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A Chlorophyll Biomass Time-Series for the Distributed Biological Observatory in the Context of Seasonal Sea Ice Declines in the Pacific Arctic Region

Lee W. Cooper * and Jacqueline M. Grebmeier

Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science,
Solomons, MD 20688, USA
* Correspondence: cooper@umces.edu

Abstract: Declines in seasonal sea ice in polar regions have stimulated projections of how primary production has shifted in response to greater light penetration over a longer open water season. Despite the limitations of remotely sensed observations in an often cloudy environment, remote sensing data provide strong indications that surface chlorophyll biomass has increased (since 2000) as sea ice has declined in the Pacific Arctic region. We present here shipboard measurements of chlorophyll-a that have been made annually in July since 2000 from the Distributed Biological Observatory (DBO) stations in the Bering Strait region. This time series as well as shipboard observations made in other months since the late 1980s implicate complexities that intrude on a simple expectation that, as open water periods increase, the production and biomass of phytoplankton will increase predictably. These shipboard observations indicate that there have not been sharp increases in chlorophyll-a, for either maxima observed in the water column or integrated over the whole water column, at the DBO stations over a time-series extending for as long as 20 years coinciding with seasonal sea ice declines. On the other hand, biomass may be increasing in other months: we provide a shipboard confirmation of a fall bloom in October as wind mixing introduced nutrients back into the upper water column. The productive DBO stations may be at a high enough production already that additional enhancements in chlorophyll-a biomass should not be expected, but our time-series record does not exclude the possibility that additional enhanced production may be present in other areas outside the DBO station grid. These findings may also reflect limitations imposed by nutrient cycling and water column structure. The increasing freshwater component of waters flowing through the Bering Strait is likely associated with increased stratification that limits the potential change in biological production associated with decreases in seasonal sea ice persistence.

Keywords: chlorophyll; Bering Sea; Chukchi Sea; seasonal sea ice; climate change; Distributed Biological Observatory

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1. Introduction

One of the expected consequences of the decline in seasonal sea ice concentrations in the Arctic is that the thinning of ice will facilitate more light penetration and result in higher biological production [1]. It is recognized that the deepening of the halocline and the stratification of the water column as a result of melted sea ice could reduce the availability of inorganic nutrients such as nitrate, phosphate and silica and provide negative feedback to the expectations of higher productivity and water column biomass [2,3]. Nevertheless, there are a wide variety of studies that have shown that biological productivity in the Arctic has increased by significant fractions, based largely upon satellite observations, but also in situ observations [1,4,5]. However, satellite observations have limitations because of the presence of deep chlorophyll layers that are not detectable or accurately measured from remotely sensed platforms [6]. Furthermore, on shallow shelves it is often uncertain whether fall blooms visible from satellite platforms [4,7] result from wind mixing that brings to the surface phytoplankton cells that are already present in the deep chlorophyll layer and on surface sediments, or if it represents new production stimulated by the mixing of inorganic nutrients into surface waters.

The establishment of observing systems and programs in the Arctic that incorporate biological sensors or regular shipboard measurements of chlorophyll provide a means to complement the ongoing satellite observations of apparent increased production and chlorophyll biomass. One such program is the Distributed Biological Observatory (DBO), originally established in the Bering Strait region to help document biological and ecosystem changes in response to the climate change, including warming ocean waters and declining seasonal sea ice [8,9]. While the DBO is now being used as a model to expand biologically oriented observations in the Atlantic Arctic and in Arctic Canada, the longest time-series records of biological measurements are available from the Pacific-influenced Arctic region. The DBO stations are sampled in some cases multiple times per year through international cooperation within the Pacific Arctic Group and were originally selected for sampling because of the evidence that certain locations in the Bering and Chukchi seas had persistently high productivity and chlorophyll biomass. These "hot-spots" are maintained by the transfer of high nutrient waters ultimately from the Pacific flowing north through the Bering Strait and the configuration of islands and land masses in relation to steering currents. While the current DBO project was established in 2010, annual data for chlorophyll-a in the water column are available for a number of years prior to that, dating back to 2000 for the stations that were designated to be part of the observing network. We report here this mid-summer in situ record over up to two decades from the five original DBO sampling areas in the northern Bering and Chukchi seas (Figure 1) with a goal of comparing it to indications of biomass and productivity increases from satellite platforms. While other sampling programs have included chlorophyll biomass at some DBO stations, e.g., [10], the previously unpublished data presented here are more extensive in regional and temporal coverage and are focused on annual surveys since 2000. Most of the collections were on very similar days of the year, in July, so year-to-year comparisons are possible. This is also, of course, a limitation because it does not address newly reported phenomena such as fall blooms and whether spring blooms have different characteristics as a result of earlier sea ice break-up [11]. Therefore, in addition to this mid-summer chlorophyll record, we also report data from a late season cruise in October 2020 that sampled a fall bloom in the Bering and Chukchi seas, including data on nutrients and water column stratification that provide insights on possible formation mechanisms.

The five DBO station areas have different characteristics and represent in some respects a time for space study, as the most southerly DBO station areas (DBO 1 and 2, both south of the Bering Strait) have a longer open water period when sea ice is not present. The break-up of sea ice typically marks the initiation of ice edge blooms, so the DBO 1 and 2 regions have the earliest blooms, beginning in April and May [12,13]. As a result, at DBO 1 there is little chlorophyll-a present in the surface water column by the time sampling occurring in July because nutrients are exhausted in the surface water column. DBO 2 varies from this pattern because the more westerly stations are located with direct access to nutrient-rich water flowing through the Anadyr Strait. The water column at DBO 3, located just north of the Bering Strait, also has persistent access to nutrients brought north through the Strait [14]. By contrast, north of the Bering Strait (DBO 4 and 5) it has not been possible to sample in some years completely due to the persistence of sea ice, but these stations are also provided with high nutrient waters that flow through the Bering Strait during the winter [15]. There has been a documented decline in sea ice persistence at each of the five DBO areas over the past 30 years, with open water periods increasing on a southwest to northeast basis [16]. We therefore saw this as an opportunity that arose from our collection of chlorophyll-a data in almost all years in July since 2000 as the DBO program evolved. We used these existing chlorophyll data to explore whether there is any association between the decline in sea ice persistence in each of the five DBO areas and integrated chlorophyll biomass in the water column in each of those areas. While other data are publicly available to help explain any variation observed, including nutrients, sediment characteristics and salinity and temperature, we chose to limit the scope of this effort to simply address the question of whether the biomass of integrated chlorophyll is increasing (or decreasing) over time.

