Decadal changes in ecological provinces of the Northwest Atlantic Ocean revealed by satellite observations

E. Devred,[1,2] S. Sathyendranath,[3] and T. Platt[4]

Received 2 July 2009; revised 20 August 2009; accepted 13 September 2009; published 13 October 2009.

[1] Detecting the effect of climate change on ocean ecosystems is facilitated if the data are partitioned into ecological provinces. It is recognised that the boundaries of such provinces are dynamic, raising the imperative for frequent observations. Using satellite data, we have assembled a time series of ecosystem delineation for the Northwest Atlantic Ocean over a period of ten years. For each province identified in the study area, we have compiled data on sea-surface temperature, and on the biomass and community composition of phytoplankton. We find significant trends in these properties but they vary according to the province concerned, which emphasizes how the physical and biological changes are correlated at large scale. Comparisons between the trends computed using the average position of the provinces and the trends derived when accounting for the movements of the boundaries underline the value of the new approach. **Citation:** Devred, E., S. Sathyendranath, and T. Platt (2009), Decadal changes in ecological provinces of the Northwest Atlantic Ocean revealed by satellite observations, *Geophys. Res. Lett.*, *36*, L19607, doi:10.1029/2009GL039896.

1. Introduction

[2] Monitoring the pelagic ecosystem of the ocean at basin scale to detect, or to help predict, change is optimised if the data are partitioned according to ecological provinces [*Platt et al.*, 1991; *Ducklow*, 2003]. Using satellite data, we have used this approach for the Northwest Atlantic Ocean, constructing time series, over a ten-year period, of sea-surface temperature, and of indices of phytoplankton biomass and community composition. When the data are suitably partitioned, we find that these properties are correlated at large scale, and that the trends differ in different provinces, whereas no systematic variation can be detected in the pooled data. Our result shows that the ocean ecosystem is highly structured, consistent with the existence of a robust, functional biogeography [*Longhurst*, 2007]. They also support the view that ecological structure and biogeochemical function of the ocean ecosystem are coupled at the province scale. What can be demonstrated well by remote sensing, however, is that the large-scale structure changes with season and between years in response to variations in the forces that drive it [*Devred et al.*, 2007].

2. Data and Methods

[3] We have studied the area from 39° to 62.5° N and 42° to 71° W (Figure 1) for ten years using data from space-borne sensors in the visible (Sea-viewing Wide Field-of-view Sensor) and infrared ranges (Advanced Very High Resolution Radiometer, AVHRR). The marine area covered is greater than 3.9×10^6 km^2 with a spatial resolution of 2.25 km^2.

[4] Satellite data consist of daily observations of remote sensing reflectance (to derive diatom occurrence), chlorophyll concentration (Chl) and sea-surface temperature (SST) that are composited into monthly images for the period 1998 to 2007. In addition, a longer time series of SST data from the AVHRR sensor was used to extend our original SST time series from 1985 to 2007. The monthly SST data were extracted from an area that spans from 55° to 58° N and from 45° to 55° W, which corresponds to a box within which the water was always identified as Arctic.

[5] We used the algorithm of *Sathyendranath et al.* [2004] to discriminate, in daily images, pixels dominated by diatoms (value of one) from those consistent with a mixed population (value of zero). Pixel values were averaged over all images available for a given month and the result expressed as the percentage probability that the phytoplankton assemblage was dominated by diatoms for that month.

[6] The method of *Devred et al.* [2007] was applied to our time series of Chl and SST to derive the boundaries of the ecological provinces. Analysis of the time series reveals the dynamic aspect of marine ecosystems: a strong north–south oscillation that follows a seasonal cycle (Figure 1a). The southernmost latitude for all the centers of masses is observed in the Spring (March) and progresses towards the north as the ocean warms up. The mean positions and names of the provinces are also shown in Figure 1b.

