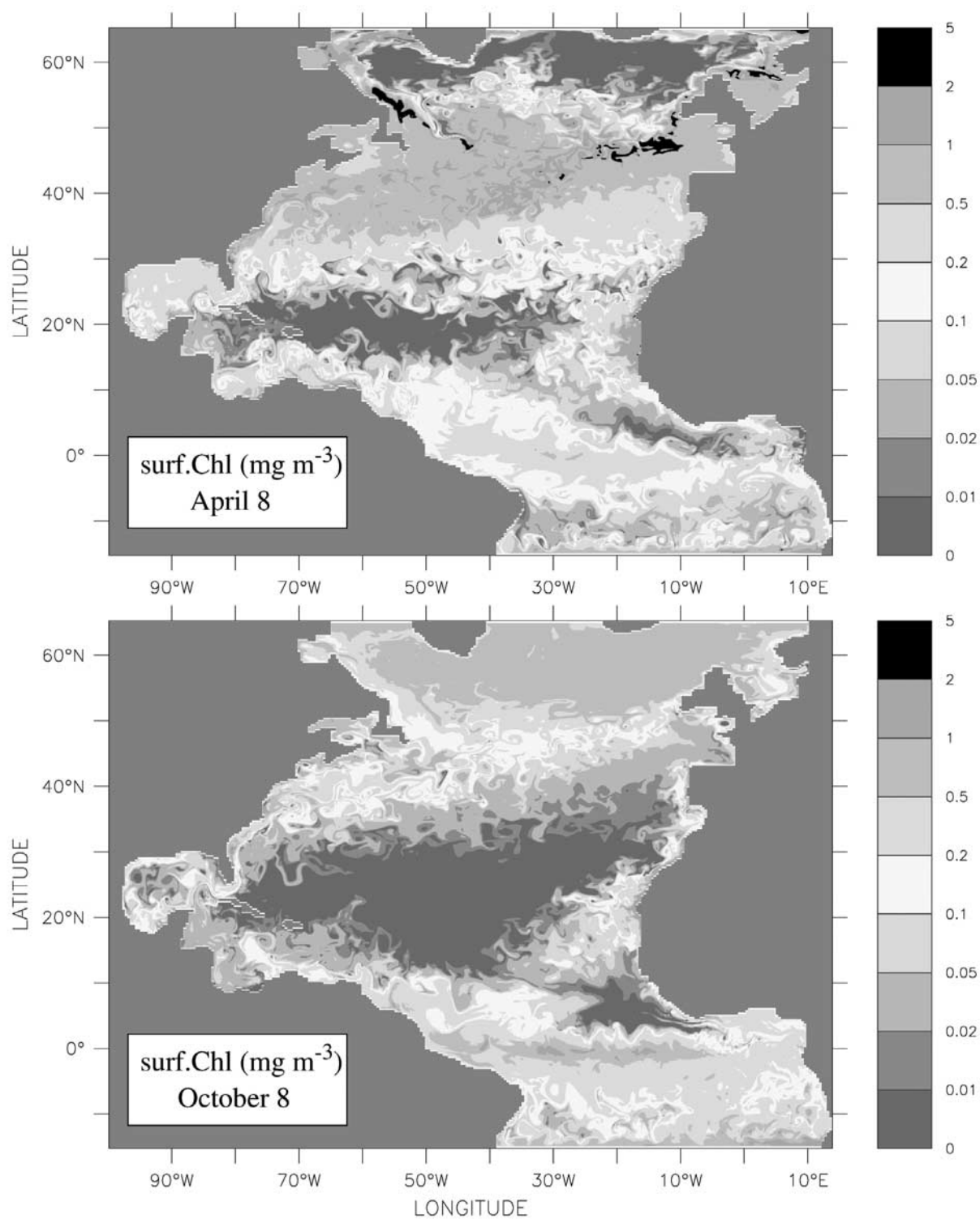
Figure 3.   Surface chlorophyll simulated by the $(1/9)°$ model for (top) April 8 and (bottom) October 8 of the third coupled year. Units are mg Chl m^{-3}. See color version of this figure at back of this issue.
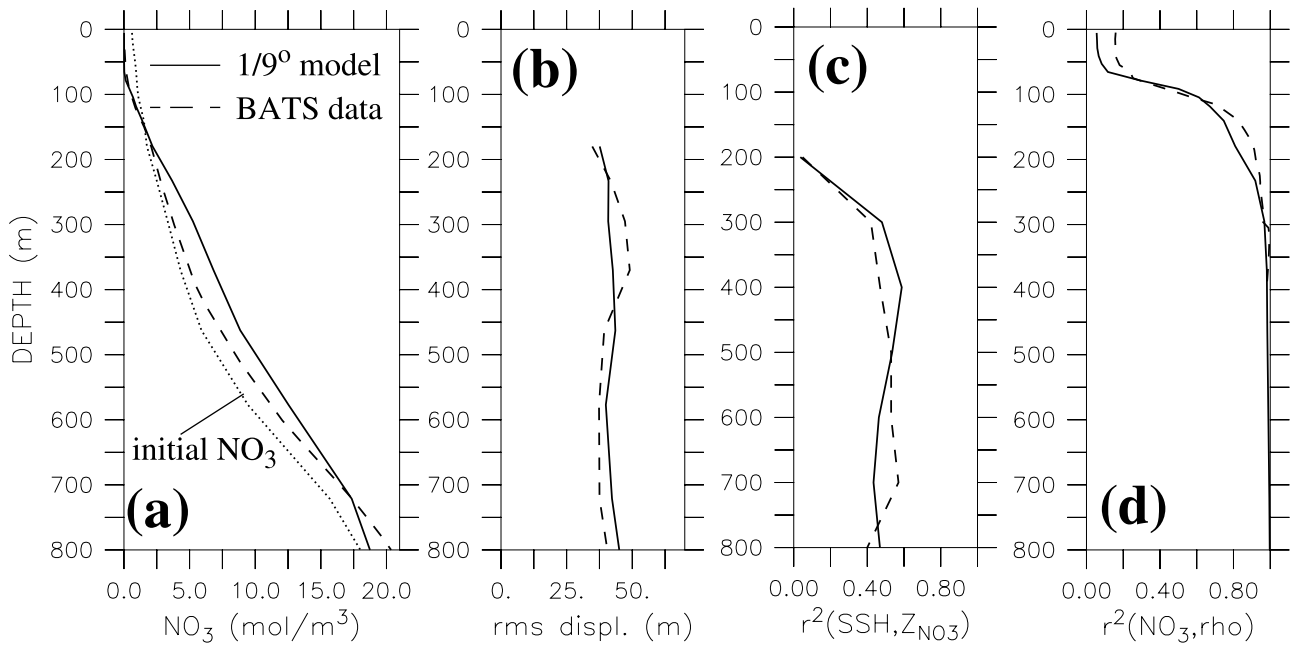
Figure 4. Comparison of simulated and observed nitrate statistics near Bermuda (32°N, 64°W). (a) Mean nitrate profile in the upper 800 m. The dotted line refers to the nitrate field used to initialize the coupled model [*Conkright et al.*, 1994]. (b) Root-mean-square vertical displacement of nitrate surfaces. (c) Squared correlation between sea surface height and vertical displacement of nitrate surfaces. (d) Squared correlation between potential density and nitrate. Model statistics are computed for the third to fifth year of the coupled biological-physical simulation, and 1989–1993 data from the Bermuda Atlantic Time series Study (BATS). The observed correlations in Figure 4c are taken from *Siegel et al.* [1999].

