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Coccolithophore bloom size variation in response to the regional environment of the subarctic North Atlantic

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Abstract

Several environmental/physical variables derived from satellite and in situ data sets were used to understand the variability of coccolithophore abundance in the subarctic North Atlantic. The 7-yr (1997–2004) time-series analysis showed that the combined effects of high solar radiation, shallow mixed layer depth ($<$20 m), and increased temperatures explained $>$89% of the coccolithophore variation. The June 1998 bloom, which was associated with high light intensity, unusually high sea-surface temperature, and a very shallow mixed layer, was found to be one of the most extensive ($>$995,000 km^2) blooms ever recorded. There was a pronounced sea-surface temperature shift in the mid-1990s with a peak in 1998, suggesting that exceptionally large blooms are caused by pronounced environmental conditions and the variability of the physical environment strongly affects the spatial extent of these blooms. Consequently, if the physical environment varies, the effects of these blooms on the atmospheric and oceanic environment will vary as well.

Emiliania huxleyi is a relatively small (about 5–10 μm diameter) phytoplankton species belonging to the taxonomic group of coccolithophores, which is capable of forming spatially extensive blooms greater than the size of the United Kingdom. As the species can be visually detected, by turning dark-blue oceanic waters milky-turquoise in color (because of scattering caused by the coccoliths), the extensive blooms that it forms are visible from space (via satellites). That is why more is known about the spatial distribution of this phytoplankton species than any other (Tyrrell and Merico 2004). Blooms exceeding 250,000 km^2 in size, like the 1991 North Atlantic bloom (based on the advanced very high resolution radiometer [AVHRR], Holligan et al. 1993), may have significant effects on the oceanic as well as atmospheric environment (Tyrrell and Merico 2004). Also, coccolithophores are major producers of several substances (e.g., dimethyl sulfide, calcium carbonate, and organic carbon) that are thought to affect the climate (Holligan 1993).

Although satellites have been characterized as excellent tools for detecting and mapping *E. huxleyi* (Tyrrell and Merico 2004), several cases have shown that not all bright waters are caused by this species. Examples of water conditions that mimic *E. huxleyi*, or in other words mimic

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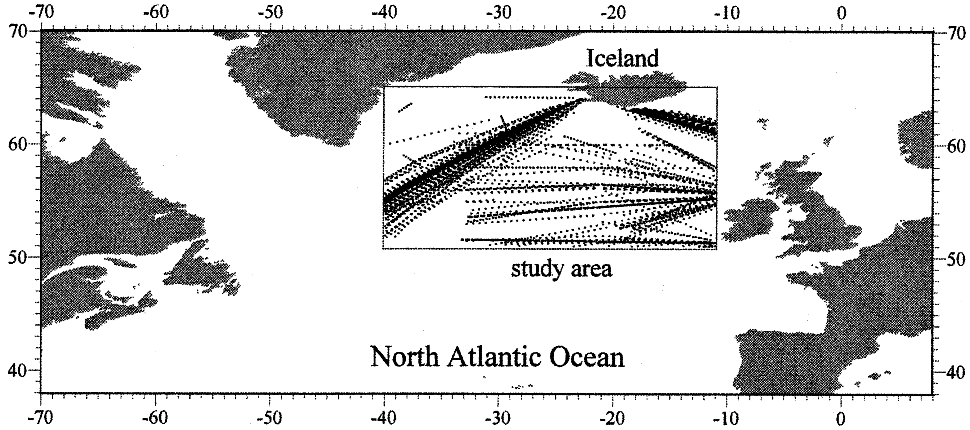

Fig. 1. Study area of the subarctic North Atlantic defined by the coordinates 51°–66°N and 11°–40°W. The black dots represent the CPR samples taken from January 1998 to December 2002 ($n = 3,977$).

the highly reflective characteristics of coccolithophore blooms with significant numbers of liths, include broken-up diatom frustules (Broerse et al. 2003), shallow carbonate shelves (Brown and Yoder 1994), and suspended sulfur particles (Weeks et al. 2002). Generally, it is only very infrequently that open ocean turquoise waters should be ascribed to species other than *E. huxleyi* (Weeks et al. 2004); however, it is essential that in situ verification is obtained before significant conclusions are drawn (Tyrrell and Merico 2004). This in situ verification can be acquired from the Continuous Plankton Recorder (CPR) survey, which has been running in the North Atlantic Ocean and North Sea for approximately 50 years (Reid et al. 2003) and contains details of the plankton from >170,000 samples taken since 1946.