[7] The X-11 census method [*Pezzulli et al.*, 2005] was used to analyse the time series of SST, chlorophyll biomass and occurrence of diatoms. The original time series was then decomposed in a seasonal cycle, a trend and a residual. Missing data were replaced using a statistical method based on principal component analysis [*Ibanez and Conversi*, 2002], which allowed the preservation of the temporal structure of the series. Times series exhibiting more than 50% of missing data were discarded (black pixels in Figures 2 and 3). A linear regression was performed on the trend signal to assess the evolution of the properties (increase or decrease).

3. Results and Discussion

[8] When the ten-year trends for chlorophyll and SST were examined using data pooled over the entire study area,

[1]Department of Oceanography, Dalhousie University, Halifax, Canada.
[2]Also at Ocean Science Division, Bedford Institute of Oceanography, Dartmouth, Canada.
[3]Plymouth Marine Laboratory, Plymouth, UK.
[4]Ocean Science Division, Bedford Institute of Oceanography, Dartmouth, Canada.

0094-8276/09/2009GL039896

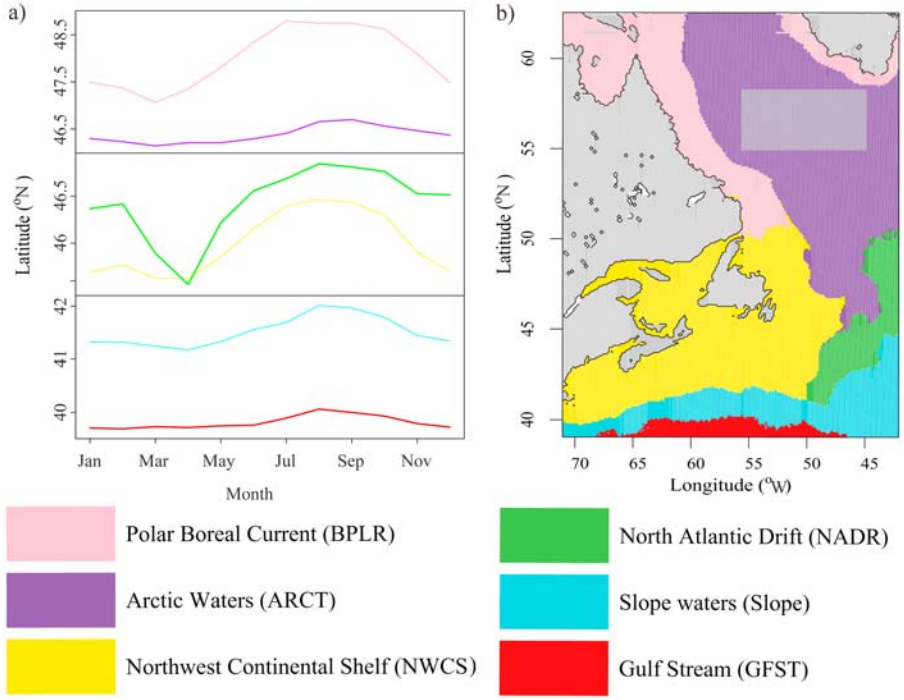

Figure 1. (a) Ten-year climatology (monthly resolution) of the latitude of the center of mass of the biogeochemical provinces. (b) Average locations of the five ecological provinces described by *Longhurst* [2007] in the Northwest Atlantic with the additional Slope province identified by *Devred et al.* [2007]. The grey box represents the location of the extended sea-surface-temperature time series (i.e., 25 years) from the AVHRR sensor.

no significant trends were found (Table 1). Only when the data were stratified by province did significant changes appear (Table 1). In the Arctic and Polar Boreal provinces, temperature increased during the study period. The timing and magnitude of the warming of the superficial layer in the northerly provinces are consistent with observations at depth [*Dengler et al.*, 2006; *Kieke et al.*, 2007]. Our analysis shows a temperature decrease in the southerly provinces (Figure 2a) in agreement with previous work [*Ivchenko et al.*, 2006]. Chl decreased in all provinces (Figure 2b) except in the Arctic province. Diatom occurrence decreased in all provinces except in the Arctic and slope provinces (Figure 2c). Experiments [*Hare et al.*, 2008] and numerical simulations [*Bopp et al.*, 2005] attempting to reproduce effects of global warming on phytoplankton community structure showed similar results.

