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Synthesis of primary production in the Arctic Ocean: I. Surface waters, 1954–2007

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ABSTRACT

The spatial and seasonal magnitude and variability of primary production in the Arctic Ocean (AO) is quantified with a pan-arctic approach. We synthesize estimates of primary production (PP), focusing on surface waters (0–5 m), using complementary methods that emphasize different spatial and temporal scales. These methods include (1) in situ observations of ^{14}C uptake mostly and possibly some O_2 production reported in units of carbon (in situ PP), (2) remotely sensed primary production (sat-PP), and (3) an empirical algorithm giving net PP as a function of in situ chlorophyll *a* (in situ Chl-PP). The work presented herein examines historical data for PP collected in surface waters only, as they form the majority of the values of a larger ensemble of PP data collected over >50 years (ARCSS-PP) by many national and international efforts. This extended set of surface and vertically-resolved data will provide pan-Arctic validation of remotely sensed chlorophyll *a* and PP, an extremely valuable tool in this environment which is so difficult to sample. To this day, PP data in the AO are scarce and have uneven temporal and spatial coverage which, when added to the AO's regional heterogeneity, its strong seasonal changes, and limited access, have made and continue to make obtaining a comprehensive picture of PP in the AO difficult.

Daily surface in situ PP averaged 70 and 21 mg C m^{-3} d^{-1} for spring and summer, respectively, for the ca. 50 year period across the AO. Average daily estimates of in situ PP in surface waters on a pan-Arctic basis were several fold higher with respect to remotely sensed PP (sat-PP) and in situ chlorophyll-derived PP (Chl-PP) in the spring period, likely due to differences in data availability and coverage. Summer daily averages for surface in situ PP and sat-PP were similar and twice as high as in situ Chl-PP. Differences among annual estimates of surface in situ PP, in situ Chl-PP and sat-PP across the Arctic Ocean are presented and discussed. The mode of all three differences was 0 mg C m^{-3} y^{-1} and the median difference was within ±400 mg C m^{-3} y^{-1}. Agreement between annual surface sat-PP and in situ PP was within ±1000 mg C m^{-3} y^{-1} for half of the data. We hope that the entire ARCSS-PP data set, especially if combined with any archiving by the latest IPY effort, will be employed to develop an improved, panarctic-specific PP remote sensing algorithm and to test hypotheses regarding the controls of PP in the AO. Furthermore, the ARCSS-PP is openly available to be used by AO modelers to calibrate, assimilate, validate and compare community ecosystem and biogeochemical numerical models and, when combined with field work, will allow for improved understanding, detection and prediction of long-term biological patterns.

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1. Introduction

Autochthonous primary production is the major source of energy for the Arctic Ocean (AO) ecosystem, as in most ecosystems. Understanding marine primary production (PP) and its controls is, therefore, a critical step towards appreciating the Arctic as a system and allowing diagnostic modeling of its current status as well as prognostic modeling of future change. In the last decade, PP levels assigned to the AO have increased considerably (Gosselin et al., 1997; Olli et al., 2007; Sakshaug, 2004 and refs. therein; Wheeler et al., 1996) as spatial (e.g., higher PP in AO central basin than previously reported, higher PP in leads) and temporal (e.g., pelagic and sub-ice blooms; continued PP beyond the spring bloom into summer) sampling have improved (Smith et al., 1991). Increased impetus for better understanding the Arctic PP regime arises from the rapid changes in nutrient fluxes, ice cover and stratification observed in recent years (Overpeck et al., 2005; Wang and Overland, 2009). While considerable progress has been made

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in assessing the present state of the AO's PP regime and in revising the total rate, the physical changes observed in recent years are likely to drastically alter the AO PP regime. Although Arctic marine PP is strongly seasonal, some Arctic shelf seas rank amongst the most productive regions in the world ocean (Gosselin et al., 1997; Hill and Cota, 2005; Klein et al., 2002; Stein and Macdonald, 2004; Tremblay et al., 2002). Yet, rates in portions of the AO basin are, today, amongst the lowest in the ocean. This difference leads to large spatial gradients in PP. Because 25% of the global sea shelf is found in the AO margins and adjacent seas, many of these shelves represent a significant national fisheries resource. Populations of pelagic and benthic higher trophic levels in the AO are directly related to regional marine PP rates (Grebmeier and Mcroy, 1989; Grebmeier et al., 1995, 2006b), as in other open ocean and shelf regions. Therefore, changes in the PP rate of the AO are likely to significantly impact the Arctic's living marine resources.

Productivity in these seas also acts to transform biogeochemical properties of inflowing and exiting waters. Changes in the Arctic's marine PP regime will impact the global carbon dioxide budget in at least two ways: (1) by directly impacting the quantity of atmospheric carbon dioxide sequestered by phytoplankton and ice algae, and (2) by impacting denitrification rates, which are globally significant over the AO's extensive shelves and slopes (e.g., Devol et al., 1997) and acutely sensitive to changes in carbon flux (Codispoti, 1989; Codispoti et al., 2001). The Arctic's global impact may be amplified by its large continental shelf and slope, and by the deep water formation that occurs in the adjacent Greenland, Iceland and Labrador Seas.

In order to quantify the spatial and seasonal magnitude and variability of PP in a pan-arctic context (Carmack and Wassmann, 2006) and to provide a systematic description of this variability across various AO regions, we have synthesized estimates of PP, focusing on surface waters (i.e., shallowest observation in the top 0–5 m of each station) in this work. The majority of the historical PP data available for the AO was collected in surface waters; the work presented herein examines this >50 year ensemble of surface PP data. Our approach pools complementary PP methods that emphasize different spatial (point to pan-Arctic) and temporal (daily to seasonal) scales. These methods include (1) in situ observations of ^{14}C uptake (mostly) and any O_2 production reported in units of carbon (possibly) (in situ PP), (2) remotely sensed primary production (sat-PP) and 3) an empirical algorithm giving net PP as a function of in situ chlorophyll *a* (in situ Chl-PP). These three methods help define regions of the AO that operate similarly with respect to PP and their range of spatio-temporal variability (Carmack et al., 2006). This pan-arctic synthesis of surface PP is complemented by a synthesis of vertically integrated PP determined with the same approaches described herein (Hill et al., 2013) and a synthesis of nutrient-based, vertically integrated net community production and PP (Codispoti et al., 2013) to arrive at a consistent, pan-AO synthesis of annual total integrated PP.

2. Methods

2.1. Assembly of data set and description of data base (Arctic System ARCSS-PP)

The original input data were mostly acquired from publicly accessible data repositories, some data were provided by individual investigators, and some were obtained from publications (Table 1) (see Appendix A for details). The data were collected by various methods and resulted from the efforts of many individual, national, and international research efforts conducted between 1954 and 2007 (Appendices A and B). Station data (cruise, station, latitude, longitude, depth), discrete data for productivity and chlorophyll *a* (value, method, phase, incubation type and length), photosynthetically available radiation (PAR) (incoming, integrated over incubation period), and some hydrographic parameters (nutrient concentration, mixed layer depth) as well as source (investigator, data base, publication, etc.) were entered into a database using Access (Microsoft Office 2003).

Table 1
Databases searched, publications scanned, and individual contributions obtained for primary production and chlorophyll *a* data located north of 60°N. See Appendix A for further details.

Databases	Published data sets	Individual contributions
AOOS	Gosselin et al. (1997)	Balch, W.
ArcNut	Müller-Niklas and Herndl (1996)	Hill, V.
BAAS 2000	Horner and Schrader (1982)	Hodal, H.
BioChem	Legendre et al. (1993)	Kristiansen, K.
BODC	Rey and Loeng (1985)	Pesant, S.
BPD	Rich et al. (1998)	Rey, F.
CEAREX	Rysgaard et al. (1999)	Stramski, D.
CABANERA	Sorokin (1999)	Vernet, M.
NSIDC/CITAO	Stefansson et al. (1987)	Wassmann, P.
ICES	Thordardottir (1986)	Whitledge, T.
JODC	Vedernikov and Gagarin (1998)	
NEW	Vedernikov et al. (1995)	
NODC	Vedernikov et al. (2001)	
NOW		
OPPWG		
ORFOIS		
PANGEA		
AOE-01		
PROMARE		
SBI		
SeaBASS		
WOCE/CLIVAR		

Quality control was performed by eliminating duplicate observations, outliers (located $\geqslant$3 standard deviations from a grid cell mean; the grid is described later), CTD fluorescence data that were erroneously reported as chlorophyll (stations with >50 observations), and checking source disagreements when included in more than one data set. This quality control was done every time a new data set was added and as analysis proceeded. Terrestrial, riverine, and lake data as well as records with a missing or partial time (month and/or year) and space (latitude and/or longitude) stamp were not included in the analysis. The data sets, publications and individual investigator contributions assembled into this database are listed in Table 1. The total ARCSS-PP data set consists of 92,061 records unevenly distributed over 14,936 stations and various vertical depths, and includes 7501 data pairs of in situ (i.e., measured) chlorophyll *a* (Chl *a*) and PP data. The majority of the stations only have Chl *a* records, with 10% having only in situ PP records and another 8% having records of both variables. The vertically resolved data within the functional regions described below (70% of the stations, of which 18% with PP and most with Chl *a* only) are analyzed in the companion paper by Hill et al. (2013) for the period 1987–2007. Herein, we present and discuss surface ($\leqslant$5 m) observations, which are the more extensive in time and space subset of the database (90% of the stations). At this time, the ARCSS-PP data are publicly available at the National Oceanographic Data Center (http://www.nodc.noaa.gov/).