Several environmental, physical, and chemical factors can induce *E. huxleyi* blooms; although one factor alone is unlikely to trigger a bloom. Briefly, this coccolithophore species inhabits the subsurface layer (mixed layer depth ~20 m; Balch et al. 1991) in highly stratified waters (caused by sunny and calm weather) where light intensity is high (Nanninga and Tyrrell 1996). An environmental parameter that may have an indirect effect on coccolithophores (through stratification) is wind stress, which is responsible for vertical mixing in the water column. It was thought (Tyrrell and Taylor 1996) that *E. huxleyi* blooms are favored by inorganic phosphate being more limiting than nitrate, but a recent review showed that the Bering Sea and other blooms occurred in nitrate-scarce, phosphate-replete waters (Lessard et al. 2005). *E. huxleyi* is also found in waters where carbonate saturation is high (Tyrrell and Merico 2004), silicate concentration is low (Brown and Yoder 1994), and iron concentration is low (Brand et al. 1983). In addition, positive temperature and negative salinity anomalies (associated with strong haline stratification) have been correlated with coccolithophore blooms in the Barents Sea (Smyth et al. 2004). Iglesias-Rodriguez et al. (2002) reported that water temperature combined with other factors, such as high light intensity, critical irradiance (stratification relative to light level), and declining nitrate concentrations appeared to be a good predictor of *E. huxleyi*. However, it is thought to be due to secondary effects, i.e., water stratification (Tyrrell and Merico 2004). Although many attempts have been made to study the biogeochemistry of these blooms, little information is known on the effect of the physical environment in the subarctic North Atlantic.

The purpose of this paper was to examine the causative physical factors and/or environmental extremes that induce extensive coccolithophore blooms, detected by the sea-viewing wide field-of-view sensor (SeaWiFS), in the subarctic North Atlantic. The geophysical variables used in the analysis are solar radiation, sea surface temperature (SST) and its anomaly (SSTA), mixed layer depth (MLD), and wind stress. Particular attention was paid to a massive *E. huxleyi* bloom that occurred in June 1998.

Data and methods

All satellite, in situ, and modeled data sets were for the same study area. The area of study, the subarctic North Atlantic, was defined by a 51°N–66°N latitude range and 40°W–11°W longitude range (Fig. 1).

Satellite data

SeaWiFS—The current reprocessed version (v5.1) produced by the Ocean Biology Processing Group was acquired from the NASA Oceancolor web site (http://oceancolor.gsfc.nasa.gov/). The data were Level 3 monthly composite products (9×9 km^2 resolution) of the normalized water-leaving radiance (nLw) at 555 nm ([nLw_555] mW cm^{-2} μm^{-1} sr^{-1}) for the period from September 1997 to December 2004 (>7 years of data). These data were used as the temporal and spatial variability of coccolithophore blooms, which has been routinely followed using SeaWiFS imagery (Cokacar et al. 2004). The size of the 1998 coccolithophore bloom (15 June 1998, Fig. 2A) detected by SeaWiFS was calculated by recording the number of pixels where nLw_555 was >0.9 mW cm^{-2} μm^{-1} sr^{-1} (Cokacar et al. 2004).

AVHRR—The nighttime AVHRR Pathfinder 5 (P5) monthly mean SSTs at 9×9 km^2 resolution were obtained from the NASA PO.DAAC web site (http://poet.jpl.nasa.gov/). Then, the monthly mean climatologies were computed from 1985–2004, and the SSTA was the deviation of the SST from the mean climatology. The nighttime SST products were used so that the solar radiation bias (the diurnal fluctuation in SST) that can occur during the daytime could be avoided.

The NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalysis data—Monthly composites of mean wind speed (m s^{-1}) data were obtained (2.5° × 2.5° spatial resolution) from which the wind stress (Pa) was calculated (September 1997 to December 2004). The stress exerted by the surface wind (at 10 m above the sea surface) is derived as a function of wind speed, nondimensional drag coefficient, and boundary layer air density (Pickard and Pond 1978):

$$\tau = \rho_a C_D |W| W$$

Where ρ_a is the average air density (~1.3 kg m^{-3}), W is the wind speed over the sea surface (for most practical purposes, a 10-m height wind speed, W_{10}, is acceptable), and C_D is the dimensionless drag coefficient that varies with wind speed as (Yelland and Taylor 1996):

$$C_D = \left(0.29 + \frac{3.1}{W_{10}} + \frac{7.7}{W_{10}^2}\right) 10^{-3} \quad \text{for } \left(3 \leq W_{10} < 6 \text{ m s}^{-1}\right)$$

$$C_D = (0.60 + 0.07\, W_{10})\, 10^{-3} \quad \text{for } \left(6 \leq W_{10} \leq 26 \text{ m s}^{-1}\right)$$

Sea surface wind stress drives the dynamics of the boundary layer and is therefore expected, on physical grounds, to be closely related to the generation of surface waves, production of wind-driven ocean surface currents, and the stirring processes that keep the upper ocean well mixed down to the thermocline. The spatial variation of wind stress over the ocean causes surface divergence of horizontal flow that in turn gives rise to vertical mass flux through Ekman pumping (Ekman 1905). Because coccolithophores are likely to be found in highly stratified waters, the wind stress (as well as MLD, *see below*) was used to confirm the presence of these conditions.