nitrate profile cannot be attributed to the model's initial nitrate field [*Conkright et al.*, 1994] (Figure 4a), but can instead be related to possibly overestimated upwelling of deeper, nutrient-rich waters along the American coast that quickly establish overly high nitrate concentrations in this recirculation region during the two spin-up years of the coupled model. Errors in the biological model (and in particularly in the sinking and remineralization rates) may well contribute to these discrepancies. Assuming monthly independent realizations during the 3-year analysis period of the model simulation, however, none of the differences in Figures 4b–4d is statistically significant (95% confidence level). Overall, the purely prognostic model shows a relatively good agreement between simulated and observed statistical properties of eddy impacts on the nitrate field near Bermuda.

[11] Interestingly, regressing vertical displacements of nitrate surfaces to SSH anomalies can explain about 40% of the variance below about 300 m whereas the explained variance approaches zero near the euphotic zone both in the observations and in the model (Figure 4c). At least near Bermuda, attempts to estimate the eddy-induced nutrient supply from satellite altimetry may therefore be problematic. This is illustrated further in Figure 5, which displays a typical annual cycle of simulated SSH, chlorophyll, and nitrate concentrations in the upper 300 m at the BATS site. Although this site was not directly hit by an eddy's center during the three-year analysis period (which seems to be consistent with the BATS time series [e.g., *Siegel et al.*,

1999]), the simulated SSH field reveals two large negative anomalies in spring and autumn, indicated by (1) and (2) in Figure 5a. These negative SSH anomalies are correlated with upward excursions of nitrate isosurfaces and isopycnals below about 200 m (Figure 5c). As indicated by the $\sigma_0 = 26.1$ kg m^{-3} isopycnal, pronounced vertical excursions of density surfaces occur also higher up in the water column. For the first event, the $\sigma_0 = 26.1$ kg m^{-3} isopycnal is displaced from a depth of about 190 m to some 60 m at the maximum of the negative SSH anomaly. However, this is not accompanied by a similar vertical excursion of nitrate isolines in the upper 200 m. This loosening of the otherwise tight correlation of nitrate and density [*McGillicuddy and Robinson*, 1997] just below the euphotic zone indicates that past excursions of this isopycnal into the light-lit surface layer have already reduced its nitrate load. Had we assumed rapid restoring to climatological mean nitrate concentrations (as was done in some previous studies), a total nitrate input of more than 0.05 mol m^{-2} would be diagnosed from the vertical displacement of isopycnals in the density range 26.0–26.18 kg m^{-3} into the euphotic zone during eddy event 1. The cumulative nitrate supply simulated by the fully prognostic model (Figure 5d) reveals that the total input that can be associated with this event is in fact less than 0.01 mol m^{-2}.

[12] The simulated cumulative nitrate supply to the euphotic zone (Figure 5d) also shows that despite realistic levels of near-surface eddy activity, most of the total annual input of 0.16 mol m^{-2} near Bermuda is due to vertical
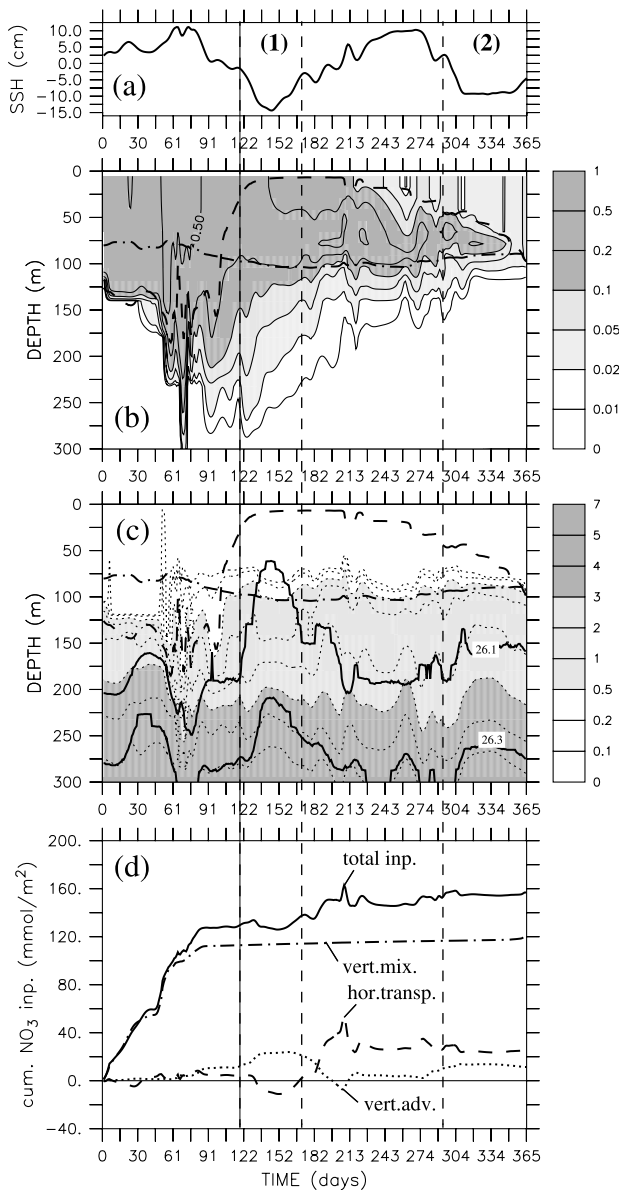
Figure 5. Annual cycle near Bermuda (32°N, 65°W) as simulated by the (1/9)° model for the third coupled year. (a) Sea surface height (in cm) referenced to the annual mean. (b) Chlorophyll concentration in mg m^{-3}. The dashed line is the depth of the surface mixed layer defined by a temperature criterion ($\Delta T = 0.2$°C), and the dash-dotted line is the depth of the euphotic zone defined by the 1% light level (see text for computational details). (c) Nitrate concentration in mmol m^{-3} and depth of the surface mixed layer and the euphotic zone defined as in Figure 5b. The two thick solid lines indicate the position of the $\sigma = 26.1$ and $\sigma = 26.3$ kg m^{-3} isopycnals. (d) Cumulative nitrate input into the euphotic zone, separated into vertical mixing, vertical advection, and horizontal transport (which combines advection and sub-grid scale mixing). The vertical lines denote begin and end points of individual SSH anomalies marked by (1) and (2) in Figure 5a.