[9] The results shown in Figures 2a–2c and Table 1 are based on analyses carried out for the mean locations of the provinces over the study period. But at any given time, the boundaries may deviate from the mean position. The trends observed in Figures 2a–2c may therefore arise either from real changes within a particular province, or from movements of the province over the period of study. To evaluate local changes within a dynamic province, we examined the mean properties of the water for those pixels always lying within the province, regardless of movements of the boundaries. The movement of the centres of mass of the provinces of the Northwest Atlantic between years is considerable (Table 1). Typically, trends in SST within dynamic provinces (Table 1) are less strong than those for fixed provinces (Table 1) and become significant in some cases (e.g. trends in SST in the NADR province or trends in Chl in the slope province), indicating that the latter are compounded by movements in location of provinces. Because analysis at province level turns out to be more illuminating than analysis after pooling all the information for the entire region, we might also ask whether it would not be even more informative to examine trends at sub-province level. In Figures 2d–2f, trends in SST, Chl and occurrence of diatoms are shown at pixel resolution. The trends in temperature seen in Figure 2a are reinforced by the analysis at the pixel level (Figure 2d). But the biological fields (Figures 2e and 2f) show more fine structures, with pockets of positive trends that are lost in the analyses at the province level. Within areas affected by excursions of boundaries of provinces, the slope of the trend (Figures 2g–2i) is not significant at p less than 0.05, making difficult any interpretation of the signal without accounting for the dynamic nature of the marine ecosystem.

[10] It is well recognized that diatom occurrence is tied closely to chlorophyll concentration [*Yentsch and Phinney*, 1989; *Uitz et al.*, 2006]. However, it has not been appreciated before that the nature of the dependence varies markedly between provinces (Figure 3a): the correlation is higher in open oceans (GFST, Slope and NADR provinces) where the average values of Chl are lower. In provinces with higher Chl, the correlation is lower, possibly due to other phytoplankton species that flourish when conditions are favorable, or even a bias from high concentrations of non-algal coloured material. Similarly, diatom occurrence is correlated with temperature in a province-specific way (Figure 3b). In the BPLR, ARCT and NWCS provinces, correlation between SST and occurrence of diatoms follows a seasonal pattern. Diatom occurrence increases in the BPLR and ARCT as the water warms up (Spring) to reach a maximum in the Summer. The NWCS province shows higher values of diatoms in the Spring and Fall. No clear pattern is observed between SST

