Annual cycles of sea ice and phytoplankton in Cape Bathurst polynya, southeastern Beaufort Sea, Canadian Arctic

Kevin R. Arrigo and Gert L. van Dijken

Department of Geophysics, Stanford University, Stanford, California, USA

Received 3 November 2003; accepted 3 March 2004; published 22 April 2004.

[1] The relationship between the dynamics of sea ice and phytoplankton abundance were investigated for the Cape Bathurst polynya region of the Canadian Arctic using five years (1998–2002) of satellite data from SSM/I and SeaWiFS. The Cape Bathurst polynya exhibited marked interannual variability in sea ice dynamics, both in the timing of initial polynya formation and in the extent and persistence of open water. Related to this, although all years exhibited two distinct phytoplankton blooms, these also varied in their intensity and timing. Generally, the late bloom of each year was the most intense, after surface waters had stratified in summer. Blooms were most intense in spring 1998, following anomalous warming and early stratification, and late summer 2002, following a summer ice melt event. Changes in the timing of phytoplankton bloom development in polar waters can impact food web structure and the relative importance of top-down versus bottom-up control of marine ecosystems. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4855 Oceanography: Biological and Chemical: Plankton; 4806 Oceanography: Biological and Chemical: Carbon cycling. **Citation:** Arrigo, K. R., and G. L. van Dijken (2004), Annual cycles of sea ice and phytoplankton in Cape Bathurst polynya, southeastern Beaufort Sea, Canadian Arctic, *Geophys. Res. Lett.*, *31*, L08304, doi:10.1029/2003GL018978.

1. Introduction

[2] The Cape Bathurst polynya, located in the Amundsen Gulf about 150 km east of the Mackenzie River mouth (Figure 1), is part of the circum-arctic system of flaw polynyas. These polynyas are important in the dynamics of the Arctic ice sheet, the formation of Arctic deep water, and in the case of the Cape Bathurst polynya, as a habitat for some of the highest densities of birds and mammals found anywhere in the Arctic [*Harwood and Stirling*, 1992; *Dickson and Gilchrist*, 2002]. Typically, sea ice begins forming in shallow areas in October, and by winter, rafting of drifting ice floes at the edge of the landfast ice has formed the stamukhi, a zone of thick ice ridges that forms parallel to the coast. Beyond the stamukhi and inshore of the central Arctic ice pack, the flaw polynya stretches along the entire Arctic shelf and widens in summer to form the Cape Bathurst polynya (Figure 1). Satellite observations show that winds with an easterly component control ice cover dynamics in this region [*Fett et al.*, 1994], with large flaw leads forming near Cape Bathurst and off the west coast of Banks Island in response to mesoscale storm or wind events.

[3] Open waters associated with polynyas in both the Arctic and the Antarctic generally exhibit enhanced primary production and higher upper trophic level populations. In most Arctic waters, low winter irradiance and a thick ice cover limit phytoplankton production to a short period in summer when diatom blooms respond to ice melt in July or August [*Hsiao*, 1992]. However, in polynyas that form in the Arctic, such as the Northeast Water (NEW) and North Water (NOW) polynyas, diatoms bloom soon after the end of the polar night in April–May [*Tremblay et al.*, 2002], markedly extending the phytoplankton growing season. In response to this increased algal production, zooplankton such as copepods and appendicularians thrive in the flaw polynya zone [*Kosobokova et al.*, 1998]. In the productive open waters of the NEW and NOW polynyas, high densities of copepods are preyed upon by the higher trophic levels such as larval and juvenile Arctic cod [*Michaud et al.*, 1996]. Therefore, polynya dynamics in the Arctic can markedly alter both the productivity and food web structure of high latitude marine environments.

[4] While a great deal has been learned in recent years about the Arctic NEW and NOW polynyas, the Cape Bathurst polynya, the third of the large Arctic polynyas, has received comparatively little attention. Here we present results from a satellite-based study of the Cape Bathurst polynya illustrating the relationship between sea ice dynamics and phytoplankton blooms over the past five years. Because the Cape Bathurst polynya is one of the primary research sites for the Canadian Arctic Shelf Exchange Study (CASES), it is important that the degree of interannual variation in sea ice extent and associated phytoplankton dynamics be described so that results from the year-long field program can be placed in a better historical context.