mixing in winter (~ 0.11 mol m^{-2}). The negative SSH anomalies (1) and (2) are associated with a small nitrate supply by vertical advection (<0.02 mol m^{-2} in the annual integral). A slightly larger input of nitrate derives from the horizontal transport term (<0.03 mol m^{-2}). On an annual basis, approximately 75% of the simulated nitrate supply near Bermuda is caused by convective mixing in winter. After winter mixing ceases, most of the nitrate supply is due to advection, with vertical mixing contributing less than 0.01 mol m^{-2} during the period between spring and autumn.

3.2. Basin Scale

[13] To obtain a basin-scale picture of the contributions of individual transport mechanisms to the annual nitrate supply, a depth level constant in time (but not in space) is defined for each grid point as the maximum depth reached by the 1% light level during the 3-year simulation. This depth has been computed from the seasonally and latitudinally varying irradiance fields and incidence angles, and absorption coefficients varying as a function of simulated phytoplankton biomass (see *Oschlies and Garçon* [1999] for a detailed description of the treatment of solar radiation). It varies from typically 90 m in subpolar regions to maximum values of 118 m in the southwestern part of the subtropical gyre (Figure 6). At high latitudes, the maximum depth of the euphotic zone, which is determined by water transparency and solar elevation, is typically reached just before the onset of the spring bloom. During the productive season the high-latitude euphotic zone is generally somewhat shallower and the maximum depth shown in Figure 6 may not be an ideal choice for associating nutrient supply with biological production. In the subtropics, which are the focus of this paper, there is little seasonality in chlorophyll concentrations and the maximum depth of the euphotic zone is usually reached in summer when solar elevation is highest. For the purpose of computing the rate at which nitrate is, on an annual basis, made available to photosynthesis, the transport across the maximum depth of the euphotic zone therefore seems adequate, with the possible exception of the high latitudes.

[14] The simulated mean nitrate transport across the maximum depth of the euphotic zone is displayed in Figure 7a. Nitrate supply exceeds 0.5 mol m^{-2} yr^{-1} in large areas north of 40°N where convective mixing dominates (Figure 7b) and in the upwelling regions along the equator and off West Africa. In the subtropical gyre, where mean vertical advection is downward and winter mixing does in general not penetrate the nitracline, nitrate input is more than an order of magnitude smaller. The small nitrate export in the southwestern part of the subtropical gyre is essentially compensated by near-surface northward advection and subsequent remineralization of organic matter from the south [*Oschlies*, 2002b]. Simulated nitrate input via vertical mixing compares well with estimates from direct measurements in the eastern part of the subtropical gyre (23°W, 28.5°N: 0.028 mol m^{-2} yr^{-1} simulated versus 0.001–0.32 mol m^{-2} yr^{-1} estimated from direct measurements [*Lewis et al.*, 1986]) and also at the BATS site at the gyre's northwestern margin (0.15 mol m^{-2} yr^{-1} simulated versus 0.17 ± 0.05 mol m^{-2} yr^{-1} estimated for the early 1990s [*Siegel et al.*, 1999]).
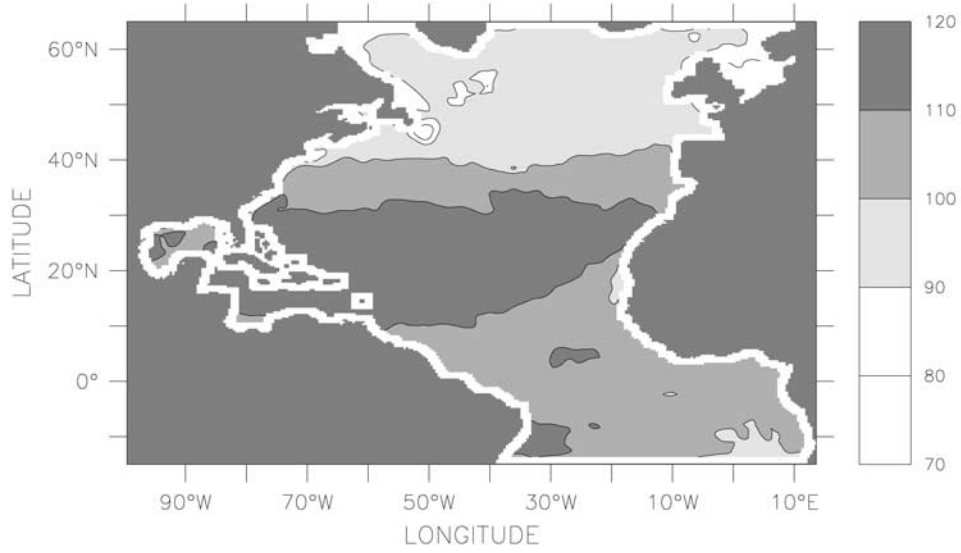
Figure 6. Maximum depth of the 1% light level reached during the 3-year analysis period of the simulation. This depth surface is used to compute the annual nitrate supply to the light-lit upper ocean (Figure 7).

[15] The advective nitrate supply into the euphotic zone can be separated into contributions from the mean flow and from the fluctuating "eddy" flow, which here includes all deviations from the 3-year mean circulation, in the following way:

$$\int_{z_{euph}}^{0} \nabla \cdot \overline{(\mathbf{u}\,\mathrm{NO_3})}dz = \overline{w\,\mathrm{NO_3}}|_{z_{euph}} + \int_{z_{euph}}^{0} \nabla_h\overline{\mathbf{u}_h\mathrm{NO_3}}dz \qquad (1)$$

with

$$\overline{w\mathrm{NO_3}}|_{z_{euph}} = \overline{w}\,\overline{\mathrm{NO_3}}|_{z_{euph}} + \overline{w'\mathrm{NO_3'}}|_{z_{euph}} \qquad (2)$$

$$\nabla_h \cdot \overline{\mathbf{u}_h\mathrm{NO_3}} = \nabla_h \cdot \overline{\mathbf{u}_h}\,\overline{\mathrm{NO_3}} + \nabla_h \cdot \overline{\mathbf{u}_h'\mathrm{NO_3'}} \qquad (3)$$

where the overbar denotes the three-year mean and the prime all deviations from the mean. Possible eddy effects on the mixing terms are not considered in this analysis. The first term on the right-hand side of equations (2) and (3), respectively, is referred to as contribution of the mean flow, and the second term as contribution of the fluctuating "eddy" flow. Note that the latter term does not only contain fluctuations associated with mesoscale eddies, but also includes submesoscale and seasonal variations.