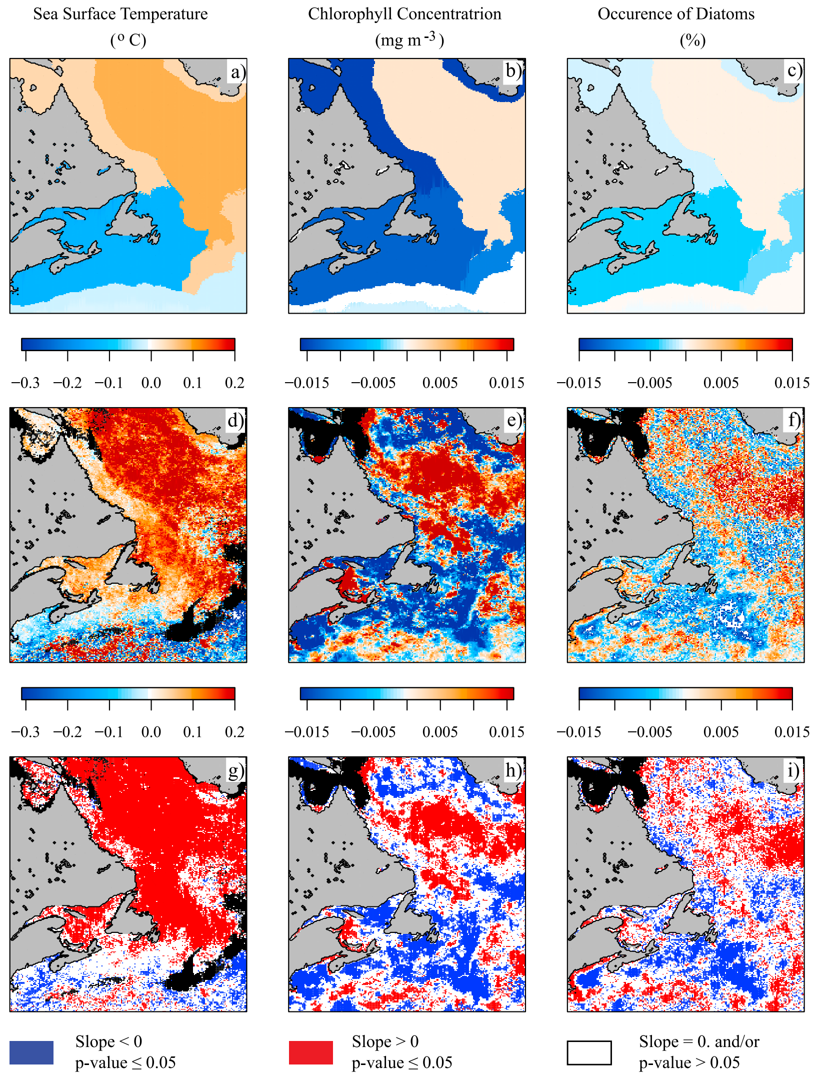

Figure 2. Slope of the trend with time of (a) SST, (b) Chl and (c) diatom occurrence for the mean location of the provinces. Slope of the trend with time of (d) SST, (e) Chl and (f) diatom occurrence computed using a pixel-by-pixel approach. (g–i) The p-value of the slopes computed in Figures 2d, 2e and 2f. Only p-values lower than 0.05 are considered significant. Note that Figures 2a and 2d have the same colour bar; this is also the case for Figures 2b and 2e, and 2c and 2f.

and diatoms in the NADR province, whereas the Slope and GFST provinces exhibit a bloom of diatoms in the Spring. On a pixel-by-pixel basis, these relationships are particularly striking (Figures 3c–3e). Contrary to expectations, the correlation between diatom occurrence and SST is positive in parts of the study area (Figure 3d), as also is that between chlorophyll and SST (Figure 3e). The data series for AVHRR is longer than that for ocean colour, allowing us to set our results in a broader context (Figure 4), and to check their consistency. It is clear that the warming trend in the Arctic Province started before the beginning of the ocean-colour series, but that variations around the trend do occur.

4. Conclusion

[11] Using a consistent set of time series data from remote sensing, highly resolved in time and space, we have shown how important ecosystem properties have changed during the last decade in the Northwest Atlantic Ocean. Because of opposing trends in different parts of the area studied, the full significance of these trends cannot be elucidated except at the province or sub-province scales. The regional implications are clear: for example, although the consequences of Arctic warming have been brought to public attention [*Anisimov et al.*, 2007], it is perhaps less well known that continental shelf and slope waters off eastern Canada are cooling. We have shown that the biological changes associated with the changes in temperature also vary with region. We cannot know whether the trends we report will continue in the same sense, given that decadal oscillations are superimposed on any secular variation due to climate change. However, the optimal way to pursue the matter would seem to be using a remote-sensing approach based on ecological provinces, as adopted here.