2. Methods

[5] Sea ice distributions were computed from daily Special Sensor Microwave Imager (SSM/I) data obtained from the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center, University of Colorado, Boulder, CO. Images were processed to 6.25 km resolution using the algorithm of *Markus and Burns* [1995], and used to calculate open water area within a 25,000 km^2 study region shown in Figure 1. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data were obtained from the Goddard DAAC. Chlorophyll *a* (Chl *a*) concentrations from the same study region were

0094-8276/04/2003GL018978$05.00

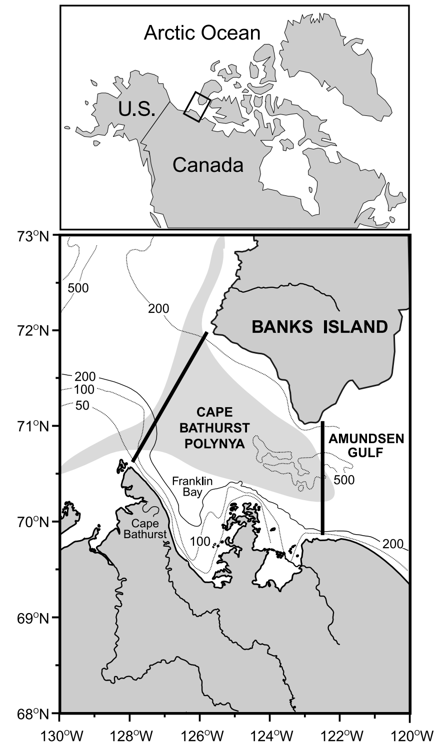

Figure 1. Map of the Cape Bathurst polynya region. The approximate location of the polynya is shown in light gray and the contour lines denote bathymetry in meters. Our study region, from which all statistics on mean Chl *a* concentration and open water area were extracted, is located between the two thick straight black lines.

derived from SeaWiFS Level 1 data and processed using the NASA SeaDAS image processing software and OC4v4 algorithm. Due to the presence of colored dissolved organic matter, the OC4v4 algorithm can overestimate Chl *a* concentrations by up to 50% in the Beaufort Sea [*Wang and Cota*, 2003]. Therefore, because of the proximity of our study site to the Mackenzie River outflow plume, we adjusted the Chl *a* retrievals from SeaWiFS using the Arc00 OC4L algorithm of *Wang and Cota* [2003] to better account for any non-chlorophyll absorption. All images used in our analyses contained a sufficient number of pixels to calculate a mean (at least 20% of the ice-free pixels were observable by SeaWiFS). Productivity was estimated from satellite data according to the method described by *Arrigo et al.* [1998]. All satellite images were mapped to a common polar-stereographic projection using the Interactive Data Language (IDL, Research Systems, Inc.) software package.

3. Polynya Dynamics

[6] The Cape Bathurst polynya exhibits marked interannual variability in the dynamics of sea ice retreat and formation (Figure 2). For the five annual cycles we studied, polynya size generally began a rapid and sustained increase in June (surpassing an open water area of at least 6,000 km^2), with the exception of 1998 when polynya expansion began two months earlier. During four of the five years of our study, sea ice began to re-freeze during the month of October (Figure 2), resulting in an average open water season in the Cape Bathurst polynya of approximately four months. The year 1998 exhibited the latest onset of sea ice freeze up in the autumn (November), making it by far the longest sustained period (7 months) of open water in the Cape Bathurst polynya of the five year record. This unusual duration is likely attributable to the large positive anomaly in atmospheric temperature that was recorded that same year [*Maslanik et al.*, 1999].

