ID: W2127830844

TITLE: Secular trends in Arctic Ocean net primary production

AUTHOR: ['Kevin R. Arrigo', 'Gert L. van Dijken']

ABSTRACT:

Journal of Geophysical Research: OceansVolume 116, Issue C9 Free Access Secular trends in Arctic Ocean net primary production Kevin R. Arrigo, Kevin R. Arrigo Department of Environmental Earth System Science, Stanford University, Stanford, California, USASearch for more papers by this authorGert L. van Dijken, Gert L. van Dijken Department of Environmental Earth System Science, Stanford University, Stanford, California, USASearch for more papers by this author Kevin R. Arrigo, Kevin R. Arrigo Department of Environmental Earth System Science, Stanford University, Stanford, California, USASearch for more papers by this authorGert L. van Dijken, Gert L. van Dijken Department of Environmental Earth System Science, Stanford University, Stanford, California, USASearch for more papers by this author First published: 14 September 2011 https://doi.org/10.1029/2011JC007151 Abstract [1] A satellite-based study was conducted to document daily changes in net primary production (NPP) by phytoplankton in the Arctic Ocean from 1998 to 2009 using fields of sea ice extent, sea surface temperature, and chlorophyll a concentrations. Total annual NPP over the Arctic Ocean exhibited a statistically significant 20% increase between 1998 and 2009 (range = 441?585 Tg C yr?1), due mainly to secular increases in both the extent of open water (+27%) and the duration of the open water season (+45 days). Increases in NPP over the 12 year study period were largest in the eastern Arctic Ocean, most notably in the Kara (+70%) and Siberian (+135%) sectors. NPP per unit area for the Arctic Ocean averaged 101 g C m?2 yr?1 with no significant change over the study period. In the western sectors, NPP ranged from 71.3 ± 11.0 g C m?2 yr?1 in the Beaufort to 96.9 ± 7.4 g C m?2 yr?1 in the Chukchi, while in the more productive eastern Arctic, annual NPP between 1998 and 2009 ranged from 101 ± 15.8 in the Siberian sector to 121 ± 20.2 in the Laptev. Results of a statistical analysis suggest that between 1979 and 1998 (prior to the launch of SeaWiFS and MODIS), total Arctic NPP likely averaged 438 ± 21.5 Tg C yr?1. Moreover, when summer minimum ice cover drops to zero sometime during the first half of this century, annual NPP in the Arctic Ocean could reach ?730 Tg C yr?1. Nutrient fluxes into Arctic surface waters need to be better understood to determine if these projected increases are sustainable. Key Points Sea ice in the Arctic Ocean has declined Primary production in the Arctic Ocean has increased This increase in production could continue in the future 1. Introduction [2] The Arctic Ocean is undergoing unprecedented change with respect to its sea ice cover. Sea ice concentrations have dropped by approximately 9% per decade over the last three decades and have been accompanied by reductions in sea ice thickness, concentration, and duration [Perovich and Richter-Menge, 2009]. Causes of this decline in sea ice cover have been attributed to a number of factors, including increased Arctic air temperatures due to higher atmospheric greenhouse gas content [Rothrock and Zhang, 2005; Lindsay and Zhang, 2005; Zhang and Walsh, 2006; Stroeve et al., 2007], atmospheric circulation patterns that favor advection of sea ice out of the Arctic Ocean through Fram Strait [Rigor and Wallace, 2004; Liu et al., 2007; Maslanik et al., 2007; Serreze et al., 2007], and increased advection of warm water into the Arctic Ocean, both from the Atlantic through the eastern Fram Strait and the Barents Sea [Steele and Boyd, 1998; Dickson et al., 2000] and from the Pacific in the form of relatively warm Pacific Surface Water [Maslowski et al., 2001; Shimada et al., 2006; Woodgate et al., 2006]. The net result is an ice pack that contains a larger proportion of first year ice that is more easily melted, either by surface heating or advection of warm waters into the Arctic Ocean. Reduction in 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]. [3] Reduced sea ice cover increases the transmission of light to the surface ocean. Consequently, the