Impact of a shrinking Arctic ice cover on marine primary production

Kevin R. Arrigo,[1] Gert van Dijken,[1] and Sudeshna Pabi[1]

Received 15 June 2008; revised 7 August 2008; accepted 25 August 2008; published 3 October 2008.

[1] Loss of Arctic sea ice has accelerated recently, culminating in a 2007 summer minimum ice extent that was 23% below the previous low. To quantify the impact of this unprecedented loss of ice on marine primary production, we have coupled satellite-derived sea ice, SST, and chlorophyll to a primary production algorithm parameterized for Arctic waters. Annual primary production in the Arctic has increased yearly by an average of 27.5 Tg C yr^{-1} since 2003 and by 35 Tg C yr^{-1} between 2006 and 2007. 30% of this increase is attributable to decreased minimum summer ice extent and 70% to a longer phytoplankton growing season. Should these trends continue, additional loss of ice during Arctic spring could boost productivity >3-fold above 1998–2002 levels, potentially altering marine ecosystem structure and the degree of pelagic-benthic coupling. Changes in carbon export could in turn modify benthic denitrification on the vast continental shelves. **Citation:** Arrigo, K. R., G. van Dijken, and S. Pabi (2008), Impact of a shrinking Arctic ice cover on marine primary production, *Geophys. Res. Lett.*, *35*, L19603, doi:10.1029/2008GL035028.

1. Introduction

[2] Between the late 1970's and the early part of the 21st century, the extent of Arctic Ocean sea ice cover has declined during all months of the year, with the largest declines reported in the boreal summer months, particularly in September (8.6 ± 2.9% per decade) [*Serreze et al.*, 2007]. The loss of Arctic sea ice has accelerated since 2002, with large winter losses reported in 2005 and 2006, a season that usually exhibits little interannual variability [*Comiso*, 2006]. Recent results from an ensemble of 11 models used in the International Panel on Climate Change Fourth Assessment Report suggested that there was a high probability of a 40% reduction of summer sea ice extent (relative to the 1979–1999 mean) in the Arctic by the year 2050 [*Overland and Wang*, 2007]. However, these predictions were made prior to the summer of 2007, which experienced by far the lowest sea ice cover ever recorded and the largest single year drop in minimum sea ice extent, with a summer minimum that was an unprecedented 23% below the previous low value observed in September 2005 and 39% below the 1979–2000 September mean [*National Snow and Ice Data Center*, 2007].

[3] Recent declines in Arctic sea ice cover have been attributed to a combination of factors, including increased advection of warm water into the Arctic Ocean [*Steele and Boyd*, 1998; *Dickson et al.*, 2000; *Maslowski et al.*, 2001; *Shimada et al.*, 2006], atmospheric circulation patterns that favor advection of sea ice out of the Arctic Ocean through Fram Strait [*Rigor and Wallace*, 2004; *Maslanik et al.*, 2007; *Serreze et al.*, 2007], and increased Arctic temperatures [*Rothrock and Zhang*, 2005; *Lindsay and Zhang*, 2005]. As thick, multi-year sea ice has been increasingly replaced by a thinner annual sea ice cover, the ice pack is more easily melted, either by surface heating or advection of warm waters into the Arctic Ocean. Reduced sea-ice extent decreases surface albedo, allowing more shortwave radiation to penetrate the ocean surface, contributing to additional ocean heat content and thus creating a positive feedback mechanism that inhibits ice growth in winter and accelerates its loss in spring and summer [*Perovich et al.*, 2007].

[4] Reported impacts of reduced Arctic sea ice extent already include increased autumn and winter temperatures, stronger wave activity and intensified coastal erosion [*Serreze et al.*, 2007], disrupted thermohaline circulation [*Peterson et al.*, 2006], impaired traditional hunting practices [*Huntington and Fox*, 2005], and improved navigation through the newly opened Northwest Passage. However, we do not yet fully understand the impact that reduced sea ice cover will have on pan-Arctic marine primary production [*Pabi et al.*, 2008]. Although Arctic sea ice itself can be biologically productive [*Gosselin et al.*, 1997; *Mock and Gradinger*, 1999], occasionally supporting large populations of diatoms and other primary producers, areal rates of CO_2-fixation in sea ice habitats tend to be much lower than rates found in the adjacent ice-free ocean [*Arrigo*, 2003]. Therefore, a loss of Arctic sea ice might be expected to increase the area favorable for phytoplankton growth and enhance the productivity of the Arctic Ocean.