Monthly composites of mean downward solar radiation flux (W m^{-2}) data were obtained for the period of 1997–2004 (2.5° × 2.5° spatial resolution). We used the NCEP/NCAR reanalyzed surface downward solar radiation flux, which was estimated at the bottom of the atmosphere (Kalnay et al. 1996) and therefore considered as the solar radiation received at the earth's surface. Reanalysis data were provided by the National Oceanic and Atmospheric Administration/Cooperative Institute for Research in Environmental Sciences Climate Diagnostics Center, Boulder, Colorado, from their web site (http://www.cdc.noaa.gov/).

OCCAM model data

The MLD data set was obtained from the Ocean Circulation and Climate Advanced Modeling Project (OCCAM) that runs a high-resolution global ocean model. The monthly mean MLD (m) product (0.25° × 0.25° resolution) for the North Atlantic and Arctic Ocean model domain was used. Then, an averaged time series was created for the period from September 1997 to December 2003.

Generally, the modeled MLDs are based on a variety of physical variables such as wind speed, wind stress, and latent heat fluxes, thus the estimation of MLDs are most consistent with a large number of data sources. For instance, the primary OCCAM model variables were potential temperature, horizontal velocity, and sea surface elevation (Webb et al. 1998). More technical details of the OCCAM model can be found elsewhere (Webb et al. 1998). The data were ordered from the official web site of the OCCAM model (http://www.noc.soton.ac.uk/JRD/OCCAM/EMODS/).

In situ data

In situ measurements of coccolithophore numbers were derived from the CPR survey, which is an upper-layer plankton monitoring program that has operated in the North Sea and North Atlantic Ocean since 1946. However, from the beginning of the CPR survey until 1993 sample analysis consisted of recording only the presence/absence of coccolithophores, whereas beginning in 1993 the number of cells was also recorded (Hays et al. 1995). Samples were collected by a high-speed plankton recorder (~27–37 km h^{-1}) that is towed behind "ships of opportunity" in the surface layer of the ocean (~6–10-m depth); one sample represents ~18 km of tow (Reid et al. 2003). Plankton are filtered onto a constantly moving (powered by an impeller) band of silk mesh (mesh size 270 μm).

Although *E. huxleyi* is only 5–10 μm in diameter, it is reported that this species has been identified repeatedly in the CPR samples (Hays et al. 1995). Hays et al. (1995) suggested two possible reasons why this small coccolithophore species is present on CPR samples: plankton clogging up the filter and its capture on the finer threads of silk that constitute the mesh-weave.

The CPR analysis does not identify coccolithophores to the species level, but the archived samples are available for re-examination. Therefore, archived samples were reanalyzed to confirm if the bloom observed from a satellite was *E. huxleyi*. Data (number of coccolithophore cells per tow) for the North Atlantic were extracted from the CPR database between 1998 and 2002 (Fig. 1). The CPR took 95 samples within 6 days (1, 20, 21, 27, 28, and 29) of June 1998, and 30 of those appeared to be dominated by coccolithophores. These archived CPR samples (preserved in buffered formalin) were re-examined, and *E. huxleyi* was identified.

Data analysis

Generalized additive models (GAMs) were used to investigate potential relationships between an index of coccolith abundance (nLw_555) and various environmental parameters (solar radiation, SST, SSTA, MLD, and wind stress). GAM is a flexible regression technique; its advantage over traditional regression methods, such as general linear models, is its ability to model nonlinearities using non-