Arctic Ocean in recent years has been characterized by increased open water area, a longer growing season, and increased annual net primary production (NPP) by phytoplankton [Arrigo et al., 2008a; Pabi et al., 2008]. Increases in NPP were particularly large on the continental shelves of the Beaufort, Chukchi, East Siberian, Laptev, and Kara seas. These results were based on a relatively short time series of satellite ocean color data and, unlike the 30+ year trend in sea ice, observed secular increases in annual NPP were not statistically significant. [4] In the present study, we have extended the NPP time series using the newly reprocessed SeaWiFS and MODIS Aqua ocean color data. Prior to reprocessing, chlorophyll a (Chl a) retrievals by SeaWiFS were approximately 15% higher than those of MODIS Aqua in the Arctic Ocean and it was not possible to construct a coherent time series by combining these two data sets. Reprocessed SeaWiFS and MODIS Aqua imagery now agree to within 2% in oligotrophic and mesotrophic waters of the global ocean (http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/validation/). This increased level of agreement between the two data products is important because SeaWiFS has not provided a continuous data record since 2007. Therefore, a long-term ocean color record will have to include data from both satellite sensors. [5] The resulting 12 year time series of combined SeaWiFS/MODIS Aqua Chl a was used as input to a NPP algorithm developed for the Arctic Ocean [Pabi et al., 2008]. This algorithm calculates rates of daily NPP at each pixel location across the Arctic Ocean from satellite fields of Chl a, sea surface temperature, and sea ice extent, and from climatological mixed layer depths. The resulting maps of depth-integrated NPP are used to quantify both spatial and temporal (seasonal and interannual) variability in productivity and relate this variability to measured environmental changes. 2. Methods Net Primary Production by Geographic Sector [6] Daily maps of NPP for the Arctic Ocean (all waters north of the Arctic Circle) were produced from satellite derived Chl a, sea surface temperature, and sea ice cover using the algorithm of Arrigo et al. [2008b] as modified by Pabi et al. [2008]. [7] For the purpose of characterizing spatial differences, we divided the Arctic Ocean into eight geographic sectors and four open water ecological regimes, as described by Pabi et al. [2008]. The geographic sectors were demarcated by longitude (Figure 1) and include the Chukchi (180° to 160°W), Beaufort (160°W to 100°W), Baffin (100°W to 45°W), Greenland (45°W to 15°E), Barents (15°E to 55°E), Kara (55°E to 105°E), Laptev (105°E to 150°E), and Siberian (150°E to 180°) sectors. Figure 1Open in figure viewerPowerPoint Map of the study region showing the locations of the eight geographic sectors referred to in the text. Algorithm Input Data 2.2.1. Chlorophyll a [8] For the years 1998 through 2007, surface Chl a concentrations were determined from Level 3 (8 day binned, 9 km resolution) of the most recently reprocessed SeaWiFS ocean color data (Reprocessing R2009.1) using the OC4v6 algorithm (http://oceancolor.gsfc.nasa.gov/REPROCESSING/R2009/ocv6/), a modified version of the OC4v4 algorithm [O'Reilly et al., 1998]. For the years 2008 and 2009, surface Chl a concentrations were determined from Level 3 MODIS Aqua ocean color data (Reprocessing R2009.1) using the OC3Mv6 algorithm [O'Reilly et al., 2000]. Despite the recent reprocessing of both SeaWiFS and MODIS ocean color data, which brought the global mean Chl a retrieval from the two sensors much closer together, an analysis of mean Chl a concentrations in Arctic waters between 2003 and 2007 (for which both SeaWiFS and MODIS Aqua data are available) show that SeaWiFS-derived Chl a concentrations still exceed those from MODIS Aqua by approximately 2.6%. Furthermore, rates of NPP computed for Arctic waters using SeaWiFS Chl a exceed those from MODIS Aqua by an average of 3.6%, depending on year and geographic sector (Table 1). Therefore, to construct a 12 year time series of NPP that was based on both SeaWiFS and MODIS Aqua data, we calculated daily NPP using