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Decadal trends in phytoplankton production in the Pacific Arctic Region from 1950 to 2012

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ABSTRACT

This paper provides a synthesis of available *in situ* primary production (PP) measurements from the Pacific Arctic Region (PAR), collected between 1950 and 2012. Seasonal integrated primary production (IPP) across the PAR was calculated from 524 profiles, 340 of which were also analyzed to determine the average vertical distribution of PP rates for spring, summer and fall months. The Chirikov Basin and Chukchi Shelf were the most productive areas, with the East Siberian Sea, Chukchi Plateau and Canada Basin the lowest. Decadal-scale changes were indicated in the southern Chukchi Sea, and across Hanna Shoal. In the southern Chukchi Sea in August, IPP increased significantly from 113 ± 35 mg C m^{-2} d^{-1} in 1959 and 1960 to 833 ± 307 mg C m^{-2} d^{-1} in the 2000 s. Increases in the magnitude of IPP were accompanied by variations in the vertical distribution, the subsurface peak observed in the 1959/60 was not present in the 2000 s. The mechanism behind this change was undetermined but could have included changes in stratification, mixing or surface distribution of water masses as well as methodological differences. Over Hanna Shoal, the phytoplankton surface bloom now occurs earlier by several weeks compared to 1993, linked to increases in light due to earlier sea- ice retreat. In 1993 with sea ice still present in the region the surface bloom occurred in August, in 2002 and 2004 this same period was characterized by open water and low surface PP and strong subsurface production. This dataset provides a region-wide quantification of IPP and decadal trends and highlights the need for a cooperative monitoring program to observe the long-term impacts of climate change in the Arctic ecosystem.

1. Introduction

The Pacific Arctic Region (PAR) encompasses areas influenced by Pacific water inflow into the Arctic. The flow of heat, freshwater, and nutrients introduced by Pacific water is a primary driver of both the physical and biological state in the Bering Sea, the Chukchi Sea, the western portion of the Beaufort Sea, the East Siberian Sea and the Canada Basin. The PAR has traditionally contained a highly seasonal and productive ecosystem which supports a diverse and high biomass benthic community (Grebmeier et al., 1988; Hill and Cota, 2005; Mathis et al., 2014).

Two areas with some of the highest integrated primary production (IPP) within the Arctic Ocean are included in the PAR, the northern Bering Sea area referred to as the Chirikov Basin, and the Chukchi Sea (Fig. 1). Both *in situ* and satellite observations in the Chirikov Basin have estimated IPP to range from ~80 g C m^{-2} yr^{-1} on the interior shelf to up to 480 g C m^{-2} yr^{-1} in the Anadyr water plume (Springer and McRoy, 1993; Springer et al., 1996 and references therein; Hill et al., 2013; Brown et al., 2011). The Chukchi Sea has long been an area of high productivity with annual IPP ranges between 170 and 720 g C m^{-2} yr^{-1} across the shelf (Sakshaug et al., 2004; Arrigo et al., 2008; Hill et al., 2013; Varela et al., 2013). In contrast, the Eastern Siberian Sea and Canada Basin are low productivity areas. Phytoplankton growth in open water in the Canada Basin can reach highs of ~100 mg C m^{-2} d^{-1} for the July to September growing season (Lee and Whitledge, 2005; Varela et al., 2013). However, on average rates are lower at 48 mg C m^{-2} d^{-1} in the Canada Basin (Varela et al., 2013) and 8 to 29 g C m^{-2} yr^{-1} in the East Siberian Sea (Codispoti et al., 2013; Slagstad et al., 2011). Due to chronic undersampling in the basin, annual rates should be taken with caution, but have been estimated at 2.5 to 21 g C m^{-2} (Lee et al., 2010). The Beaufort shelf (Fig. 1) while not as productive as the Chukchi Sea can have high growth rates associated with the ice edge, reaching 200 mg C m^{-2} d^{-1} (Carmack et al., 2004; Mundy et al., 2009).

