GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 9, PAGES 1751-1754, MAY 1, 2001

NAO-induced long-term changes in nutrient supply to the surface waters of the North Atlantic

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Abstract. Since the late 1980s extensive observational campaigns like the Joint Global Ocean Flux Study (JGOFS) and the World Ocean Circulation Experiment (WOCE) have helped to considerably improve our understanding of marine biogeochemistry. By chance, this period corresponded to a phase of a positive swing of the North Atlantic Oscillation (NAO), whereas earlier studies in the North Atlantic generally took place during more negative phases of the NAO (Figure 1). This study demonstrates by means of a coupled ecosystem-circulation model that the long-term change in the NAO between the 1960s and 1990s may have induced significant regional changes in the upper ocean's nutrient supply. These include a decrease of nitrate supply by about 30% near Bermuda and in mid-latitudes, and a simultaneous 60% increase in the upwelling region off West Africa. The results suggest that a synthesis of biogeochemical observations taken during the past decades must take into account NAO-related climate variability.

Introduction

The North Atlantic Oscillation (NAO) is the dominant mode of atmospheric variability over the Atlantic sector of the northern hemisphere [*Cayan*, 1992]. Characteristic for the NAO is a simultaneous strengthening and weakening of the Iceland Low and Azores High and a corresponding change in strength and position of the westerly winds across the Atlantic onto Europe [*Walker*, 1924]. Observed variability in sea surface temperatures, depth of winter convection, water mass formation, as well as in the intensity of the large-scale ocean circulation and the associated oceanic heat transport have been related to the NAO [*Dickson et al.*, 1996; *Curry et al.*, 1998; *Eden and Jung*, 2001]. Significant correlations have also been reported between interannual fluctuations of the NAO and primary production rates measured within the Bermuda Atlantic Times-series Study (BATS) during the 1990s [*Bates*, 2001]. On longer time scales, a compilation of historical hydrographic observations near Bermuda revealed a shift from relatively deep winter mixing (200-400 m) in the 1960s to shallower mixing (150-200 m) in the late 1980s and early 1990s, from which a concomitant decrease in seasonal nutrient supply to the surface was inferred [*Michaels and Knap*, 1996]. A substantial decrease of wintertime surface nitrate concentrations can be found in data available from the same period. Results from a suite of one-dimensional models showed substantial correlations of convective nutrient supply with the NAO over the central and western North Atlantic but not in the eastern basin [*Williams et al.*, 2000]. To investigate NAO-related long-term changes in upper ocean nutrient supply, and hence new and export production [*Eppley and Peterson*, 1979], during past decades on a basin scale in greater detail, a three-dimensional high-resolution coupled ecosystem-circulation model of the North Atlantic Ocean is employed in this study.

Paper number 2000GL012328.
0094-8276/01/2000GL012328$05.00

Experiments

The numerical model consists of a simple nitrogen-based, four-component (nitrate, phytoplankton, zooplankton, detritus) ecosystem model embedded into a $2/5° \times 1/3°$ resolution circulation model with a turbulence closure scheme adequate to simulate the seasonal mixed layer cycle and diffusion in the main thermocline [*Oschlies and Garçon*, 1999]. In a high-NAO experiment, the model is forced by monthly varying surface heat fluxes and wind stress fields derived from the European Centre for Medium-Range Weather Forecasts reanalysis [*Gibson et al.*, 1997] and averaged over the high-NAO period 1989-1993. In a corresponding low-NAO experiment monthly anomalies of surface heat flux and wind stress are added to the forcing fields. These anomalies were obtained by regressing monthly surface fluxes for the period 1958–1997 onto the NAO index [*Eden and Jung*, 2001]. The proportion of the total observed atmospheric variability explained by the NAO-related flux anomalies is largest in winter, exceeding 50% for the surface heat flux in the subpolar North Atlantic and 20-30% in the northwestern and southeastern parts of the subtropical gyre (e.g., Figure 1 of *Eden and Jung* [2001]). The amplitude of the flux anomalies applied in the low-NAO experiment is chosen as to match the NAO status typical of the early 1960s (Figure 1). Both simulations were integrated for five years, starting from a common spun-up state of the coupled model that was reached under the same atmospheric forcing as used in the high-NAO experiment. For the low-NAO simulation, the five-year period investigated therefore includes the adjustment phase on switching from high-NAO to low-NAO forcing. However, adjustment processes to changes in the forcing were found to have little effect on the results presented here.