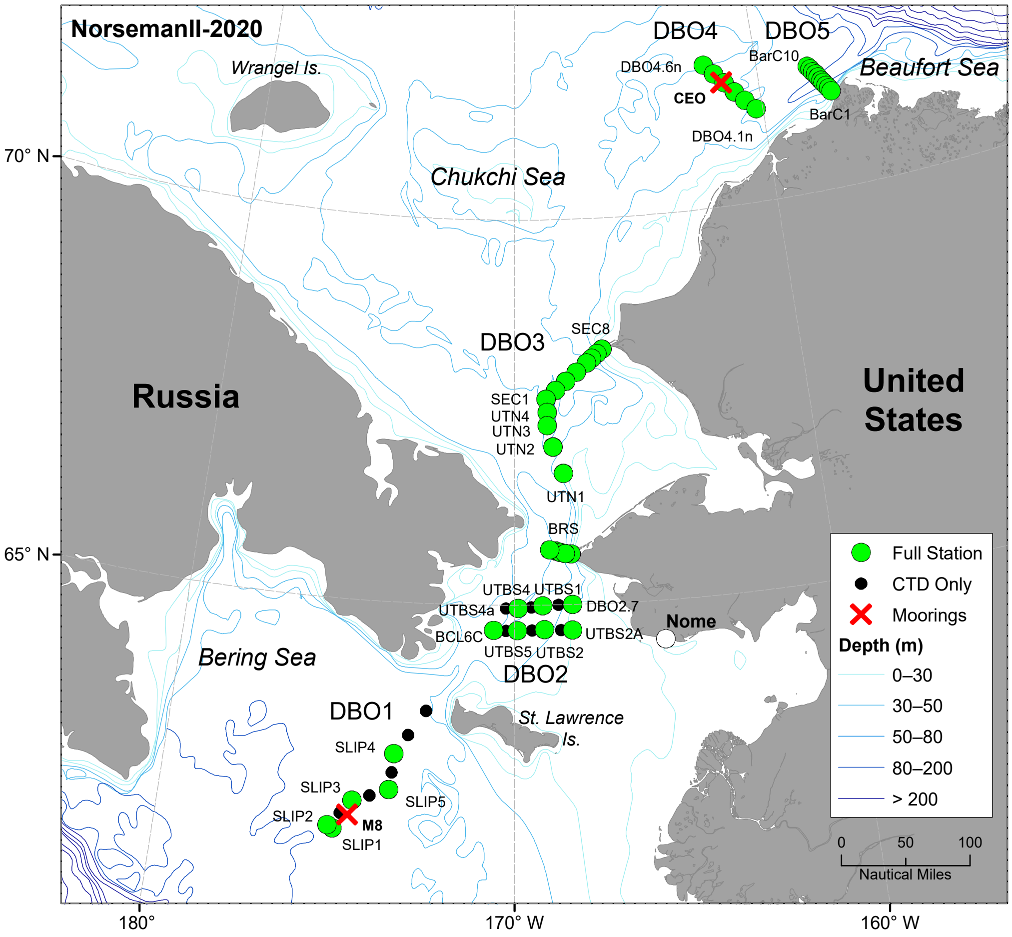

Figure 1. Distributed Biological Observatory station framework in the northern Bering and Chukchi seas.

2. Materials and Methods

Stations sampled were part of the Distributed Biological Observatory grid (five transect lines) in the northern Bering and Chukchi seas (Figure 1). These stations are considered to be the areas of the highest biological productivity on this continental shelf and are now being sampled regularly through the internationally coordinated Distributed Biological Observatory. Our sampling for water column chlorophyll-a was first undertaken in July 2000 with sampling in all years through July 2019 thereafter except in July 2009. Not all DBO stations were sampled initially; the DBO 4 transect line off the northwest coast of Alaska was added in 2010 during a period of interest in oil and gas leasing in that area. In addition, the density of sampling for most of the individual DBO areas increased over time. Data from a fall cruise in October 2020 are also presented here, and the same sampling methodology and overall DBO grid were used. Sampling was from the Canadian Coast Guard ship Sir Wilfrid Laurier, which transits the Bering and Chukchi seas annually at about the same dates in July enroute to undertaking work in the Canadian Arctic. The October 2020 cruise was undertaken from the RV Norseman II, departing and returning to Nome, Alaska, 2–22 October 2020.

All chlorophyll-a analyses presented here were measured using the Welschmeyer non-acidification method [17]. All waters sampled consisted of 250 mL collected from the CTD rosette from at least six depths, which was filtered through Whatman GFF glass fiber filters under gentle vacuum. Filters were immediately frozen for at least 1 h to fracture cell walls, followed by immersion in 10 mL of a 90%:10% acetone–water mixture for 24 h with storage in the dark at 4 °C. Concentrations of chlorophyll-a in the 10 mL were then measured shipboard using a Turner Designs 10AU field fluorometer (San Jose, CA, USA). Calibration with a certified chlorophyll-a standard was undertaken on each research cruise where data are reported (Turner Designs Part No. 10-850), and solid standards manufactured by Turner Designs (Part 10-AU-904) were used to verify instrument drift.