One characteristic ubiquitous across the PAR in summer is a

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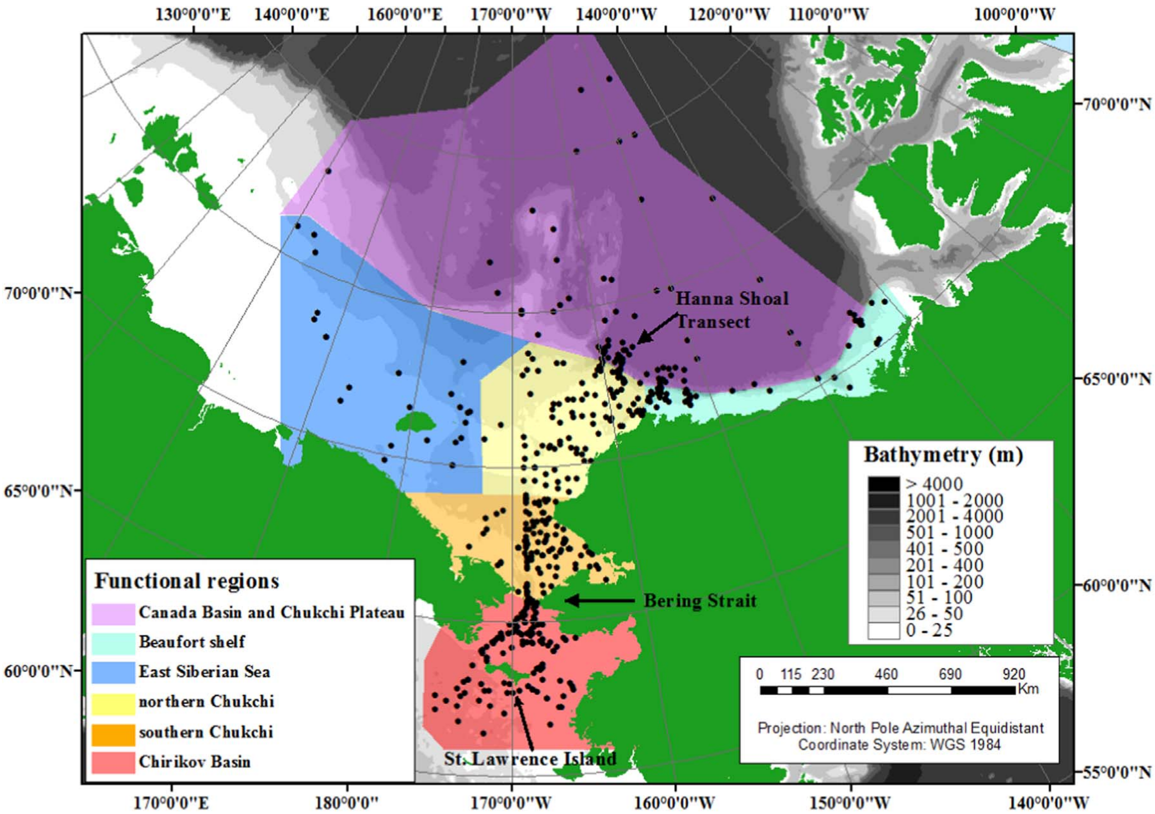

Fig. 1. Map of the Pacific Arctic Region (PAR) with functional regions highlighted in different colors and all stations mapped (black dots). Saint Lawrence Island in the Chirikov Basin and Hanna Shoal in the northern Chukchi and Canada Basin regions are identified. Bathymetry taken from IBCAO version 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

subsurface primary production maximum (SPM) (Arrigo et al., 2011; Ardyna et al., 2013; Hill and Cota, 2005; Hill et al., 2013; Martin et al., 2010; McLaughlin and Carmack, 2010; Martini et al., 2016). This feature forms after the surface phytoplankton bloom declines due to nutrient limitation, induced by stratification of the water column. An SPM forms at the nutraline, where light availability is still adequate to stimulate primary production (PP). In a modeling exercise, Popova et al. (2010) estimated that the SPM accounts for 46% of annual Arctic Ocean production. Hill et al., (2013) concluded that 70% of Arctic IPP in the summer (July to September) occurred in the SPM, and Martin et al., (2013) observed 65 to 90% of annual IPP in the Beaufort Sea occurring at the SPM, driven by stratification and surface oligotrophic conditions.