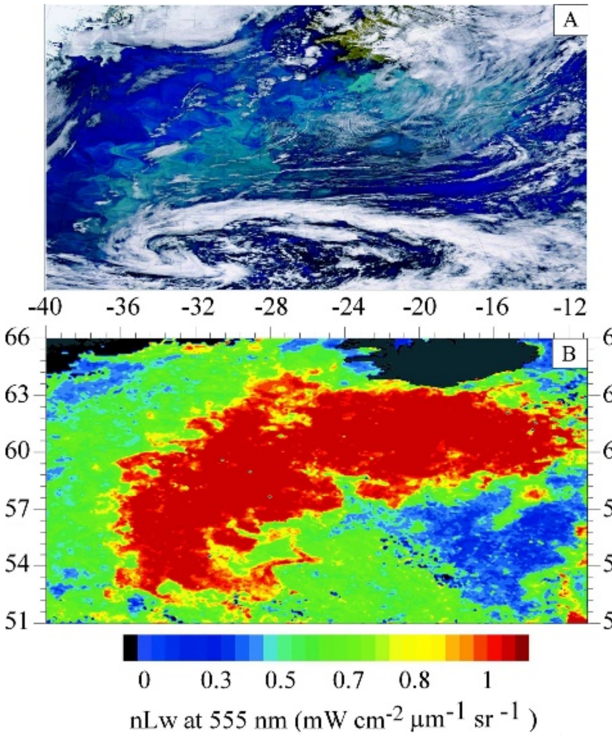

Fig. 2. (A) True color image of the coccolithophore bloom taken by SeaWiFS on 15 June 1998 in the study area of the subarctic North Atlantic. Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center (GSFC), and ORBIMAGE. (B) Pseudocolor image presenting monthly mean of SeaWiFS nLw_555 for June 1998.

parametric smoothers (Hastie and Tibshirani 1990). However, the algorithm that fits the curve is usually iterative and nonparametric, masking a great deal of complex numerical processing. A detailed description of GAMs can be found elsewhere (Hastie and Tibshirani 1990).

Seventy-six (number of monthly averages) data points were employed to develop the relationships for each parameter. The least squared weighted smoother (loess) was used to estimate the nonparametric function, and the Gaussian error distribution was assumed after consideration of diagnostic residual plots (Hastie and Tibshirani 1990; Maravelias 2001). To construct the GAM, a forward and backward stepwise model fitting approach was used based on the Akaike's information criterion (AIC) statistic (Chambers and Hastie 1992). All predictors in the model were included as smoothed terms. By using the AIC, the significance of each term in the model could be assessed. Also, the stepwise approach enabled the removal of the nonsignificant variables (predictors) from the final model. Hence, the final models showed the combined effect of each predictor (physical variable) on response (nLw_555).

Results

To explore the seasonal cycle of coccolithophores, the monthly means of both time series data (CPR and SeaWiFS nLw_555) were plotted against time for the period 1998–2002 (Fig. 3). A clear visual agreement can be seen, and the results suggest that both patterns exhibit seasonal cycles with similar trends: increasing during early summer (both peaked during June) and gradually decreasing during autumn/winter. However, there is a noticeable difference from July to September when the CPR values drop off rapidly while the nLw_555 values remain high. Once the coccolithophore bloom starts to decline, the coccoliths are detached from the cells and float separately in the water. Therefore, the satellite still detects the reflectance resulting from these blooms (for optical properties of coccoliths see Voss et al. 1998), whereas the CPR is counting only the live cells and not the empty liths. It has been reported that when the coccolithophore bloom of 1991 aged, the number of the detached coccoliths increased (Balch et al. 1996*a*) and that suspended coccoliths were causing up to 80% of the total backscattering in the center of the bloom (Balch et al. 1996*b*). However, Figure 3 clearly shows that in the subarctic North Atlantic the favorable month for coccolithophores is June.

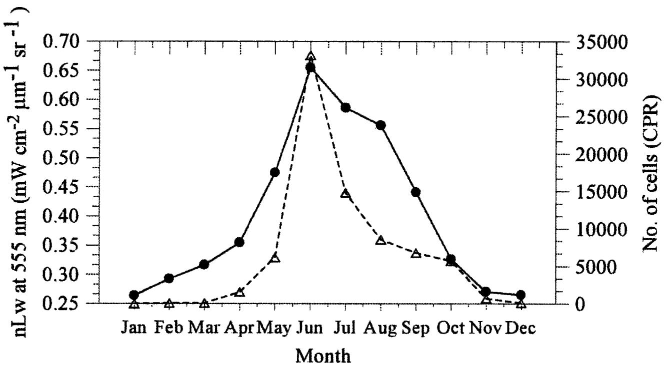

Fig. 3. Monthly mean of SeaWiFS nLw_555 (solid line) and CPR coccolithophore numbers (dashed line) from January 1998 to December 2002 (3,977 samples) in the study area. The spatial distribution of the samples can be seen in Figure 1.

The time series composed of >7 years monthly nLw_555 data indicated that the highest values (primarily from coccolithophores) occurred during the summer months and specifically June (Fig. 4A). The highest nLw annual mean occurred during 1998, and June appeared to have the highest nLw mean (~0.8) in this 7-yr time series; it showed an increase of ~25% when compared to the overall mean of the remaining June months. In addition, June 1998 appeared to occupy the largest aerial extent. Figure 2B shows that the spatial extent of the June 1998 coccolithophore bloom, and the calculated size (based on SeaWiFS) of this extensive bloom was >995,000 km^2 (15 June 1998). Also, an analysis of the archived in situ samples confirmed that this bloom was primarily composed of coccolithophores; *E. huxleyi* was present in almost all the samples. Coccolithophore blooms also occur in the other years, but their spatial extent appeared to be less pronounced (Fig. 4A).

