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The impact of sea ice on the initiation of the spring bloom on the Newfoundland and Labrador Shelves

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The relationship between sea ice and the phytoplankton spring bloom over the Newfoundland and Labrador shelves is examined using remotely-sensed chlorophyll data and sea-ice data for the period 1998–2004. A regression analysis between the two data sets shows that the retreat of sea ice precedes the spring bloom, and the inter-annual variation of the spring bloom is closely correlated with the start time of ice retreat. The spring bloom off Canada's east coast usually starts on the eastern Grand Banks. Here, the water properties are strongly influenced by sea ice on the Newfoundland shelves in early spring when accelerated ice melting causes the ice edge to retreat north and the melt water is advected south by the Labrador Current. After the ice retreat, the water on the eastern Grand Banks is rapidly stratified and the mixed layer shallows as a result of surface freshening. The shallow mixed layer promotes phytoplankton growth. The regression analysis also reveals that an early spring bloom or ice retreat tends to prolong the duration of the spring bloom.

INTRODUCTION

The spring phytoplankton bloom off Canada's east coast usually starts on the eastern Grand Banks along the shelf edge (Fig. 1). The area of the bloom spreads west and north with the progression of the season, and by the end of April covers the entire northeast Newfoundland Shelf and the Grand Banks. Satellite data show that the location of the initial bloom does not change much from year to year, but the timing of the bloom is highly variable. This suggests that the location of the bloom initiation is related to both the mixed-layer depth and solar radiation in early spring. As sea ice is an important factor in early spring when ice melting accelerates, we propose that the inter-annual variation of the onset of the spring bloom is controlled by the timing of sea-ice retreat on the northern Grand Banks.

BACKGROUND

The presence of sea ice in high-latitude oceans can influence both physical and biological processes. On the one hand, sea ice insulates the ocean from the atmosphere and alters air–sea heat and momentum exchanges. In the marginal ice zones of the Labrador Sea, the fresh water released from ice melting strengthens stratification, which, in turn, affects the salinity and temperature distributions within the upper mixed layer (Tang, 1991, 1992). On the other hand, retreat of sea ice influences the biogeochemical cycle of the ocean by altering the timing and magnitude of the phytoplankton bloom, penetration of photosynthetic available radiation (PAR) into the water column and stratification (Legendre *et al.*, 1992). In general, sea ice affects the phytoplankton bloom in two ways. First, persistent ice coverage reduces primary production markedly by blocking the solar

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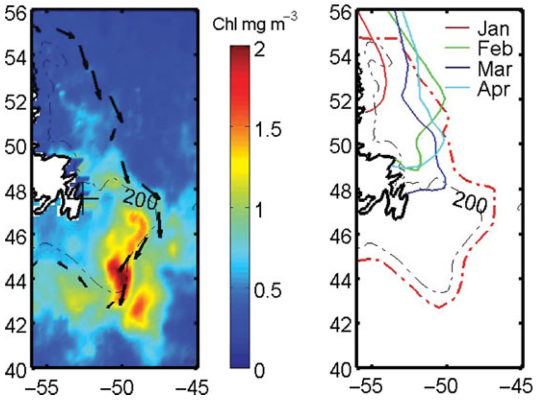

Fig. 1. Left panel is the 7-year (1998–2004) surface chlorophyll (mg Chl-*a* m^{-3}) composite in the second half of March. The vectors indicate the Labrador Current. The cross indicates the location of Station 27. The contour line is the 200 m isobath. The study area (right panel) is indicated by the red dotted line. The ice-edge positions are indicated by the red line for January, the green line for February, the blue line for March and the cyan line for April.

irradiance essential for photosynthesis, and prevents the occurrence of the phytoplankton blooms (Rysgaard *et al.*, 1999; Arrigo and van Dijken, 2004; Carmack *et al.*, 2004). Secondly, melting of sea ice can promote ice edge blooms by increasing the upper ocean stability since the fresh water is released into the upper layer during ice retreat (e.g. Schandelmeier and Alexander, 1981; Smith *et al.*, 1987; Lancelot *et al.*, 1993). In mid- and high-latitudes oceans, this surface freshening plays a more important role for the development of the stratification in the upper ocean than the seasonal heating in early spring when the solar radiation is weak.