The PAR has experienced a dramatic change in seasonal ice retreat and subsequent thinning of the ice pack. In the Chukchi Sea, ice survival declined by 30 d dec^{-1} between 1979 and 2008 (Frey et al., 2014), due to a combination of earlier melt and later freeze-up (Stroeve et al., 2014). Ice breakup now starts in April in the southern Chukchi and in June along the Chukchi Sea shelf break (Frey et al., 2015). In the Beaufort Sea, a 1.24 d yr^{-1} decline in the presence of sea ice between 1970 and 2012 accelerated to 12.84 d yr^{-1} over the 2000 to 2012 period (Frey et al., 2015). There is also a general thinning of the Arctic ice pack, which goes in hand with losing much of the multiyear ice. The overall mean ice thickness for the Arctic has decreased from 3.64 m in 1980 to 1.89 m in 2008 (Kwok and Rothrock, 2009). The thickness of the ice pack has undergone the greatest change in September, with a thinning equivalent to 51 cm dec^{-1} in the Chukchi Sea, leading to current projections that the PAR is moving towards an entirely first-year ice pack (Frey et al., 2014). Linked with changes in the ice pack are summertime warming anomalies as high as 2.5 °C, due to radiative heating in ice-free water (Steele et al., 2008; Timmermans and Proshutinsky, 2015). The loss of sea ice has resulted in an Arctic-wide increase in primary production estimated from satellite retrievals, equivalent to 27.5 Tg C yr^{-1} since 2003. Much of this has been associated with increased ice retreat in the Chukchi and Siberian Seas (Arrigo et al., 2008). A recent study indicated that Arctic NPP increases reached a plateau in 2011 (Kahru et al., 2016), suggesting that the region may have reached its maximum supportable phytoplankton growth.

Ultimately the impact of changes in the physical and chemical properties of the PAR are yet to be determined, but will likely include modifications in plankton phenology and carbon cycling, linked to shifts in the water temperature, timing, and length of growth seasons. Recent observations of high under-ice phytoplankton accumulations within ~100 km of the ice edge may be an indication of a changing IPP regime, in which water column phytoplankton growth can be initiated and sustained under the ice due to increased light transmission (Perovich et al., 2008; Arrigo et al., 2012; Churnside and Marchbanks, 2015). If the spring bloom now occurs earlier than historically observed, then the net result of an Arctic-wide shift from multiyear to seasonal ice could be a permanent change in the timing of the pelagic bloom, with consequences for secondary producers and higher trophic levels. For example, for copepod offspring to survive, copepod reproduction has to match the timing of the ice algal bloom, and copepodite growth has to match the timing of the following pelagic bloom (Soreide et al., 2010; Leu et al., 2011). When the pelagic bloom is shifted earlier due to increased light availability, resulting copepod biomass can decrease dramatically (Soreide et al., 2010; Leu et al., 2011). Reduced or lack of zooplankton grazing under these conditions would lead to greater settling of algal carbon to the seafloor benefiting benthic consumers. It is critical, therefore, in this time of environmental variability, to quantify water column IPP, and identify changing patterns in distribution, timing, and magnitude.

By delineating the PAR into regions (Chirikov Basin, southern and northern Chukchi, Beaufort, East Siberian Seas, Chukchi Plateau and Canada Basin), we reveal here a diversity of productive regimes and