2.2. Data manipulation

The AO was divided into functional regions as outlined in Carmack et al. (2006) to analyze regional patterns. The analysis domain is defined as 65–90°N in the Atlantic sector (excluding the Baltic Sea), and 60–90°N in the Pacific sector (excluding the Gulf of Alaska) (Fig. 1). The domain is divided into thirteen regions that include a deep central basin delimited by the 1000 m isobath

in the IBCAO data base (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html) and its surrounding shelf seas, delimited by latitude and longitude boundaries. Some of these shelf seas are further sub-divided into southern and northern regions by the 1979–2000 September median ice extent (obtained from the National Snow and Ice Data Center: http://nsidc.org/data/G02135.html).

The surface in situ data discussed here include the shallowest observation taken from the uppermost 5 m of the water column in each station (Fig. 2). During the analysis stage, hourly in situ production rates were converted to daily production rates (original data left in ARCSS-PP) by multiplying the reported hourly rate by a spatially and temporally- specific day length (hrs); day length was calculated for latitudes 60–90°N at 0° longitude, as the average of each interval of one degree of latitude, for each calendar day, using the web form at http://aa.usno.navy.mil/data/docs/Dur_OneYear.php. Most of the historical data do not include metadata with specifics on incubation length or photosynthetic parameters that would allow taking into account the daily evolution of light (quantity and quality changes). This fact may introduce uncertainty to some PP daily estimates. Spring is defined from the 89th (March 30) to the 185th (July 4) day of the year while summer extends from the 186th (July 5) to the 272nd (September 29) day of the year; these dates were selected to match the 8-d composites available for the remotely-sensed data used. Decadal variations were calculated over the arbitrary decades of 1978–1987, 1988–1997 and 1998–2007, combining the onset of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) satellite observations (R2007.0 reprocessing 5.2) and the last full year of observations available at the time this analysis was begun.

Remotely sensed surface chlorophyll *a* (sat-Chl) concentrations were retrieved from the 8-day SeaWiFS weighed level 3 product, from April 1998 to September 2007, downloaded from the NASA image archive (http://oceancolor.gsfc.nasa.gov/seadas/). Matlab was used for all image analysis. Sat-Chl was retrieved from maximum band ratios of the remote sensing reflectance (443 > 490 > 510/555 nm) using the AO tuned algorithm OC4L

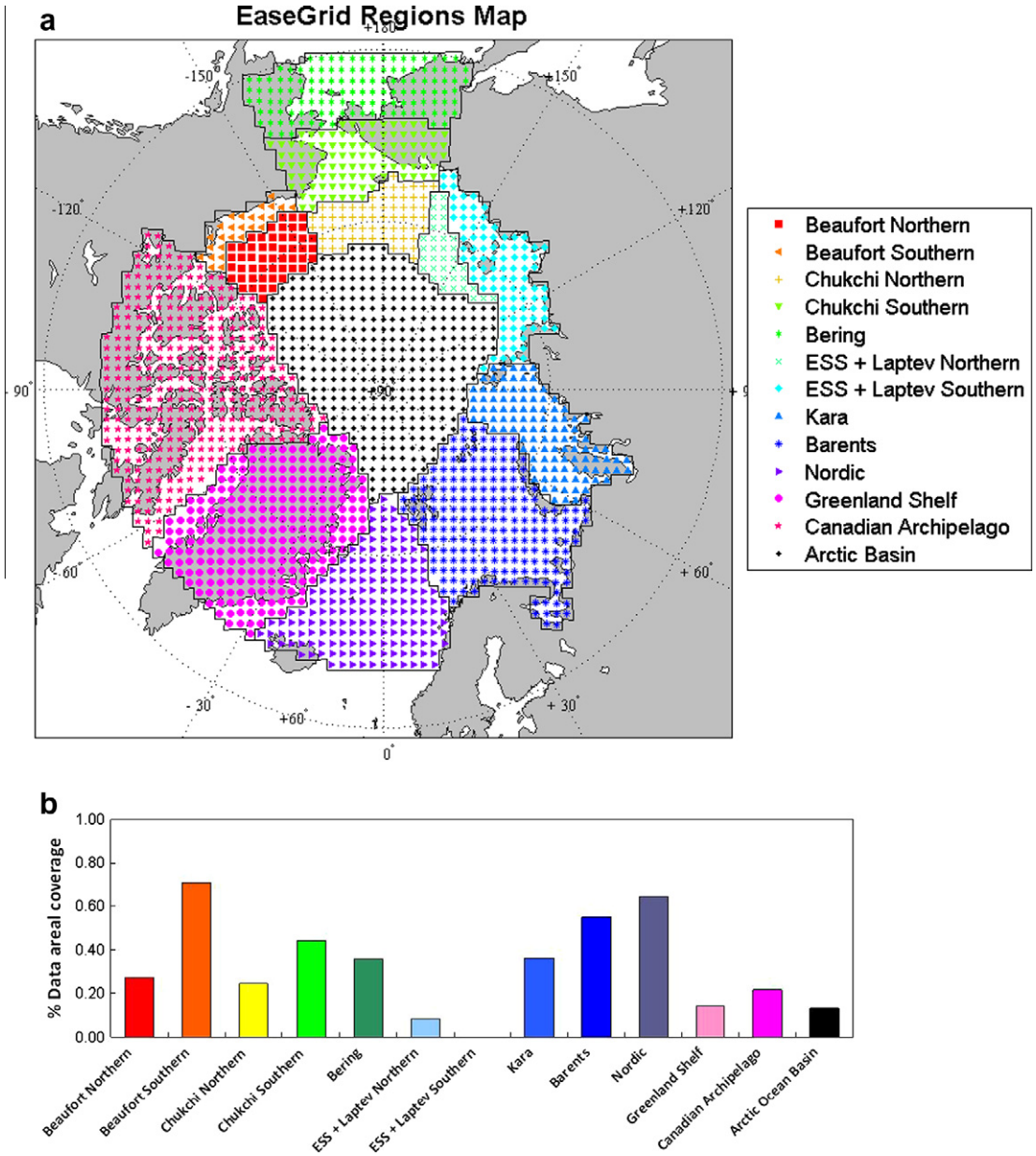

Fig. 1. (a) Eco-typological regions of the Arctic Ocean (cf. Carmack et al., 2006) used here in. (b) Percentage areal data coverage for each region (1954–2007).

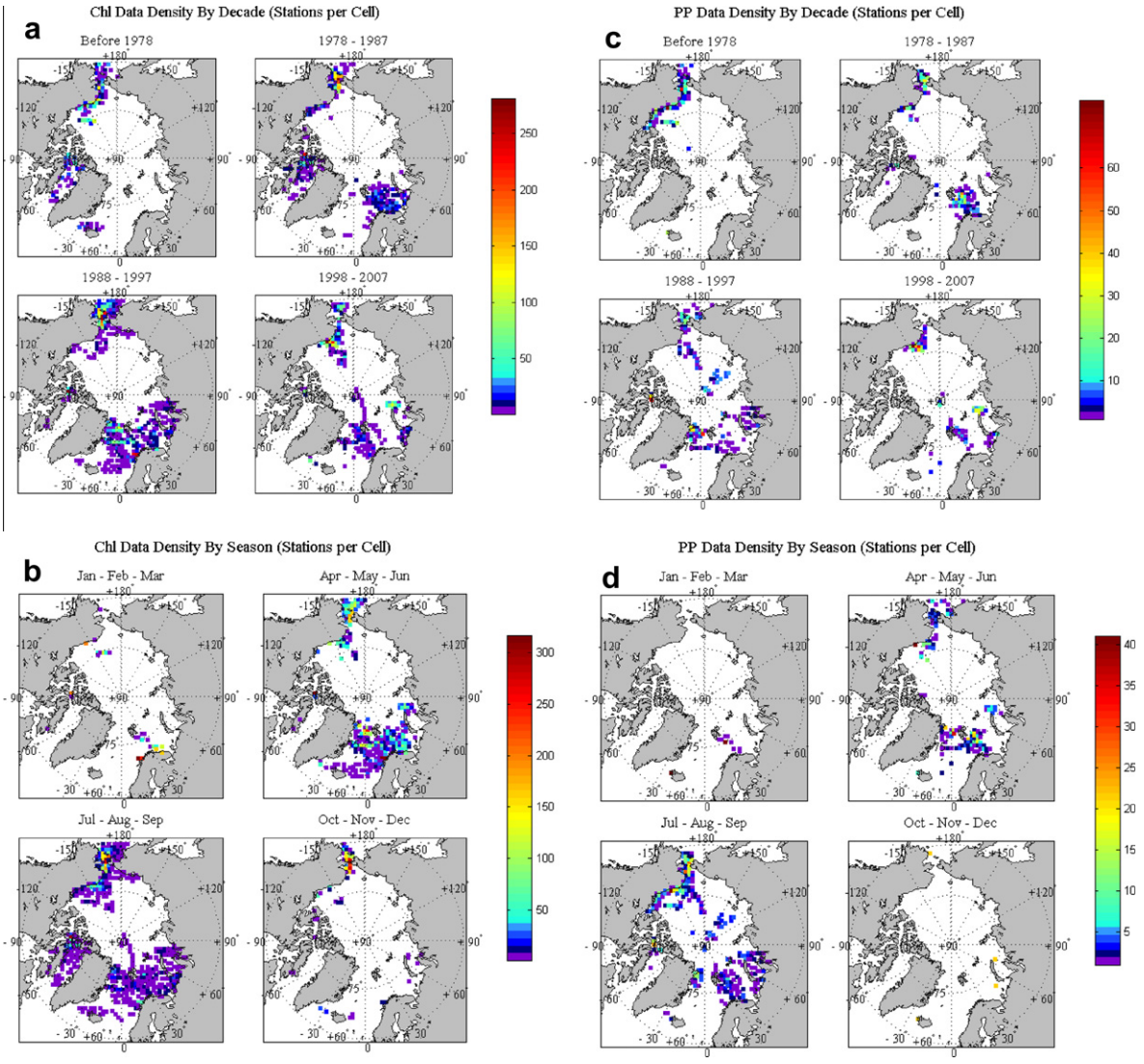

Fig. 2. Spatial, decadal and seasonal distribution of in situ data of chlorophyll *a* (Chl) (a and b) and primary production (PP) (c and d) data in the Arctic Ocean during 1954–2007. Color scale indicates the number of data points in each EASE grid cell. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