[5] To quantify the change in marine primary productivity in Arctic waters resulting from recent losses of sea ice cover, we implemented a primary productivity algorithm that accounts for variability in sea ice extent, sea surface temperature, sea level winds, downwelling spectral irradiance, and surface chlorophyll *a* (Chl *a*) concentrations. The algorithm was parameterized and validated specifically for use in the Arctic [*Pabi et al.*, 2008] and utilizes forcing variables derived either from satellite data or NCEP reanalysis fields (see auxiliary material for further details).[1]

2. Sea Ice Extent

[6] Satellite imagery of sea ice extent shows that the average amount of open water in the Arctic Ocean (defined

[1]Department of Environmental Earth System Science, Stanford University, Stanford, California, USA.

0094-8276/08/2008GL035028$05.00

[1]Auxiliary material is available in the HTML. doi:10.1029/2008GL035028.

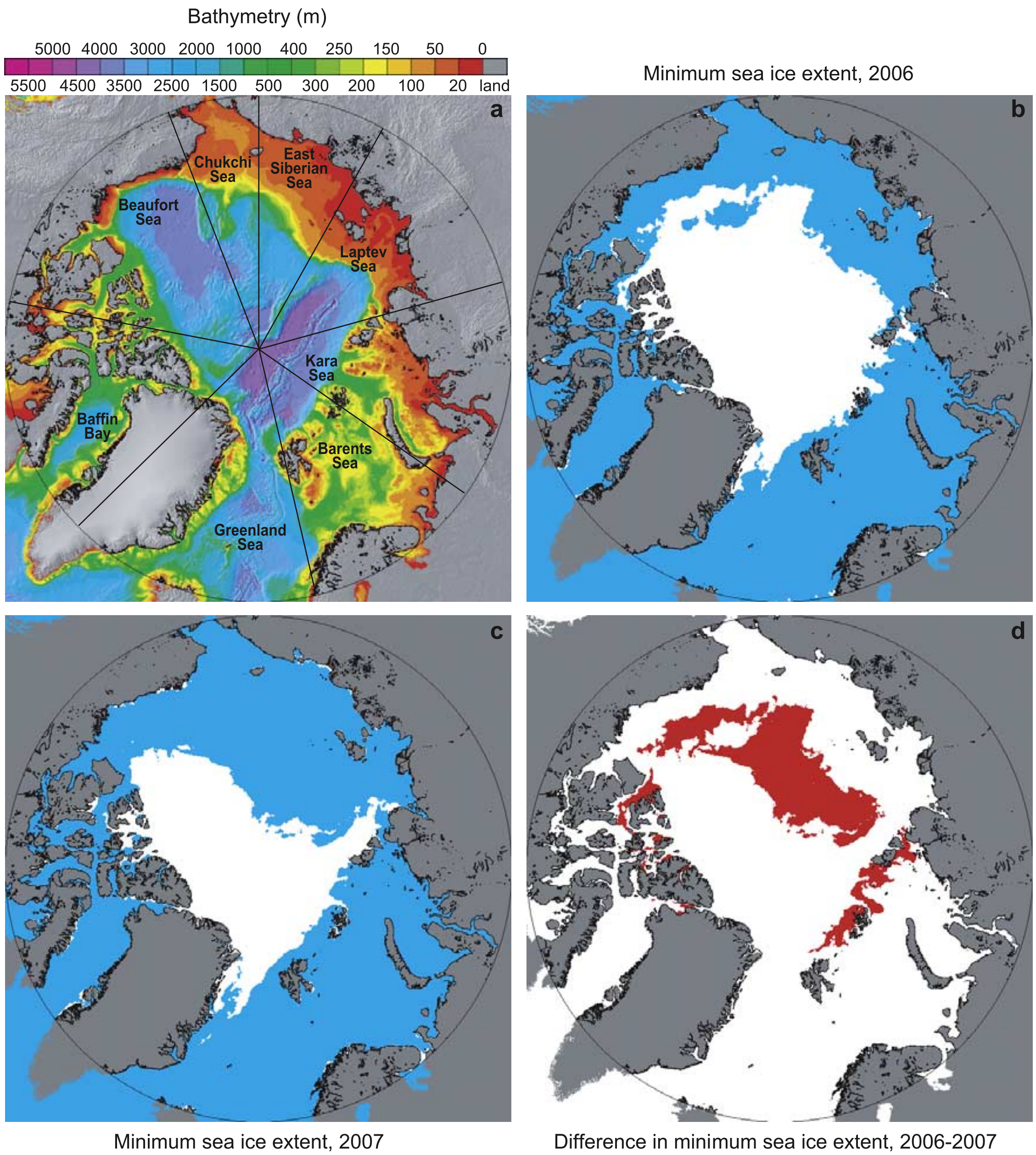

Figure 1. Arctic study region showing (a) bathymetry and location of the major geographic sectors discussed in the text, (b) the minimum sea ice extent of 2006 (reached on 22 September), (c) the minimum sea ice extent of 2007 (reached on 16 September), and (d) the difference in the minimum sea ice extent between 2006 and 2007. Red denotes areas with open water in 2007 that were ice covered in 2006. Much of this area had never been ice-free for as long as measurements have been available.

here as all waters north of the Arctic circle, Figure 1a) has steadily increased each year since 2003. During this time, mean annual open water area has risen by 14.5%, from 4.1×10^6 km^2 in 2003 to 4.7×10^6 km^2 in 2007 (Figure 2a), the latter being largest open water area measured during the 30 year satellite record. More importantly, during the peak of the phytoplankton spring bloom in May–June, open water area rose even more rapidly, from 3.2×10^6 km^2 in 2003 to 3.9×10^6 km^2 in 2007, an increase of 23.6% over five years (Figure 2b). However, the most dramatic changes in open water area in the Arctic are associated with the summer minimum sea ice extent in August–September (Figure 2c). In 2007, open water area during the summer sea ice minimum (Figure 1c) was 25% greater than in 2006 (Figure 1b) and 22.4% larger than in 2005, the previous minimum sea ice year (Figure 2c). This drop between 2006 and 2007 represents by far the biggest single-year decrease in summer minimum sea ice extent ever recorded in the Arctic. Losses of summer sea ice in 2007 were largest in the Laptev, Chukchi, and Siberian sectors of the Arctic