The Newfoundland/Labrador Shelf is a seasonal ice zone. Sea ice generally starts to appear in mid-January. It extends southward progressively, and retreats north after the ice reaches the northern Grand Banks at the end of March (Fig. 1). The impact of sea ice on the oceanographic conditions on the Newfoundland/Labrador shelf has been studied by several investigators (e.g. Myers *et al.*, 1990; Petrie *et al.*, 1991, 1992; Tang, 1992; Petrie and Buckley, 1996; Tang and De Tracey, 1998). Ice melting can reduce the surface salinity and create a shallow mixed layer. Sea-ice data indicate that both the ice area and the time of retreat vary from year to year (Wang *et al.*, 1994; Prinsenberg *et al.*, 1997). The relationship between sea ice and the spring bloom has been studied by many researchers, but less attention has been paid to the coastal waters of Atlantic Canada. In this paper, we use sea ice, oceanographic and chlorophyll data to investigate this relationship and the environmental conditions under which the spring bloom is initiated.

APPROACH

Our study area comprises the northeast Newfoundland Shelf and the Grand Banks (Fig. 1). The chlorophyll concentrations for the period 1998–2004 were derived from SeaWiFS data using the SeaDAS OC4v4 software package. To minimize the impact of data gaps due to cloud cover, seven-day composites of the SeaWiFS data were averaged over the study area. The resulting time series give the variation of the mean surface chlorophyll concentration in the study area. To quantify the variation (e.g. time, duration and intensity), the time series are fitted with a four-parameter Gaussian curve:

$$C(t) = C_0 + C_H \cdot e^{-((t-t_p)^2/2\omega^2)} \qquad (1)$$

in which C_0 (mg m^{-3}) is the background value of chlorophyll concentration, C_H (mg m^{-3}) the amplitude, t (day) the time, t_p (day) the time of the peak and ω (day) is the bloom duration parameter. The parameters were determined using the Gauss–Newton Method based on the nonlinear least-square fit.

Three sea-ice parameters, the start time of ice retreat, t_{ice}, the southernmost ice edge position, E_{ice}, and ice area south of 55°N, A_{ice}, were derived from daily sea-ice data from the Canadian Ice Service (CIS). The ice data are extracted on a 10 km grid from daily digital ice charts produced by CIS. The ice charts provide information on total ice concentration, as well as partial concentration and predominant floe size for the various ice types representing different ice thicknesses. Daily ice area south of 55°N and east of Newfoundland was computed from the gridded total ice concentration data from February to April, and the maximum value was extracted for each year. The latitude of the southernmost ice-covered grid point east of 56°W was also extracted from the gridded ice data. In some years, there was more than one local minimum for the daily southernmost latitude. The average date and average value of last two local minima were chosen for the start time of ice retreat and the annual southernmost ice edge position, respectively. In all cases, the last local minimum latitude was within 0.5° of the overall minimum latitude for the given year.

RESULTS

Relationship between ice retreat and the spring bloom

Data on the surface chlorophyll concentrations from 1998 to 2004 show that the timing of the spring bloom varies from year to year (Fig. 2). The onset of the spring bloom (hereinafter, t_{sb}), for simplicity, is defined as the time when the chlorophyll concentration increases to the threshold of 1.0 mg m^{-3}. The quantity t_{sb} has a wide range, for example, Day 70 in 1999 and Day 95 in 2003, a difference of 25 days, and tends to increase with t_{ice} (Fig. 3). A linear regression analysis of t_{sb} on t_{ice} gives

$$t_{sb} = 28.96 + 0.6587 t_{ice}, \qquad (2)$$

with a correlation coefficient of 0.96.

To ensure that the results were robust and not sensitive to the method of data analysis, we repeated the analysis with an alternative definition for t_{sb} (e.g. 25% of the relative amplitude scale, (Chl-C_0)/C_H). The main results were basically unchanged.

As shallow mixed layers promote higher phytoplankton growth rates (Platt *et al.*, 1991), we examined available oceanographic data to assess the influence of ice melting on stratification on the Grand Banks. Temperature and salinity data around the times of ice retreat were obtained from the Atlantic Zone Monitoring Program (see http://www.meds-sdmm.dfo-mpo.gc.ca/zmp /main_zmp_.html) at Station 27 (47.55°N, 52.59°W, see Fig. 1 for location). In this study, only the 2000 and 2004 data are used because the times of measurement in other years were not suitable for our study. The data show that before the start of ice retreat, the upper ocean is not stratified (Fig. 4A and C). After the ice retreat, the surface water becomes fresher and warmer (Fig. 4B and D). In 2000, the surface temperature increased slightly (0.2°C) and the salinity decreased by 0.3. A well-mixed surface layer 15 m thick formed. In 2004, the temperature increase, 1.1°C, was large but the salinity decrease, 0.1, was relatively small.

