ENHANCED ARCTIC PRIMARY PRODUCTIVITY FOLLOWING SEA ICE RAPID DECLINE

Josefino C. Comiso
NASA Goddard Space Flight Center, josefino.c.comiso@nasa.gov

ABSTRACT: Satellite sea ice data from 1978 to the present reveal that the perennial ice (or ice that survives the summer) has been rapidly declining at almost 10% per decade. Warming due to increases in greenhouse gases in the atmosphere is now also being reflected in winter with drastic reductions in the maximum extent observed in 2005 and 2006. The retreat of the perennial ice also exposes more open water and has revealed an asymmetric distribution of chlorophyll *a* pigment concentration in the Arctic basin. Phytoplankton blooms are most dominant at high latitudes, partly on account of sea ice, but in the Arctic basin, it appears that pigment concentrations in the Eastern (Laptev Sea) Region are on the average three times higher than those in the Western (Beaufort Sea) Region. Such asymmetry suggests that despite favorable conditions provided by the melt of sea ice, there are other factors that affects the productivity of the region. The asymmetry is likely associated with much wider shelf areas in the East than in the West, with sea ice processes that inhibits the availability of nutrients near the surface in deep water regions, and river run-off that affects nutrient availability. The primary productivity in the pan-Arctic region have been estimated using the pigment concentrations and PAR derived from SeaWiFS data and the results show large seasonal as well as interannual variability during the 1998 to 2005 period. The data points towards increasing productivity for later years but with only 9 years of data it is too early to tell the overall effect of the sea ice retreat.

KEYWORDS: Ocean color, productivity, sea ice, Arctic

1. INTRODUCTION

High latitude oceanographic regions are among the most productive regions in the world, in part because of the presence of sea ice. During spring melt, sea ice provides low density water that floats on the surface. With the initial innoculum of plankton (partly from brown ice), ample nutrients, and abundant sunlight, this stable layer has all the necessary conditions needed for an accelerated phytoplankton growth, and large standing stocks accumulate (Alexander and Niebauer, 1985; Smith and Nelson, 1985). The material and energy produced is ultimately transferred within the food web, resulting in some of the richest marine ecosystems known. They not only harbor extensive concentrations of birds and marine mammals, but support some of the most important marine fisheries resources known to man. Unfortunately, these systems are subject to change. Among the purpose of this study is to evaluate how productivity is impacted by recently observed changes in the Arctic, especially in the sea ice cover.

Overall, sea ice and snow cover in the entire northern hemisphere had been basically stable and retreating only slightly by about 1.5 to 2% per decade. Because of the large interannual variability in the sea ice cover, changes in wind circulation, the presence of the Arctic Oscillation, and the relatively short data record, such trends have been difficult to distinguish from "normal" variations. However, some distinct patterns have emerged in recent years, the most remarkable of which is the rapid decline in the integrated Arctic perennial sea ice cover of about 10% per decade (Comiso 2006a). The lowest extent of the perennial ice cover on record during the satellite era occurred in 2005, which is also regarded as the warmest year since instruments started being used for meteorological studies more than a century ago. The area of the perennial ice cover has been abnormally low in 8 of the last 9 years. Moreover, the ice cover in the winter has now been showing significant declines. The ice maximum extent in the winter of 2005 declined by about 6% from average and in 2006, the extent was even lower than that of 2005 (Comiso, 2006b). This means faster retreat of the ice cover in spring and even less ice cover in the subsequent summer. This also means that the anticipated impact of warming due to increases in atmospheric greenhouse gases in winter has finally arrived.

During the aforementioned changes in last decade it is fortuitous that we also have continuous ocean color data from various sources including SeaWiFS and MODIS. This allowed simultaneous monitoring of phytoplankton concentrations in the same region and provide the means to assess associated changes in the primary productivity. In this paper, we present results from analysis of the seasonal and interannual variabilities of ocean color data as observed by SeaWiFS and how they are correlated with sea ice observations observed from passive microwave (SSM/I) sensor and also with surface temperatures as observed from thermal infrared (AVHRR) sensor. As the perennial ice cover continuous to retreat and the seasonal ice cover becomes more dominant in the central Arctic, we will also assess how such changes will impact the overall productivity of the Arctic Ocean.