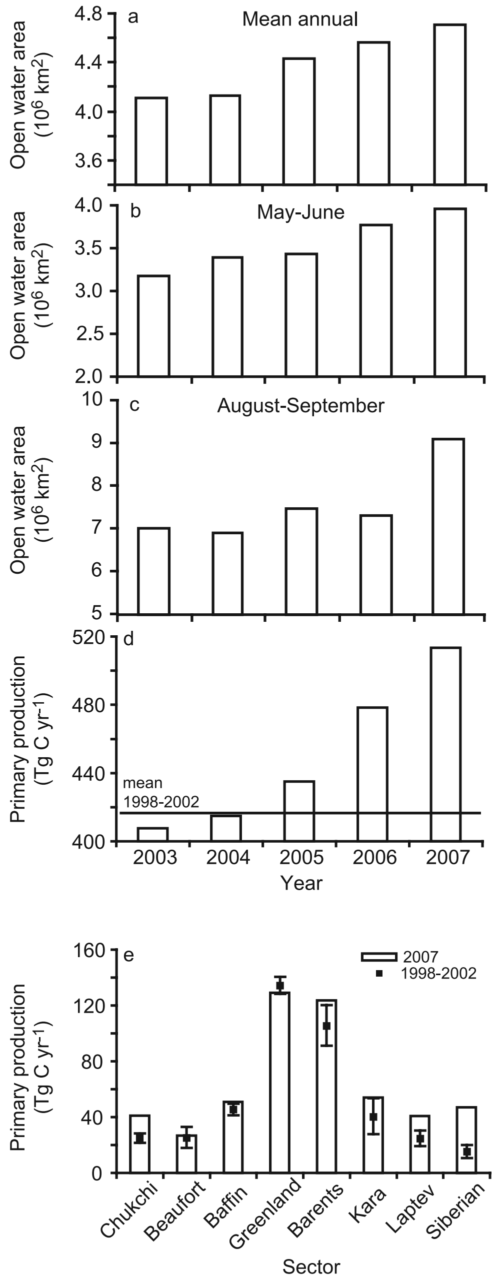

Figure 2. Open water area in the Arctic between 2003 and 2007 averaged (a) over the entire year, (b) during the peak of the spring phytoplankton bloom in May–June, and (c) during the summer minimum sea ice extent in August–September, as well as (d) corresponding increases in annual primary production in the Arctic (the solid horizontal line represents the mean annual primary production in the Arctic for the years 1998–2002). (e) Primary production by geographic sector in 2007 compared to the average values from 1998–2002.

Ocean (Figure 1d), although the Barents, Kara, and Beaufort seas also experienced reductions in ice cover.

3. Primary Production

[7] As a result of the progressive loss of sea ice in recent years, annual pan-Arctic primary production increased of by an average of 27.5 Tg C yr^{-1} each year between 2003 and 2007 (Figure 2d), with annual production in 2007 (513 Tg C yr^{-1}) exceeding the 1998–2002 mean (416 Tg C yr^{-1}) by 23%. Despite its generally low rates of primary productivity (Figures 3a and 3b), the Siberian sector experienced the largest increase in 2007, with an annual rate (47 Tg C yr^{-1}) that was >3-fold higher than the mean for 1998–2002 (Figure 2e). Similarly, annual production in both the Laptev and Chukchi sectors was substantially higher (65%) in 2007 than it was in 1998–2002. Changes in annual production in the other Arctic sectors were somewhat smaller, ranging from a 33% increase in the Kara sector in 2007 to a slight decrease (4%) in the Greenland sector (Figure 2e).

[8] Because of the large recession of sea ice in the summer of 2007, approximately 1.7 × 10^6 km^2 of the Arctic Ocean became ice-free for the first time in recorded history, effectively increasing the size of the open water habitat of the Arctic Ocean by an additional 20–25% (Figures 1c and 1d). Although most of the newly ice-free waters were located in deep basins that are of generally low productivity (Figures 3a and 3b), some continental shelf regions also were exposed, including portions of the Laptev Sea, East Siberian Sea, and the Canadian Archipelago. Primary productivity in all newly exposed waters in 2007 (red area shown in Figure 1d) amounted to 10.6 Tg C yr^{-1}. By comparison, productivity in these same regions reached only 0.7 Tg C yr^{-1} in 2006, less than 7% of the 2007 value. These results show that of the 35 Tg C yr^{-1} increase in annual primary production in the Arctic between 2006 and 2007, approximately 30% can be explained by the increased area of open water area in 2007.

[9] Much of the remaining 70% of the 2007 increase in annual production (24.6 Tg C yr^{-1}) is attributable to the longer phytoplankton growing season (expressed as the number of ice-free days) experienced throughout much of the Arctic. In some regions, the combination of accelerated sea ice melt in the spring and delayed freeze-up in the autumn produced an ice-free season that was >100 days longer in 2007 than in 2006 (Figure 3d). Over much of the Laptev, Siberian, and Chukchi seas, including continental shelf regions not impacted by the dramatic reduction in summer sea ice extent in 2007, the phytoplankton growing season in 2007 was 25–75 days longer than it was in 2006. Not surprisingly, areas with lengthened growing seasons (Figure 3d) also exhibited higher annual production in 2007 than in 2006 (Figure 3c). Increases were especially large on the already productive continental shelves, particularly in the Siberian and Laptev sectors, where the growing season was 50–80 days longer and annual primary production was 150–250 g C m^{-2} yr^{-1} higher in 2007 than it was in 2006. However, in most regions with a longer growing season in 2007, annual production was 25–75 g C m^{-2} yr^{-1} higher than in 2006. Virtually the only waters that experienced a decline in annual production between 2006 and 2007 were those that either had a shorter growing season in 2007 (blue areas near the Laptev/Kara and Laptev/Siberian boundaries in Figure 3d) or were located outside of the annual sea ice zone, such as the eastern Greenland, the Norwegian, and the southern Barents seas.