Inorganic nutrients (nitrate + nitrite, phosphate, silica and ammonium) were measured in all years, with frozen, filtered samples returned to the lab for measurements using autoanalyzers at the University of Maryland Center for Environmental Science and the Marine Science Institute Laboratory at the University of California, Santa Barbara. Nutrient data presented here are for the October 2020 research cruise and were used to assess water column nutrient profiles that influenced the chlorophyll biomass that was observed. Data for other years are available through the Arctic Data Center (https://arcticdata.io/catalog/portals/DBO, accessed on 8 August 2022) and through the Pacific Marine Arctic Regional Synthesis project page (http://pacmars.eol.ucar.edu, accessed on 8 August 2022). These two data archives are also where all of the annual July chlorophyll data are posted and are publicly available. We analyzed these data using the software package JMP 15.2 (SAS Institute) and also used the visualization software Ocean Data View [18]

Chlorophyll samples were collected throughout the entire water column, with target depths of 5 m, 15 m, 25 m, 35 m, 50 m and bottom water if deeper than 50 m. Integration of chlorophyll-a data was performed by averaging concentrations between each pair of depths sampled and summing the averages over the whole water column.

3. Results

3.1. DBO 1

Generally, maximum chlorophyll-a concentrations were present at depth (>25 m) in most years at the DBO 1 stations (Table 1) south of St. Lawrence Island. This is consistent with an early bloom and is different from the pattern observed at the DBO 2 stations, where chlorophyll maxima were often nearer the surface (<10 m) in July and integrated chlorophyll biomass was higher (Table 2).

Table 1. DBO 1 Stations, south of St. Lawrence Island, 20-year time series for chlorophyll.

Year	Station	DBO 1 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2}) over Water Column
2019	SLIP1	2.34	25.7	78.6
	SLIP2	2.95	35.6	113.5
	SLIP3	3.30	25.7	109.0
	SLIP5	9.44	25.9	296.6
	SLIP4	8.52	26.0	183.4
2018	SLIP1	2.37	25.2	58.1
	SLIP2	3.33	25.3	74.7
	SLIP3	1.30	50.1	58.0
	SLIP5	1.18	25.2	50.1
	SLIP4	2.16	24.8	81.6
2017	SLIP1	0.66	49.8	28.6
	SLIP2	1.71	49.3	45.7
	SLIP3	0.72	35.0	22.7
	SLIP5	1.33	35.3	32.2
	SLIP4	2.06	35.3	52.4
2016	SLIP1	1.22	35.5	32.7
	SLIP2	1.49	35.4	38.4

Table 1. *Cont.*

Year	Station	DBO 1 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2}) over Water Column
	SLIP3	1.24	67.0	37.7
	SLIP5	1.10	35.6	34.7
	SLIP4	1.11	67.5	35.5
2015	SLIP1	0.54	35.9	27.2
	SLIP2	0.90	34.9	33.4
	SLIP3	0.46	25.2	18.1
	SLIP5	0.39	60.7	12.1
	SLIP4	0.53	68.0	13.7
2014	SLIP1	0.96	50.1	39.6
	SLIP2	1.09	50.1	44.7
	SLIP3	1.01	34.4	37.1
	SLIP5	1.84	50.3	94.0
	SLIP4	5.76	25.2	81.3
2013	SLIP1	0.96	51.8	37.2
	SLIP2	1.23	34.4	31.6
	SLIP3	0.43	67.8	12.1
	SLIP5	1.79	35.5	45.3
	SLIP4	1.79	14.6	112.6
2012	SLIP1	2.91	35.5	54.9
	SLIP2	3.73	24.4	82. 9
	SLIP3	2.34	35.0	68.9
	SLIP5	0.68	34.7	17.7
	SLIP4	4.92	35.2	89.2
2011	SLIP1	3.69	34.3	62.7
	SLIP2	5.84	5.8	58.3
	SLIP3	0.84	25.3	20.8
	SLIP5	0.42	59.8	14.0
	SLIP4	0.44	34.9	17.7
2010	SLIP1	0.14	51.1	4.7
	SLIP2	0.07	78.5	2.7
	SLIP3	0.20	24.68	4.6
	SLIP5	0.10	61.2	2.6
	SLIP4	0.08	67.3	3.1
2008	SLIP1	1.58	26.1	4.7
	SLIP2	1.01	41.0	2.7
	SLIP3	1.26	41.0	4.7
	SLIP5	4.40	26.0	2.6
	SLIP4	0.63	51.2	3.1
2007	SLIP1	17.36	39.5	144.0
	SLIP2	23.56	29.5	387.1
	SLIP3	5.80	30.8	172.8
	SLIP5	4.72	30.6	128.9
	SLIP4	5.08	36.4	92.2
2006	SLIP1	1.29	50.3	53.1
	SLIP2			
	SLIP3	1.33	50.6	44.0
	SLIP5			
	SLIP4	6.48	40.6	67.7
2005	SLIP1	2.43	41.1	55.4
	SLIP2	2.10	41.4	8.6
	SLIP3	2.36	41.2	4.0
	SLIP5	2.39	30.7	59.7

Table 1. *Cont.*

Year	Station	DBO 1 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2}) over Water Column
	SLIP4	2.81	31.1	
2004	SLIP1	0.62	70.5	23.6
	SLIP2	3.17	40.7	55.4
	SLIP3	0.20	69.6	8.6
	SLIP5	0.18	49.0	4.0
	SLIP4	2.40	40.5	59.7
2003	SLIP1	0.94	39.4	21.6
	SLIP2	0.24	2.4	8.9
	SLIP3	2.07	34.9	40.4
	SLIP5	1.34	31.8	33.9
	SLIP4	2.10	31.4	33.9
2002	SLIP1	0.59	51.8	26.1
	SLIP2	0.44	51.0	18.9
	SLIP3	1.90	32.2	37.1
	SLIP5	4.60	36.2	53.4
	SLIP4	0.90	31.4	27.6
2001	SLIP1	2.75	31.1	46.9
	SLIP2	5.08	24.9	91.5
	SLIP3	4.56	23.5	66.4
	SLIP5	2.21	26.0	45.3
	SLIP4	4.12	22.8	57.3
2000	SLIP1	1.06	25.0	37.7
	SLIP2	1.07	25.0	37.8
	SLIP3	0.90	25.6	40.8
	SLIP5	0.45	60.0	22.5
	SLIP4	0.51	25.0	21.0

Table 2. DBO 2 Stations, south of St. Lawrence Island, 20-year time series for chlorophyll.