SeaWiFS Chl a data for the years 1998 through 2007. Then for 2008 and 2009 (for which limited SeaWiFS data are available), we used MODIS Aqua Chl a data as algorithm input, but adjusted the resulting NPP estimates using the mean correction factors shown in Table 1. Table 1. Correction Factors Used to Adjust Primary Productivity Estimates Made Using MODIS Aqua Chl a Year Mean SD 2003 2004 2005 2006 2007 Greenland 1.115 1.004 1.075 1.106 1.035 1.067 0.047 Barents 1.112 1.025 1.108 1.090 1.018 1.071 0.046 Kara 1.067 0.897 0.972 0.983 0.965 0.977 0.061 Laptev 1.127 0.968 1.062 0.997 1.024 1.035 0.062 Siberian 0.952 0.893 0.936 0.767 0.947 0.899 0.077 Chukchi 0.998 0.889 0.995 0.981 0.941 0.961 0.046 Beaufort 1.053 1.006 1.030 0.995 1.021 1.021 0.023 Baffin 1.080 1.059 1.074 1.090 1.102 1.081 0.016 Arctic 1.087 0.983 1.052 1.050 1.008 1.036 0.041 [9] Nearshore Chl a pixels suspected of being contaminated by sediment or CDOM from river discharge, as identified by their anomalously high Chl a concentration (compared to coastal pixels not influenced by rivers) or high remote sensing reflectance in the red and near-infrared wavelengths, were removed, which reduced the pan-Arctic NPP by less than 10%. 2.2.2. Sea Surface Temperature [10] Daily sea surface temperature (SST) is based on the Reynolds Optimally Interpolated SST (OISST) Version 2 product [Reynolds et al., 2002] obtained from NOAA (http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/). 2.2.3. Sea Ice Cover [11] Sea ice cover was estimated from Special Sensor Microwave Imager (SSM/I) 37 and 85 GHz bands using the Polynya Signature Simulation Method (PSSM) algorithm [Markus and Burns, 1995], which allows determination of sea ice presence/absence at 6.25 km resolution. According to this algorithm, a given pixel is defined as being ice covered wherever the sea ice concentration is greater than approximately 10%. [12] The date of sea ice retreat was defined as the date when open water area in a given region of interest (e.g., the Arctic or one of its geographic sectors) first exceeded 50% of the average annual amplitude for that region. For example, in the Arctic Ocean, open water area ranges seasonally from an average low of 2 × 106 km2 in February-March to an average peak of about 8 × 106 km2 in September. Therefore, the date of sea ice retreat would be the date when open water first exceeded 5 × 106 km2 (i.e., 2 × 106 + 0.5 (8 × 106 ? 2 × 106)).

Similarly, the date of sea ice advance would be defined as the date when total sea ice area in the Arctic Ocean first fell below 5 × 106 km2. Thresholds defining sea ice retreat and advance having values of 4 × 106 km2, 5 × 106 km2, and 6 × 106 km2 are shown in Figure 2. As will be seen, these different threshold values, which range from 25 to 65% of the annual amplitude in open water area, yield similar trends in sea ice retreat over the 12 year time series. Figure 2Open in figure viewerPowerPoint Annual cycle of open water area in the Arctic Ocean (all waters north of the Arctic Circle) for the years 1998?2009. Thin horizontal lines show the three different threshold values used to estimate dates of sea ice retreat and sea ice advance shown in Figure 7. [13] The length of the open water season (or phytoplankton growing season) is defined as the number of days elapsed between the date of sea ice retreat and the date of sea ice advance. Impact of High CDOM and Subsurface Chlorophyll Maxima on Estimated NPP [14] Matsuoka et al. [2007, 2011] noted that the optical properties of Arctic waters differ from the rest of the global ocean, due to both higher pigment packaging by phytoplankton and elevated CDOM concentrations. As a result, the standard OC4v4 algorithm of SeaWiFS overestimates surface Chl a concentrations in Arctic waters, exhibiting a root mean square error (RMSE) of 0.21 mg m?3 when compared to in situ data. This error is likely to be smaller for the OC4v6 algorithm used in the most recent reprocessing (and used here), which shows improved agreement with in situ values in coastal waters. However, because surface Chl a is an important input parameter to our NPP algorithm, we quantified the impact that a 0.21 mg