[16] Simulated nitrate supply by the mean flow is positive only along the equator where upwelling dominates, and near the margins of the subtropical gyre where lateral Ekman transport can flux nutrients across streamlines associated with the geostrophic flow of the mean gyre circulation into the oligotrophic gyre [*Williams and Follows*, 1998] (Figure 7c). Nitrate input by the fluctuating flow (Figure 7d), in contrast, is positive over almost the entire subtropical gyre and in two zonal bands straddling the equatorial upwelling. Separating this contribution into vertical and horizontal components reveals that the vertical eddy-related nitrate flux, which includes the eddy-pumping mechanism discussed above, is largest in the northwestern part of the gyre (Figure 7e) where the Gulf Stream is a source of relatively high eddy activity. This is consistent with earlier idealized model results showing that nutrient upwelling is strongest during formation and intensification of cyclonic eddies generally associated with frontal regions [*Dadou et al.*, 1996; *McGillicuddy and Robinson*, 1997; *Spall and Richards*, 2000]. Near the quieter southern and eastern margins of the subtropical gyre, where EKE levels are much lower than in the Gulf Stream region, eddies supply nitrate predominantly via lateral advection (Figure 7f). This mainly reflects isopycnal stirring by eddies perpendicular to the mean gyre circulation. Because density surfaces tend to deepen towards the centre of the subtropical gyre, isopycnal influx of surrounding nutrient-rich waters has a small downward component. This is most pronounced at the southeastern flank of the gyre and, since counteracting nutrient upwelling by intensifying eddies is relatively weak in this region, results in net nitrate export by vertical eddy advection (Figure 7e).

[17] Lateral supply of nitrate reaches only a few hundred kilometers into the oligotrophic gyre because of its short lifetime (days to weeks) in the euphotic zone. Eddy-induced transport of more refractory dissolved organic nitrogen (DON) from productive regions might in principle bridge larger distances [*Lee and Williams*, 2000]. However, at present there is no observational evidence for the existence of lateral gradients in near-surface DON concentrations required for a net DON transport into the oligotrophic gyre [*Kähler and Koeve*, 2001]. (Lateral influx arguments might, however, still hold for DOP, which could then help to sustain nitrogen fixation; see *Abell et al.* [2000] for an analysis of data in the North Pacific.) In addition to dissolved forms of nitrogen, particulate organic nitrogen (PON) may as well be subject to lateral transport. This need not imply that a single cell or particle travels long distances, but may involve many recycling loops of nitrogen in the
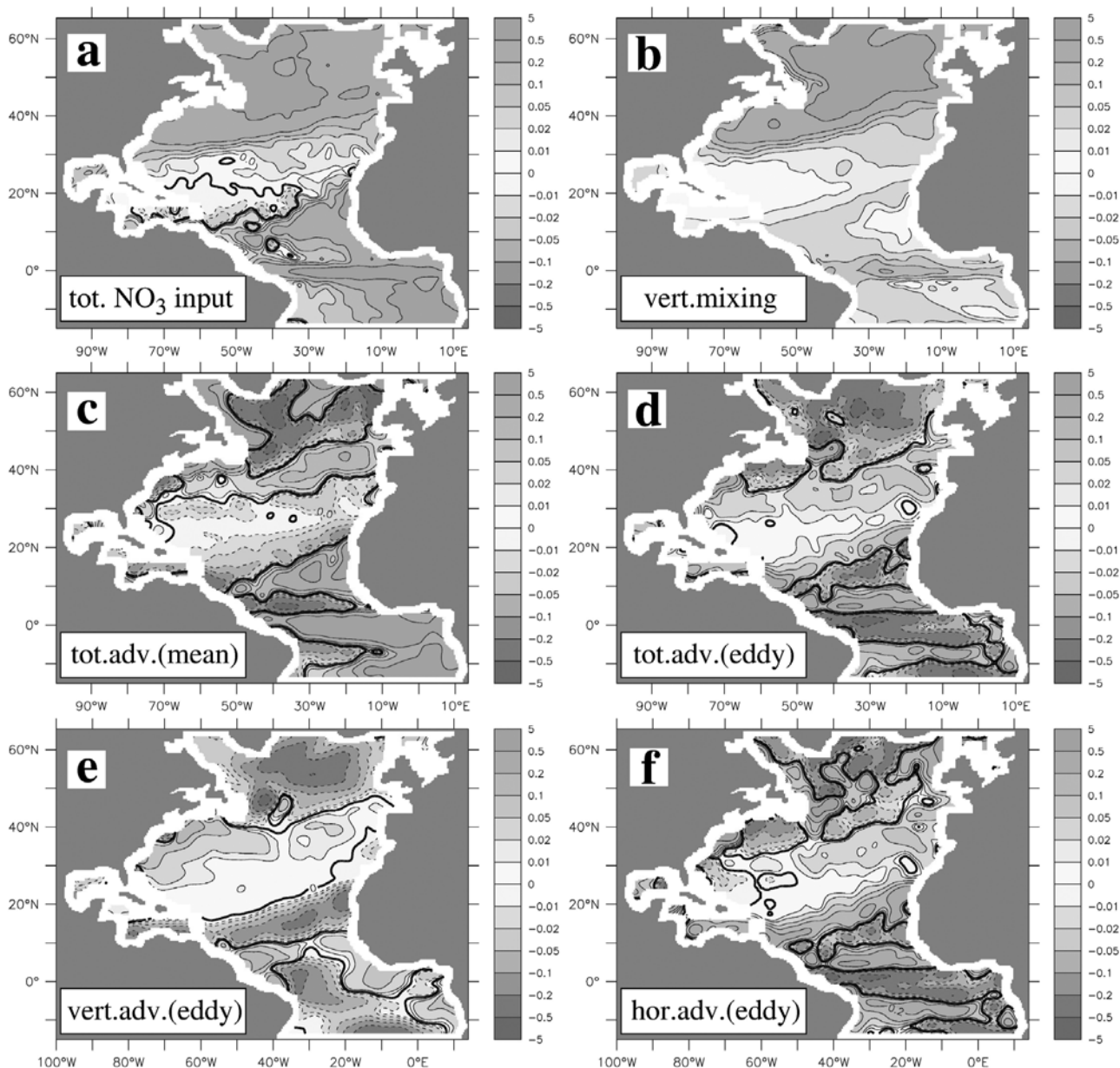
Figure 7. Simulated 3-year mean nitrate supply across the maximum depth reached by the 1% light level (Figure 5). (a) Total nitrate supply. (b) Nitrate supply by vertical mixing, including convective overturning. (c) Advective nitrate input by the mean flow. (d) Advective nitrate input by deviations from the mean flow. (e) Vertical advective nitrate input by deviations from the mean flow. (f) Horizontal advective nitrate input by deviations from the mean flow. Units are mol m^{-2} yr^{-1}. See color version of this figure at back of this issue.