Results

Compared to the low-NAO run, winter mixed layers of the high-NAO simulation turn out to be shallower by some 20 to 100 m along the northern flank of the subtropical gyre, reflecting the anomalous oceanic heat gain by up to 20 W m^{-2} in the annual mean. Associated with shallower mixing is a reduction in wintertime surface nitrate concentrations. As shown by Figure 2, the simulated shift at the BATS site toward shallower winter mixed layers and reduced wintertime surface nitrate concentrations from low-

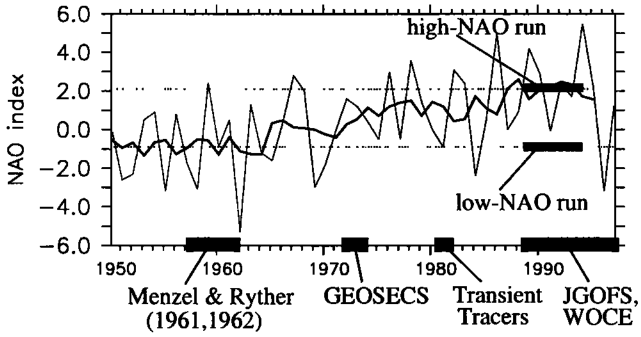

Figure 1. Time series of the North Atlantic Oscillation (NAO) index, defined here as the difference of sea level pressures (each normalized by its long-term standard deviation) between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland from 1865 through June 1998. The thin line refers to winter (JFM) averages, the thick line is a running 5-year mean of winter averages. The dotted lines refer to the index values of the high-NAO and low-NAO simulations. Also indicated are time periods of major observational campaigns in the North Atlantic.

NAO to high-NAO conditions agrees well with historical observations. In the five-year average, simulated maximum surface nitrate concentrations decrease by 50% from $1.32 \pm 0.51\,\mathrm{mmol\,m^{-3}}$, ($1.16 \pm 0.52\,\mathrm{mmol\,m^{-3}}$ in the observations; the variance given is the standard deviation computed over the five years considered) during the low-NAO period to $0.66 \pm 0.54\,\mathrm{mmol\,m^{-3}}$ ($0.37 \pm 0.17\,\mathrm{mmol\,m^{-3}}$ in the observations) in the high-NAO period. In addition to convective mixing in winter, nitrate can also be supplied by turbulent diffusion through the nitracline, by upwelling, or by lateral advection. As shown below, the effectiveness of these processes may as well vary with the NAO. Near Bermuda, simulated nitrate supply by vertical mixing decreases by $0.18\,\mathrm{mol\,N\,m^{-2}\,yr^{-1}}$, whereas supply by lateral advection increases by $0.03\,\mathrm{mol\,N\,m^{-2}\,yr^{-1}}$ and supply by vertical advection by $0.01\,\mathrm{mol\,N\,m^{-2}\,yr^{-1}}$ on changing from low-NAO to high-NAO forcing. Total annual-mean nitrate input into the upper 126 m, which here is taken as synonym for the euphotic zone, is reduced by 30% (i.e., less than the 50% decrease in simulated winter nitrate concentrations) from $0.46 \pm 0.01\,\mathrm{mol\,m^{-2}\,yr^{-1}}$ in the low-NAO run to $0.32 \pm 0.08\,\mathrm{mol\,m^{-2}\,yr^{-1}}$ in the high-NAO experiment.