developed for SeaWiFS by Cota et al. (2004), which has been documented as an improvement in sat-Chl retrieval over the SeaWiFS OC4v4 global algorithm for the Western Arctic in the presence of higher CDOM (Matsuoka et al., 2007). Remotely sensed surface 2primary production (sat-PP) estimates were derived from the SeaWiFS retrieved sat-Chl (1998–2007), using an empirical relationship developed from the ARCSS-PP database (see below). The presence of sea ice on the surface is a barrier to retrieving valid ocean color data from space, as it not only obscures the underlying water column, but the intense reflectance can invalidate adjacent pixels. Valid data are described as those where the remote sensing reflectance was not contaminated by sea ice (>10% per pixel), clouds, sun glint or land; this analysis is conducted by the NASA ocean color group during the level 2 processing when abnormal pixels are flagged and removed.

To allow inter-comparison of in situ and remotely sensed parameters which are of different spatial resolution, the data were gridded using the National Snow and Ice Data Center's Equal-Area Scalable Earth Grid (EASE-Grid). All statistics were based on data grouped according to the Ease-Grid with grid cells of 100 km^2. Grid cell means for remotely sensed estimates required at least three data points to be included; missing data were usually due to cloud obstruction, presence of sea ice, or proximity to land. This requirement can restrict the number of EASE grid cells with viable data but controls the bias imposed by a single or double values at a point location being extrapolated across a 100 km^2 cell. This requirement was not implemented for the in situ data due to their scarcity; for example, if three or more in situ data points were required to include a grid cell in a calculation, total annual surface in situ PP would have been determined by $N = 133$ data points, while the absence of this requirement would almost triple the sample size ($N = 345$), showing how many grid cells were populated by only 2 or fewer in situ values (Fig. 2). All data sets were checked for normality or log normality before analysis (Fig. 3). Matlab was used for all standard least square regression and curve fitting routines. Most statistics were computed on log10 transformed data. In addition, we calculate four model skill statistics: an estimate of bias (B, also known as average error, or expressed exponentially, F_{med}), the total root-mean square difference (RMSD) or error (Friedrichs et al., 2009), the mean (or average) absolute error (MAE), and the model efficiency (ME) (Stow et al., 2009).

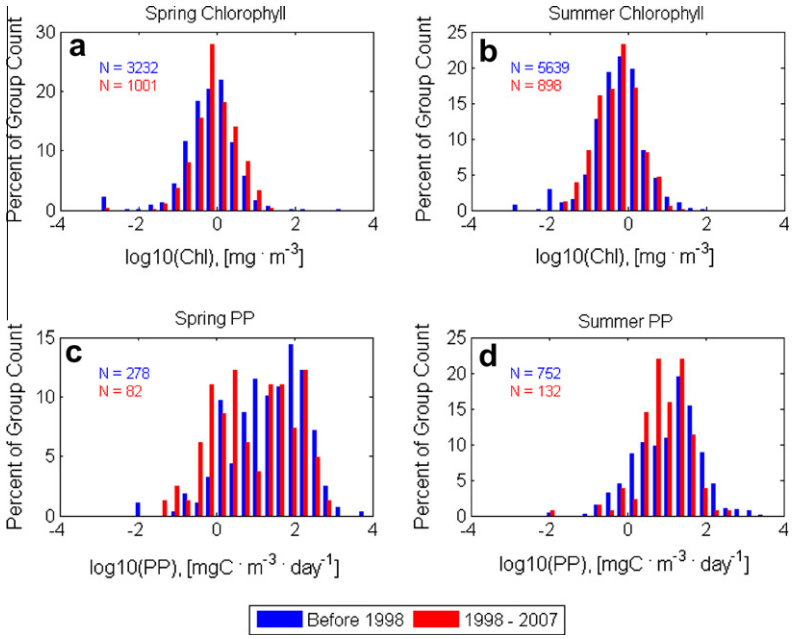

Fig. 3. Distribution of in situ chlorophyll *a* (Chl; a and b) and primary production (PP; c and d) magnitude in surface waters in spring and summer prior to (pre-1998) (top N) and during (bottom N) the SeaWiFS remote sensing period sampled (1998–2007).

The total annual calculations for all PP estimates were accomplished by first calculating an average daily PP of all data available for each grid cell for each month of every year. This average was then multiplied by the number of light days in each month, thus determining an average monthly surface PP in each year. This step does not assume that light, rather than nutrients, is the only bottom-up process controlling PP, but rather reflects the minimum light requirement for PP to occur. It also precluded a bias due to high PP measurements made in months with some fraction of dark days. Each regional monthly average (as per Fig. 1) was then multiplied by the $\geqslant$50% sea ice free area (see below) specific to each month, year, and region. Multi-year, monthly averages were then calculated for each region; these were summed to estimate the regional and panarctic total annual production for areas with $\leqslant$50% mean sea ice coverage, integrated over the top 1 m only (to reflect the surface characteristic of the data).

In order to estimate regional or annual PP totals, we estimated regional, monthly sea ice free areas for each year using the HadISST ice concentrations for the period 1954–2009 (Horton et al., 2003), available as a 25 km EASE-grid weekly snow cover and sea ice extent version 3 dataset (http://nsidc.org/data/nsidc-0046.html) (Armstrong and Brodzik, 2005).

Caveats to these estimates of annual, surface PP include issues associated with ice cover, cloud cover, and sampling. Whereas some PP occurs in waters with $\geqslant$50% ice cover, such as high Arctic leads (Gosselin et al., 1997; Olli et al., 2007), extrapolating PP to the entire area of a certain region (e.g., Arctic basin), regardless of ice cover, resulted in PP values that were clearly too high. However, a criterion of <10% ice cover (SeaWiFS sea ice default flag) ignores the strong growth in the seasonal ice zone (e.g., Apollonio and Matrai, 2011; Arrigo et al., 2012; Mundy et al., 2009). The Chl-PP algorithm does not have a light term data and was derived from in situ data collected under different levels of cloud cover. Chl *a* was estimated directly from each 8-d SeaWiFS image which were averaged (weighed) over a course of a month. Hill and Zimmerman (2010) show that the Chl-PP model applied to Chukchi Sea waters returns estimates of integrated PP equal to, or better than, some other models which use light, while Hill et al. (2013) report that the Chl-PP relationship is constant across regions and at differing light depths, indicating there is no need for a light term in this model. Although cloud cover is not continuous or constant across the AO during the course of a day, the sky over the AO is for the most part always cloudy (3% average clear sky conditions in the summers of 1954–2007) (Eastman and Warren, 2010). On the other hand, the period 1998–2007 showed approx. 60% observable open water area by SeaWiFS' 8d-imagery (Hill et al., 2013). Months with no data were ignored, so that the annual total for a region may be calculated from as few as 1 and as many as 10 multi-year average months; the smallest number of grid cells included in a monthly average was 3 for the month of August in the northern Chukchi region for in situ Chl-PP. The percentage of each region's surface covered by grid cells with valid in situ values of Chl *a* ranged from 9% in the Arctic Ocean Basin region to 79% in the Nordic Seas region.

3. Results

3.1. Description of the in situ data

The in situ PP and Chl *a* data covered a 50-y period, extending from 1954 to 2007; however, the spatial and temporal distributions of these data were sparse and patchy (Fig. 2). It can be seen that station density was highest in the Bering, Chukchi, northern Beaufort, Barents and Greenland Seas. Chl *a* data were most abundant in the 1988–1997 decade and during the summer period (July–September), with the highest number of stations sampled in July. In situ PP data were equally sparse in all decades but most prevalent in summer, with the highest number of stations sampled in August. It should be noted that although the maximum number of data points in any one 100 km^2 grid cell in any one day was $N = 60$ and 300 for in situ PP and in situ Chl *a*, respectively, the average was $n < 10$ and <5, respectively; these represent individual stations for the surface waters addressed herein. Hill et al. (2013) addresses the depth-resolved and depth-integrated data. In spring and summer, most of the in situ PP and in situ Chl *a* data were collected before 1998 (Fig. 3), which was prior to the advent of ocean color remote sensing by SeaWiFS (1998–present).