[7] The average amount of ice cover present within the polynya region during spring and summer varied by approximately ±40% between years, with some years remaining relatively ice free between the onset of melting and the initiation of re-freezing (e.g., 1999 and to a lesser degree 1998), and others exhibiting intermittent ice build up and retreat throughout the spring and summer (e.g., 2002). Sea ice cover was particularly heavy in the Cape Bathurst polynya during the spring and summer of 2002. Ice retreat began rapidly in early June, with open water area expanding from 2,000 km^2 to 12,000 km^2 in the span of a few days (Figure 2e). Ice retreat stalled soon thereafter, with open water area actually declining to 8,000 km^2 in late June. By early July, ice retreat had commenced again, with open water area increasing to 21,000 km^2 at the beginning of August. However, ice retreat then stalled a second time, as open water area decreased to 14,000 km^2 in late August. Finally, the maximum open water area of approximately 25,000 km^2 was reached in mid-September but lasted less than a month, as the Cape Bathurst polynya region began to re-freeze in early October.

4. Phytoplankton Bloom Dynamics

[8] The most striking feature of the five annual cycles of phytoplankton Chl *a* from the Cape Bathurst polynya is

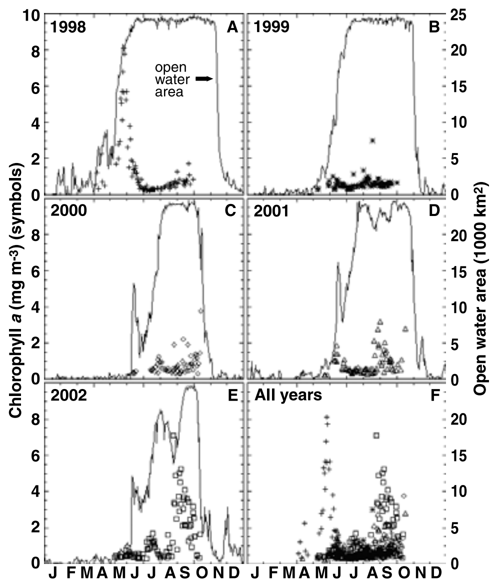

Figure 2. Interannual variations in open water area (solid line) and phytoplankton (symbol) dynamics within the Cape Bathurst study region shown in Figure 1. Chl *a* values represent spatial means of all cloud-free pixels within the study region for each day.

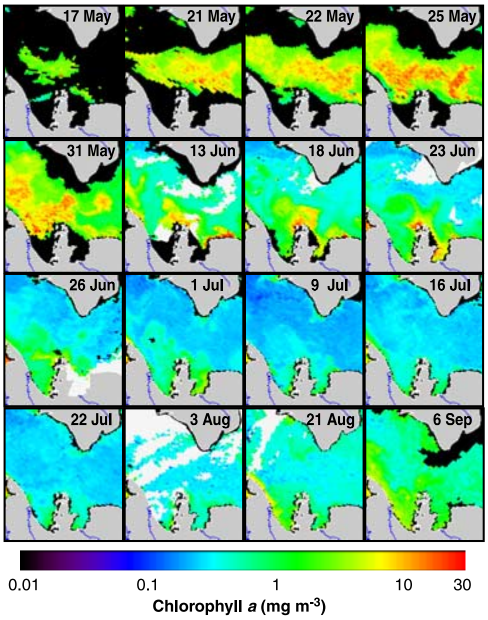

Figure 3. SeaWiFS time series of the 1998 phytoplankton bloom in the Cape Bathurst polynya region. Black areas are ice covered; white areas are cloud covered; gray is land.

their marked interannual variation, in terms of both the relative strength of the blooms and their timing. For example, an intense phytoplankton bloom formed during May in 1998, with a mean Chl *a* concentration within the study region as high as 8 mg m^{-3} (Figure 2a), exceeding 20 mg Chl *a* m^{-3} in some locations (Figure 3). The spring bloom of 1998 was the largest of the five year study, having developed much earlier than in any other year, with daily rates of primary productivity in 1998 peaking at 2.8 g C m^{-2} d^{-1}. This unusually warm year would have lead to higher than normal surface heating and stratification within the Cape Bathurst polynya region, creating a favorable light environment for phytoplankton growth. This year was also the most cloud-free of the five year study (for example, see Figure 3), further favoring rapid phytoplankton growth. Despite the persistent open water and cloudless conditions of 1998, the phytoplankton bloom declined in June, and Chl *a* remained at low levels throughout most of the summer (Figure 3), likely due to nutrient exhaustion. Autumn cooling and increased storm frequency generally result in increased vertical mixing and replenishment of nutrients in surface waters. As a result, a smaller (mean of 1.5 mg Chl *a* m^{-3}) autumn bloom developed in the polynya during the month of September (Figures 2a and 3).