[10] Regression of annual primary production against mean annual open water area suggests that between 2003

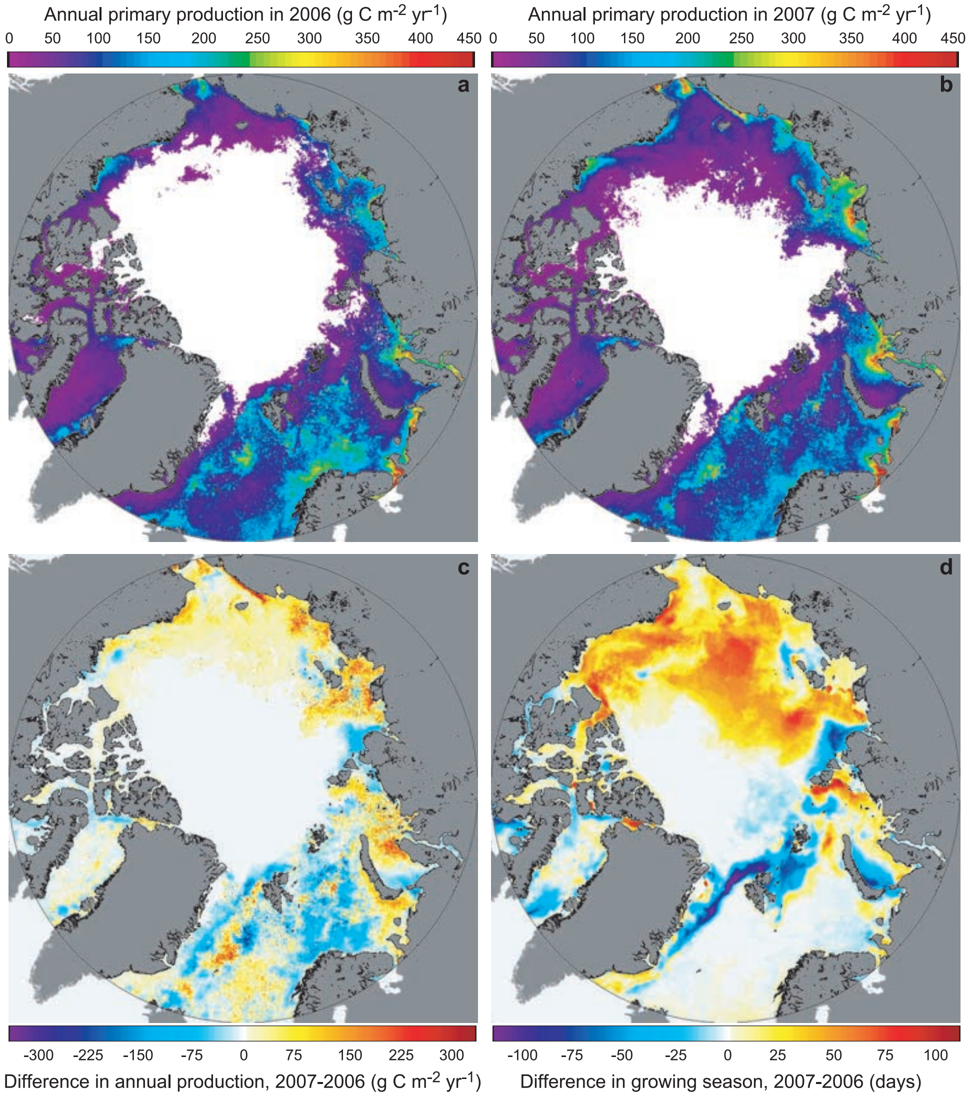

Figure 3. Annual primary production in (a) 2006 and (b) 2007. The change in (c) annual primary production (warm-colored areas were more productive in 2007) and (d) length of the phytoplankton growing season between 2006 and 2007 was calculated for each pixel by subtracting the value in 2007 from that in 2006. The change in the phytoplankton growing season was calculated for each pixel by subtracting the total number of days of ice cover between 1 March and 30 September 2007 from the total number of days of ice cover between 1 March and 30 September 2006. Warm-colored areas had a longer growing season in 2007.