pelagic ecosystem before it is eventually exported out of the euphotic zone. In the present model configuration, in which detritus is the only component that sinks relative to the water, lateral advection of PON contributes up to 0.05 mol m^{-2} yr^{-1} to the annual nitrogen budget in an approximately zonal band at the northern margin of subtropical gyre. These results are very similar to those of the $(1/3)°$ version investigated by *Oschlies* [2002b] and are therefore not discussed in more detail here. The advection of PON is mostly due to the mean flow, with the eddy part of the flow field acting to extend the PON supply into the gyre by a few hundred kilometers. Over that part of the subtropical gyre

that receives nitrate input by the eddying flow (Figure 7d), nitrogen input via PON is typically much smaller (by about a factor 5) than the eddy supply of nitrate. Note, however, that the simulated advective flux of PON may be underestimated as, for example, bacteria and different planktonic size classes are not explicitly considered in the presently very simple ecosystem model.

4. Concluding Discussion

[18] When compared to the earlier $(1/3)°$ simulation, there is at first sight surprisingly little change in the basin-scale

nitrate supply to the euphotic zone. The basin-mean nitrate supply increases by less than 10% from 0.24 mol N m^{-2} yr^{-1} in the (1/3)° run to 0.26 mol N m^{-2} yr^{-1} in the (1/9)° simulation. As Figure 8 reveals, this increase is restricted mainly to the tropics, whereas the zonally averaged nitrate input decreases with finer resolution in the subtropics and mid latitudes. Smaller nitrate supply in mid latitudes is related to systematically shallower (and more realistic) winter mixed layers in the (1/9)° model [*Oschlies*, 2002a]. In the subtropics, a reduction in spurious upwelling along the American coast in the (1/9)° simulation is responsible for the lower nitrate input in the zonal average. When excluding coastal zones by restricting the zonal average to the region between 25°W and 70°W, this difference among the two models vanishes (Figure 8b). Away from coastal upwelling regions, nitrate supply to the subtropical gyre is on average smaller than 0.02 mol N m^{-2} yr^{-1}. This is far less than the 0.63 ± 0.15 mol N m^{-2} yr^{-1} that would be required to meet oxygen utilization rates of 5.7 ± 0.06 mol O$_2$ m^{-2} yr^{-1} estimated from oxygen and Helium-Tritium age measurements in the eastern part of the subtropical gyre [*Jenkins*, 1982] and assuming a standard $-O_2$:N reminer-alization ratio of 9.1 ± 0.4 [*Minster and Boulahdid*, 1987]. Simulated low rates of nitrate supply, on the other hand, agree well with the direct measurements reported by *Lewis et al.* [1986] for the same region.

[19] Near Bermuda, a comparison with previous estimates of the nutrient budget also bears some surprises: In this region the model predicts an average eddy-induced nitrate supply of only 0.029 mol m^{-2} yr^{-1} (of which 0.027 mol m^{-2} yr^{-1} is due to vertical advection). This is only about 15% of previous estimates based on methods that restore to climatological nutrient concentrations below the euphotic zone [*McGilli-cuddy and Robinson*, 1997; *Siegel et al.*, 1999]. Applying the method of *Siegel et al.* [1999] (also used by *McGillicuddy et al.* [1998]) to infer nutrient supply from satellite altimetry and statistics derived from in situ data to the (1/9)° model output turns out to overestimate the "true" simulated eddy-induced nitrate supply by more than 600%. In fact, this overestimate (0.18 mol m^{-2} yr^{-1}) is very close to the original estimates derived from satellite and in situ data. Given the (at least at BATS) relatively realistic model statistics (Figure 4), this suggests that these earlier estimates of eddy-induced nutrient supply near Bermuda may have been considerably too high, presumably because of overestimated nutrient recharging on isopycnals below the euphotic zone.

[20] Another, at first sight surprising result is that the annual nitrate supply near Bermuda is much smaller in the new (1/9)° model (0.16 mol m^{-2} yr^{-1}) than in earlier simulations at (1/3)° resolution (0.75 mol m^{-2} yr^{-1}, [*Oschlies and Garçon*, 1998; *Oschlies et al.*, 2000]). This is closely related to shallower winter mixed layers of about 180 m in the present version (Figure 5) compared to 260 m in the earlier experiment described by *Oschlies et al.* [2000]. In both models, nitrate input is dominated by winter mixing (~75% and ~95%, respectively), consistent with nitrate assimilation measurements at BATS reported by *Lipschultz* [2001] (which themselves seem to indicate a limited role of eddy pumping). Differences in winter mixing depth and associated nutrient supply among the two simulations
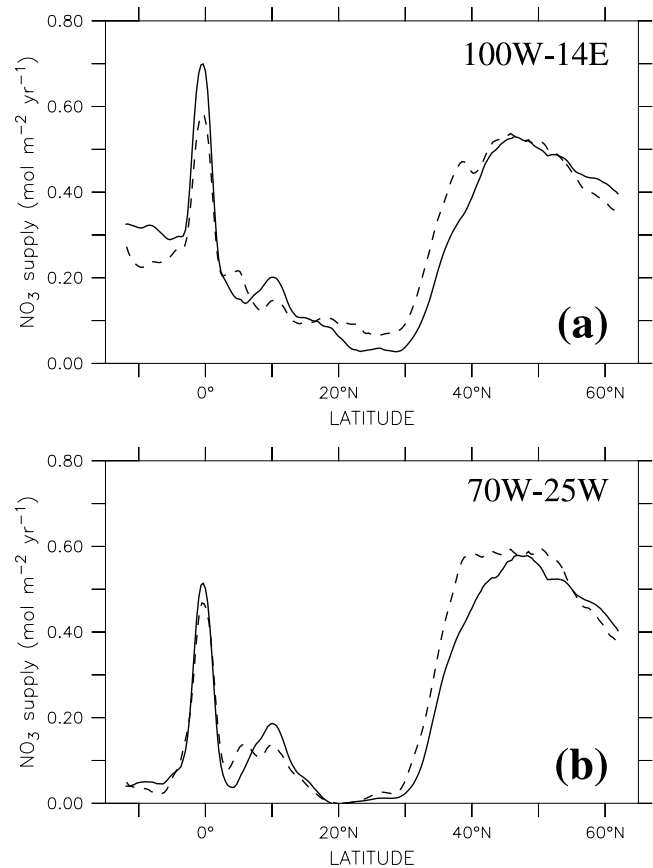
Figure 8. Zonally averaged 3-year mean nitrate input into the euphotic zone defined by the depth surface of Figure 6. Shown are results of the (1/9)° model (solid line) and the corresponding (1/3)° simulation (dashed line). Displayed are (a) the basin average (100°W–14°E) and (b) an average between 70°W and 25°W to exclude coastal upwelling regions in the subtropics.