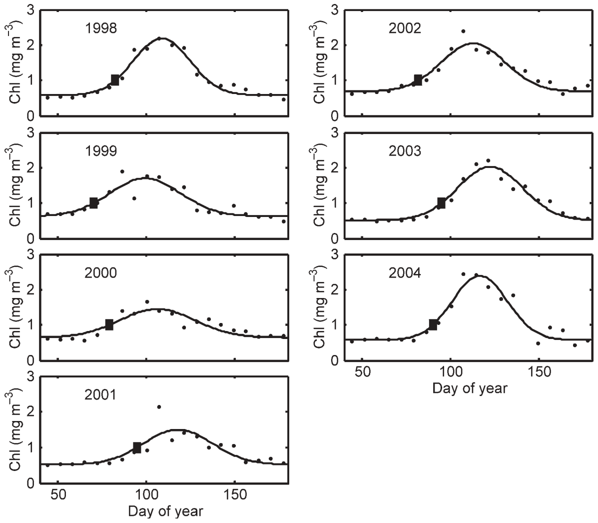

Fig. 2. Mean chlorophyll concentration for 1998–2004. The number in the parentheses in each panel is the Julian day of the initiation of the spring bloom. The short bar is the timing of the spring bloom.

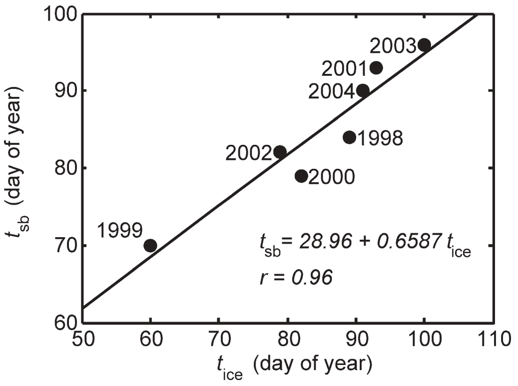

Fig. 3. Scatter plot of t_{sb} and t_{ice} and the linear fit.

The stratification is more affected by the change in salinity than by the temperature change at low water temperatures. This is demonstrated in the T–S diagrams (Fig. 5). From the density contour lines, it is clear that change in density is dominated by changes in salinity. In 2000, the density change at the surface from the pre-retreat to the post-retreat periods was almost entirely attributed to the salinity decrease. In 2004, there was a large temperature increase from the pre-retreat to the post-retreat periods. The density difference at the surface between these two periods is 0.142 kg m^{-3}, of which 0.089 kg m^{-3} is attributed to salinity decrease and 0.053 kg m^{-3} is attributed to temperature increase. This means that a small decrease in salinity can lead to a relatively big decline in density. This also implies that the ice melt, which releases the fresh water, controls the water stratification and thus influences the timing of the spring bloom.

Other spring bloom parameters

Other parameters in equation (1) that define the time evolution of chlorophyll concentration are the amplitude concentration, C_H, and duration, ω. Environmental properties other than t_{ice} which may be related to the spring bloom include the latitude of the southernmost ice edge, E_{ice}, maximum ice area south of 55°N, A_{ice}, and the mean air temperature, T_{air}. The air temperature data are from NCEP reanalysis 2 (Kalnay *et al.*, 1996). For consistency, we used the same location, Station 27 for T_{air}. The correlation coefficients from linear regression analyses between each pair of parameters are shown in a matrix form (Table I).

The pairs with significant correlation coefficients (Table I) are (t_{sb}, t_{ice}), (t_{sb}, ω), (t_{ice}, ω), (A_{ice}, T_{air}) and