[9] In contrast, 1999 was characterized by a small initial bloom in early June, with mean Chl *a* (1 mg m^{-3}) reaching barely above pre- and post-bloom concentrations (0.3–0.8 mg Chl *a* m^{-3}). A slightly larger bloom developed in August, as Chl *a* abundance exceeded 3 mg m^{-3}, but only for a short time (Figure 2b). The two phytoplankton blooms of 2000 were similar in intensity to those of 1999, but were delayed by about a month, with an early bloom in late July and the second bloom in September (Figure 2c). Chl *a* during the spring bloom of 2001 reached 2 mg m^{-3}, twice that of 1999, while the peak level in the late summer bloom in 2001 was similar to that of 1999 (3 mg Chl *a* m^{-3}), although it persisted for much longer (Figure 2d). The year 2002 was characterized by a modest initial bloom in July (~1.5 mg Chl *a* m^{-3}) but an intense bloom later in the summer, peaking at >7 mg Chl *a* m^{-3} in late August (Figure 2e), with a maximum production rate of 2.7 g C m^{-2} d^{-1}. Chl *a* exhibited its highest degree of interannual variation during May and September (Figure 2f), the months of the peak spring and late summer blooms, respectively, and markedly less from June through August.

[10] The primary generalization that can be made based upon these Chl *a* time series is that the Cape Bathurst polynya generally harbors two temporally distinct phytoplankton blooms per year, with one Chl *a* peak in spring or early summer and a second in late summer or early autumn. In addition, in four out of the five years studied, the late bloom was significantly larger than the early bloom, suggesting that this may be the typical pattern for the region. Only in 1998, when the polynya formed unusually early due to anomalously high air temperatures, was the initial bloom more intense than the later bloom.

[11] Maximum rates of production in the Cape Bathurst polynya calculated from satellite data are comparable to those measured in other productive Arctic waters. For example, peak production on the Chukchi Shelf is estimated to be 2.4 g C m^{-2} d^{-1} [*Chen et al.*, 2002], slightly less than our estimates for the Cape Bathurst polynya, while productivity of the western Greenland sea is slightly greater, with a peak rate of 3.2 g C m^{-2} d^{-1} [*Jensen et al.*, 1999]. In addition, productivity of the Cape Bathurst polynya appears to lie between that of the two other large Arctic polynyas. *Smith* [1995] measured a peak rate of production in the NEW polynya at a modest 1.1 g C m^{-2} d^{-1}, similar to values measured in the Barents Sea [*Luchetta et al.*, 2000]. In contrast, *Mei et al.* [2003] reported daily production rates in the NOW polynya as high as 6 g C m^{-2} d^{-1}.

[12] Annual primary production in the Cape Bathurst polynya varied nearly 2-fold over the five year time series, from 90 g C m^{-2} yr^{-1} in 2000 to 175 g C m^{-2} yr^{-1} in 1998. Production values for 1999, 2001, and 2002 were 110, 140, and 160 g C m^{-2} yr^{-1}, respectively. Although these are well below maximum values reported for the highly productive Bering Sea (720–840 g C m^{-2} yr^{-1}) [*Springer and McRoy*, 1993], they place the Cape Bathurst polynya among the more productive of the Arctic pelagic marine ecosystems. By comparison, annual production in Lancaster Sound and the northern Barents Sea are estimated to be only 60 and 25–30 g C m^{-2} yr^{-1}, respectively [*Welch et al.*, 1992; *Hegseth*, 1998].