Several environmental/physical parameters were plotted to examine their importance on coccolithophores (Fig. 4).

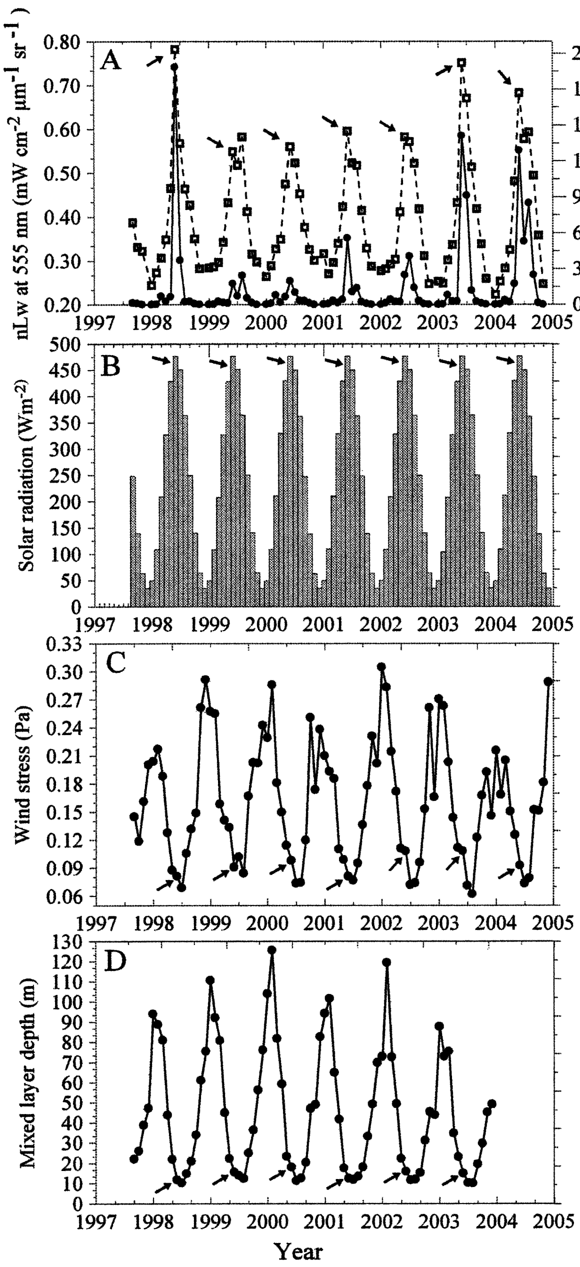

Fig. 4. Satellite time series: (A) The dashed line presents the nLw_555 (coccolithophore abundance) from September 1997 to December 2004, and the solid line presents the number of nLw_555 pixels >0.9 mW cm^{-2} μm^{-1} sr^{-1} (blooms areal extent). (B) solar radiation from September 1997 to December 2004. (C) Wind stress from September 1997 to December 2004. (D) MLD from September 1997 to December 2003. The arrows represent June of every year.

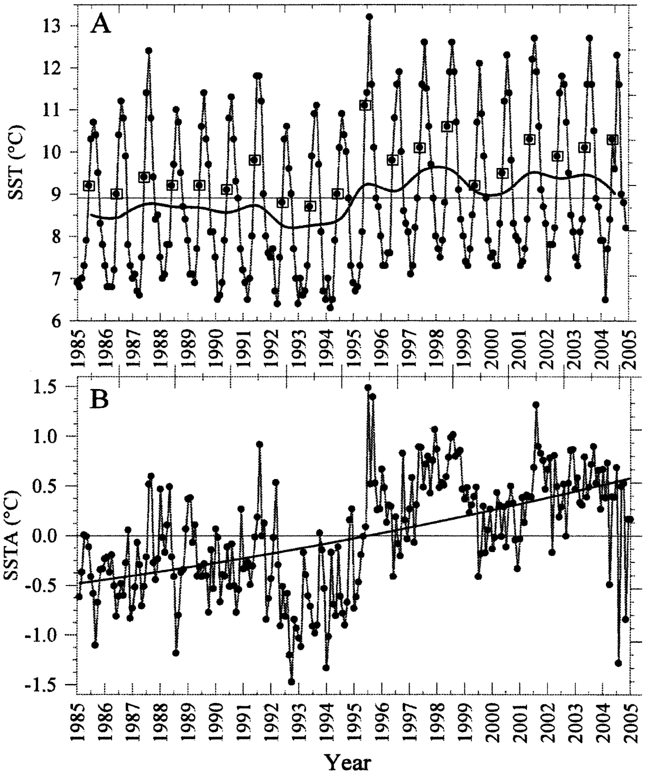

Fig. 5. (A) SST from January 1985 to December 2004. The thin horizontal line is the overall mean, and the thick line is the annual mean. The open boxes surrounding the dots represent June of every year. (B) SSTA from January 1985 to December 2004 (the black curve is a second order polynomial).