2. PHYTOPLANKTON CONCENTRATION AND PRIMARY PRODUCTIVITY

The Nimbus-7 CZCS data enabled the mapping of the first pan-Arctic distribution of phytoplankton concentrations (Muller Karger et al. 1990, Mitchell et al., 1991). The data showed that pigment concentrations at high latitudes are elevated, but the data coverage for the region was very limited due to ice and cloud cover and satellite angle, despite relatively long (1978 to 1986) record of CZCS data. No ocean color data were available for several years until the launch of the Ocean Color Temperature Sensor (OCTS) aboard ADEOS-1, which provided the first comprehensive data for the Arctic region starting in the fall 1996. Unfortunately, the coverage was discontinued in the summer of 1997 due to hardware problems with the ADEOS-1 satellite but the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was launched shortly thereafter and enabled unprecedented continuous ocean color data up to the present. Also, temporal coverage was enhanced with the launch of Terra/MODIS in 1999 and the Aqua/MODIS in 2002. Although the length of continuous data (1996 to the present) is still relatively short, the availability of co-registered and spatially detailed distributions of phytoplankton chlorophyll concentrations and associated environmental parameters provides a unique opportunity to do comparative studies and gain insights into the possible impact of the changing Arctic to the productivity of the region. For simplicity in the analysis and interpretation, we will present in this paper results from SeaWiFS data only. Assessments of the algorithms used to derive phytoplankton concentrations from the radiance data have been made previously by Cota et al (2004) and Wang et al. (2005).

The large seasonality of phytoplankton blooms in the Northern Hemisphere is illustrated by the set of monthly images (April through November 1998) in Figure 1. The monthly changes in the pattern and sizes of blooms are large and illustrate the complex evolution of the chlorophyll distribution in the Arctic from the beginning of the ice melt season to the freeze up season during the same year. The peak of the bloom in the peripheral seas appears to be in May-June, while within the marginal seas of the Arctic basin it is approximately August. On a region to region basis, rapid changes are evident. For example, the western side in the Bering Sea (near 180°) shows very intense blooms in May, but the pattern disappeared in June. Also, very intense blooms appeared at the Sea of Okhotsk (about 140°E) in June, but the bloom disappeared by July. Short-term changes are thus important, since month-to-month variations are very large. On the other hand, there are regions like the James and Hudson Bays (around 90°W) in which the bloom patterns were nearly constant from June through October.

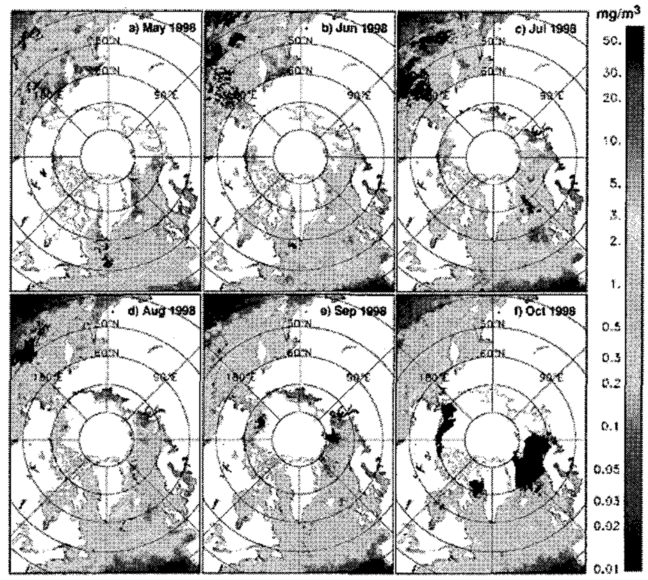

Figure 1. Monthly average pigment concentrations from April 1998 to October 1998.