The basin-scale response of the simulated nitrate input into the upper 126 m to the NAO is shown in Figures 3a and 3b. The dominant feature is an approximately zonal band between 30°N and 40°N where nitrate supply in the high-NAO run is lower by $0.1\text{-}0.2\,\mathrm{mol\,m^{-2}\,yr^{-1}}$ amounting to an average reduction of more than 30% in this latitude range. In the western and central part of the basin, this reduction is mainly due to a decrease in nitrate supply by vertical mixing (Figure 3c). NAO-related changes in the advective supply become more important further east (Figure 3d), where changes in the wind stress curl and associated Ekman pumping are largest. In the open eastern North Atlantic, Ekman downwelling increases by up to $20\,\mathrm{m\,yr^{-1}}$ on switching from low- to high-NAO forcing, thereby reducing net nitrate supply to the upper ocean by about $0.2\,\mathrm{mol\,m^{-2}\,yr^{-1}}$ in this region. At the same time, an increase in south-westerly winds along the coast off Portugal and West Africa leads to enhanced coastal upwelling and associated nutrient supply. Close to the West African coast, nitrate input is larger by up to $0.5\,\mathrm{mol\,m^{-2}\,yr^{-1}}$ (~ 60%) in the high-NAO scenario. NAO-related changes in the distribution of eddy activity and associated eddy-induced nitrate supply [*Oschlies and Garçon*, 1998] were found to be negligible in this eddy-permitting model.

Somewhat unexpectedly, there is relatively little impact of the NAO on simulated nutrient supply over the subpolar gyre, where NAO-related variations in surface heat fluxes, in oceanic mixed layer depths, and in the wind stress curl are largest [*Hurrel*, 1995; *Dickson et al.*, 1996]. Integral effects on simulated nitrate supply are small for two reasons: firstly, changes in winter mixed layer depths have relatively little effect on entrained nutrient concentrations because vertical concentration gradients are relatively low near the base of the winter mixed layer. Secondly, NAO-related changes in the wind stress and hence in associated advective supply