to 2007, annual primary production in the Arctic increased by 163 Tg C yr^{-1} for every 1×10^6 km^2 drop in mean annual sea ice extent ($n = 5$, $R^2 = 0.92$, $p = 0.011$). If we extend this analysis to also include similar primary production and sea ice cover data from 1998–2002 [*Pabi et al.*, 2008], the increase in annual production resulting from an equivalent loss of sea ice drops to 122 Tg C yr^{-1} ($n = 10$, $R^2 = 0.68$, $p = 0.003$). Thus, the most recent losses of sea ice elicited larger increases in annual production than did the losses of ice from 6–10 years ago. Extrapolation of the more conservative 10-year trend suggests that annual primary production in the Arctic could increase by an additional 160 Tg C (reaching almost 700 Tg C yr^{-1}) if the ice pack melted completely in the summer and by >1300 Tg C if the Arctic became ice-free by the spring (assuming a current May–June sea ice extent of 12×10^6 km^2 and an increase in annual production of 113 Tg C yr^{-1} for each 1×10^6 km^2 drop in sea ice extent). This latter value represents a 3-fold increase in annual primary production above the 1998–2002 mean (416 Tg C yr^{-1}).

[11] Given that surface nutrients in the Arctic are generally low, it is possible that future increases in production resulting from decreased sea ice extent and a longer phytoplankton growing season will slow as surface nutrient inventories are exhausted. This could reduce primary productivity in waters downstream of the Arctic, such as in the western north Atlantic. On the other hand, nitrate concentrations in subsurface Arctic waters are relatively abundant (approximately 5 μM and 5–15 μM at 50 m and 100 m, respectively). Currently, these nutrients seldom reach the surface due in part to the presence of a cold halocline layer that resides at a depth of 50–100 m and separates deeper

high-nutrient waters from the surface layer [*Aagaard et al.*, 1981]. However, as multi-year ice continues to retreat from the continental shelf, where most of the primary production currently takes place, wind-driven shelf-break upwelling is likely to be initiated [*Carmack and Chapman*, 2003], increasing the rate of nutrient upwelling onto the shelves and fueling additional increases in productivity.

4. Implications

[12] Continued reductions in Arctic sea ice and the associated increase in pelagic primary productivity are almost certain to impact local marine ecosystems, which are relatively sensitive to changes in primary production due to their low number of trophic links [*Grebmeier et al.*, 2006]. Whether or not the observed increase in phytoplankton production resulting from greater open water area and a longer growing season would be expected to enhance the flux of organic matter from surface waters to the sediments and increase pelagic-benthic coupling is unclear. Earlier sea ice melt and the subsequent release of ice algal communities to the water column at a time when zooplankton abundance is relatively low reduces grazing losses, thereby increasing the sinking flux of particulate matter from the sea ice to the sediments [*Michel et al.*, 2006]. Similarly, *Hunt et al.* [2002] reported that earlier loss of sea ice in the Bering Sea stimulated phytoplankton blooms at a time when surface waters were still cold and zooplankton growth rates were low, thereby increasing the export of organic matter. This scenario could apply to the Arctic Ocean if changes in atmospheric circulation are primarily responsible for the observed loss of sea ice in recent years. However, if advection of increasingly warm surface waters into the Arctic is responsible for the early losses of sea ice observed in recent years [*Shimada et al.*, 2006], zooplankton growth may not be negatively impacted by the earlier loss of sea ice and carbon export may remain unchanged or even be diminished. Furthermore, reduced sea ice cover in the Arctic has been proposed to favor a 'phytoplankton–zooplankton' dominated ecosystem over the more typical 'sea-ice algae–benthos' ecosystem [*Piepenburg*, 2005]. This ecosystem switch could reduce the export of organic carbon and decrease pelagic-benthic coupling, despite concurrent increases in phytoplankton productivity.