The incoming solar radiation time series indicated that the highest light intensity occurred during the summer months and peaked in June every year (mean of 477 W m^{-2}), whereas the lowest light occurred during the winter months, with the lowest values during December (mean of 35 W m^{-2}) (Fig. 4B).

Figure 4C shows that overall, July appeared to have had the lowest wind stress every year. The wind stress shows the opposite pattern (negatively related) to SST (Fig. 5A); it is high during the autumn and winter months and decreases rapidly during the summer months, enabling summer stratification (favorable conditions for *E. huxleyi*). June 1998 and 2001 appeared to have the lowest mean wind stress (0.08 Pa) in comparison with the Junes of other years. However, the overall average for all Junes (0.095 Pa) does not differ considerably from the monthly mean of June 1998.

Figure 4D indicates that during autumn–winter months the MLD reaches the highest values, whereas during the summer months the MLD is decreasing rapidly (lowest in July). During June months (highest nLw_555 values), the overall MLD mean for the study area is 14.6 m, whereas the shallowest MLD of this time series appeared during June 1998 (11.6 m). These results confirm the presence of highly stratified and shallow mixed layer depth waters within the study area (during June months) that favor *E. huxleyi.* Note that the x-axis scale is different in Figure 4D than the preceding plots in Figure 4, because the MLD data was not available for 2004.

Figure 5A shows AVHRR SST (1985–2004) that has a pronounced change in this 20-yr time series, with evidence for a stepwise increase in 1996. It can be clearly seen that after this year the annual SST mean remains above the overall mean, whereas the opposite occurred before 1996. The annual mean showed that 1998 was the warmest year