Summer in situ PP as well as spring and summer in situ Chl *a* values were log normally distributed (Kolgomorov–Smirnov, $p < 0.05$), with the highest frequencies being in the range of ca. 0.5–2.0 and 0.5–1.0 mg Chl *a* m^{-3} for spring and summer, respectively. On the other hand, spring values of in situ PP showed a wider range, but similar frequency of occurrence, from ca. 0.5–250 mg C m^{-3} d^{-1}, compared to the narrower range of observations from the summer period (ca. 4–30 mg C m^{-3} d^{-1}) (Fig. 3). Overall, few differences were observed in the dominant mode(s) of PP and Chl *a* in situ values in surface waters before and after 1998 (Anova single factor, $p < 0.001$); in the last decade (1998–2007), the most frequent spring in situ Chl *a* concentrations (0.5–1 mg Chl *a* m^{-3}) were lower than in previous decades (1–2 mg Chl *a* m^{-3}), but no difference was seen in summer. Summer in situ PP values in the 1998–2007 period were bimodally distributed, with peaks in the ranges of 4–8 and 15–31 mg C m^{-3} d^{-1}; while the second range has the same frequency of occurrence in the pre-1998 decades, the first range has a lower frequency of occurrence prior to 1998. The differences between the SeaWiFS period analyzed (1998–2007) and the previous years were not statistically significant (*t* test independent, $p < 0.05$ for spring and summer in situ Chl *a* and summer in situ PP; Mann–Whitney, $p < 0.05$ for spring in situ PP), such that the entire record (1954–2007) can be used when comparing in situ and remotely-sensed surface patterns. However, these frequency data give no indication of geographical distribution or change over time, which are harder to evaluate due to highly irregular and scarce regional sampling, as will be addressed below.

For the period 1954–2007, the average Chl *a* concentration in surface waters was higher in spring (1.98 ± 0.07 mg Chl *a* m^{-3}, $N = 4233$; mean, standard error of mean) than in summer (1.45 ± 0.03 mg Chl *a* m^{-3}, $N = 6537$) and 3-fold higher in summer than in either fall or winter (Table 2). The maximum value of the spring range and the 1988–1997 decadal range for chlorophyll concentration was measured on 29 May 1990 at 60.29°N, 19.29°W, south of Iceland, during the JGOFS North Atlantic expeditions; it represented <0.01% of the data evaluated (Fig. 3a). For the same period of ca. 50 years, seasonal differences were more pronounced for daily in situ PP in surface waters with spring rates approx. twice as high (107.87 ± 7.58 mg C m^{-3} d^{-1}, $N = 350$) as in summer (46.73 ± 2.36 mg C m^{-3} d^{-1}, $N = 884$) and, as expected, much lower in fall and winter. The upper end of the winter in situ PP range (98 mg C m^{-3} d^{-1}, Table 2) was sampled on 28–30 March 1966 at 66°N off southwest Iceland, and may reflect early "spring" growth recorded in our seasonal settings in the pan-Arctic "winter" month of March. The upper end of the spring in situ PP range and the 1978–1987 decadal range was sampled on 31 May 1982 at 74.35°N, 21.61°W in the Barents Sea, during the Pro Mare expeditions. No interdecadal change in daily, surface in situ PP was clear, despite having a similar number of data points in the years prior to 1978 and in each decade thereafter; it can be argued that the irregular sampling in space and time of the daily in situ PP data likely precludes the deduction of any pattern. For example, the 1978–1987 decadal average daily in situ PP rate was 2–3-fold, and significantly, higher than in earlier and later decades, but it is likely so due to enhanced spring field sampling between 1978 and 1987 (Table 2). It is not possible to contrast these surface water trends with recent suggestions of a large increase (Arrigo and Dijken, 2011; Arrigo et al., 2008; Pabi et al., 2008), or conflicting uncertainty (Popova et al., 2012) in integrated pan-Arctic PP in recent years, due to the difference in vertical integration scale used.

3.2. PP algorithms

The AO, defined herein as in Section 2.2 above, is heterogeneous. To deal with this diversity, we chose a functional, rather than solely geographical, approach and attempted to define regions of the AO (Fig. 1) that function similarly with respect to PP, building on the "eco-typological region" concept defined by Carmack et al. (2006). It should be noted that no remote sensing-in situ data matches were available for the East Siberian Sea and northern and southern Laptev Sea regions.

Sat-Chl (and primary production, sat-PP) can be determined from 1-day or 8-day composite images; for any one location, a longer observation period is more likely to provide a larger number of cloud-free pixels and, thus, ocean color partially or completely free of clouds, especially during the summer when clouds are more prevalent (Eastman and Warren, 2010; Intrieri et al., 2002). Remotely sensed 1-d and 8-d sat-Chl values were highly correlated (slope and standard error of slope = 0.91 ± 0.04, $r^2 = 0.81$, $N = 145$, $p < 0.001$; data not shown), but obviously not identical since an 8-d image is the average of the 1-d images over that 8 day period (see also Hill et al., 2013). A higher fraction of the variability is explained between satellite and in situ chlorophyll using single day than with 8-d matched data (Fig. 4a), but it should be noted that 8-d matched data result in a larger sample size ($N = 542$). However, this 8-d pan-Arctic sat-Chl validation accounts for only 18% of the total variance (Fig. 4b), less than that reported in the western Arctic solely with the same algorithm (Matsuoka et al., 2007), and it overestimates the in situ Chl *a* by a factor of 3 (RMSD = 0.54; bias = −0.34). The validation of remotely-sensed chlorophyll *a* requires more than a match with in situ data. It will need derivation and/or comparison of radiance-based algorithms, such as OC4v4 optimized for Case I waters and OC4L optimized for western AO waters (Matsuoka et al., 2007), as well as to address the optics of the coastal and ice-influenced Case II waters of the AO. This is beyond the goal of this paper. Much work remains to be done in the derivation of an accurate and precise satellite chlorophyll algorithm on a pan-Arctic basis.

Table 2
Mean, range and standard error of the mean for in situ daily primary production and chlorophyll *a* in surface waters of the Arctic Ocean during 1954–2007.

	Primary production				Chlorophyll *a*			
	Mean	Range	SE	*N*	Mean	Range	SE	*N*
Seasonal	mg C m^{-3} d^{-1}				mg Chl *a* m^{-3}			
Spring	107.87	0.01–6178	7.58	360	1.98	0.001–1390	0.07	4233
Summer	46.73	0.01–3646	2.36	884	1.45	0.001–90	0.03	6537
Fall	9.56	1.9–35	2.81	19	0.53	0.001–8	0.02	1072
Winter	13.91	0.01–98	2.61	30	0.54	0.001–10	0.05	188
Annual	mg C m^{-3} y^{-1}				mg Chl *a* m^{-3}			
Before 1978	36.4	0.01–1056	1.78	414	1.29	0.001–29	0.04	1292
1978–1987	129.48	0.01–6178	14.56	277	1.52	0.001–169	0.06	3039
1988–1997	54.6	0.01–1024	2.63	381	1.73	0.001–1390	0.06	5453
1998–2007	36.24	0.01–710	3.42	219	1.22	0.001–17	0.03	2238

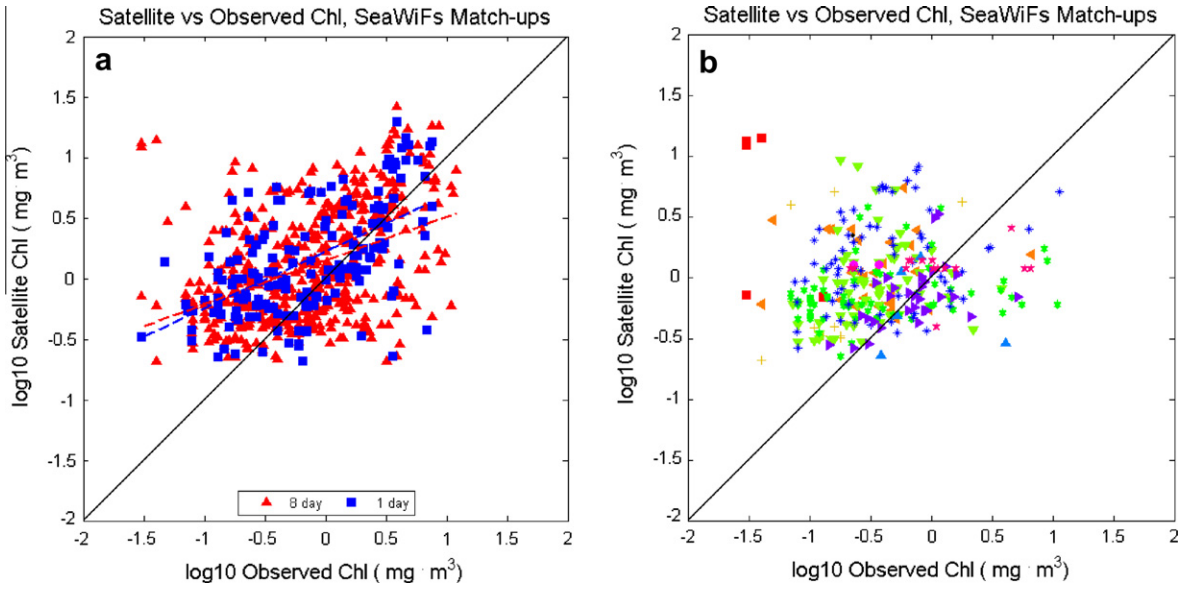

Fig. 4. (a) Remotely sensed chlorophyll (daily and 8-day retrievals) vs. in situ, surface chlorophyll *a* EASE grid match-ups for all data located north of 60°N (1-day: slope = 0.47, r^2 = 0.32, p < 0.001, N = 177; 8-day: slope = 0.36, r^2 = 0.18, p < 0.001, RMSD = 0.5, N = 542), and (b) remotely sensed (8-day retrieval) chlorophyll *a* vs. in situ chlorophyll *a* in surface waters (panel a) only for the pre-defined regions (as in Fig. 1) in the Arctic Ocean during 1998–2007. A 1:1 line is indicated.