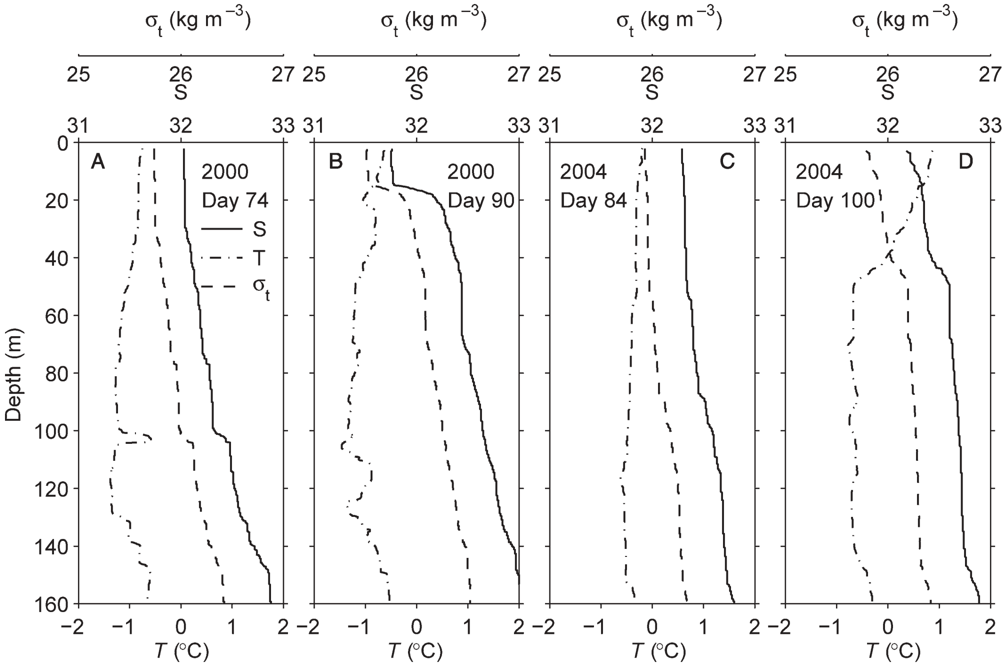

Fig. 4. Temperature, salinity and density (σ_t) profiles at Station 27 (47.55°N, 52.59°W) taken in 2000 (**A**, **B**) and 2004 (**C**, **D**). (A) and (C) are before the start of ice retreat. (B) and (D) are after the start of ice retreat.

(E_{ice}, T_{air}). The relationship between t_{sb} and t_{ice} has been discussed in the previous section. These two parameters are highly correlated and both are correlated with ω (Fig. 6A and B). The parameter ω is inversely proportional to t_{ice}, i.e. an early spring bloom or ice retreat corresponds to a longer duration and vice versa.

The close relationship between T_{air}, A_{ice} and E_{ice} is a result of ice thermodynamics (Fig. 6C and D). Previous studies indicate that air temperature is one of the most important factors that determines ice melt rate and the time of ice retreat on the Newfoundland shelves (e.g. Tang, 1991; Peterson *et al.*, 2000). In the springtime, a higher-than-normal air temperature not only results in a shallower mixed layer depth, but also a higher water temperature, a higher rate of ice melt, a smaller ice extent and a more northerly ice edge.

An unexpected result of the regression analysis is that there is no significant correlation between A_{ice} and any of the bloom parameters. This suggests that the mechanism of spring bloom off Canada's east coast is different from that operating in other high-latitude oceans where the spring bloom is initiated at ice edges and spreads to areas occupied by sea ice before ice retreat (Rysgaard *et al.*, 1999; Arrigo and van Dijken, 2004; Carmack *et al.*, 2004). Their results showed that sea ice blocked solar radiation and thus prevented phytoplankton growth in ice-covered waters. On the Newfoundland shelves, however, the primary effect of sea ice on phytoplankton growth is not to block the

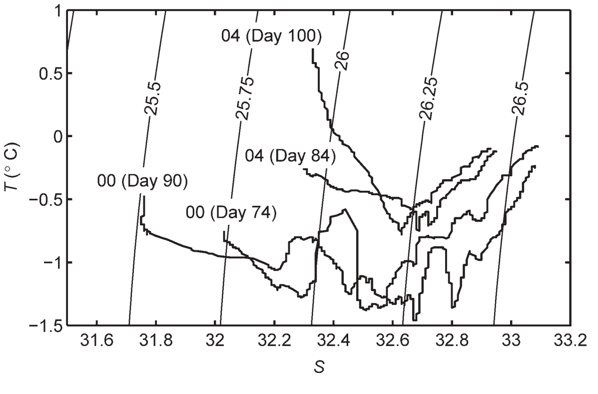

Fig. 5. T–S diagram for the 4 profiles in Fig. 4. Year and date are given at the beginning of the T-S curve (surface). The smooth solid lines are contours of σ_t (kg m^{-3}).

Table I: Matrix of correlation coefficients

	t_{sb}	t_{ice}	E_{ice}	C_H	ω	A_{ice}	T_{air}
t_{sb}	1	0.96^a	0.64	0.48	0.90^a	0.29	0.73
t_{ice}		1	0.54	0.47	0.94^a	0.19	0.71
E_{ice}			1	0.051	0.22	0.53	0.83^a
C_H				1	0.61	0.27	0.43
ω					1	0.29	0.60
A_{ice}						1	0.77
T_{air}							1

^{a}indicates coefficient significant at the 95% confidence level.