m?3 overestimate of Chl a by SeaWiFS, resulting from higher pigment packaging and elevated CDOM concentrations, would have on calculated NPP (see below). [15] Furthermore, because the upwelling radiance received by satellite ocean color sensors originates almost exclusively from the upper optical depth of the ocean, features deeper in the water column cannot be resolved. Therefore, depth-integrated rates of NPP calculated from satellite-based measurements of Chl a will be underestimated in regions of the Arctic Ocean that have a well-developed subsurface chlorophyll maximum (SCM). To date, the impact of ignoring the SCM when estimating depth-integrated NPP from surface Chl a has not been explicitly quantified, although Hill and Zimmerman [2010] did examine the impact of vertical distribution of Chl a on the performance of a satellite-based primary production model using in situ measurements. [16] To investigate the impact that both overestimates in Chl a concentration by the OC4v6 and OC3Mv6 algorithms and omission of the SCM from vertical profiles of Chl a have on estimates of depth-integrated NPP in the Arctic Ocean, we used in situ data from the ARCSS-PP database (see Matrai et al. [2011] for details) to characterize vertical distributions of Chl a and primary production for the eight geographic sectors of the Arctic Ocean used in our analysis. The database consisted of 9484 Chl a stations and 1931 primary production stations. Both data types were binned monthly (e.g., January, February, March?), seasonally (January-March, April-June?), and annually (January-December, Figure 3) for each geographic sector. Figure 3Open in figure viewerPowerPoint Annual mean vertical profiles of in situ Chl a for the Arctic Ocean from the ARCSS-PP database. Note that the vertical profile for the Laptev Sea is based on only two in situ samples. [17] The mean vertical profile of Chl a from the ARCSS-PP database for each time bin was then used as input to our NPP algorithm. This was done using three different approaches. First, we used the mean vertical profile for each time bin with the SCM intact (Figure 4a, solid line). NPP was then calculated using our algorithm [Arrigo et al., 2008b; Pabi et al., 2008] at each depth for which Chl a data were available and these depth-dependent values were integrated vertically to calculate total water column NPP. Second, we increased vertical profiles of Chl a by an amount equivalent to the RMSE of SeaWiFS for Arctic waters (0.21 mg m?3) to mimic the effect overestimating surface Chl a by SeaWiFS and MODIS. The difference in NPP estimated by our algorithm using in situ Chl a and in situ Chl a + 0.21 mg m?3 as input provides an estimate of the error in NPP for each time bin and in each geographic location resulting from our use of satellite-based surface Chl a, rather than in situ data. Third, we applied the surface Chl a concentration from the ARCSS-PP database to the entire mixed layer (Figure 4a, dashed line), essentially removing the SCM, and recalculated total water column NPP using the new vertical Chl a profile as input. The difference in vertically integrated NPP between this and the approach where we kept the SCM intact reflects the amount of NPP associated with the SCM and was used to estimate the degree to which our algorithm underestimates vertically integrated NPP for each time bin and in each geographic location as a consequence of SeaWiFS missing the SCM. Figure 4Open in figure viewerPowerPoint Example vertical profiles of (a) Chl a and (b) NPP with the SCM and SPM intact and with them removed. To remove subsurface maxima, any depth where the Chl a or NPP value exceeded the surface value was replaced by the surface value. 