During the summer, what becomes obvious is the large asymmetry in the pigment distributions between the eastern and western region - the average pigment concentration in the eastern region is at least three times higher than that of the western region. The difference may in part be caused by differences in the contribution of river run-off water (which not only can provide nutrients, but also can be high in dissolved organic matter, some of which can interfere with accurate pigment retrieval). However, differences in the bathymetry may also be crucial in providing nutrients and creating the spatial asymmetry.

To study the impact of warming and yearly variability of the ice cover, monthly average chlorophyll pigment concentrations during minimum ice extents (September) are presented in Fig. 2 for the years 1997 to 1998. Data in black correspond to either sea ice covered or cloud covered data. It is apparent, that pigment concentrations are consistently high at the Siberian/Laptev Seas region while in the western region, the concentrations can be very low (e.g., 2002, 2003 and 2004). Some year to year variability is also evident, especially in connection with the location of the perennial ice cover. It is interesting to note that the retreat of the sea ice in the Beaufort Sea in 2002, 2003, 2004 and 2005 did not lead to phytoplankton blooms in the region. This is not consistent with the expected effect of the introduction of melt water from the retreat of the sea ice cover. We can only hypothesize for now that it can be caused in part due to other factors such as nutrient limitations in these regions, which are located in the deeper part of the Arctic Ocean.

This can come about by a process in which nutrients in the region are mixed with high salinity and cold water during ice formation and eventually end up at the bottom of the deep ocean.

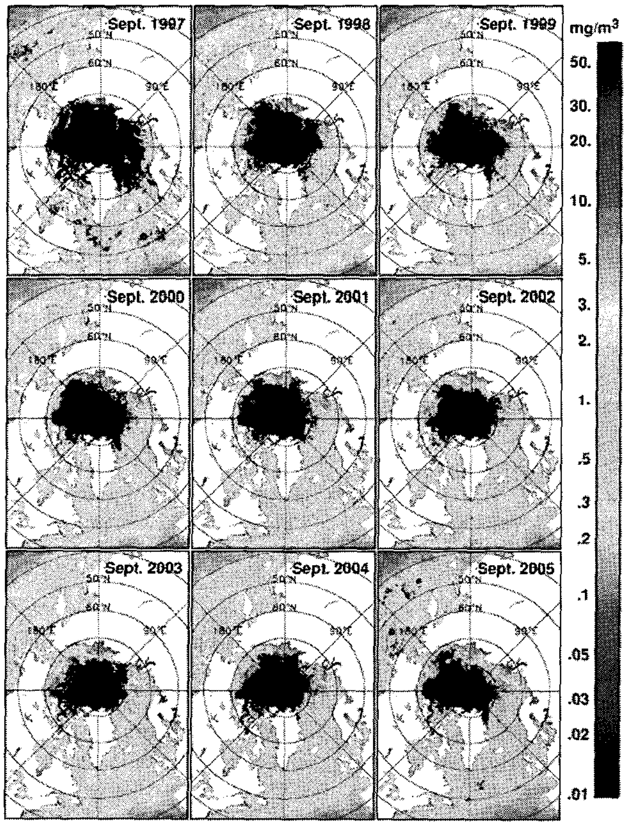

Figure 2. Yearly average pigment concentrations from September 1998 to September 2005.

One interesting result of our analysis of data in the Bering Sea and Okhotsk Sea regions is a strong correlation (r^2=0.84) of average phytoplankton concentration with the loss of sea ice cover (or availability of melt water) during the early part of the spring season. This is the expected influence of sea ice as discussed earlier. After mid-spring, however, the correlation is still strong but in the opposite direction. It could be that in mid-spring, nutrient supply gets depleted. Also, there is strong correlation (r^2= 0.82) of the average phytoplankton concentration with surface temperature in early spring, but a correlation in the opposite direction after mid spring when the temperature reaches about 277K. Recent studies in the Bering Sea (Dave Hutchins, private communication, 2006) is that temperature is the single most important factor in controlling phytoplankton assemblage composition. The experiment ran a semi-continuous culture on deck under trace metal clean conditions. The small increase (about 2 or 3 degrees) in temperatures drove a huge change in phytoplankton assemblage composition. It is thus possible that the ideal temperature for phytoplankton bloom occurs in early spring and after mid spring when the sea surface temperature exceeds about 278K, the performance of the planktons starts to decline. Such phenomenon is intriguing but requires further study.