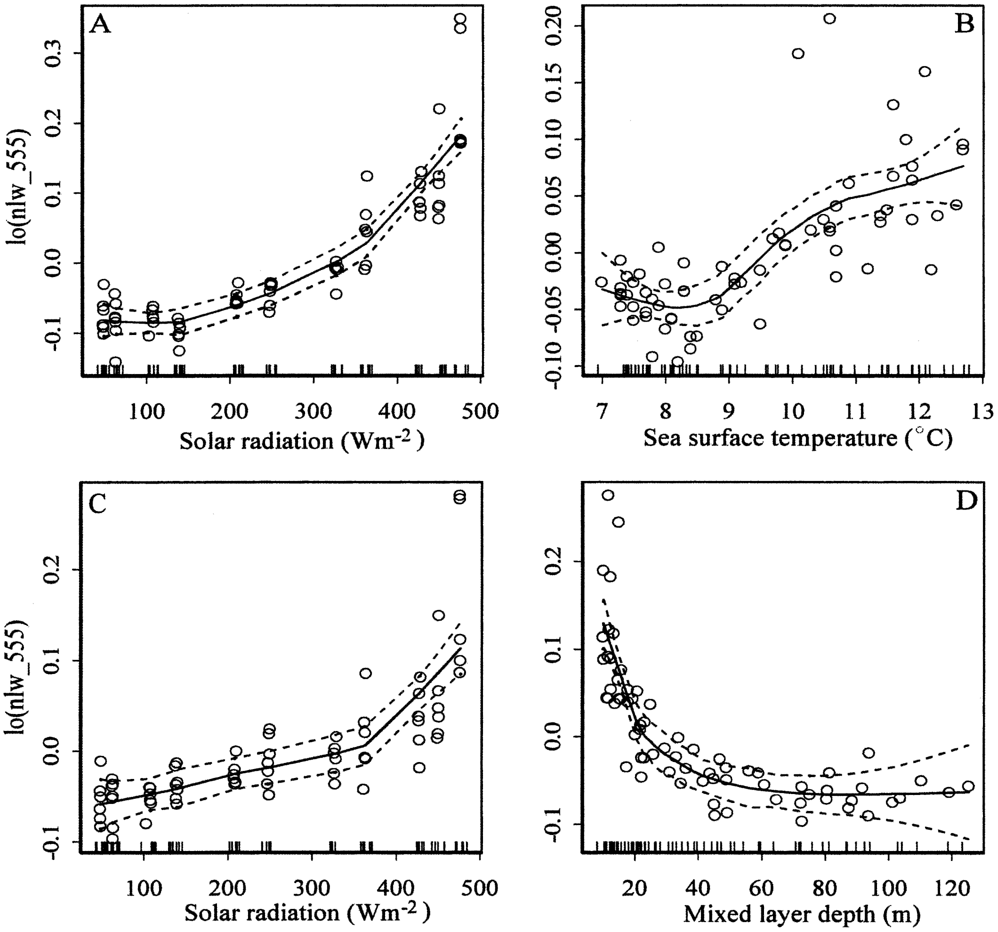

Fig. 6. GAM plots illustrate nonlinear relationships between the nLw_555 variable (lo stands for loess smoother) and each predictor. Circles represent the raw data, the connected line is the spline, and the dashed lines are the 95% confidence intervals. (A) and (B) illustrate the final product of model 1 ($r^2 = 0.896$), which incorporated solar radiation (A) and SST (B). (C) and (D) illustrate the final result of model 2 ($r^2 = 0.894$), which incorporated solar radiation (C) and MLD (D).

(9.6°C) and June 1998 (when the extensive coccolithophore bloom occurred) and June 1995 appeared to be the warmest Junes of the 20-yr time series. Overall, the average temperature during all June months was 9.6°C, whereas in 1998 the monthly mean was 10.6°C (1°C above the mean).

It should be noted that *E. huxleyi* may trap light near to the surface layer; consequently, surface waters that are dominated with this species tend to have increased temperatures. In other words, the temperature might be increased because of *E. huxleyi* presence rather than the bloom benefiting from an already present increased temperature. The subarctic North Atlantic 1998 monthly SST data were warmer than the monthly SST data from other years for both the area within and outside of the bloom, which suggests that the temperature influenced the size of the bloom rather than the other way around in this particular case. In addition, it has been reported that 1998 was the warmest year in the record of instrumental measurements (Lu 2005). SSTA confirmed the SST observations and also showed that 1998 was the most anomalous SST year, with June 1998 and 1995 being the most positively anomalous Junes of the time series (Fig. 5B); note that the spike in 2001 is July. In the study area, another extensive bloom was reported (based on AVHRR) during the summer of 1991 (Holligan et al. 1993). In Fig. 5 it can be seen that this year was relatively warm, with a high positive temperature anomaly and generally higher than average temperature (July 1991).

GAMs were also used to identify relationships between nLw_555 and the environmental/physical parameters. It has to be noted that if two predictors (parameters) are highly correlated with each other, i.e., are not independent, then they can cause a problem in fitting a model involving both of them. The problem is usually that the parameter estimates are unstable and the model cannot be fitted (Scott pers. comm.). To avoid this, two different models should be used that will have all the independent variables. In our case, MLD and SST were highly negatively correlated (Spearman rank order correlation coefficient: $r_s = -0.85$,

$p < 0.0001$); probably because of the fact that MLD was derived from temperature (*see Methods*). Consequently, model 1 (Fig. 6A,B) incorporated solar radiation, SST, SSTA, and wind stress, whereas model 2 (Fig. 6C,D) incorporated solar radiation, MLD, SSTA, and wind stress.

Using a stepwise approach, which enabled the removal of nonsignificant variables, model 1 indicated that the parameters to predict coccolithophore abundance (nLw_555) should be solar radiation and SST (Fig. 6A,B). Both parameters were highly significant and explained 89.6% of the variation in coccolithophore abundance. Figure 6A indicated that coccolithophore abundance increased as the solar radiation (insolation) increased with this significant relationship ($p < 0.00001$) exhibiting an early exponential increase that became linear after 370 W m^{-2} of solar radiation. For SST (Fig. 6B), the significant model ($p = 0.0185$) showed that the coccolithophore abundance was low and reasonably constant until ~8.5°C of SST, after which it increased rapidly as SST increased and then reached an optimal reflectance (nLw_555) at 12.5°C. Although both parameters appeared to be significant, solar radiation explained the nLw_555 variability more than SST.

Model 2 indicated that coccolithophore abundance should be predicted using solar radiation and MLD (Fig. 6C,D) and that the other factors were not significantly related to bloom formation; the combination of these two parameters explained 89.4% of the variation in coccolithophore abundance. As expected, solar radiation ($p = 0.0002$) in Fig. 6C exhibited a similar pattern as in model 1, where it increased progressively along with coccolithophore abundance until the relationship increased rapidly and became linear after 370 W m^{-2} of solar radiation. The MLD appeared to be highly significantly negatively related ($p < 0.00001$) with coccolithophore abundance. As can be seen from Fig. 6D, the coccolithophore abundance increased as the MLD values decreased. Specifically, below 20 m of MLD (shallow mixed layer) the relationship was linearly negative, whereas after that an exponential decay can be observed until it became stable below 65 m of MLD. In terms of significance, model 2 indicated that MLD was the most important parameter, because it explained the nLw_555 variability more than solar radiation.