depend sensitively on the different atmospheric forcing fields applied. These represent different states of interdeca-dal climate variability linked to the North Atlantic Oscil-lation (NAO) [e.g., *Cayan*, 1992] and generate a model response in good agreement with historical data near Ber-muda [*Michaels and Knap*, 1996; *Oschlies*, 2001]. In addition, atmospheric variability other than the NAO may affect convective nutrient supply [*Williams et al.*, 2000]. The large sensitivity of simulated nutrient supply in this region to changes in atmospheric forcing may also help explain apparent discrepancies between observations taken at different times. Similarly, at least part of the discrepancy between the *Jenkins*' [1988] observational estimate of nitrate supply for the 1980s and the (1/9)° model results reflecting the 1990s (whereas agreement was good for the earlier (1/3)° version [*Oschlies and Garçon*, 1998] run under atmospheric forcing that corresponded to a more negative phase of the NAO) may be attributed to interannual and longer-term variability.

[21] Obviously, even a (1/9)° model grid is not yet fine enough to fully resolve the small-scale vertical exchange

associated with frontal instability processes and therefore might still underestimate nutrient supply to the euphotic zone. Idealized model studies indeed suggest a net increase of near-frontal biological production on further refining the horizontal grid [*Lévy et al.*, 2001]. However, more vigorous vertical (i.e., diapycnal) exchange also leads to generally colder and denser surface waters as found, for example, by *Mahadevan and Archer* [2000]. The present model's relatively realistic description of surface heat budget and mixed layer depths [*Oschlies*, 2002a] therefore imposes some limitations on the possible strength of as yet unresolved exchange processes. Because this argument relies on presently poorly known surface heat fluxes, it still would allow for a possible contribution of frontal-scale, ageostrophic nutrient fluxes quantitatively similar to that of mesoscale eddies reported here. However, together with the relatively small changes in the subtropical gyre's nitrogen budget on refining the grid resolution from $(1/3)°$ to $(1/9)°$ (Figure 8) and the relatively realistic statistical properties of the model (Figure 4), it seems difficult to envisage a significant upward revision of the estimate of eddy-induced nutrient supply reported here. Alternative pathways of nitrogen supply, deviations from standard elemental stoichiometry, and possible effects of interannual variability in the ocean-atmosphere system must probably be taken into account to disentangle apparent observational discrepancies and to correctly assess the strength of the biological pump in the subtropical ocean.
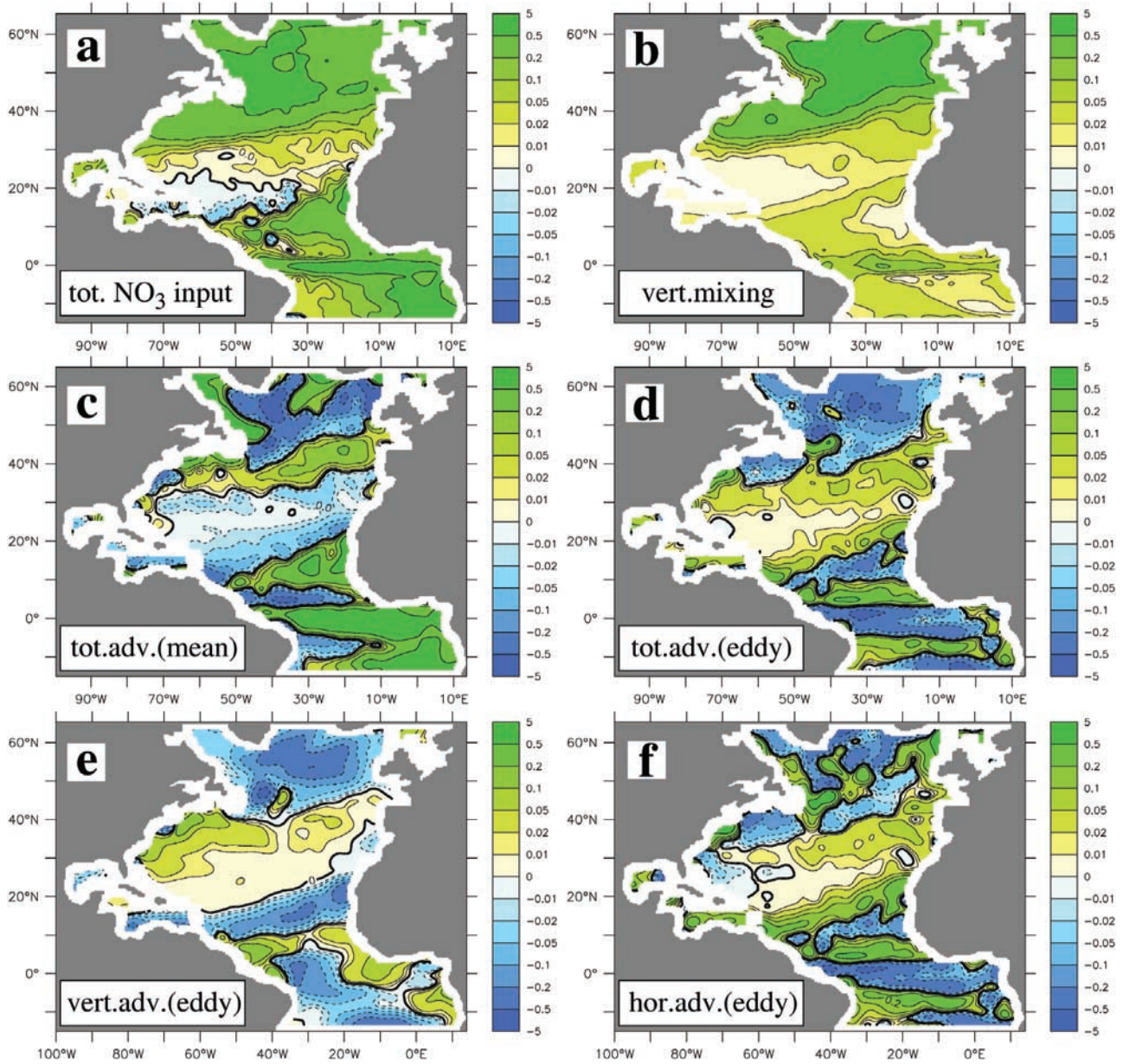
References

Abell, J., S. Emerson, and P. Renaud, Distributions of TOP, TON and TOC in the North Pacific subtropical gyre: Implications for nutrient supply in the surface ocean and remineralization in the upper thermocline, *J. Mar. Res.*, 58, 203–222, 2000.