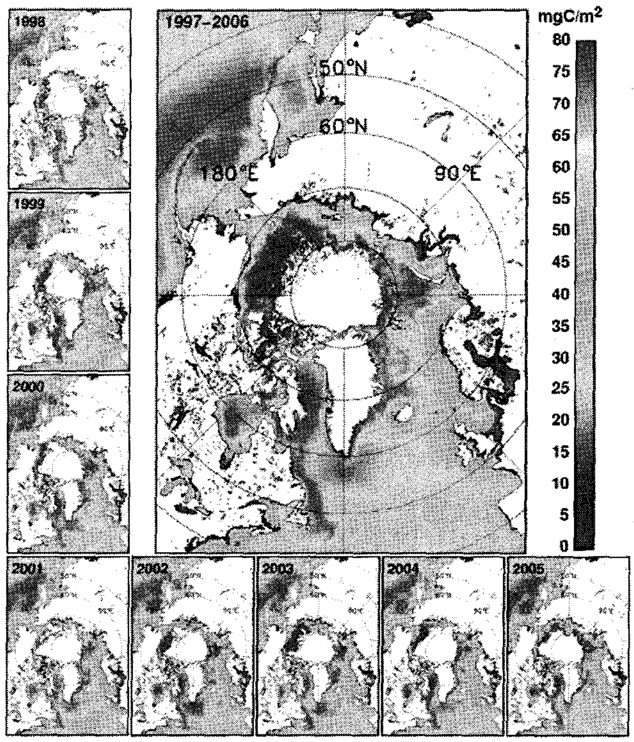

Figure 3. Multiyear and yearly productivity in the Arctic from 1998 to 2005.

The ocean color images represent the concentration of chlorophyll *a* pigments in the upper few meters of the ocean only. Much progress has been made in improving the utility of these data through the calculation of the real primary productivity of the ocean. The simplest version was to estimate time and depth-integrated primary production as a function of surface chlorophyll. This technique has been enhanced to utilize the product of depth-integrated chlorophyll, daily surface irradiance and a constant, water-column averaged quantum yield. The most advanced version to date makes use of bio-optical models that account for photosynthetically active radiation (PAR) through water column and vertical and spatial variability in phytoplankton optical absorption cross section and photosynthesis versus irradiance parameters (Behrenfeld and Falkowski, 1997). This technique has been applied to available SeaWiFS data and the key results are summarized in Figure 3. Figure 3 provide the means to assess the regions of the Arctic and peripheral seas which are highly productive and which ones are not. The large image in Figure 3 provides the climatology of the pan-Arctic primary productivity as derived from 9-years of ocean color data. The image provides the baseline in which to assess yearly changes. For this data set, the averages represent the average of clear sky data that is not covered by sea ice. Since the perennial ice moves from one year to the next, the data shows less ice than what is observed in any single year. It is apparent that the deep-ocean regions of the Arctic basin are not very productive while the shallow shelf regions are very productive. This indicates that despite favorable conditions provided by meltwater and abundant sunlight for photosynthesis, there are other factors that inhibits productivity in the region. Because of the lack of data, we don't know for sure, but it is likely that the lack of nutrients and iron are among the key factors. The smaller images shows the yearly averages from 1998 to 2005. Significant year to year changes are apparent in the images, specially near areas covered by sea ice (in white) but overall, there is consistency in the location of high productivity regions. Since the light levels during the summer is likely high enough for optimum productivity, it is not surprizing that the productivity images have spatial distributions that are very similar to those of the basic Chlorophyll images.