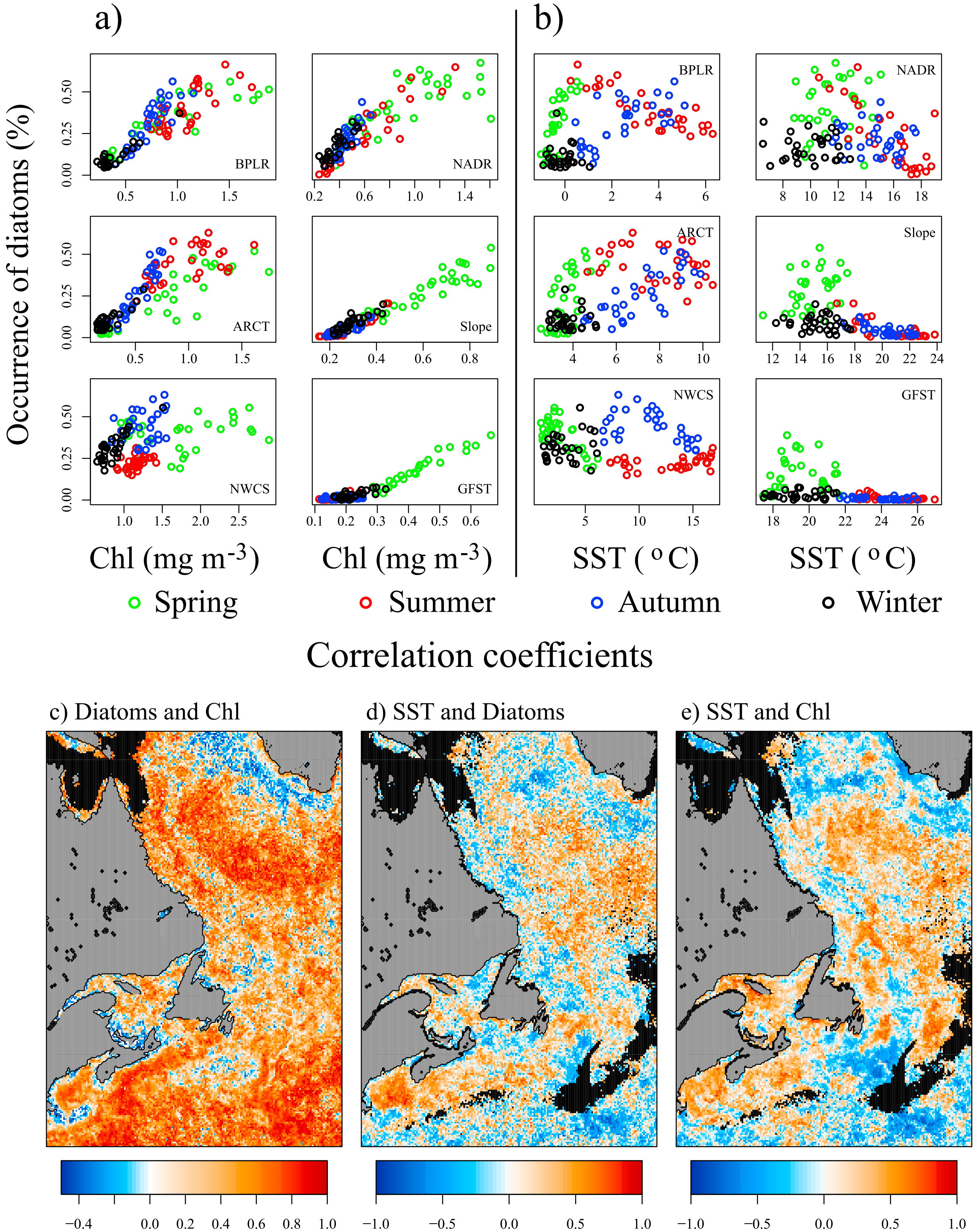

Figure 3. Occurrence of diatoms as a function of (a) Chl and (b), SST for the six provinces identified in the study area, between 1998 and 2007. Seasonal variations are colour coded: green, red, blue and black open circles represent monthly composite images computed for the spring, summer, autumn and winter seasons respectively. The correlation coefficients computed using the pixel-by-pixel approach of the trend between (c) diatom occurrence and chlorophyll concentration, (d) SST and diatoms and (e) SST and chlorophyll concentration.

Table 1. Slopes and Standard Errors of the Linear Regression of the Trend for the Sea-Surface Temperature, the Chlorophyll-a Concentration and Diatom Occurrence for the Entire Area, the Average Position and the Dynamic Assignment of the Six Provinces Identified in This Area[a]