Cayan, D. R., Latent and sensible heat flux anomalies over the northern oceans: The connection to monthly atmospheric ciculation, *J. Clim.*, 5, 354–369, 1992.

Conkright, M. E., S. Levitus, and T. P. Boyer, *World Ocean Atlas 1994*, vol. 1, *Nutrients*, Natl. Environ. Satell. Data and Inf. Serv., Natl. Oceanic and Atmos. Admin., Silver Spring, Md., 1994.

Dadou, I., V. Garçon, V. Andersen, G. R. Flierl, and C. S. Davis, Impact of the North Equatorial Current meandering on a pelagic ecosystem: A modeling approach, *J. Mar. Res.*, 54, 311–342, 1996.

Falkowski, P. G., D. Ziemann, Z. Kolber, and P. K. Bienfang, Role of eddy pumping in enhancing primary production in the ocean, *Nature*, 352, 55–58, 1991.

Gaspar, P., Y. Gregoris, and J.-M. Lefevre, A simple eddy kinetic energy model for simulations of the oceanic vertical mixing: Tests at station Papa and Long-Term Upper Ocean Study site, *J. Geophys. Res.*, 95, 16,179–16,193, 1990.

Gibson, J. K., P. Kallberg, S. Uppala, A. Hernandez, A. Nomura, and E. Serrano, ERA Description, *ECMWF Re-Analysis Project Rep. Ser. 1*, 72 pp., Eur. Cent. for Medium-Range Weather Forecasting, Reading, England, 1997.

Jenkins, W. J., Oxygen utilization rates in North Atlantic subtropical gyre and primary production in oligotrophic systems, *Nature*, 300, 246–248, 1982.

Jenkins, W. J., Nitrate flux into the euphotic zone near Bermuda, *Nature*, 331, 521–523, 1988.

Kähler, P., and W. Koeve, Marine dissolved organic matter: Can its C:N ratio explain carbon overconsumption?, *Deep Sea Res., Part I*, 48, 49–62, 2001.

Kawamiya, M., and A. Oschlies, Formation of a basin-scale surface chlorophyll pattern by Rossby waves, *Geophys. Res. Lett.*, 28, 4139–4142, 2001.

Ledwell, J. R., A. J. Watson, and C. S. Law, Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment, *Nature*, 364, 701–703, 1993.

Ledwell, J. R., A. J. Watson, and C. S. Law, Mixing of a tracer in the pycnocline, *J. Geophys. Res.*, 103, 21,499–21,529, 1998.

Lee, M.-M., and R. G. Williams, Examining how eddies affect biological production through the lateral transport and diffusion of nutrients, *J. Mar. Res.*, 58, 895–917, 2000.

Le Traon, P. Y., F. Nadal, and N. Ducet, An improved mapping method of multi-satellite altimeter data, *J. Atmos. Ocean. Technol.*, 15, 522–534, 1998.

Levitus, S., R. Burgett, and T. P. Boyer, *World Ocean Atlas 1994*, *NOAA Atlas NESDIS 3*, vol. 3, *Salinity*, 99 pp., U.S. Gov. Printing Off., Washington, D. C., 1994.

Lévy, M., P. Klein, and A.-M. Treguier, Impacts of sub-mesoscale physics on phytoplankton production and subduction, *J. Mar. Res.*, 59, 535–565, 2001.

Lewis, M. R., W. G. Harrison, N. S. Oakey, D. Herbert, and T. Platt, Vertical nitrate fluxes in the oligotrophic ocean, *Science*, 234, 870–873, 1986.

Lipschultz, F., A time-series assessment of the nitrogen cycle at BATS, *Deep Sea Res., Part II*, 48, 1897–1924, 2001.

Lohrenz, S. E., G. A. Knauer, V. L. Asper, M. Tuel, A. F. Michaels, and A. H. Knap, Seasonal variability in primary production and particle flux in the northwestern Sargasso Sea: US JGOFS Bermuda Atlantic Time-Series Study, *Deep Sea Res.*, 39, 1373–1391, 1992.

Mahadevan, A., and D. Archer, Modeling the impact of fronts and mesoscale circulation on the nutrient supply and biogeochemistry of the upper ocean, *J. Geophys. Res.*, 105, 1209–1225, 2000.

McGillicuddy, D. J., Jr., and A. R. Robinson, Eddy-induced nutrient supply and new production in the Sargasso Sea, *Deep Sea Res., Part I*, 44, 1427–1450, 1997.

McGillicuddy, D. J., Jr., A. R. Robinson, D. A. Siegel, H. W. Jannasch, R. Johnson, T. D. Dickey, J. McNeil, A. F. Michaels, and A. H. Knap, Influence of mesoscale eddies on new production in the Sargasso Sea, *Nature*, 394, 263–266, 1998.

McNeil, J. D., H. W. Jannasch, T. Dickey, D. McGillicuddy, M. Brzezinski, and C. M. Sakamoto, New chemical, bio-optical, and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda, *J. Geophys. Res.*, 104, 15,537–15,548, 1999.

Michaels, A. F., and A. H. Knap, Overview of the U.S. JGOFS Bermuda Atlantic Time-series Study and the Hydrostation S program, *Deep Sea Res., Part II*, 43, 157–198, 1996.

Minster, J. F., and M. Boulahdid, Redfield ratios along isopycnal surfaces-A complementary study, *Deep Sea Res.*, 34, 1981–2003, 1987.

Nurser, A. J. G., and J. W. Zhang, Eddy-induced mixed layer shallowing and mixed layer/thermocline exchange, *J. Geophys. Res.*, 105, 21,851–21,868, 2000.

Oschlies, A., NAO-induced long-term changes in nutrient supply to the surface waters of the North Atlantic, *Geophys. Res. Lett.*, 28, 1751–1754, 2001.

Oschlies, A., Improved representation of upper ocean dynamics and mixed layer depths in a model of the North Atlantic on switching from eddy-permitting to eddy-resolving grid resolution, *J. Phys. Oceanogr.*, 32, 2277–2298, 2002a.