Year	Station	DBO 1 Maximum Chlorophyll mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2})
2019	BCL6a	2.59	34.5	86.8
	BCL-6c/DBO 2.0	2.38	43.1	78.2
	UTBS-5/DBO 2.1	2.67	4.9	82.4
	UTBS-2/DBO 2.2	3.25	5.7	76.7
	UTBS-2a/DBO 2.3	2.85	6	65.7
	UTBS-1/DBO 2.5	10.04	4.5	257.5
	UTBS-4/DBO 2.4	17.2	4.7	143.8
	DBO 2.7			
2018	BCL6a	0.92	25.4	29.2
	BCL-6c/DBO 2.0	3.42	4.9	59.6
	UTBS-5/DBO 2.1	1.78	41.7	60.5
	UTBS-2/DBO 2.2	6.88	5.1	141.5
	UTBS-2a/DBO 2.3	1.94	24.5	46.1
	UTBS-1/DBO 2.5	6.20	5.4	136.9
	UTBS-4/DBO 2.4	6.10	5.4	126.9
	DBO 2.7	1.10	1.1	52.4
2017	BCL6a	0.90	24.9	34.7
	BCL-6c/DBO 2.0	0.97	5.3	26.3
	UTBS-5/DBO 2.1	3.68	5.3	43.4
	UTBS-2/DBO 2.2	5.12	15.3	67.7
	UTBS-2a/DBO 2.3	4.80	33.4	110.7

Table 2. *Cont.*

Year	Station	DBO 1 Maximum Chlorophyll mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2})
	UTBS-1/DBO 2.5	2.01	5.4	34.2
	UTBS-4/DBO 2.4	2.89	5.0	46.6
	DBO 2.7	12.5	35.1	239.0
2016	BCL6a	2.40	44.4	47.0
	BCL-6c/DBO 2.0	1.10	42.3	21.9
	UTBS-5/DBO 2.1	0.77	14.7	25.0
	UTBS-2/DBO 2.2	1.70	24.8	31.7
	UTBS-2a/DBO 2.3	1.60	4.9	30.9
	UTBS-1/DBO 2.5	0.90	24.9	24.7
	UTBS-4/DBO 2.4	2.05	34.7	42.0
	DBO 2.7	2.38	44.4	47.0
2015	BCL6a			
	BCL-6c/DBO 2.0	1.29	5.3	35.9
	UTBS-5/DBO 2.1	4.20	14.9	85.16
	UTBS-2/DBO 2.2			
	UTBS-2a/DBO 2.3	1.84	5.2	48.8
	UTBS-1/DBO 2.5	2.1	14.9	43.5
	UTBS-4/DBO 2.4			
	DBO 2.7			
2014	BCL6a	14.18	1.0	39.4
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.99	42.1	34.1
	UTBS-2/DBO 2.2	5.92	35.3	160.3
	UTBS-2a/DBO 2.3	3.18	14.8	
	UTBS-1/DBO 2.5	6.04	44.0	103.2
	UTBS-4/DBO 2.4	2.97	4.6	154.5
	DBO 2.7			
2013	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.48	15.8	16.8
	UTBS-2/DBO 2.2	0.59	34.9	17.4
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	0.36	4.4	22.3
	UTBS-4/DBO 2.4	0.74	15.6	11.8
	DBO 2.7			
2012	BCL6a	0.79	49.2	22.9
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.54	41.8	11.8
	UTBS-2/DBO 2.2	3.64	40.5	82.3
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	3.14	24.8	51.5
	UTBS-4/DBO 2.4	1.858	35.1	49.85
	DBO 2.7			
2011	BCL6a	1.04	35.0	38.3
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	4.04	5.3	50.8
	UTBS-2/DBO 2.2	1.14	15.2	31.6
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	1.77	5.4	35.4
	UTBS-4/DBO 2.4	1.29	15.5	23.8
	DBO 2.7			
2010	BCL6a	0.77	50.4	22.6
	BCL-6c/DBO 2.0			

Table 2. *Cont.*

Year	Station	DBO 1 Maximum Chlorophyll mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2})
	UTBS-5/DBO 2.1	1.24	35.2	31.3
	UTBS-2/DBO 2.2	3.09	4.4	49.23
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	5.76	15.1	55.9
	UTBS-4/DBO 2.4	2.09	45.0	76.8
	DBO 2.7			
2008	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.70	31.2	31.3
	UTBS-2/DBO 2.2			49.2
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	2.12	6.5	55.9
	UTBS-4/DBO 2.4	1.24	21.0	76.8
	DBO 2.7			
2007	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	2.15	30.0	81.9
	UTBS-2/DBO 2.2	5.24	10.7	150.0
	UTBS-2a/DBO 2.3	6.2	1.8	
	UTBS-1/DBO 2.5	3.63	2.1	86.9
	UTBS-4/DBO 2.4			
	DBO 2.7			
2006	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.35	35.5	8.4
	UTBS-2/DBO 2.2			
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5			
	UTBS-4/DBO 2.4	0.34	5.1	8.7
	DBO 2.7			
2005	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	1.38	11.0	32.2
	UTBS-2/DBO 2.2	1.78	10.8	40.1
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	9.48	5.8	204.2
	UTBS-4/DBO 2.4	14.56	10.6	140.6
	DBO 2.7			
2004	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.59	46.2	20.8
	UTBS-2/DBO 2.2	4.12	5.8	65.9
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	1.53	10.5	20.8
	UTBS-4/DBO 2.4	0.80	6.0	32.1
	DBO 2.7			
2003	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	1.368	1.3	32.0
	UTBS-2/DBO 2.2	9.64	15.6	108.8
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	7.80	17.7	310.6
	UTBS-4/DBO 2.4	18.08	21.4	187.1
	DBO 2.7			