[13] The lack of a substantial spring bloom in most years is likely due to an unfavorable physical environment at that time of year (except in 1998). The Cape Bathurst polynya is formed as a result of high winds advecting annual ice offshore away from the land fast ice, leaving open water in between [*Carmack and Macdonald*, 2002]. New ice can continue to form under these conditions (as evidenced by a decline in open water after an initial rapid increase in 2000, 2001, and 2002), resulting in brine rejection from the newly-formed ice (Figure 2). Consequently, the surface waters of the young polynya are subjected to both convective [*Carmack and Macdonald*, 2002] and wind-driven [*Hunt et al.*, 2002] vertical mixing. Despite ample springtime nutrients, the light environment may be unfavorable for

phytoplankton growth until surface waters stratify in summer, either because of solar heating, sea ice melting, or freshwater input from the Mackenzie River. If high temperatures melt substantial amounts of sea ice before it is blown offshore, then surface waters stratify early, and an intense phytoplankton bloom can develop (e.g., 1998). The intense late summer bloom in 2002 also may have been enhanced by increased stratification resulting from melting of sea ice that had recently formed or been advected into the region prior to the start of the bloom (Figure 2e). In support of this idea, the second largest late summer/early autumn bloom (in 2001) is also associated with intermittent increases and subsequent reduction of sea ice (Figure 2d), albeit to a lesser degree than in 2002.

5. Ecological Implications

[14] Understanding the dynamics of polynya formation and phytoplankton bloom development is important because of their ramifications for other components of the marine ecosystem. For instance, fish species such as Arctic cod exploit polynyas as feeding and nursery grounds because of their relatively high temperatures and long open water season. Because early feeding success in Arctic cod is a function of temperature rather than food supply, large interannual differences in polynya timing and extent could directly impact survival and recruitment of this economically important species [*Michaud et al.*, 1996]. It is likely that first-feeding success by Arctic cod would be higher in 1998 when temperatures were relatively high than it would be in years when colder conditions prevailed (L. Fortier, unpublished manuscript).

[15] Furthermore, the timing of the phytoplankton blooms in the Cape Bathurst polynya can also affect food web dynamics, both in the pelagic and the benthic environments. For instance, it has been proposed that when phytoplankton bloom in cold water, as they likely do in the Cape Bathurst polynya during spring (except in 1998), diminished grazing rates at these low temperatures result in a food web that is predominantly under bottom-up control (i.e., controlled by resource limitation rather than by grazing). This scenario favors the flux of energy to the benthic community at the expense of the pelagic environment [*Walsh and McRoy*, 1986; *Stabeno et al.*, 1998; *Hunt et al.*, 2002]. However, during the late summer bloom when waters are relatively warm, high zooplankton grazing should favor transfer of energy within the pelagic food web, with little export to the benthos. Therefore, seasonal and interannual differences in the timing of phytoplankton blooms in the Cape Bathurst polynya can have consequences for the entire marine food web. It has been shown that shifts in energy flow within food webs on the eastern Bering Sea shelf between top-down and bottom-up control can affect the recruitment of commercially important fish populations, such as pollock [*Hunt et al.*, 2002]. A similar situation may exist in the Cape Bathurst polynya.

[16] **Acknowledgments.** We thank M. Fortier and L. Fortier for their insightful discussions that ultimately lead to the production of this manuscript. This research was supported by NASA grant NAG5-11264 to K. Arrigo.