		BPLR		ARCT		NWCS		NADR		Slope		GFST	
	Entire Area	A	D	A	D	A	D	A	D	A	D	A	D
						SST (°C)							
Sl.	0.016	**0.048**	**0.042**	**0.097**	**0.085**	0.003	0.008	−0.004	**0.050**	**−0.040**	**−0.021**	−0.005	−0.013
s.e.	0.009	0.009	0.008	0.011	0.011	0.013	0.012	0.016	0.009	0.008	0.008	0.006	0.007
						Chl (mg m^{-3})							
Sl.	−0.005	**−0.013**	**−0.014**	0.0002	0.002	**−0.009**	**−0.013**	**−0.007**	**−0.011**	−0.0004	**−0.002**	−0.002	−0.001
s.e.	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.0006	0.0007	0.0005	0.0004
						Diatom (%)							
Sl.	0.0008	−0.001	−0.001	**0.005**	**0.006**	**−0.003**	**−0.004**	−0.003	**−0.003**	0.001	0.0003	−0.001	−0.0003
s.e.	0.0006	0.0005	0.0006	0.001	0.001	0.0006	0.0007	0.001	0.001	0.0004	0.0004	0.0003	0.0003
						Size (km^2)							
Sl.			4800		**2500**		**5000**		260		**−2500**		−450
s.e.			550		600		500		300		750		450
						Lat (°N)							
Sl.			**0.015**		−0.002		0.001		**−0.019**		**−0.014**		**−0.007**
s.e.			0.003		0.001		0.001		0.007		0.002		0.002
						Long (°W)							
Sl.			**−0.028**		**0.004**		**0.014**		**0.010**		**0.032**		**0.070**
s.e.			0.003		0.001		0.002		0.002		0.007		0.016

[a]Slopes of the linear regression on the trend of the size, latitude and longitude of the time series are also presented for the monthly delineation of the boundaries of the provinces. Sl. is slope and s.e. is standard error. The letters A and D stand respectively for the province average position and the dynamic assignment of the boundaries of the provinces. Slopes with p-values $\leq$ 0.01 are shown in bold, slopes with 0.01 < p-value < 0.05 are underlined and slopes with p-values $\geq$ 0.05 are shown in normal font.

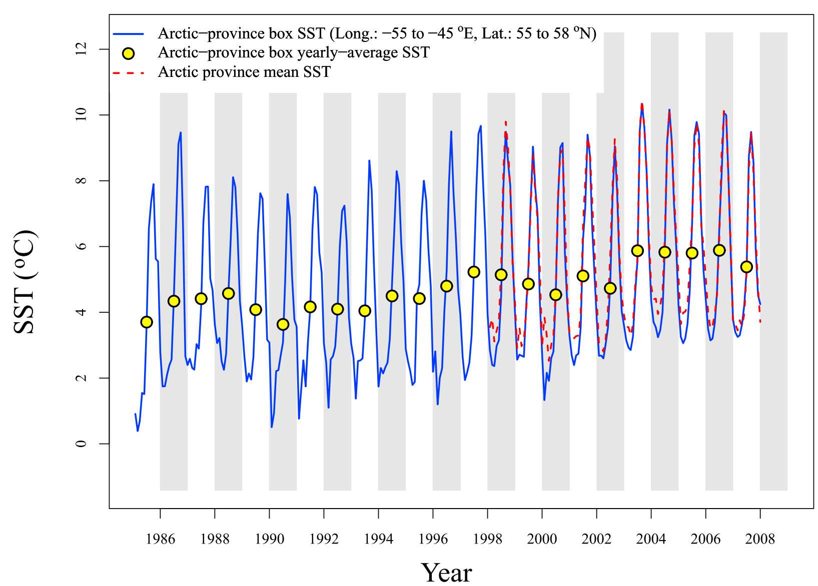

Figure 4. The blue line corresponds to the AVHRR time series of SST from 1985 to 2007 extracted for a given area, the yellow circles correspond to the yearly averages and the red dashed line corresponds to the mean sea-surface temperature computed in the Arctic province from 1998 to 2007.

[12] **Acknowledgments.** We thank H. Maass and G. White for processing support. Pathfinder SST fields (25-year time series) were produced by Robert Evans, Kay Kilpatrick, Vicki Halliwell and Susan Walsh, RSMAS in conjunction with Jorge Vazquez, JPL PO.DAAC and Ken Casey, NODC. This work was funded by the Canadian Space Agency under the GRIP program. This work is a contribution to the Oceans2025 and NCEO programmes of NERC (UK).