Table 2. *Cont.*

Year	Station	DBO 1 Maximum Chlorophyll mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2})
2002	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.64	21.5	20.0
	UTBS-2/DBO 2.2	0.92	5.9	27.4
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	1.25	11.0	28.8
	UTBS-4/DBO 2.4	0.84	15.2	33.8
	DBO 2.7			
2001	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	0.37	43.0	12.0
	UTBS-2/DBO 2.2	4.32	3.6	100.6
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	12.04	0.9	49.5
	UTBS-4/DBO 2.4	4.48	5.8	109.1
	DBO 2.7			
2000	BCL6a			
	BCL-6c/DBO 2.0			
	UTBS-5/DBO 2.1	1.50	25.0	54.5
	UTBS-2/DBO 2.2	1.91	25.0	64.85
	UTBS-2a/DBO 2.3			
	UTBS-1/DBO 2.5	1.63	35	113.3
	UTBS-4/DBO 2.4	3.18	25.3	61.1
	DBO 2.7			

3.2. DBO 2

Particularly at DBO 2 stations UTBS-1/DBO 2.5 and UTBS-4/DBO 2.4, and DBO 2.7, located on the northern edge of the DBO 2 region, where nutrients are typically high and waters well-mixed from flow northwest through the Anadyr Strait, chlorophyll concentrations integrated over the whole water column can reach inventories >100–200 mg m^{-2} in July (Table 2). As a result, the depth of the chlorophyll maximum is typically higher in the water column than at DBO 1 and the maximum chlorophyll biomass in the water column is also high, up to 15 mg m^{-3} (Table 2). This high chlorophyll biomass often coincides with maximum chlorophyll concentrations high in the water column, indicating active blooms are often present on the west side of the DBO 2 areas. Higher integrated chlorophyll biomass is observed on a west to east gradient, decreasing to the east. While this pattern applies in particular to chlorophyll, summer water temperatures increase moving west to east, while salinity and inorganic nutrients decrease. These water mass characteristics are consistent with prior observations in the DBO sites (e.g., [10,12–15]).

3.3. DBO 3

The highest maximum water column concentrations and integrated inventories are found in the DBO 3 area to the north of the Bering Strait, where a well-known biological "hot-spot" occurs [14] as a well-mixed and nutrient rich water mass flows through the Bering Strait and sustains production persistently (Table 3). Integrated chlorophyll-a over the whole water column can reach >500 mg m^{-2}. Low integrated chlorophyll-a concentrations (<30 mg m^{-2}) are consistently observed at stations close to the Alaska coast, e.g., DBO 3.1 and 3.2, where Alaska Coastal Water is present and nutrients are limited [15]. Because of well-mixed nutrient rich waters flowing through the Bering Strait, maximum chlorophyll concentrations occur in the western side of this area, particularly at the UTN series stations and higher numbered DBO 3 series stations, e.g., DBO 3.5, 3.6, 3.7 and 3.8. These stations are located in the center of the Bering Strait inflow (Figure 1), but by July these waters containing high chlorophyll (and nutrients) are typically at depths of 25 m or greater.

Table 3. DBO stations north of Bering Strait; “hot-spot” area.

Year	Station	DBO 3 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2}) over Water Column
2019	UTN-1	2.59	34.5	86.8
	UTN-2	2.38	43.1	78.2
	UTN-3	2.67	4.9	82.4
	UTN-4	3.25	5.7	76.7
	UTN-6	2.85	6.0	65.7
	SEC-8/DBO 3.1	1.87	15.7	40.7
	SEC-7/DBO 3.2	1.47	15.5	50.2
	SEC-6/DBO 3.3	1.07	5.8	38.5
	SEC-5/DBO 3.4	1.71	25.3	61.9
	SEC-4/DBO 3.5	12.6	15.3	234.7
	SEC-3/DBO 3.6	3.58	33.7	119.8
	SEC-2/DBO 3.7	3.18	46.8	108.6
	SEC-1/DBO 3.8	5.68	35.5	220.2
	UTN-7	6.24	53.7	181.3
2018	UTN-1	1.16	5.1	23.5
	UTN-2	1.97	5.4	35.5
	UTN-3	11.6	15.6	188.2
	UTN-4	1.62	15	40.2
	UTN-6	7.60	15.6	150.3
	SEC-8/DBO 3.1	1.64	5.6	30.6
	SEC-7/DBO 3.2	1.20	15.3	32.0
	SEC-6/DBO 3.3	1.43	15.2	35.2
	SEC-5/DBO 3.4	0.99	5.4	28.5
	SEC-4/DBO 3.5	1.34	15.3	45.2
	SEC-3/DBO 3.6	1.53	16.5	36.6
	SEC-2/DBO 3.7	4.16	25.3	106.4
	SEC-1/DBO 3.8	1.11	5.4	34.0
	UTN-7	3.78	15.4	145.9
2017	UTN-1	5.04	29.4	75.9
	UTN-2	7.44	4.8	167.3
	UTN-3	12.64	5.2	364.7
	UTN-4	10.76	25.2	206.5
	UTN-6	18.12	25.3	479.0
	SEC-8/DBO 3.1	1.40	24.7	28.9
	SEC-7/DBO 3.2	1.53	25.0	43.4
	SEC-6/DBO 3.3	1.38	43.2	49.1
	SEC-5/DBO 3.4	2.21	45.3	61.5
	SEC-4/DBO 3.5	22.34	45.9	541.6
	SEC-3/DBO 3.6	20.48	25.3	442.7
	SEC-2/DBO 3.7	15.08	15.3	251.0
	SEC-1/DBO 3.8	8.04	34.7	379.0
	UTN-7	26.12	25.2	488.3
2016	UTN-1	1.28	24.9	26.7
	UTN-2	6.44	4.5	164.4
	UTN-3	24.08	14.6	612.9
	UTN-4	34.04	25.5	930.8
	UTN-6	39.92	14.5	672.1
	SEC-8/DBO 3.1	6.70	30.7	29.1
	SEC-7/DBO 3.2	1.08	24.9	27.4
	SEC-6/DBO 3.3	0.73	24.7	23.1
	SEC-5/DBO 3.4	0.80	24.8	22.5