Discussion

During June 1998 an extensive coccolithophore bloom occurred in the North Atlantic, and to our knowledge, this bloom is the most extensive coccolithophore bloom recorded by SeaWiFS (>995,000 km^2). This bloom has been compared to blooms reported in the literature and exceeds their size by a considerable margin, but these were analyzed with AVHRR (at least until 1997), which has a reduced sensitivity and broad waveband in the visible region of the electromagnetic spectrum.

In situ and satellite measurements indicated that coccolithophores in the subarctic North Atlantic occur at their highest abundance during late spring/early summer and peak in June. The environmental variables used in the analysis suggested that the solar radiation was very high during June 1998 (as it was during every June), while the MLD was shallow (11.6 m). These results are in agreement with those of Balch et al. (1991) who mentioned that the MLD within coccolithophore blooms is shallow (~20 m). In addition, June 1998 together with 1995 were the warmest and most positively anomalous Junes of the last 201years.

Using the results of the time series, GAMs were used to identify which environmental/physical parameters were the most important for the formation of coccolithophore blooms. The two GAM models supported the observations and indicated that the combined effect of high solar radiation, shallow MLD, and increased SST were highly correlated with coccolithophore abundance (nLw_555). Compared to other phytoplankton groups, such as diatoms, this coccolithophore species has an unusual tolerance for high light intensity (i.e., lacks photoinhibition) (Nanninga and Tyrrell 1996). Both models also indicated that wind stress was not a major factor contributing to bloom formation.

The 7-yr time series (Fig. 4C) indicated that there are no anomalous fluctuations (relatively stable seasonal cycle, at least during June months) that can be related to the bloom occurrence; nevertheless, it is suggested that the typical low wind stress (vertical mixing) during all Junes indirectly benefits bloom formation as it contributes to water-column stability. However, it must be noted that whenever high SST anomalies occur it does not mean that a bloom will be formed, but when it co-occurs with the timing of coccolithophores it will probably benefit the bloom. For instance, November 1997 (Fig. 5B) appeared to be the most positively anomalous month during 1997, but the nLw was very low because it was the wrong time of the year in terms of other parameters (Fig. 4A).

The in situ measurements (CPR) confirmed that the 1998 bloom was *E. huxleyi*, and the area of study is a well known region where large coccolithophore blooms and their relationships to the biogeochemical environment have been reported in the past (Holligan et al. 1993). Although the subarctic North Atlantic can be characterized as ideal for studying *E. huxleyi* blooms, information regarding the link between the extensive blooms of this species and the physical environment are limited. The use of physical/environmental data sets in the present study suggested that large blooms may be caused by distinct environmental conditions, i.e., high light intensities, very shallow MLDs, and positive SST anomalies. Also, our understanding of the coccolithophore bloom distribution pattern can be improved by learning more about their ecology. Knowing the effect of the physical as well as biogeochemical environment on this species, we may convey additional knowledge on the potential impact of climate change on coccolithophores.

It is thought that increasing levels of atmospheric carbon dioxide, which consequently cause significant changes in surface ocean pH (acidification), will be responsible for a reduction in calcifying phytoplankton such as coccolithophores (Riebesell et al. 2000). An indirect effect of climate warming is that increasing temperatures alone or by contributing to ice melting (freshwater runoff) and consequently decreased salinity can lead to increased stratification in surface waters and stabilize the water column for longer (favorable conditions for *E. huxleyi*). Positive temperature and negative salinity anomalies have been correlated with *E. huxleyi* bloom occurrence in the Barents Sea (Smyth et al. 2004). In addition, a potential *E. huxleyi* bloom was detected in the Barents Sea in June 1998 that was less intense than other years. In the same study it was reported that the frequency of coccolithophore blooms in the Barents Sea may be increased if global warming persists and stimulates warming and increased runoff. Our results, based on a 20-yr time series (AVHRR), showed that there was a pronounced temperature shift from 1996 to 2004 in the subarctic North Atlantic. The results also suggested that coccolithophores are probably favored by anomalously warm temperatures, when this increase co-occurs with their seasonal peak (usually June in the area of study). A possible reaction of coccolithophore blooms to this warmth is an increase in their abundance. If the latter is true, it can have a major affect on the oceanic and atmospheric environment of the North Atlantic as these blooms are thought to play a key role in biogeochemical cycling and contribute in a major way to climatic processes (Tyrrell et al. 1999; Holligan et al. 1993; Westbroek et al. 1993). However, the short time series of SeaWiFS (1997–present) does not allow us to draw any significant conclusions on the decadal changes of coccolithophores. Nevertheless, if their spatial extent varies significantly, then their contribution to these cycles or the impacts to the environment will vary too.

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