References

Arrigo, K. R., A. Schnell, D. L. Worthen, and M. P. Lizotte (1998), Primary production in Southern Ocean waters, *J. Geophys. Res.*, *103*, 15,587–15,600.
Carmack, E. C., and R. W. Macdonald (2002), Oceanography of the Canadian Shelf of the Beaufort Sea: A setting for marine life, *Arctic*, *55*, 29–45.
Chen, M., Y. P. Huang, L. D. Guo, P. H. Cai, W. F. Yang, G. S. Liu, and Y. S. Qiu (2002), Biological productivity and carbon cycling in the Arctic Ocean, *Chin. Sci. Bull.*, *47*, 1037–1040.
Dickson, D. L., and H. G. Gilchrist (2002), Status of marine birds of the southeastern Beaufort Sea, *Arctic*, *55*, 46–58.
Fett, R. W., S. D. Burk, W. T. Thompson, and T. L. Kozo (1994), Environmental phenomena of the Beaufort Sea observed during the LEADS experiment, *Bull. Am. Meteorol. Soc.*, *75*, 2131–2144.
Harwood, L. A., and I. Stirling (1992), Distribution of ringed seals in the southeastern Beaufort Sea during late summer, *Can. J. Zool.*, *70*, 891–900.
Hegseth, E. N. (1998), Primary production of the northern Barents Sea, *Polar Res.*, *17*, 113–123.
Hsiao, S. I. C. (1992), Dynamics of ice algae and phytoplankton in Frobisher Bay, *Polar Biol.*, *12*, 645–651.
Hunt, G. L., Jr., P. Stabeno, G. Walters, E. Sinclair, R. D. Brodeur, J. M. Napp, and N. A. Bond (2002), Climate change and control of the southeastern Bering Sea pelagic ecosystem, *Deep Sea Res., Part II*, *49*, 5821–5853.
Jensen, H. M., L. Pedersen, A. Burmeister, and B. W. Hansen (1999), Pelagic primary production during summer along 65 to 72 degrees N off west Greenland, *Polar Biol.*, *21*, 269–278.
Kosobokova, K. N., H. Hanssen, H. J. Hirche, and K. Knickmeier (1998), Composition and distribution of zooplankton in the Laptev Sea and adjacent Nansen Basin during summer, 1993, *Polar Biol.*, *19*, 63–76.
Luchetta, A., M. Lipizer, and G. Socal (2000), Temporal evolution of primary production in the central Barents Sea, *J. Mar. Syst.*, *27*, 177–193.
Markus, T., and B. A. Burns (1995), A method to estimate subpixel-scale coastal polynyas with satellite passive microwave data, *J. Geophys. Res.*, *100*, 4473–4487.
Maslanik, J. A., M. C. Serreze, and T. Agnew (1999), On the record reduction in 1998 western Arctic sea-ice cover, *Geophys. Res. Lett.*, *26*, 1905–1908.
Mei, Z. P., L. Legendre, Y. Gratton, J. E. Tremblay, B. LeBlanc, B. Klein, and M. Gosselin (2003), Phytoplankton production in the North Water Polynya: Size-fractions and carbon fluxes, April to July 1998, *Mar. Ecol. Prog. Ser.*, *256*, 13–27.
Michaud, J., L. Fortier, P. Rowe, and R. Ramseier (1996), Feeding success and survivorship of Arctic cod larvae, *Boreogadus saida*, in the Northeast Water polynya (Greenland Sea), *Fish. Oceanogr.*, *5*, 120–135.
Smith, W. O. (1995), Primary productivity and new production in the Northeast Water (Greenland) polynya during summer-1992, *J. Geophys. Res.*, *100*, 4357–4370.
Springer, A. M., and C. P. McRoy (1993), The paradox of pelagic food webs in the northern Bering Sea. 3. Patterns of primary production, *Cont. Shelf Res.*, *13*, 575–599.
Stabeno, P. J., J. D. Schumacher, R. F. Davis, and J. M. Napp (1998), Under-ice observations of water column temperature and spring phytoplankton dynamics: Eastern Bering Sea Shelf, *Mar. Res.*, *56*, 239–255.
Tremblay, J. E., Y. Gratton, J. Fauchot, and N. M. Price (2002), Climatic and oceanic forcing of new, net, and diatom production in the North Water, *Deep Sea Res., Part II*, *49*, 4927–4946.
Walsh, J. J., and C. P. McRoy (1986), Ecosystem analysis in the southeastern Bering Sea, *Cont. Shelf Res.*, *5*, 259–288.
Wang, J., and G. F. Cota (2003), Remote-sensing reflectance in the Beaufort and Chukchi Seas: Observations and models, *Appl. Opt.*, *42*, 2754–2765.
Welch, H. E., M. A. Bergmann, T. D. Siferd, K. A. Martin, M. F. Curtis, R. E. Crawford, R. J. Conover, and H. Hop (1992), Energy-flow through the marine ecosystem of the Lancaster Sound region, Arctic Canada, *Arctic*, *45*, 343–357.

K. R. Arrigo and G. L. van Dijken, Department of Geophysics, Stanford University, Mitchell Building #355, Stanford, CA 94305-2215, USA. (arrigo@pangea.stanford.edu)