Table 3. *Cont.*

Year	Station	DBO 3 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2}) over Water Column
	SEC-4/DBO 3.5	1.75	25.4	68.0
	SEC-3/DBO 3.6	12.36	53.9	269.4
	SEC-2/DBO 3.7	18.24	14.7	471.7
	SEC-1/DBO 3.8	13.52	24.6	417.8
	UTN-7	29.44	34.2	560.8
2015	UTN-1	2.02	24.8	37.5
	UTN-2	8.52	5.4	168.4
	UTN-3	12.64	15.2	185.8
	UTN-4	4.72	5.3	90.1
	UTN-6	15.52	5.0	185.8
	SEC-8/DBO 3.1	1.28	15.0	26. 8
	SEC-7/DBO 3.2	1.63	4.8	43.9
	SEC-6/DBO 3.3	1.72	25.0	50.4
	SEC-5/DBO 3.4	1.47	34.6	49.0
	SEC-4/DBO 3.5	5.92	15.2	79.77
	SEC-3/DBO 3.6	22.08	5.0	238.0
	SEC-2/DBO 3.7	16.76	4.98	175.9
	SEC-1/DBO 3.8	6.28	5.02	65.1
	UTN-7	3.41	36.7	516.8
2014	UTN-1	7.72	15.1	169.3
	UTN-2	15.96	41.8	456.5
	UTN-3	19.28	45.0	582.4
	UTN-4	11.24	46.3	301.7
	UTN-6	20.48	45.2	380.0
	SEC-8/DBO 3.1	1.00	25.2	23.3
	SEC-7/DBO 3.2	1.11	5.7	25.1
	SEC-6/DBO 3.3	0.92	42.9	28.6
	SEC-5/DBO 3.4	0.93	25.1	32.9
	SEC-4/DBO 3.5	0.61	47.9	22.2
	SEC-3/DBO 3.6	3.15	25.5	96.6
	SEC-2/DBO 3.7	7.60	14.4	234.0
	SEC-1/DBO 3.8	8.32	25.7	234.1
	UTN-7	1.18	25.6	31.7
2013	UTN-1	0.76	25.3	16.4
	UTN-2	1.41	42.4	33.9
	UTN-3	10.84	4.6	309.0
	UTN-4	12.00	35.1	330.9
	UTN-6	18.96	4.8	462.2
	SEC-8/DBO 3.1	0.72	5.2	12.7
	SEC-7/DBO 3.2	0.53	15.7	15.1
	SEC-6/DBO 3.3	1.68	34.9	48.1
	SEC-5/DBO 3.4	1.69	15.3	40.4
	SEC-4/DBO 3.5	0.38	48.9	13.5
	SEC-3/DBO 3.6	13.28	25.0	524.9
	SEC-2/DBO 3.7	20.16	5.3	461.4
	SEC-1/DBO 3.8	19.04	5.03	345.0
	UTN-7	23.72	24.7	600.5
2012	UTN-1	0.26	15.2	5.6
	UTN-2	4.44	35.4	121.4
	UTN-3	3.90	44.7	71.0
	UTN-4	4.44	45.3	55.2
	UTN-6	1.10	44.6	35.9
	SEC-8/DBO 3.1	0.26	15.3	5.5
	SEC-7/DBO 3.2	0.33	25.0	