2.3.1. Use of SeaWiFS and MODIS Versus in Situ Chl a [18] The impact on NPP of increasing in situ Chl a concentrations by 0.21 mg m?3 throughout the Arctic (to simulate errors in satellite-derived Chl a) varied seasonally and by region. Not surprisingly, estimated errors in NPP were largest for those months and locations where Chl a concentrations (and NPP) were low and an absolute increase of 0.21 mg Chl a m?3 represented a large percentage change. For example, increasing Chl a by the RMSE in the Barents Sea in February resulted in a 25-fold overestimate of NPP. This was by far the most extreme case, and was based on relatively few in situ data. Nevertheless, NPP over the entire Arctic Ocean was still overestimated by 44% in March when in situ Chl a was increased by an amount equivalent to the RMSE of SeaWiFS. Overestimates of NPP were even larger in November (61%). However, errors in all other months were much smaller, ranging from only 4.5% to 19.6%. Furthermore, during the most productive months of May-August, errors in NPP for the Arctic Ocean resulting from likely overestimates of surface Chl a by satellites ranged from only 4.5?5.8%. Consequently, errors in annual NPP for the entire Arctic Ocean resulting from the use of SeaWiFS Chl a are only on the order of 6.1%, although within specific geographic sectors, errors were as large as 15.4% (Barents sector). 2.3.2. Omission of the SCM [19] Results of this analysis show that neglecting the SCM results in a 7.6% underestimate of annual primary production by our algorithm when averaged over the entire Arctic Ocean. Errors are largest in the Chukchi (7.6%) and the Beaufort (11.7%) seas and are negligible (<1%) in the Kara, Siberian, and Laptev seas. As also shown by Pabi et al. [2008], errors in NPP due to missing the SCM were larger in summer than they were in spring. It should be noted, however, that despite the large amount of data in the ARCSS database, some geographic regions still suffer from a lack of data during parts of the year. Nevertheless, existing data suggest that while our algorithm underestimates NPP due to its inability to resolve the SCM, particularly in the western Arctic, this effect never exceeds 11.7% for any geographic region and is usually far smaller. [20] We performed a similar analysis using vertical profiles of primary production from the ARCSS-PP database. For any time bin exhibiting a subsurface productivity maximum (SPM), we replaced elevated production values in the SPM with the lower surface productivity values, just as we did with the SCM (Figure 4b), and calculated the change in vertically integrated primary production resulting from the removal of the SCM. Surprisingly, results of this analysis indicate that omission of the SPM has an even smaller impact on estimates of annual NPP than the removal of the SCM. Seasonally averaged data (Figure 5) indicate that SPM are only present in July-September (Figure 5b), and only in the Beaufort, Barents, and Siberian sectors. Surprisingly, when all data are averaged over the entire year, no SPM is apparent (Figure 5d). Based on the seasonally averaged data shown in Figure 5, primary production between April and December is approximately 202 g C m?2 when the SPM is left intact. When the SPM is removed from all vertical profiles and primary production is recalculated, the value for April to December drops to 196 g C m?2, a decline of only 2.9%, further demonstrating that while satellite-based estimates of NPP will underestimate production in waters with a SPM, the magnitude of the error is relatively small. Figure 5Open in figure viewerPowerPoint Mean vertical profiles of in situ primary production for the Arctic Ocean from the ARCSS-PP database averaged for (a) spring, (b) summer, (c), autumn, and (d) annually. [21] The presence of relatively high CDOM and phytoplankton pigment packaging causes satellite-based approaches to overestimate surface Chl a, resulting in estimates of NPP for the Arctic Ocean that are 6.1% too high. Conversely, satellites also miss the SCM, which results in estimates of NPP for the Arctic Ocean that are 7.6% too low. Therefore, the combined effects of these two processes virtually offset each other. The net effect of using satellite-based surface Chl a values as input to the NPP model is likely to be a small underestimate in annual NPP (<2%). It must be noted, however, that the eastern Arctic is not well represented in the ARCSS database and as more data become available, estimated errors associated with omission of the SCM and use of SeaWiFS Chl a as model input may change. 