[13] Changes in the flux of organic matter to continental shelf sediments also could have important impacts on ocean biogeochemistry. Shelves in the Chukchi Sea currently are sites of enhanced denitrification [*Devol et al.*, 1997]. Changes in carbon export on the shelves could alter rates of sediment and water column denitrification, changing the amount of excess phosphorus that advects from the Arctic into the Atlantic Ocean. Currently, losses of fixed nitrogen in the Arctic are compensated for by increased fixation of atmospheric nitrogen (N_2) in the north Atlantic [*Yamamoto-Kawai et al.*, 2006]. However, while N_2-fixation is favored in waters with a low nitrogen:phosphorus ratio [*Tyrrell*, 1999], this process also requires high iron concentrations [*Zehr et al.*, 1993]. If increased production in the Arctic were to result in greater rates of denitrification, it will be critical to understand whether iron fluxes into the north Atlantic are sufficient to offset future losses of fixed nitrogen.

[14] Changes in local ecosystems in the Arctic as well as in regional climate dynamics are likely to be complex. Here we show that the progressive loss of sea ice has led to a marked increase in pan-Arctic productivity. However, while food supplies for lower trophic levels may indeed be greater, the loss of sea ice could precipitate profound ecological shifts away from the ice-obligate predators, such as spectacled eiders, ringed seals, and polar bears that dominate the system today, toward a more pelagic fauna. In addition, continued changes in the timing of sea ice melt could pose problems for organisms that have evolved to utilize the seasonal pulse in productivity, either through migratory patterns that bring them to the Arctic at the most productive times of year or through life history strategies that ensure an ample food supply for developing juveniles. Finally, a positive feedback between global greenhouse warming and an increasingly ice-free Arctic Ocean has been projected by others [*Perovich et al.*, 2007]. However, if the 26% increase in annual net CO_2-fixation in the Arctic between 2003 and 2007 resulting from the 0.6×10^6 km^2 decrease in mean annual sea ice extent is associated with an increase in CO_2 uptake by the ocean, then this would represent a weak negative feedback on climate change. The broader impacts of this added oceanic uptake of CO_2 to the global carbon cycle require more study, but it is clear that careful monitoring of coupled climate and ecosystem change in the Arctic is necessary to determine the longer-term implications of substantial losses of Arctic sea ice.

[15] **Acknowledgment.** This work was supported by NASA grant NNG05GC92G to K. Arrigo.

References

Aagaard, K., L. K. Coachman, and E. Carmack (1981), On the halocline of the Arctic Ocean, *Deep Sea Res., Part A*, *28*, 529–545.

Arrigo, K. R. (2003), Primary production in sea ice, in *Sea Ice-An Introduction to Its Physics, Chemistry, Biology and Geology*, edited by D. N. Thomas and G. S. Dieckmann, pp. 143–183, Blackwell Sci., Oxford, U.K.

Carmack, E. C., and D. Chapman (2003), Wind-driven shelf/basin exchange on an Arctic shelf: The joint roles of ice cover extent and shelf-break bathymetry, *Geophys. Res. Lett.*, *30*(14), 1778, doi:10.1029/2003GL017526.

Comiso, J. C. (2006), Abrupt decline in Arctic winter sea ice cover, *Geophys. Res. Lett.*, *33*, L18504, doi:10.1029/2006GL027341.

Devol, A. H., L. A. Codispoti, and J. P. Christensen (1997), Summer and winter denitrification rates in western Arctic shelf sediments, *Cont. Shelf Res.*, *17*(9), 1029–1033.

Dickson, R. R., T. J. Osborn, J. W. Hurrell, J. Meincke, J. Blindheim, B. Adlandsvik, T. Vinje, G. Alekseev, and W. Maslowski (2000), Arctic ocean response to the North Atlantic oscillation, *J. Clim.*, *13*, 2671–2696.

Gosselin, M., M. Levasseur, P. A. Wheeler, R. A. Horner, and B. C. Booth (1997), New measurements of phytoplankton and ice algal production in the Arctic Ocean, *Deep Sea Res., Part II*, *44*, 1623–1644.

Grebmeier, J. M., L. W. Cooper, H. W. Feder, and B. I. Sirenko (2006), Ecosystem dynamics of the Pacific-influenced Northern Bering and Chukchi Seas in the Amerasian Arctic, *Prog. Oceanogr.*, *71*(2–4), 331–361.

Hunt, G. L., 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.

Huntington, H. P., and S. Fox (2005), The changing Arctic: Indigenous perspectives, in *Arctic Climate Impact Assessment* (*ACIA)*, chap. 3, pp. 61–98, Cambridge Univ. Press, New York.