Table 3. *Cont.*

Year	Station	DBO 3 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2}) over Water Column
	SEC-6/DBO 3.3	0.10	35.5	3.2
	SEC-5/DBO 3.4	0.29	45.7	9.4
	SEC-4/DBO 3.5	0.94	49.0	27.5
	SEC-3/DBO 3.6	7.84	53.8	179.7
	SEC-2/DBO 3.7	1.06	45.3	17.1
	SEC-1/DBO 3.8	5.08	45.5	70.0
	UTN-7	4.84	50.1	88.5
2011	UTN-1	0.71	25.6	16.1
	UTN-2	1.12	35.2	27.3
	UTN-3	18.24	25.2	416.8
	UTN-4	7	45.4	194.1
	UTN-6	2.48	25.7	80.4
	SEC-8/DBO 3.1	2.228	5.4	20.2
	SEC-7/DBO 3.2	0.53	25.4	15.2
	SEC-6/DBO 3.3	0.65	15.6	19.7
	SEC-5/DBO 3.4	0.95	15.4	30.8
	SEC-4/DBO 3.5	1.755	34.9	38.4
	SEC-3/DBO 3.6	15.47	21.6	266.5
	SEC-2/DBO 3.7	0.76	15.6	28.3
	SEC-1/DBO 3.8	5.52	5.2	112.8
	UTN-7	22.44	5.4	166.8
2010	UTN-1	1.23	29.8	12.0
	UTN-2	2.22	5.2	35.8
	UTN-3	0.89	46.2	18.9
	UTN-4	1.04	45.2	27.2
	UTN-6	0.79	24.82	20.9
	SEC-1/DBO 3.8	2.89	14.7	47.9
	UTN-7	0.53	54.1	11.2
2008	UTN-1	0.63	11.8	12.0
	UTN-2	2.34	41.6	35.8
	UTN-3	3.10	50.4	18.9
	UTN-4	4.28	50.3	27.2
	UTN-6	14.08	6.7	20.9
	SEC-1/DBO 3.8	8.24	11.7	47.9
	UTN-7	22.20	21.5	11.2
2007	UTN-1	9.00	31.3	191.1
	UTN-2	23.96	5.4	608.0
	UTN-3	15.36	46.8	501.0
	UTN-4	13.64	46.7	287.8
	UTN-6	14.68	45.8	266.9
	SEC-1/DBO 3.8	0.34	48.4	4.3
	UTN-7	11.28	54.0	309.23
2006	UTN-1	0.444	24.7	9.0
	UTN-2	6.04	25.2	171.5
	UTN-3	0.56	44.2	14.7
	UTN-4			
	UTN-6			
	SEC-1/DBO 3.8	0.12	40.8	3.5
	UTN-7	16.84	5.1	244.9
2005	UTN-1	0.75	6.3	6.2
	UTN-2	2.38	26.0	76.3
	UTN-3	14.28	5.9	351.3
	UTN-4	11.24	20.6	322.9

Table 3. *Cont.*

Year	Station	DBO 3 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2}) over Water Column
	UTN-6	3.34	40.6	142.6
	SEC-1/DBO 3.8	7.88	36.0	189.3
	UTN-7	2.13	51.6	83.6
2004	UTN-1	3.83	43.9	109.4
	UTN-2	5.00	45.3	145.26
	UTN-3	11.80	48.6	329. 7
	UTN-4	13.16	45	330.6
	UTN-6	13.16	45	330.6
	SEC-1/DBO 3.8	6.60	49.4	226.8
	UTN-7	6.56	30.6	188.5
2003	UTN-1	1.39	10.9	29.3
	UTN-2	6.16	25	134.5
	UTN-3	6.44	15.2	164.8
	UTN-4	7.84	44.3	250.7
	UTN-6	5.28	10.7	160.4
	SEC-1/DBO 3.8	5.92	20.5	178.9
	UTN-7	4.049	1.3	1133.9
2002	UTN-1	0.63	15.7	15.4
	UTN-2	1.16	40.2	32.6
	UTN-3	14.84	41.2	426.1
	UTN-4	18.88	35.9	519.7
	UTN-6	27.70	25.4	498.9
	SEC-1/DBO 3.8	18.40	21.1	380.9
	UTN-7	8.88	15.9	336.8
2001	UTN-1	1.05	2.6	27.0
	UTN-2	2.57	6.5	62.5
	UTN-3	11.16	48.0	291.2
	UTN-4	23.48	0.1	708.7
	UTN-6	16.64	0.1	301.5
	SEC-1/DBO 3.8	18.20	19.2	287.3
	UTN-7	32.96	6.1	628.9
2000	UTN-1			
	UTN-2	0.82	35.8	28.2
	UTN-3	19.32	5.0	745.4
	UTN-4	14.92	45.0	528.5
	UTN-6	27.68	5.0	719.3
	SEC-1/DBO 3.8	21.92	55.0	784.8
	UTN-7	25.72	5.0	620.3

3.4. DBO 4

Further north, at the DBO 4 stations, chlorophyll concentrations are typically higher at the more offshore stations, e.g., DBO 4.3, 4.4, 4.5 and 4.6, again consistent with higher nutrients concentrations present at depth (>25 m; Table 4). Total chlorophyll-a inventories are not generally as high as at DBO 3, although in some years chlorophyll biomass is >300 mg m^{-2} in July at stations DBO 4.4 and 4.5, considered to be another benthic "hot-spot" [14].

Table 4. DBO 4 Stations, northwest Chukchi shelf, 7-year time series for chlorophyll.

Year	Station	DBO 4 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2})
2019	DBO 4.6n	16.88	25.2	247.2
	DBO 4.5n	2.58	40.4	36.3
	DBO 4.4N	7.16	7.16	122.0
	DBO 4.3n	2.42	43.2	85.0
	DBO 4.2	2.49	25.3	57.7
	DBO 4.1n	1.34	52.4	95.4
2018	DBO 4.6n	8.68	25.1	161.4
	DBO 4.5n	9.56	38.6	102.6
	DBO 4.4N	6.96	42.5	152.7
	DBO 4.3n	4.64	43.8	398.7
	DBO 4.2	8.60	43.9	216.4
	DBO 4.1n			
2017	DBO 4.6n	0.71	24.9	19.6
	DBO 4.5n	0.83	24.6	19.5
	DBO 4.4N	0.77	25.0	20.3
	DBO 4.3n	1.30	15.3	35.8
	DBO 4.2	0.83	41.6	38.5
	DBO 4.1n	1.41	35.0	44.7
2016	DBO 4.6n	3.65	24.8	52.2
	DBO 4.5n			
	DBO 4.4N			
	DBO 4.3n	14.56	25.4	170.3
	DBO 4.2	9.44	24.6	150.4
	DBO 4.1n	3.39	35.1	78.4
2015	DBO 4.6n	5.80	25.4	84.9
	DBO 4.5n	4.52	25.1	73.8
	DBO 4.4N	4.84	25.5	91.9
	DBO 4.3n	23.48	25.3	440.5
	DBO 4.2	8.60	34.8	113.7
	DBO 4.1n	3.16	35.1	57.5
2014	DBO 4.6n	8.40	37.3	106.0
	DBO 4.5n	18.84	14.4	334.4
	DBO 4.4N	15.12	14.9	313.9
	DBO 4.3n	2.512	41.7	66.3
	DBO 4.2	1.72	25.1	39.2
	DBO 4.1n	9.80	24.9	116.8
2013	DBO 4.6n	7.52	15.3	137.6
	DBO 4.5n	3.89	25.1	76.6
	DBO 4.4N	7.84	24.8	195.3
	DBO 4.3n	10.76	15.5	176.3
	DBO 4.2			179.0
	DBO 4.1n	3.392	42.2	62.5