References

Anisimov, O. A., D. G. Vaughan, T. V. Callaghan, C. Furgal, H. Marchant, T. D. Prowse, H. Vilhjálmsson, and J. E. Walsh (2007), Polar regions (Arctic and Antarctic), in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry et al., pp. 653–685, Cambridge Univ. Press, Cambridge, U. K.

Bopp, L., O. Aumont, P. Cadule, S. Alvain, and M. Gehlen (2005), Response of diatoms distribution to global warming and potential implications: A global model study, *Geophys. Res. Lett.*, *32*, L19606, doi:10.1029/2005GL023653.

Dengler, M., J. Fischer, F. A. Schott, and R. Zantopp (2006), Deep Labrador Current and its variability in 1996–2005, *Geophys. Res. Lett.*, *33*, L21S06, doi:10.1029/2006GL026702.

Devred, E., S. Sathyendranath, and T. Platt (2007), Delineation of ecological provinces using ocean colour radiometry, *Mar. Ecol. Prog. Ser.*, *346*, 1–13, doi:10.3354/meps07149.

Ducklow, H. W. (2003), Biogeochemical provinces: Towards a JGOFS synthesis, in *Ocean Biogeochemistry: A New Paradigm*, edited by E. M. J. R. Fasham, pp. 3–18, Springer, Berlin.

Hare, C. E., K. Leblanc, G. R. DiTullio, R. M. Kudela, Y. Zhang, P. A. Lee, S. Riseman, and D. A. Hutchins (2008), Consequences of increased temperature and CO_2 for phytoplankton community structure in the Bering Sea, *Mar. Ecol. Prog. Ser.*, *352*, 9–16, doi:10.3354/meps07182.

Ibanez, F., and A. Conversi (2002), Prediction of missing values and detection of exceptional events: A single algorithm, *Ecol. Modell.*, *154*, 9–23.

Ivchenko, V. O., N. C. Wells, and D. L. Aleynik (2006), Anomaly of heat content in the northern Atlantic in the last 7 years: Is the ocean warming or cooling?, *Geophys. Res. Lett.*, *33*, L22606, doi:10.1029/2006GL027691.

Kieke, D., M. Rhein, L. Stramma, W. M. Smethie, J. L. Bullister, and D. A. LeBel (2007), Changes in the pool of Labrador Sea Water in the subpolar North Atlantic, *Geophys. Res. Lett.*, *34*, L06605, doi:10.1029/2006GL028959.

Longhurst, A. (2007), *Ecological Geography of the Sea*, 2nd ed., 542 pp., Elsevier, San Diego, Calif.

Pezzulli, S., D. B. Stephenson, and A. Hannachi (2005), The variability of seasonality, *J. Clim.*, *18*, 71–88.

Platt, T., C. Caverhill, and S. Sathyendranath (1991), Basin-scale estimates of oceanic primary production by remote sensing: The North Atlantic, *J. Geophys. Res.*, *96*, 15,147–15,159.

Sathyendranath, S., L. Watts, E. Devred, T. Platt, C. Caverhill, and H. Maass (2004), Discrimination of diatoms from other phytoplankton using ocean-colour data, *Mar. Ecol. Prog. Ser.*, *272*, 59–68.

Uitz, J., H. Claustre, A. Morel, and S. B. Hooker (2006), Vertical distribution of phytoplankton communities in open ocean: An assessment based on surface chlorophyll, *J. Geophys. Res.*, *111*, C08005, doi:10.1029/2005JC003207.

Yentsch, C. S., and D. A. Phinney (1989), A bridge between ocean optics and microbial ecology, *Limnol. Oceanogr.*, *34*, 1694–1704.

E. Devred and T. Platt, Ocean Science Division, Bedford Institute of Oceanography, Box 1006, Dartmouth, NS B2Y 4A2, Canada. (devrede@mar.dfo-mpo.gc.ca; tplatt@dal.ca)

S. Sathyendranath, Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK. (ssat@pml.ac.uk)