Previous efforts have shown that empirical algorithms based on remotely sensed chlorophyll *a* can be used to estimate primary production in surface waters (Balch et al., 1992; Behrenfeld and Falkowski, 1997; Dierssen et al., 2000; Eppley et al., 1985). In the AO, an increase of in situ Chl *a* concentration is not a photoacclimation strategy as in oligotrophic oceans, but a real increase in phytoplankton biomass and productivity per unit Chl *a* (Hill and Cota, 2005), making it an excellent proxy for PP. A highly significant relationship between in situ Chl *a* and in situ PP data explains 46% of the variance in the relationship between these two parameters when all available data are used ($\log_{10}$PP = 0.86 ± 0.02 ∗ $\log_{10}$Chl + 1.04 ± 0.02; r^2 = 0.46, N = 6067, p < 0.001) (Fig. 5a); if we only include data stated as resulting from 24 h incubations, more variance (62%) is explained, but only approx. 10% of the available data are used ($\log_{10}$PP = 0.87 ± 0.02 ∗ $\log_{10}$Chl + 1.43 ± 0.02, N = 557, F factor, p < 0.001) (Fig. 5b). A similar relationship between PP derived from Chl *a* measured in situ (Chl-PP) and in situ PP for surface waters is obtained when only data points identified within regions defined in this work (Fig. 6a) are used for the period 1954–2007 (r^2 = 0.46, RMSD = 0.70, N = 1114, F factor p < 0.001). The resulting in situ Chl-PP vs. in situ PP relationship had a high RMSD (0.74) (Table 3), which may be

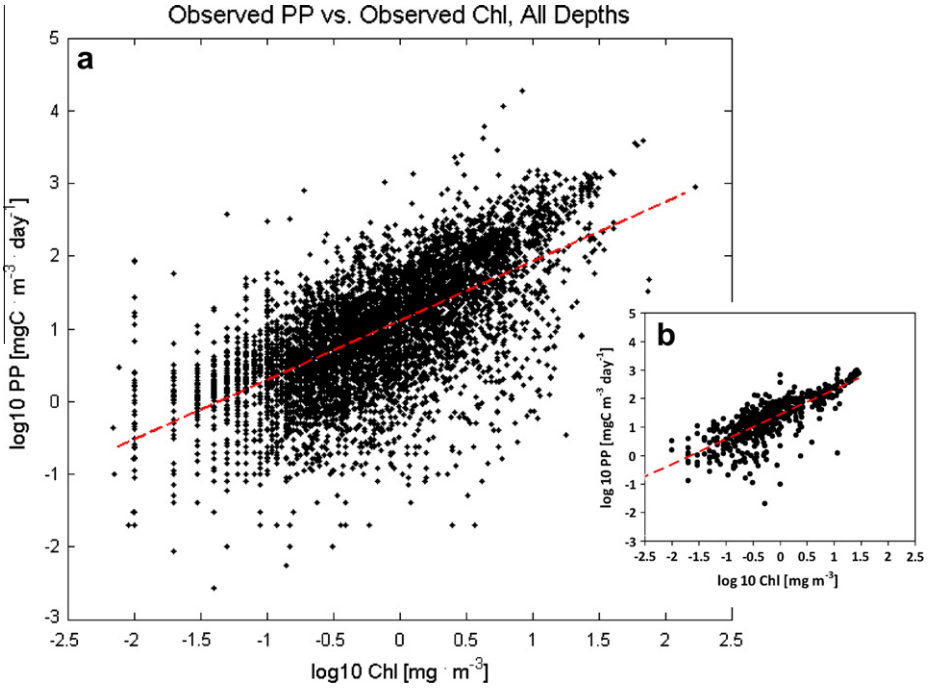

Fig. 5. (a) In situ primary production (PP) vs. in situ chlorophyll *a* (Chl) for the period 1954–2007, including all depths ($\log_{10}$PP = 0.86 ± 0.02 ∗ $\log_{10}$Chl + 1.04 ± 0.02; r^2 = 0.46, N = 6067, p < 0.001). (b) Insert shows only the 24 h incubation data ($\log_{10}$PP = 0.87 ± 0.02 ∗ $\log_{10}$Chl + 1.43 ± 0.02; r^2 = 0.62, N = 557, p < 0.001).

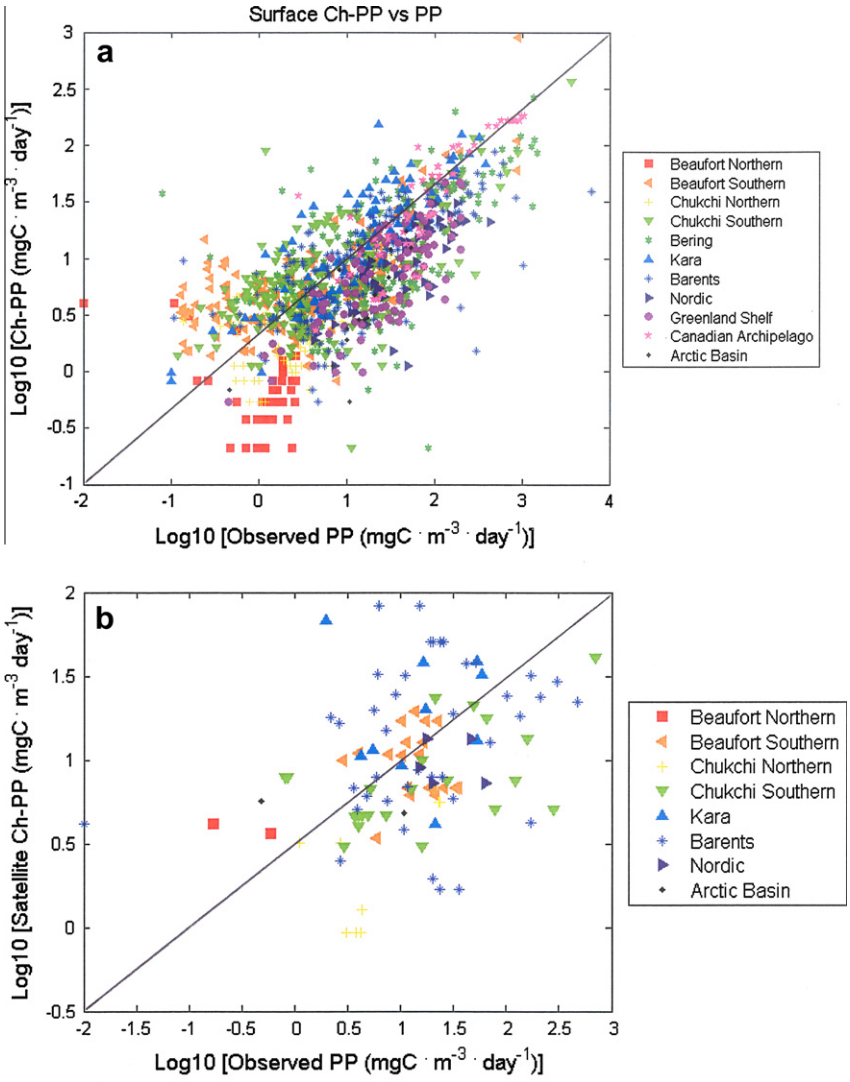

Fig. 6. Daily primary production derived from chlorophyll measured (a) in situ (Chl-PP) for all depths ($r^2 = 0.47$, $N = 1114$, $p < 0.001$) and (b) remotely (sat-PP) for specific match-ups for surface waters only ($r^2 = 0.11$, $N = 112$) vs. in situ primary production (PP) for each region for the period 1954–2007.

Table 3
Algorithm skill statistics computed for in situ chlorophyll-derived primary production (Chl-PP) with respect to in situ primary production (PP) (log–log) in the Arctic Ocean, for all depths, for the period 1954–2007. Statistics for surface waters are presented for comparison only; the Chl-PP algorithm derived from all depths was used herein. See text for definitions.

	Bias	F_{med}	$RMSD_{total}$	R	MAE	ME	N
Chl-PP (all depths)	0.18	1.50	0.74	0.68	0.60	0.44	6067
Chl-PP (surface)	0.23	1.71	0.68	0.48	0.55	0.59	892

attributed as much to uncertainties in the input variable (Chl *a* concentration) as to PP; the Chl-PP relationship will always show a certain amount of variability. The low difference between the means of in situ Chl-PP and the reference in situ PP ($B = 0.18$) (Table 3) indicates a close match between measured in situ PP and predicted in situ Chl-PP, which may be expected given that Chl-PP is computed on the regression between in situ Chl *a* and in situ PP. While these F probability values allow us to reject the null hypothesis (in situ PP and in situ Chl-PP are different) with a very high probability, this conclusion is influenced by the size of the data set. Finally, the forecast error of the in situ Chl-PP to in situ PP time series is lower when estimated by the MAE (0.60), rather than RMSD (0.74), as expected, as MAE places a lesser penalty on large predicting errors (Willmott and Matsuura, 2005). In comparison, the average RMSD found for 12 sat-PP models tested for a Pacific Ocean exercise was 0.29–0.32 (Campbell et al., 2002; Friedrichs et al., 2009), and 0.15–0.44 for different data sets (including marginal seas, but not the AO) in Saba et al. (2011). Our in situ Chl-PP analysis is hampered by the lack of an independent in situ data set for validation and the statistics given here were computed on the training data set.