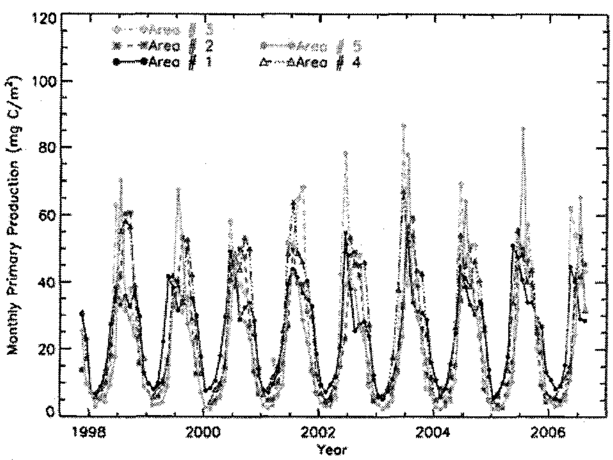

Figure 4. Average primary production in 360 by 360 study areas in the (1) Labrador Sea; (2) Greenland Sea; (3) Barents Sea; (4) Bering Sea; and (5) Okhotsk Sea.

For more quantitative comparison, we show in Figure 4, averages of monthly primary productivity in 5 study areas, the location of which are described in the figure caption. The seasonal cycle is apparent and the peak period varies from on study area to another. Also, it is evident that for some regions, the peak period occurs twice during the year. It is apparent from the plots that higher values occured in the latter years. Trend analysis indicate increasing productivity which is consistent with the expected effect of decreasing sea ice cover but with only nine-years of data, it is too early to make definitive conclusions.

3. DISCUSSION AND CONCLUSIONS

More than nine years of ocean pigment concentrations in the Arctic region, as derived from SeaWiFS data, have been analyzed. These years coincided with big changes in the ice cover and warming in the Arctic region. The results of the analysis show that the increasing areas of open water in the Arctic basin are not accompanied by intense phytoplankton bloom that had been expected from more meltwater from the sea ice retreat. There is instead a large asymmetry in the coverage with the eastern region having on the average three times higher values than those of the western region. This indicates that there are other important factors (in addition to the melt of sea ice) that affects the productivity of the region. The asymmetry is likely associated with the presence of large areas of shallow shelf regions in the eastern regions compared to those of the western regions. This in turn influences the difference in the availability of nutrients and iron in the two regions.

4. Acknowledgements: The author wish to thank Larry Stocks of SGT for superb programming support in the analysis of the SeaWiFS data. This paper was supported by NASA's Cryospheric Sciences Program.

REFERENCES

Alexander, V., H.J. Niebauer, 1981. Oceanography of the eastern Bering Sea ice-edge zone in spring. *Limnol. Oceanogr.* 26, pp. 1111-1125.

Behrenfield, M., P. Falkowski, 1997. A consumer's guide to phytoplankton primary productivity models. Limnol. Oceanogra. 42, pp 1-20.

Comiso, J.C., 2006a. Arctic warming signals from satellite observations, *Weather,* 61(3), 70-76.

Comiso, J. C., 2006b. Abrupt Decline in the Arctic Winter Sea Ice Cover, *Geophys. Res. Lett.,33,* L18504, doi:10.1029/2006GL027341.

Cota, G., G. Wang, and J. C. Comiso, 2004. Transformation of global satellite chlorophyll retrievals with a regionally tuned algorithm, *Rem. Sensing of the Environment*, 90, pp. 373-377.

Mitchell, B.G., E. Brody, E.N. Yeh, C. McClain, J. C. Comiso, and N.C. Maynard, 1991. Meridional zonation of the Barents Sea ecosystem inferred from satellite remote sensing and in-situ Bio-optical observations, Pro Mare Symposium, *Polar Research, 10*(1), pp. 147-162.

Smith, W.O. Jr., D.M. Nelson, 1985. Phytoplankton bloom produced by a receding ice edge in the Ross Sea: Spatial coherence with the density field, Science 227, pp. 163-166.

Wang, Jian, G. F. Cota, and J. C. Comiso, 2005. Phytoplankton in the Beaufort and Chukchi Seas; Distributions, dynamics, and environmental forcing, *Deep Sea Res. II, 52*, 3355-33688, (2005).