Lindsay, R. W., and J. Zhang (2005), The thinning of Arctic sea ice, 1988–2003: Have we passed a tipping point?, *J. Clim.*, *18*, 4879–4894.

Maslanik, J., S. Drobot, C. Fowler, W. Emery, and R. Barry (2007), On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions, *Geophys. Res. Lett.*, *34*, L03711, doi:10.1029/2006GL028269.

Maslowski, W., D. C. Marble, W. Walczowski, and A. J. Semtner (2001), On large-scale shifts in the Arctic Ocean and sea-ice conditions during 1979–98, *Ann. Glaciol.*, *33*, 545–550.

Michel, C., R. G. Ingram, and L. R. Harris (2006), Variability in oceanographic and ecological processes in the Canadian Arctic Archipelago, *Prog. Oceanogr.*, *71*(2–4), 379–401.

Mock, T., and R. Gradinger (1999), Determination of Arctic ice algal production with a new in situ incubation technique, *Mar. Ecol. Prog. Ser.*, *177*, 15–26.

National Snow and Ice Data Center (2007), Arctic sea ice shatters all previous record lows, http://nsidc.org/news/press/2007_seaiceminimum/20071001_pressrelease.html, Boulder, Colo.

Overland, J. E., and M. Wang (2007), Future regional Arctic sea ice declines, *Geophys. Res. Lett.*, *34*, L17705, doi:10.1029/2007GL030808.

Pabi, S., G. L. van Dijken, and K. R. Arrigo (2008), Primary production in the Arctic Ocean, 1998–2006, *J. Geophys. Res.*, *113*, C08005, doi:10.1029/2007JC004578.

Perovich, D. K., B. Light, H. Eicken, K. F. Jones, K. Runciman, and S. V. Nghiem (2007), Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback, *Geophys. Res. Lett.*, *34*, L19505, doi:10.1029/2007GL031480.

Peterson, B. J., J. McClelland, R. Curry, R. M. Holmes, J. E. Walsh, and K. Aagaard (2006), Trajectory shifts in the Arctic and subarctic freshwater cycle, *Science*, *313*, 1061–1066.

Piepenburg, D. (2005), Recent research on Arctic benthos: common notions need to be revised, *Polar Biol.*, *28*(10), 733–755.

Rigor, I. G., and J. M. Wallace (2004), Variations in the age of Arctic sea-ice and summer sea-ice extent, *Geophys. Res. Lett.*, *31*, L09401, doi:10.1029/2004GL019492.

Rothrock, D. A., and J. Zhang (2005), Arctic Ocean sea ice volume: What explains its recent depletion?, *J. Geophys. Res.*, *110*, C01002, doi:10.1029/2004JC002282.

Serreze, M. C., M. M. Holland, and J. Stroeve (2007), Perspectives on the Arctic's shrinking sea-ice cover, *Science*, *315*, 1533–1536.

Shimada, K., T. Kamoshida, M. Itoh, S. Nishino, E. Carmack, F. McLaughlin, S. Zimmerman, and A. Proshutinsky (2006), Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean, *Geophys. Res. Lett.*, *33*, L08605, doi:10.1029/2005GL025624.

Steele, M., and T. J. Boyd (1998), Retreat of the cold halocline layer in the Arctic Ocean, *J. Geophys. Res.*, *103*, 10,419–10,435.

Tyrrell, T. (1999), The relative influences of nitrogen and phosphorus on oceanic primary production, *Nature*, *400*, 525–538.

Yamamoto-Kawai, M., E. Carmack, and F. McLaughlin (2006), Nitrogen balance and Arctic throughflow, *Nature*, *443*, 43.

Zehr, J. P., M. Wyman, V. Miller, L. Dugay, and D. G. Capone (1993), Modification of the iron protein of nitrogenase in natural populations of *Trichodesmium thiebautii*, *Appl. Environ. Microbiol.*, *59*(3), 669–676.

K. R. Arrigo, S. Pabi, and G. van Dijken, Department of Environmental Earth System Science, Stanford University, Y2E2 Room 141, Stanford, CA 94305, USA. (arrigo@stanford.edu)