The derivation of PP from the much larger remotely sensed chlorophyll (sat-Chl *a*) data set provided more extensive spatial and temporal coverage for the Arctic Ocean. However, despite a significant correlation of in situ Chl *a* with in situ PP, a much lower fraction of the variance was explained when this empirical algorithm was used to estimate sat-PP from sat-Chl in surface waters ($N = 111$, $r^2 = 0.11$, F factor $p < 0.001$; $B = -1.2$, RMSD = 1.40) (Fig. 6b). Comparisons for water-column integrated data are presented in Hill et al. (2013).

The uncertainty in the Chl-PP algorithm incorporates the methodological errors for each method, the various methods used, and the spatial and regional variability of thousands of field data. There are uncertainties associated with the determination of in situ Chl *a*

(6–21%, Lorenzen and Jeffrey, 1980; e.g., fluorometric vs. HPLC data) and with sat-Chl (Fig. 4b) (satellite pigment accuracy ±0.17 log units, O'Reilly et al., 1998). Balch et al. (1992) report a variance in simulated PP of up to 48% and 67% for semi-empirical and empirical models, respectively, based on a global compilation of in situ Chl *a* and in situ PP data that, however, excludes any AO data. Recent PP model intercomparisons assign a 15–50% (Friedrichs et al., 2009) or 35–65% (Saba et al., 2011) maximum uncertainty to the in situ Chl *a* input variable, estimated in 10 different marine regions (not including the AO). The cumulative maximum error of PP propagated from field measurement precision to algorithm precision has been shown to account for 39% of RMSD in the case of a classical empirical model also dependent on chlorophyll only (Eppley et al., 1985) and has been estimated as 72% (Saba et al., 2011) to ±100% (Balch et al., 1992; Campbell et al., 2002) in more complex models. It should be noted that these model intercomparisons dealt with integrated PP estimates that respond differently to environmental perturbations than surface PP (Balch et al., 1992; Saba et al., 2010). High RMSD has also been related to observational year and observational methodology (Campbell et al., 2002; Friedrichs et al., 2009); in our work, we did not see differences between in situ Chl-*a* and in situ PP before and after the onset of SeaWiFS observations (Fig. 3). On the other hand, Brown et al. (2011) estimate only a 6% RMSD cumulative error for their input variables in their Bering Sea satellite PP annual estimates. The awareness in the climate modelling community of the need to include not only the physics of the Arctic Ocean but also biogeochemical processes generated a recent intercomparison of five global and AO-specific regional models (Popova et al., 2012). Although similar spatial distributions of simulated open water and simulated annual integrated primary production were produced, the exercise focused on the disagreement among the models to pinpoint the likely bottom-up control(s) of AO primary production; neither the observed distributions of mixed layer depth or nutrient concentrations could be reproduced. No model skill statistics were provided.

Modeling primary production requires both biomass and photoadaptive information which would enhance the performance of a simple Chl - PP empirical algorithm, regardless of whether ship or satellite-derived data are used (Balch et al., 1992). This is especially so in optically complex areas (Saba et al., 2011) like the AO. Sat-PP is derived from sat-Chl observations. To the extent that satellite retrievals of ocean color are affected by atmospheric correction, phytoplankton pigment packaging, CDOM absorption, backscattering of non-algal particles (Matsuoka et al., 2007 and refs. therein, 2009) and the satellite Chl algorithm used, these uncertainties will affect the accuracy of estimates of sat-PP. Finally, the mismatch in the spatial and temporal coverage among the three different PP estimates described herein must also be considered, with sat-PP and in situ PP affording the most and least spatial coverage, respectively, while Chl-PP provides the longest interannual coverage.

The search for a single ocean color algorithm that applies equally well to all oceanic regions continues, even though most large scale biogeochemical and/or coupled models show opposing biases for neritic vs. pelagic zones (Saba et al., 2011). In addition, in the AO, most waters available to ocean color remote sensing in the absence of sea ice are optically complex and regionally variable; while open water regions have mostly included shelves in the recent past, this situation is quickly changing with predictions for a summer ice-free, but not cloud-free, AO within the next 30 years (Davies et al., 2011; Wang and Overland, 2009; Bélanger et al., 2012). A PP algorithm specific to the AO may need to be implemented; ideally, an actual validation analysis of currently used AO PP and Chl algorithms should be performed with a large enough independent AO data set.

3.3. Spatial and temporal patterns for daily PP in surface waters

The available data for in situ PP averaged over all years for the 1954–2007 period for each 100 km^2 EASE grid cell have been separated into the spring and summer seasons (Fig. 7a and d); most of the data were located in the Chukchi and Beaufort Seas, on the Pacific side, and in the Barents and Greenland Seas, on the Atlantic side of the Arctic Ocean. When the estimates of in situ PP, in situ Chl-PP and sat-PP in surface waters were compared on a pan-Arctic perspective, the extensive spatial coverage afforded by remote sensing contrasted with the scant in situ spatial coverage (Fig. 7). Nonetheless, similar spatial patterns in PP can be seen for all three estimates with lower values (<16 mg C m^{-3} d^{-1}) in open, deeper waters and higher values on the shelves, especially closest to shore.

The high in situ PP surface values seen in the Barents Sea in spring (sometimes a single datum per EASE grid cell) were not seen in in situ Chl-PP and sat-PP estimates probably because they are averaged, as the number of data points in each EASE grid cell increased for each of these latter two estimates. The possibility of erroneous in situ PP values due to trace metal contamination (Fitzwater et al., 1982) prior to the 1980s is minimized in the data set as only 164 data points, out of a total of 5195 data points of vertically-resolved PP measurements, were collected prior to 1983; only 8% of the stations with coincident Chl *a* and PP in situ data were sampled prior to 1983 and were primarily located in the Beaufort and Barents Seas. Most importantly, there was no statistical difference in the range of in situ PP values pre- and post-1980s (data not shown). In other regions, such as the inflow shelves of the northern Bering Strait and Chukchi Sea and close to shore, the PP regime is compressed into a much narrower depth range (Carmack and Wassmann, 2006; Codispoti et al., 2013) and better agreement was observed there among these three estimates of PP (Fig. 7d–f). On the other hand, high sat-PP values shown for the immediate coastline of the East Siberian and Laptev Seas in spring and summer (Fig. 7c and f) could be an artifact resulting from high concentrations of river-borne, colored dissolved organic matter, which affects the retrieval of ocean color from which sat-Chl and sat-PP are derived (Cota et al., 2004); unfortunately, scarce or no in situ data were available in this region for validation. High sat-PP values in the southern Chukchi Sea region, however, were likely real since high springtime averages of in situ PP were also measured (Fig. 7a).

4. Discussion

The spatial and temporal distribution and magnitude of primary production in surface waters of the Arctic Ocean are clearly heterogeneous. In order to provide a systematic synthesis to describe this heterogeneity, we assembled the ARCSS-PP data set (Figs. 2 and 3) and the data were averaged and gridded in a consistent manner. Because of the paucity of direct determinations of PP in the Arctic Ocean, particularly early in the growing season when rates can be highest (Codispoti et al., 1991; Smith et al., 1991), we produced a synthesis of surface PP by employing three different approaches that emphasize different spatial and temporal scales, with varying data availability: (1) historical, in situ, experimental measurements based mostly on ^{14}C uptake and possibly carbon-expressed O_2 production (instantaneous, local gross PP to net PP, found from 1954 to the present, mostly in coastal waters and in spring and summer), and applying an empirical algorithm using (2) in situ and (3) remotely sensed Chl *a* (seasonal, regional, and real-time pan-arctic primary production; 1997–2008). Because the heterogeneity in primary production is also vertical since blooms start in and under the ice and then proceed downwards in the water column into the nutricline, vertical and vertically-integrated patterns for these three approaches are discussed in a parallel publication by Hill