Oschlies, A., Nutrient supply to the surface waters of the North Atlantic: A model study, *J. Geophys. Res.*, 107, doi:10.1029/2000JC000275, in press, 2002b.

Oschlies, A., and V. Garçon, Eddy-induced enhancement of primary production in a model of the North Atlantic Ocean, *Nature*, 394, 266–269, 1998.

Oschlies, A., and V. Garçon, An eddy-permitting coupled physical-biological model of the North Atlantic, I, Sensitivity to advection numerics and mixed layer physics, *Global Biogeochem. Cycles*, 13, 135–160, 1999.

Oschlies, A., W. Koeve, and V. Garçon, An eddy-permitting coupled physical-biological model of the North Atlantic, II, Ecosystem dynamics and comparison with satellite and JGOFS local studies data, *Global Biogeochem. Cycles*, 14, 499–523, 2000.

Pacanowski, R., K. Dixon, and A. Rosati, The G.F.D.L Modular Ocean Model users guide version 1, *Tech. Rep. 2*, GFDL Ocean Group, Geophys. Fluid Dyn. Lab., Princeton, N. J., 1991.

Siegel, D. A., D. J. McGillicuddy, and E. A. Fields, Mesoscale eddies, satellite altimetry, and new production in the Sargasso Sea, *J. Geophys. Res.*, *104*, 13,359–13,379, 1999.

Spall, S. A., and K. J. Richards, A numerical model of mesoscale frontal instabilities and plankton dynamics, 1, Model formulation and initial experiments, *Deep Sea Res., Part I*, *47*, 1261–1301, 2000.

Williams, R. G., and M. J. Follows, The Ekman transfer of nutrients and maintenance of new production over the North Atlantic, *Deep Sea Res., Part I*, *45*, 461–489, 1998.

Williams, R. G., A. J. McLaren, and M. J. Follows, Interannual variability in export production implied by changes in convection over the North Atlantic, *Global Biogeochem. Cycles*, *14*, 1299–1313, 2000.

———————————

A. Oschlies, Institut für Meereskunde an der Universität Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany. (aoschlies@ifn.uni-kiel.de)
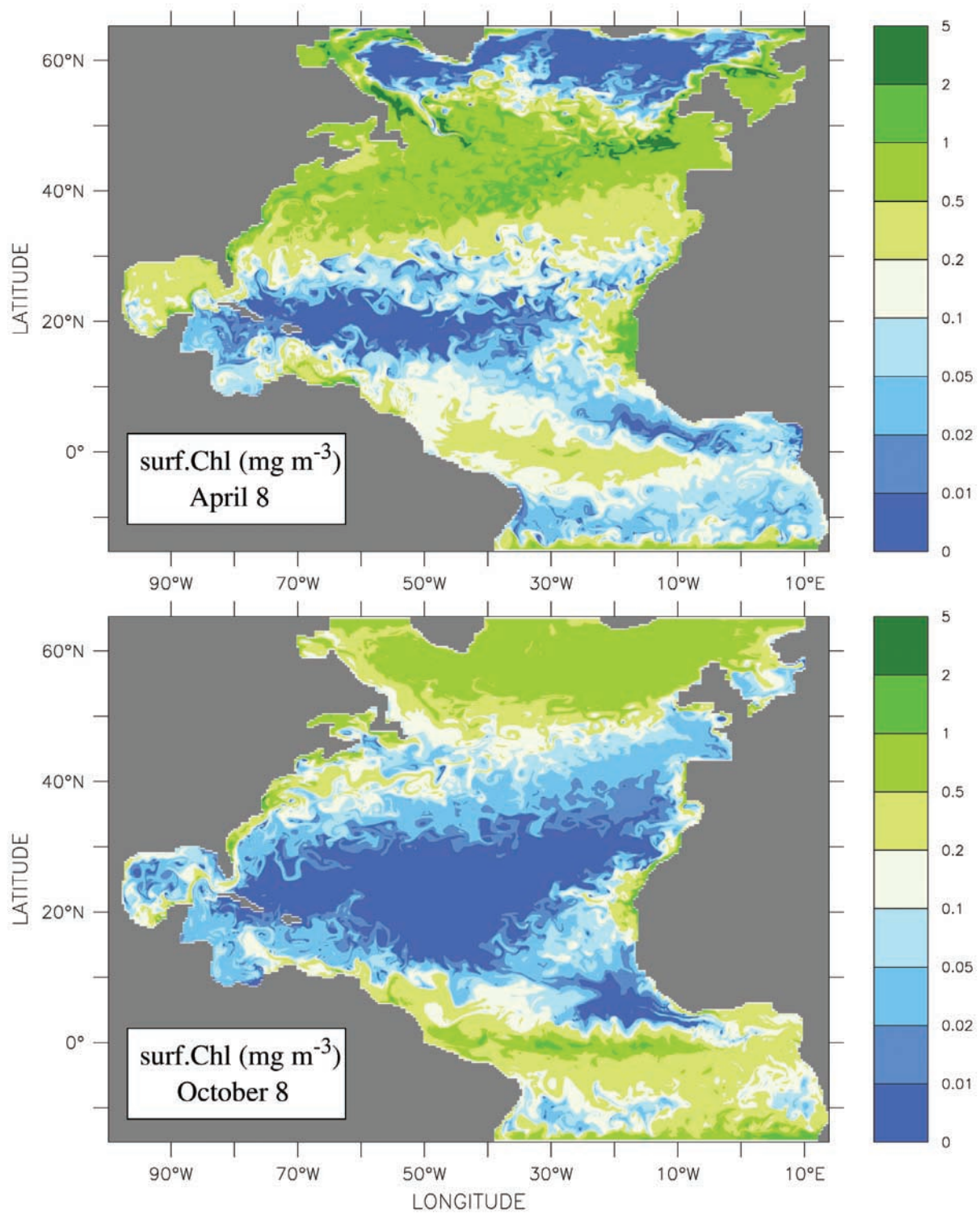
Figure 3. Surface chlorophyll simulated by the $(1/9)^\circ$ model for (top) April 8 and (bottom) October 8 of the third coupled year. Units are mg Chl m^{-3}.

Figure 7. Simulated 3-year mean nitrate supply across the maximum depth reached by the 1% light level (Figure 5). (a) Total nitrate supply. (b) Nitrate supply by vertical mixing, including convective overturning. (c) Advective nitrate input by the mean flow. (d) Advective nitrate input by deviations from the mean flow. (e) Vertical advective nitrate input by deviations from the mean flow. (f) Horizontal advective nitrate input by deviations from the mean flow. Units are mol m^{-2} yr^{-1}.