3. Results Pan-Arctic Ocean 3.1.1. Open Water Area [22] The annual cycle of open water area in the Arctic Ocean exhibits a relatively long annual minimum period that lasts from January through the beginning of April (Figure 2). Minimum open water area at that time ranges interannually from approximately 2 × 106 km2 in 1998 to 3 × 106 km2 in 2007. Open water area increases exponentially between April and August, reaching its annual peak sometime in September. In contrast to the annual minimum, the annual peak in open water area is much more short-lived, lasting only about a month and usually centered around September 10 (±7 days) (Table 2). Interannual differences in peak open water area are larger than differences in the annual minimum, ranging from 7.3 × 106 km2 in 2001 to 9.5 × 106 km2 in 2007. After September, sea ice advances at a faster rate than its retreat, resulting in a rapid drop in open water area in the autumn. Table 2. Mean Productivity Metrics by Geographic Sector in the Arctic Ocean for 1998?2009a Bloom Length (Days) Open Water Season (Days) Productivity Peak (Date) Open Water Peak (Date) Annual Primary Production (g C m?2 yr?1) Annual Primary Production (Tg C yr?1) Mean SD Mean SD Mean SD Mean SD Mean SD Mean SD Greenland 73.8 13.2 133 29.5 June 11 12.7 Aug 27 10.3 86.0 6.5 148 10.8 Barents 108* 21.5 212* 63.3 May 24 11.4 Sep 14 16.0 110 8.6 132 18.0 Kara 114 21.2 103* 27.1 July 8 23.5 Sep 15 13.5 113 17.8 56.8* 15.1 Laptev 108 23.8 72.3 23.5 July 21 28.4 Sep 8 10.7 121 20.2 42.6 13.3 Siberian 107 19.8 63.4* 30.9 July 9* 13.0 Sep 8 11.4 101 15.8 26.0* 10.4 Chukchi 119 16.1 105* 25.2 June 10 24.7 Sep 5 9.8 96.9 7.4 29.1* 5.3 Beaufort 61.2 15.8 96.6 30.6 July 5 15.3 Sep 6 9.4 71.3 11.0 24.1 7.3 Baffin 48.5 21.2 127* 14.0 May 26* 13.0 Sep 10 11.1 73.7 4.9 34.3 3.8 Arctic 107 9.65 100* 12.4 May 23 9.2 Sep 10 6.8 101 4.8 493* 41.7 a Bold indicates significant negative secular trend between 1998 and 2009 (p < 0.05). An asterisk indicates significant secular trend between 1998 and 2009 (p < 0.05). [23] Mean annual open water area in the Arctic Ocean averaged 4.31 ± 0.34 × 106 km2 between 1998 and 2009. During that time, mean annual open water area increased by an average of 84,000 km2 each year (Figure 6a), for a total increase of 27% over the 12 year time series (R2 = 0.75, p < 0.001). Mean annual open water area was at its peak in 2007, dipping somewhat thereafter, with the last five years exhibiting the highest open water area of the 30 year satellite record. Figure 6Open in figure viewerPowerPoint Yearly trends in (a) mean open water area and (b) total annual net primary production for the Arctic Ocean. 3.1.2. Length of Open Water Season [24] Associated with the secular increase in mean annual open water area has been an increase in the length of the open water season (the time between the start dates of ice retreat and ice advance), which averaged 100 ± 12.4 days between 1998 and 2009 (Table 2). The start of sea ice retreat in the Arctic Ocean, defined here as the date when open water area first exceeded 5 × 106 km2, ranged from June 30 to July 24 and began an average of 2.4 days earlier each year between 1998 and 2009 (Figure 7a). In aggregate, sea ice retreated a total of 28 days earlier at the end than at the beginning of our 12 year study period. In addition, sea ice advanced an average of 1.4 days later each year between 1998 and 2009 (Figure 7b), resulting in a 17 day delay in the timing of ice advance over the same 12 year period. Taking into account changes in the timing of both sea ice advance and retreat, the length of the open water season in the Arctic Ocean increased by an average of 3.8 days each year between 1998 and 2009 (Figure 7c), resulting in a 45 day increase in the length of the open water season over the 12 year period. Figure 7Open in figure viewerPowerPoint Yearly trends in (a) the day of the year of initial sea ice retreat, (b) the day of the year of initial sea ice advance, and (c) the length of the open water season (defined as the difference between Figures 7a and 7b) for the Arctic Ocean. The three sets of values shown in Figures 7a and 7b were determined using thresholds of either 4 × 106 km2, 5 × 106 km2, or 6 × 106 km2, which are shown in Figure 2. 