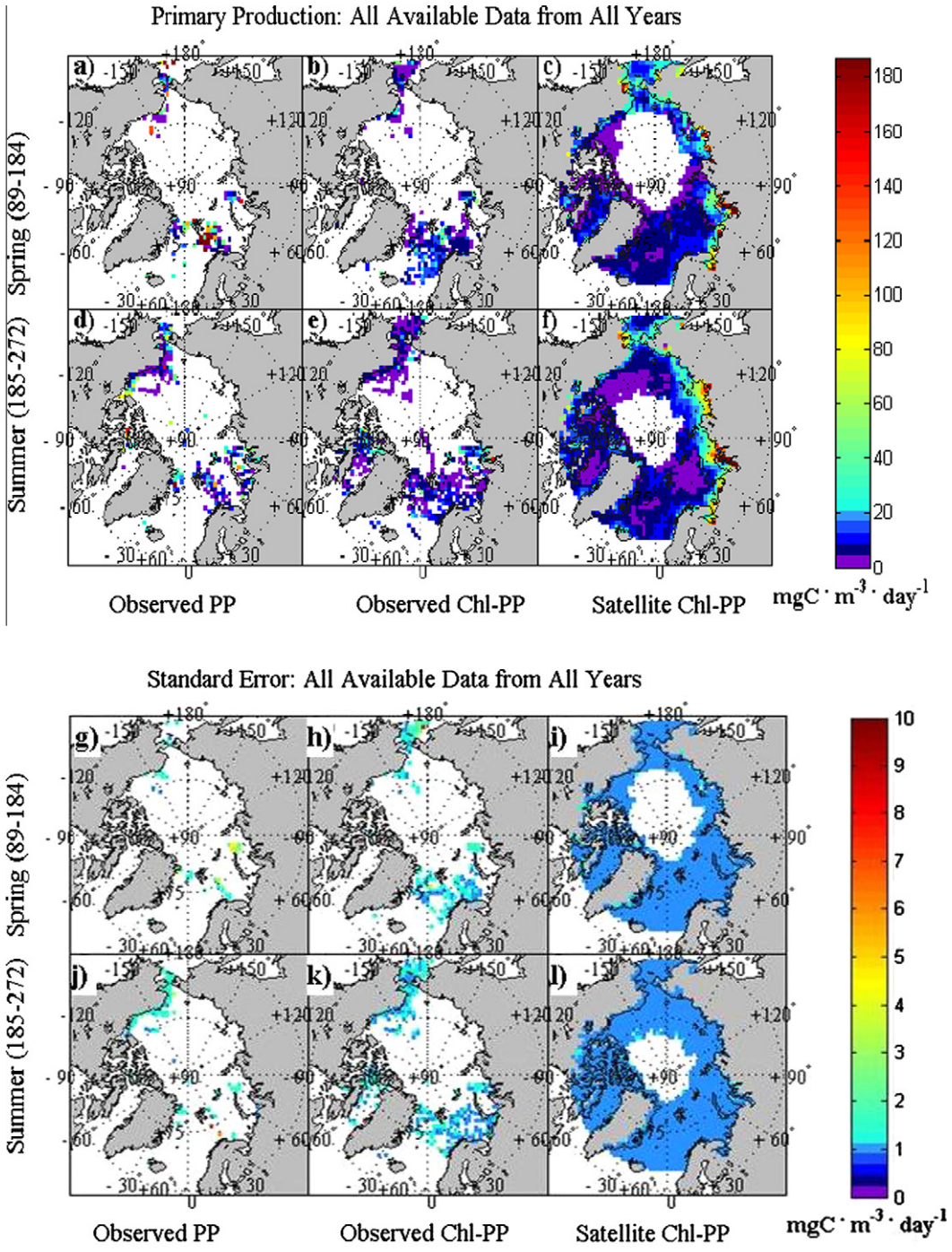

Fig. 7. Mean (top) and standard error of the mean (bottom) of daily primary production derived from in situ measurements (PP; a and d) as well as in situ (Chl-PP; b and e) and SeaWiFS-sensed (sat-PP; c and f) chlorophyll *a* in surface waters of the Arctic Ocean in spring and summer (range given in julian days) for all years (1954–2007), except for sat-PP (1998–2007).

et al. (2013). A fourth approach based on inorganic nutrient consumption (seasonal and regional scale net community production) is discussed in a parallel publication by Codispoti et al. (2013).

Our estimates of surface PP do not include ice algal primary production. Based on current pan-Arctic estimates of annual, ice-bound PP being $\leqslant$5% of open water PP (Sakshaug, 2004 and refs. therein), and given ongoing sea ice loss in the Arctic (Overpeck et al., 2005), it could be argued that ice PP may not, in general, be a large component of annual, total PP in the Arctic Ocean and is likely to decrease in the future. However, the central AO is ice-covered and summer PP in leads can be high (Gosselin et al., 1997; Olli et al., 2007), although their relative area is small. Furthermore, sub-ice microalgal production can be high (Apollonio and Matrai, 2011; Mundy et al., 2009) and not a function of advection under the ice (Arrigo et al., 2012). Whereas the loss of pack ice leads to more open water, it will be followed by formation of a higher fraction of seasonal ice that will likely incorporate ice algae in the bottom ice skeletal layer, where algal growth will be a function of the ambient temperature, irradiance, nutrient concentration, salinity and loss resulting from bottom ice melting. Whether ice algal PP remains a small fraction of surface PP in early spring on a pan-arctic basis remains to be seen.

4.1. Daily PP in surface waters

Polar marine ecosystems are traditionally known for their strong, classic spring phytoplankton blooms that usually move with the receding ice within the seasonal ice zone (Carmack and Wassmann, 2006; Sakshaug, 2004). In certain AO regions, a summer to fall bloom has been observed (Fig. 7) (Hill and Cota, 2005; Matrai et al., 2007; Michel et al., 2006) or hypothesized and modeled due to changes in bottom-up processes (light and nutrient regulation) (Carmack et al., 2006; Zhang et al., 2010). More recently, it has been shown that seasonal patterns of PP in the AO are highly dependent on sea ice extent (Arrigo et al., 2008; Pabi et al., 2008; Wassmann et al., 2006b), on the extent of permanently open, more mixed waters (Grebmeier et al., 2006a; Wassmann et al., 2006a) and on the cloud-influenced radiation regime (Bélanger et al., 2012); in the latter cases, chlorophyll *a* and PP appear not to increase much, but persist at a somewhat high level during the productive season (Carmack and Wassmann, 2006).

The synthesis herein shows that surface in situ PP averaged 70 ± 12.6 mg C m^{-3} d^{-1} (mean; standard error of the mean) for spring for the ca. 50 year period (Table 4), in areas with ⩾50% open water in the regions defined as in Fig. 1. Surface sat-PP and in situ Chl-PP were lower than in situ PP by several fold for the spring period (Table 4); both are ultimately based on the measurement of chlorophyll *a*, a proxy for biomass, which has a statistically significant relationship with primary production (Fig. 5). The surface sat-PP and in situ Chl-PP estimates were calculated from a larger number of data points, including both high and low values, while the higher in situ PP values may reflect a sampling bias towards bloom areas and high growth periods, when field logistics were more feasible. In addition to the methodological factors indicated earlier, there are also ecological factors involved in the resulting variance of the Chl-PP algorithm, such as phytoplankton physiology and community composition. The abundant supply of light and nutrients in spring is likely to support a high rate of PP that has yet to result in an accumulation of biomass. In addition, the spatial resolution of the satellite observations cannot resolve ice edge blooms or see sub-ice blooms, thus potentially missing the high PP measured in situ and causing sat-PP to be underestimated, as remote sensing measurements are visible only after the bloom initiation. In the summer period, on the other hand, the averages for sat-PP and in situ PP are similar (ca. 21 mg C m^{-3} d^{-1}) but twice as high as in situ Chl-PP. That summer in situ PP values are lower than in spring is the net result of simultaneous growth-limiting processes, such as grazing, nutrient limitation, and diminished physical mixing, as well as the sedimentation of phytoplankton from surface waters. The fact that, at least for surface waters, average sat-PP is high compared to in situ Chl-PP suggests a possible positive interference of colored dissolved organic matter and/or riverine sediment load, as discussed earlier. As expected, all seasonal averages are highly variable in space, given their pan-arctic nature; on the other hand, each PP average shows a narrow range of values within each season, as indicated by the rather constant, but not always low, standard error of the mean (SE) values (Fig. 7d–f) especially for sat-PP (SE < 1 mg C m^{-3} d^{-1}). The mismatch in spatial and temporal coverage between the three different PP estimates and the errors in the chlorophyll and primary production algorithms are also likely enough to explain these seasonal differences.

Table 4
Spring and summer gridded daily means (and standard error of the mean) of remotely sensed PP (sat-PP), in situ Chl-PP and in situ PP in surface, ⩾50% open waters of the Arctic Ocean for the period 1954–2007, except for sat-PP (1998–2007). Each EASE grid cell required a number of data points of $n \geqslant 3$ for sat-PP to be calculated.

Season	Value	PP	SE	*N*
		mg C m^{-3} d^{-1}		
Spring	Sat-PP	20.2	0.63	4267
Spring	Chl-PP	11.0	0.64	373
Spring	PP	70.0	12.6	117
Summer	Sat-PP	20.8	0.66	4602
Summer	Chl-PP	9.1	0.47	546
Summer	PP	21.0	1.96	216

4.2. Reconciling different estimates of surface annual PP

Can these different estimates of surface PP be reconciled? Annual totals of surface PP show similar patterns in spatial magnitude and variability (Fig. 8A) to the seasonal PP averages (Fig. 7a–f). The importance of the shelves as biologically active sites is emphasized. For those regions with overlapping grid cells that contain data, we assessed the differences between our three estimates (Fig. 8B). In general, surface in situ Chl-PP agrees (highest frequency in the 0 g C m^{-3} y^{-1} bin) with in situ PP for ca. 1/3 of the available data (Fig. 8C, left panel) and is lower than in situ PP by ca. 0.1–1 g C m^{-3} y^{-1} (northern Barents, Nordic, southern Beaufort Seas) for another ca. 1/3 of the data. On the other hand, annual surface in situ Chl-PP is higher than in situ PP by <1 g C m^{-3} y^{-1} in <3% of the data. Annual surface sat-PP and in situ Chl-PP showed no difference in 39% of the data (Fig. 8C, middle panel) and 74% of the data are included in a range of ca. 0 ± 1 g C m^{-3} y^{-1}, which is to be expected as both estimates respond to the same input parameter, but surprising given the possible errors in sat-Chl in AO waters. Furthermore, the higher number of overlapping grid cells available for the in situ Chl-PP and sat-PP comparison shows better-defined patterns, i.e., in the northern Barents Sea and Nordic Seas regions the difference is ca. 0 ± 2 g C m^{-3} y^{-1} while sat-PP in the Kara and Bering shelf regions is higher than in situ Chl-PP by as much as 5 g C m^{-3} y^{-1}, both being optically complex regions (Brown et al., 2011). Agreement between annual surface sat-PP and in situ PP (Fig. 8B, right panel), the ultimate algorithm validation, is within ±1 g C m^{-3} y^{-1} for half of the data (Fig. 8C, right panel), despite the underwhelming sat-Chl and sat-PP validations reported earlier. Sat-PP is higher than in situ PP in the Bering, Chukchi and Kara Seas and lower in the Barents and S Beaufort Seas. More significantly, the difference between the two in situ data sets of PP and Chl-PP (0 ± 1 g C m^{-3} y^{-1}, accounting for 62% of the cases) is similar to that seen between sat-PP and in situ Chl-PP (ca. 0 ± 1 g C m^{-3} y^{-1}, accounting for 74% of the cases). In all three comparisons, the differences are normally distributed (Fig. 8C); the mode of all three differences is always 0 g C m^{-3} y^{-1} and the median is within ±0.4 g C m^{-3} y^{-1}. Given the dependence of Chl-PP and sat-PP on in situ and satellite observations of Chl *a*, respectively, the chlorophyll *a* methodological precisions and spatial and temporal ranges will determine how representative their derived primary production estimates are at any one place and time, especially with respect to the observed variability for in situ PP (>100%) in the AO (Carmack and Wassmann, 2006; Cota et al., 1996).