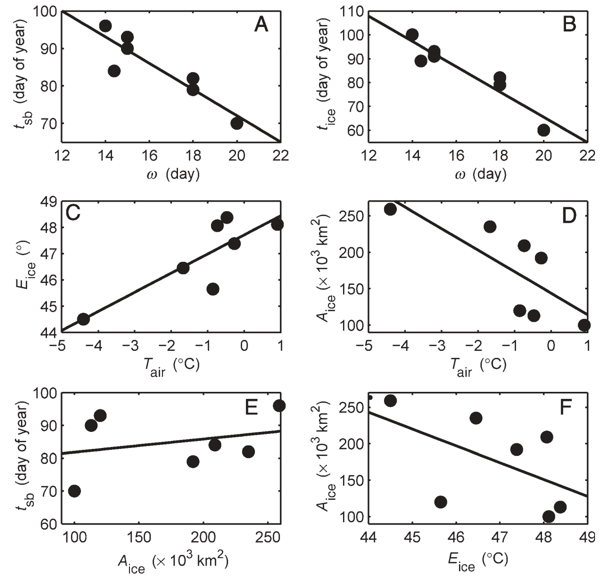

Fig. 6. Scatter plot of (**A**) t_{sb} and ω, (**B**) t_{ice} and ω, (**C**) E_{ice} and T_{air}, (**D**) A_{ice} and T_{air}, (**E**) T_{sb} and A_{ice} and (**F**) A_{ice} and E_{ice}.

solar radiation, but to release freshwater from ice melting. The freshwater is transported to the Grand Banks by the strong Labrador Current where the spring bloom starts. The quantity A_{ice} is thus not correlated with C_H, ω and t_{sb} (Fig. 6E). Another pair of variables with relatively weak correlation is E_{ice} and A_{ice} (Fig. 6F). This is because the position of the eastern ice edge is variable. A large ice area may not always correspond to a greater distance of the southern excursion of the pack ice.

DISCUSSION

It has been well established that sea-ice retreat and ice extent are sensitive to changes in air temperature. Our analysis shows that an early ice retreat will result in an early and prolonged spring bloom. It has been shown for the continental shelves of Nova Scotia (Platt *et al.*, 2003) and of the Labrador Sea (Fuentes-Yaco *et al.*, 2007; Koeller *et al.*, 2007) that interannual fluctuations in the characteristics of the spring bloom are significant for higher trophic levels, including exploited stocks. We can therefore expect that the variation between years in ice extent and time of melting are significant for the ecosystem dynamics of Newfoundland. To the degree that ice dynamics are affected by climate change, it is clear that ecosystem dynamics are also vulnerable. In the present climate, earlier-than-average blooms are associated with strong year classes of haddock, for example. But we cannot be certain what would be the effect of a shift in the mean timing towards the extreme value experienced so far.

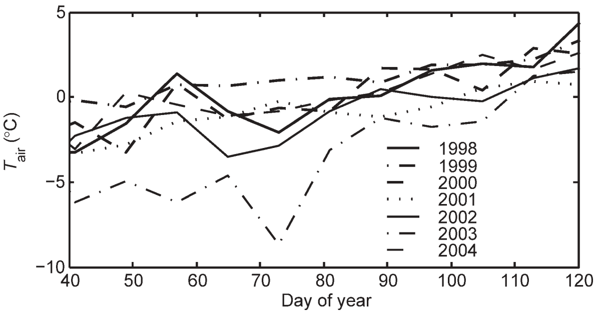

Fig. 7. Air temperature at Station 27 for 1998–2004.

The parameters T_{air} and t_{sb} are moderately correlated (Table I). In 1999, the air temperature was higher than that in all the other years (Days 50 to 80) by up to 2.0°C (Fig. 7). As a consequence, the ice melted early (Day 60) and the bloom started early (Day 70). In contrast, the very low temperature in 2003 resulted in a late spring bloom (Day 95) and relatively late ice retreat (Day 100). This raises the question of how the marine ecosystem off Canada's east coast may respond to global warming. According to numerical models, global warming could increase the air temperature by 1.5 to 6°C over the next 100 year (IPCC, 2001). This increase in air temperature significantly influences sea-ice melting and ecosystems in high latitudes oceans (Rysgaard *et al.*, 1999; Walther *et al.*, 2002; Smetacek and Nicol, 2005). It is tempting to use the relationship between T_{air} and t_{sb} to predict the impact of global warming on the spring bloom. Our analysis of the confidence level indicates that the correlation between T_{air} and t_{sb} is not significant. Obviously, the spring bloom is a complicated process associated with many physical and biological mechanisms. More data and advanced models are required for a reliable prediction of t_{sb} in response to global warming.

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