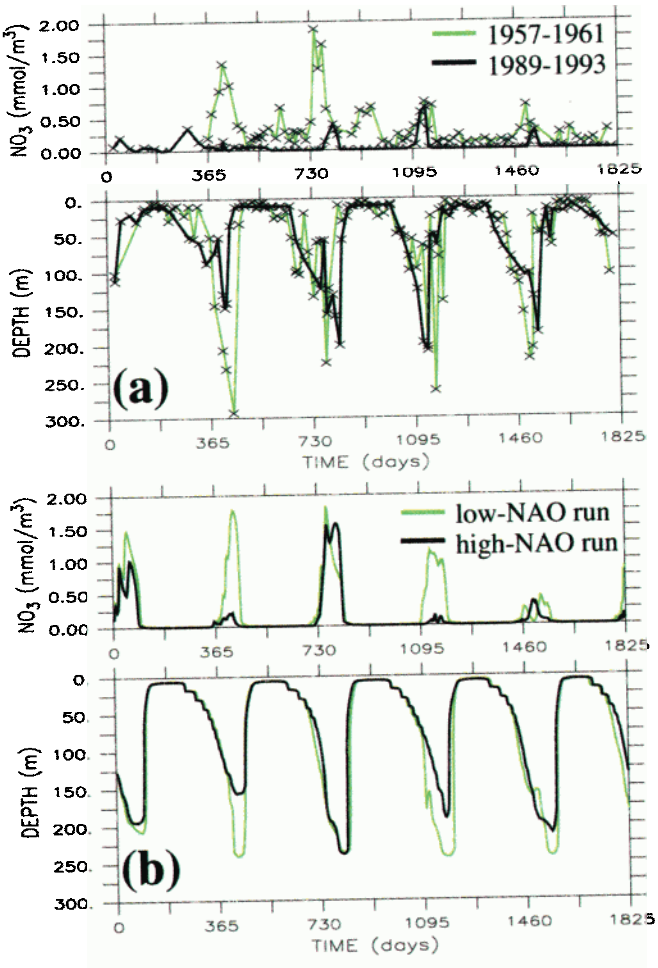

Figure 2. (a) Surface nitrate concentrations and mixed layer depth observed near Bermuda for the low-NAO period 1957-1961 [*Menzel and Ryther,* 1960, 1961] and the high-NAO period 1989-1993. Data were kindly provided by Rod Johnson via `http://www.bbsr.edu/users/ctd/batdataex.html`. For the surface nitrate, all available measurements in the top 10 m were used, the mixed layer depth was computed by a $\Delta T = 0.2°C$ criterion. (b) Surface nitrate concentrations and mixed layer depth near Bermuda computed as in (a) from the low-NAO and high-NAO model simulations. Since the model results were obtained for annually repeating atmospheric forcing, all interannual variability in (b) results from internal dynamics of the high-resolution model [*Oschlies and Garçon*, 1998].