During the 1998-to-present time-frame, summer sea ice decline has been spectacular (e.g., Boé et al., 2009; Zhang et al., 2008) but uneven over the Arctic Ocean. It is suggested that its effect on primary production results primarily from changes in open water over time, thus reducing the importance of light as a limiting factor for photosynthesis (Arrigo et al., 2008; Pabi et al., 2008; Rysgaard et al., 1999), at least in a regional scale. However, Tremblay and Gagnon (2009) indicate that, on a pan-Arctic level, PP will increase only when an enhanced exposure of surface waters to solar radiation is matched by annually recurring nutrient inputs which, in turn, will be a function of simultaneous changes in the freshwater balance, horizontal nutrient loading and/or atmospheric forcing of the upper Arctic Ocean (Rabe et al., 2011). An extreme example of this complication exists in the Northern Beaufort sub-region (and

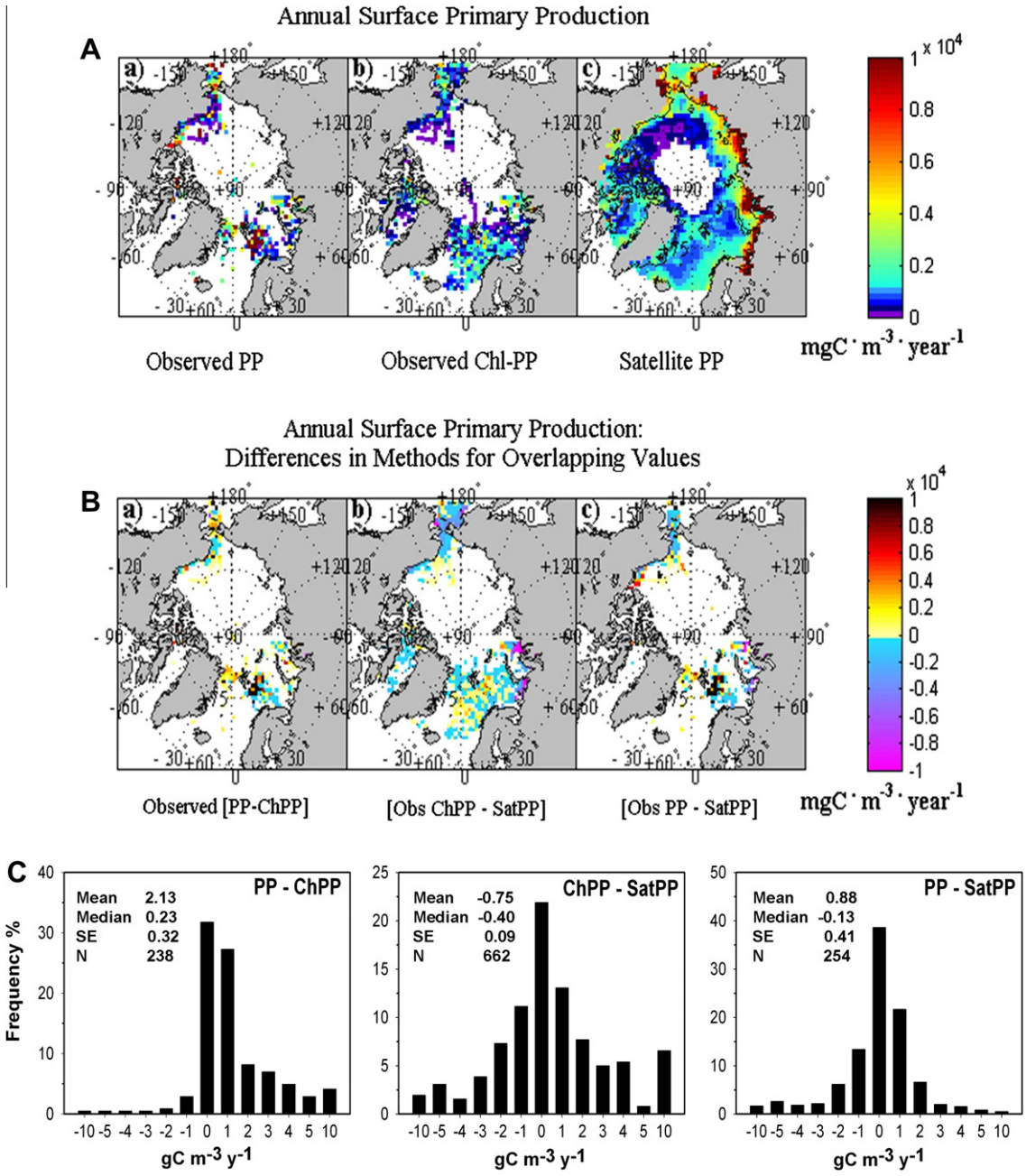

Fig. 8. (A) Annual in situ (PP, a) and predicted (in situ Chl-PP, Sat-PP; b and c) primary production in surface waters of the Arctic Ocean derived from in situ (b) and remotely sensed (c) chlorophyll *a* observations. (B) The differences between the various primary production estimates are shown: in situ PP and in situ Chl-PP (a); in situ Chl-PP and sat-PP (b); in situ PP and sat-PP (c). (C) Frequency distribution of the differences (0 to ±10 g C m^{-3} d^{-1}) shown in panel B.

presumably adjacent portions of the Amerasian Basin) where nitrate concentrations of ~0 μM from the surface to ~50 m even in winter suggest that a decrease in ice-cover might not have a large impact on PP because of nutrient limitation (Codispoti et al., 2013), further enhanced by recent surface thermal stratification (Jackson et al., 2010; Steele et al., 2011). Recently, the role of increasing cloud cover on the AO light regime and its effect on PP are debated (Bélanger et al., 2012). Although these environmental controls play a major role in the magnitude of primary production that results from phytoplankton growth, the composition of the phytoplankton community also plays an important role. Indeed, most historical observations describe net or microplankton as diatom-dominated, especially during the spring bloom, with picoplankton being dominant later in the summer. Recently, the relative abundance of picoplankton appears to be increasing with respect to nanoplankton, as the Canada Basin stratifies (Li et al., 2009; Tremblay et al., 2012). Smaller-sized microalgal species appear to be physiologically more efficient or adaptable to absorb available light (Matsuoka et al., 2009), especially in the fall. Thus, the debate over light or nutrient availability, temperature, or phytoplankton species composition and succession being the ultimate controlling factor(s) for enhanced primary production in newly ice-free, surface waters of the Arctic Ocean will continue until additional field data are available.

5. Summary

In summary, we have synthesized the longest vertically-resolved data set (1954–2007) available for PP in the AO (ARCSS-PP) arranged into a consistently gridded pan-AO data set (also

see Codispoti et al., 2013; Hill et al., 2013). The results presented herein are based only on estimates of PP in surface waters (0–5 m), using complementary methods that emphasize different spatial and temporal scales. In order to reduce the horizontal variability resulting from the different spatial and temporal resolution of in situ and satellite measurements, all estimates were adapted to a constant grid cell size (100 km^2) and daily or annual values were scaled up using consistent, Arctic-based factors.

On a daily basis, over 50 years, surface in situ PP averaged 70 and 21 mg C m^{-3} d^{-1} in spring and summer, respectively. In situ PP was lower than in situ Chl-PP and sat-PP during the spring period, but not in summer when in situ PP and sat-PP agreed well. On an annual basis, Chl-derived PP, whether based on in situ or remotely-sensed chlorophyll, agreed with in situ PP within ±1 g C m^{-3} y^{-1} for a third to half of the gridded data; otherwise, in situ PP was either higher by 1 g C m^{-3} y^{-1} for certain regions (1/3 of data) or lower by varying amounts.

The examination of the ARCSS-PP data set at longer (monthly and annual) and larger (regional and pan-arctic) scales has shown the uneven spatial and temporal coverage of the available data and sampling efforts. This assessment revealed areas that require renewed field efforts and/or data exchange, either because of large gaps in the coverage or apparently erroneous prior estimates. The future exchange of any existing in situ data from the East Siberian and Laptev Seas, for example, should be encouraged. Complementary seasonal, annual, and regional analyses of vertically-resolved and/or integrated PP and nutrient-based, integrated net community production are discussed elsewhere (Codispoti et al., 2013; Hill et al., 2013). We hope that the entire ARCSS-PP data set, especially if combined with any archiving by the latest IPY effort, will be employed to develop an improved, panarctic-specific PP remote sensing algorithm, will be used by AO modelers to calibrate, assimilate, validate and compare community ecosystem and biogeochemical numerical models, will be applied to test hypotheses regarding the controls of PP and, when combined with field work, will allow for improved understanding, detection and prediction of long-term biological patterns.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pocean.2012.11.004.

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