3.1.3. Net Primary Production 3.1.3.1. Annual Cycle [25] Because of low solar insolation, rates of daily NPP in open waters of the Arctic Ocean remain low until early March (Figure 8). At that time, NPP begins to increase despite the fact that open water area is still at its annual minimum. This early increase in NPP is due to increased solar insolation in the Greenland and Barents sectors, which contain a large amount of open water throughout the year (see below) and are able to support substantial early rates of phytoplankton productivity. As sea ice retreats in the other geographic sectors, exposing surface waters to increased solar insolation in April, mean rates of daily NPP for the Arctic Ocean begin to accelerate, eventually reaching their annual peak of ?850 mg C m?2 d?1 around May 23 (±9.2 days) (Table 2). The value for mean annual peak NPP exhibits substantial interannual variability (Figure 8), ranging from 786 mg C m?2 d?1 in 2009 to 1240 mg C m?2 d?1 in 2003. Rates of daily NPP remain relatively high throughout June and July (600?700 mg C m?2 d?1), during which time the sea ice begins to retreat more rapidly. In August, daily NPP begins to decline, reaching ?425 mg C m?2 d?1 by the end of the month and falling to ?100 mg C m?2 d?1 by the end of September, as the sea ice begins to advance again (Figure 8). In general, the phytoplankton bloom (defined as the period when mean daily NPP exceeds 500 mg C m?2 d?1) in the Arctic Ocean lasted an average of 107 ± 9.7 days and exhibited no significant secular trend over the 12 year study period (Table 2). Figure 8Open in figure viewerPowerPoint Annual cycle of mean open water area (thin black line) and mean daily net primary production (thick black line) for the Arctic Ocean averaged for the years 1998?2009. Also shown for reference are the net primary production time series for the 12 different years (thin gray lines). 3.1.3.2. Annual NPP per Unit Area [26] Annual NPP per unit area in the Arctic Ocean averaged a surprisingly uniform 101 ± 4.8 g C m?2 yr?1 between 1998 and 2009 (Table 2). There was no statistically significant secular trend in annual NPP per unit area during this 12 year period and productivity per unit area was not significantly correlated with either the mean annual open water area (R2 = 0.08, p = 0.360) or the length of the open water season (R2 = 0.02, p = 0.659) (Table 3). Table 3. R2 Values for Regression Analysis of Annual Primary Production Against Year, Mean Open Water Area (106 km2), and Length of Growing Season (Days) by Geographic Sector for 1998?2009a Annual Primary Production (g C m?2 yr?1) Annual Primary Production (Tg C yr?1) Year Open Water Area Open Water Season Year Open Water Area Open Water Season Greenland 0.46* 0.04 0.12 0.41* 0.02 0.00 Barents 0.00 0.02 0.00 0.21 0.57** 0.40* Kara 0.00 0.01 0.02 0.40* 0.66*** 0.64** Laptev 0.00 0.17 0.04 0.14 0.77*** 0.61** Siberian 0.01 0.11 0.04 0.43* 0.91*** 0.71*** Chukchi 0.03 0.00 0.00 0.49* 0.76*** 0.69*** Beaufort 0.11 0.01 0.03 0.03 0.90*** 0.80*** Baffin 0.29 0.00 0.00 0.06 0.31 0.13 Arctic 0.16 0.08 0.02 0.49* 0.77*** 0.73*** a Bold indicates significant negative secular trend between 1998 and 2009. Asterisks indicate significant secular trend between 1998 and 2009 (*, p < 0.05; **, p < 0.01; ***, p < 0.001). 3.1.3.3. Total Annual NPP [27] Annual phytoplankton NPP integrated over the entire Arctic Ocean averaged 493 ± 41.7 Tg C yr?1 between 1998 and 2009. This value should be considered conservative since it does not include productivity under the sea ice, which can be substantial [Lee et al., 2010]. The high degree of interannual variability was marked by a statistically significant 20% secular increase in annual NPP over that 12 year

SOURCE: Journal of geophysical research

PDF URL: https://onlinelibrary.wiley.com/doi/pdfdirect/10.1029/2011JC007151

PUBLICATION YEAR: 2011

TYPE: article

CONCEPTS: ['Arctic', 'Environmental science', 'Primary production', 'Sea ice', 'SeaWiFS', 'Oceanography', 'Arctic sea ice decline', 'Climatology', 'Canada Basin', 'Arctic ice pack', 'Phytoplankton', 'Geology', 'Ecosystem', 'Nutrient', 'Drift ice', 'Ecology', 'Biology']