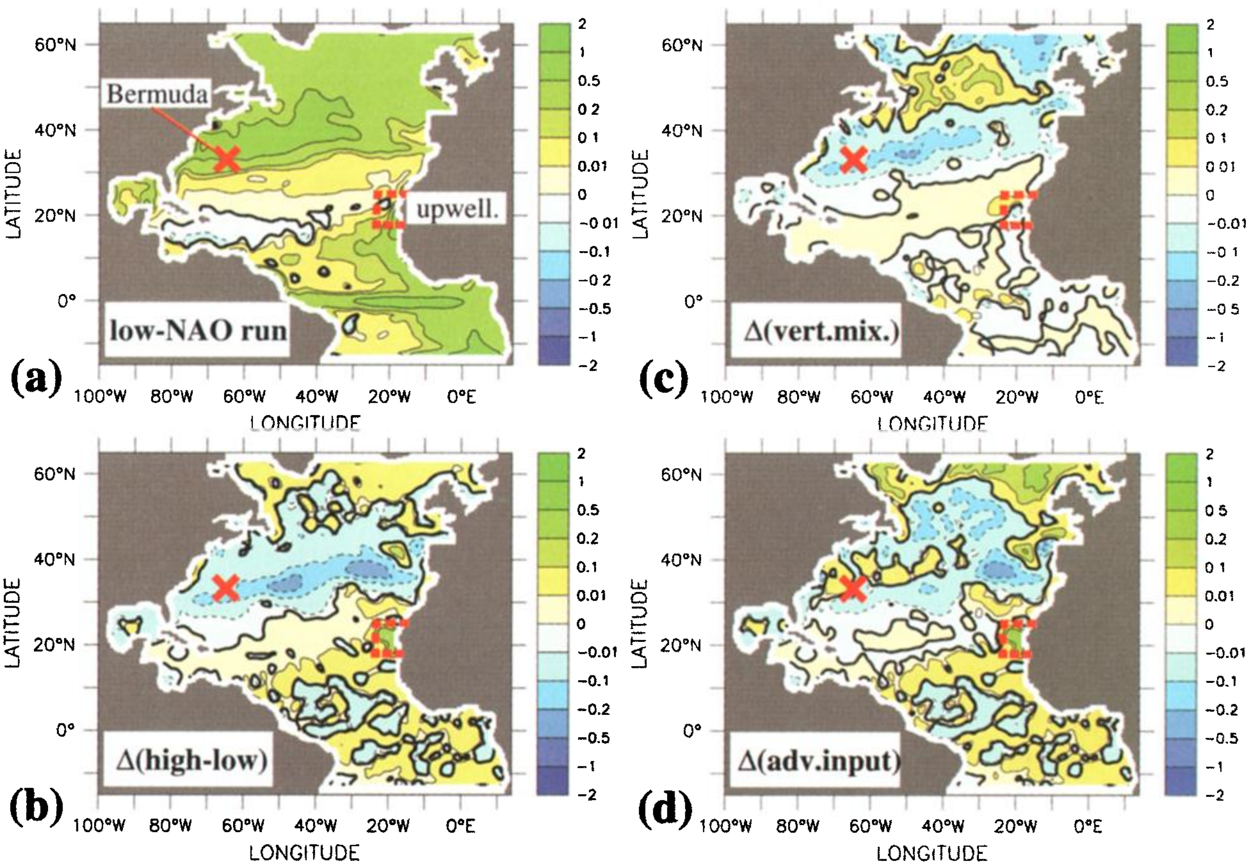

Figure 3. (a) 5-year mean nitrate input into the upper 126 m of the model in the low-NAO experiment. The 5-year mean difference in simulated nitrate supply between high-NAO and low-NAO runs is shown in (b), its portion attributed to vertical mixing in (c), and to advection (vertical plus horizontal) in (d). Units are mol $m^{-2} yr^{-1}$. Indicated are the location of Bermuda and the upwelling region for which regional averages are given in the text. Note the non-equidistant contour intervals.

are strongest in winter. With phytoplankton growth being severely limited by deep mixing and low wintertime solar irradiation over the subpolar gyre, any surface nitrate anomalies arising from changes in advective supply will be effectively diluted by vertical mixing throughout the deep winter mixed layer [*Dutkiewicz et al.*, 2001]. As a result, changes in nitrate supply by advection are approximately canceled by changes in vertical mixing north of approximately 45°N (Figures 3c and 3d).

Conclusion

While the basin-averaged nitrate supply is smaller by only 4% in the high-NAO experiment, the model results indicate that the NAO has had a significant impact on regional long-term variations in nutrient supply over the subtropical North Atlantic during past decades. Between 30°N and 40°N simulated nutrient supply decreases by more than 30% and it increases by about 60% in the upwelling region off West Africa for the observed swing in the NAO between the early 1960s and 1990s. This model result is corroborated by historical time-series observations near Bermuda. There is also good agreement with a related model study [*Williams et al.*, 2000] that combined one-dimensional mixed-layer models with climatological nitrate profiles to investigate interannual variability in nutrient supply by convection and Ekman transport to the north of 20°N.

An at first sight surprising result of this study is that the areas of largest NAO-related changes in nutrient supply are in the subtropics, whereas changes in physical variables are considered to be most pronounced at higher latitudes [*Dickson et al.*, 1996]. Apparently, the transition region from the oligotrophic subtropical gyre to the eutrophic regions surrounding it is most sensitive to NAO-related climate fluctuations. In this region even small changes in the depth of winter mixing can determine whether the mixed layer penetrates the nutricline, and even in winter there is sufficient light to allow significant levels of nutrient uptake via phytoplankton growth and thus an immediate biological response to alterations in nutrient supply. Note, however, that for the real ocean's nutrient budget NAO-impacts other than changes in the nitrate supply examined here may contribute. For example, NAO-related changes in mixed layer depth have been suggested to affect the amount of nitrogen fixation in the subtropical North Atlantic [*Hood et al.*, 2001] which might partly offset changes in nitrate supply reported above. While a synthesis of biogeochemical observations taken during different periods, as well as an analysis of model results achieved with different atmospheric forcing fields, should take into account NAO-induced variations in ocean biogeochemistry, NAO-related variability may, on the other hand, provide a valuable test case for better understanding and estimating effects of possible future climate changes on marine biogeochemical cycles.

Acknowledgments. I thank the BATS staff for making available the Bermuda time-series data, Markus Schartau, Carsten Eden, and Paul Kähler for discussion and help with the data, and two anonymous reviewers for helpful comments on the manuscript.

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(Received September 11, 2000; revised January 5, 2001; accepted January 30, 2001.)