3.5. DBO 5

The DBO 5 stations span the Barrow Canyon area offshore of the northern most point in Alaska. The deeper stations over the apex of the canyon in DBO 5, DBO 5.4, 5.5 and 5.6 typically have the highest chlorophyll biomass, whether integrated or individual bottle measurements (Table 5).

Table 5. DBO 5 Stations, Barrow Canyon area, 6-year time series for chlorophyll.

Year	Station	DBO 5 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2})
2019	BarC-10/DBO 5.10	7.60	35.2	135.2
	Bar-C-9/DBO 5.9	3.68	34.1	76.7
	BarC-8/DBO 5.8	2.48	35.3	65.6
	BarC-7/DBO 5.7	0.93	77.7	31.7
	BarC-6/DBO 5.6	2.58	35.0	66.7
	BarC/DBO 5.5	3.12	35.1	136.9
	BarC-4/DBO 5.4	1.34	75.6	63.0
	BarC-3/DBO 5.3	1.03	15.7	80.0
	BarC-2/DBO 5.2	0.81	35.5	39.3
	BarC-1/DBO 5.1	1.96	4.5	54.7
2017	BarC-10/DBO 5.10	3.86	34.7	79.8
	Bar-C-9/DBO 5.9	3.09	34.3	56.7
	BarC-8/DBO 5.8	1.66	35.6	50. 6
	BarC-7/DBO 5.7	2.36	24.9	75.5
	BarC-6/DBO 5.6	12.24	35.3	255.7
	BarC/DBO 5.5	1.62	34.8	106.2
	BarC-4/DBO 5.4	0.72	75.7	65.1
	BarC-3/DBO 5.3	0.91	14.4	54.6
	BarC-2/DBO 5.2	1.08	4.7	37.0
	BarC-1/DBO 5.1	1.12	4.8	33.9
2015	BarC-10/DBO 5.10	6.64	25.4	127.5
	Bar-C-9/DBO 5.9	13.68	25.1	234.6
	BarC-8/DBO 5.8	2.28	15.4	61.6
	BarC-7/DBO 5.7	12.04	35.1	235.96
	BarC-6/DBO 5.6	24.64	15.2	361.16
	BarC/DBO 5.5	14.64	99.8	476.56
	BarC-4/DBO 5.4	15.08	25.1	438.26
	BarC-3/DBO 5.3	6.28	86.9	333.4
	BarC-2/DBO 5.2	2.016	24.7	70.5
	BarC-1/DBO 5.1	1.188	24.6	33.1
2014	BarC-10/DBO 5.10	6.64	25.4	127.5
	Bar-C-9/DBO 5.9			
	BarC-8/DBO 5.8			
	BarC-7/DBO 5.7			
	BarC-6/DBO 5.6			
	BarC/DBO 5.5	8.96	34.7	244.4
	BarC-4/DBO 5.4	1.09	15.6	63.1
	BarC-3/DBO 5.3	0.9	75.2	45.5
	BarC-2/DBO 5.2			
	BarC-1/DBO 5.1			
2013	BarC-10/DBO 5.10	7.6	35.2	135.2
	Bar-C-9/DBO 5.9			
	BarC-8/DBO 5.8			
	BarC-7/DBO 5.7			
	BarC-6/DBO 5.6			
	BarC/DBO 5.5	4.72	35.4	163.5
	BarC-4/DBO 5.4	0.77	25.3	24.5
	BarC-3/DBO 5.3	11.10	14.7	15.7
	BarC-2/DBO 5.2	10.12	24.9	511.8
	BarC-1/DBO 5.1	10.28	35.6	509.8
2012	BarC-10/DBO 5.10	3.08	50.1	46.4
	Bar-C-9/DBO 5.9	0.58	59.4	10.6
	BarC-8/DBO 5.8	1.24	25.7	25.4
	BarC-7/DBO 5.7	0.76	35.4	30.2

Table 5. *Cont.*

Year	Station	DBO 5 Maximum Chlorophyll (mg m^{-3})	Depth of Maximum Chlorophyll (m)	Integrated Chlorophyll (mg m^{-2})
	BarC-6/DBO 5.6	7.36	35.3	222.5
	BarC/DBO 5.5	4.60	35.7	274.3
	BarC-4/DBO 5.4	0.79	35.7	53.9
	BarC-3/DBO 5.3	0.62	86.5	40.4
	BarC-2/DBO 5.2	0.54	25.1	21.4
	BarC-1/DBO 5.1	0.85	25.9	26.4

3.6. Time-Series Synthesis of All DBO Stations Sampled

Analysis of both the maximum chlorophyll-a concentration present within the water column as well as concentrations per m^2 integrated over the whole water column indicate that the area immediately north of the Bering Strait, DBO 3, has the highest integrated chlorophyll biomass in July (Figure 2). Higher integrated chlorophyll-a over the whole water column was also well correlated with higher maximum concentrations at any specific depth (Figure 3). In the case of all DBO sites (1–5), there is no significant correlation ($p < 0.05$) between integrated chlorophyll biomass and sampling year (Figure 2). There were also no trends observed between maximum chlorophyll-a concentrations observed in the water column and year of sampling (data not graphed, but available in Tables 1–5).

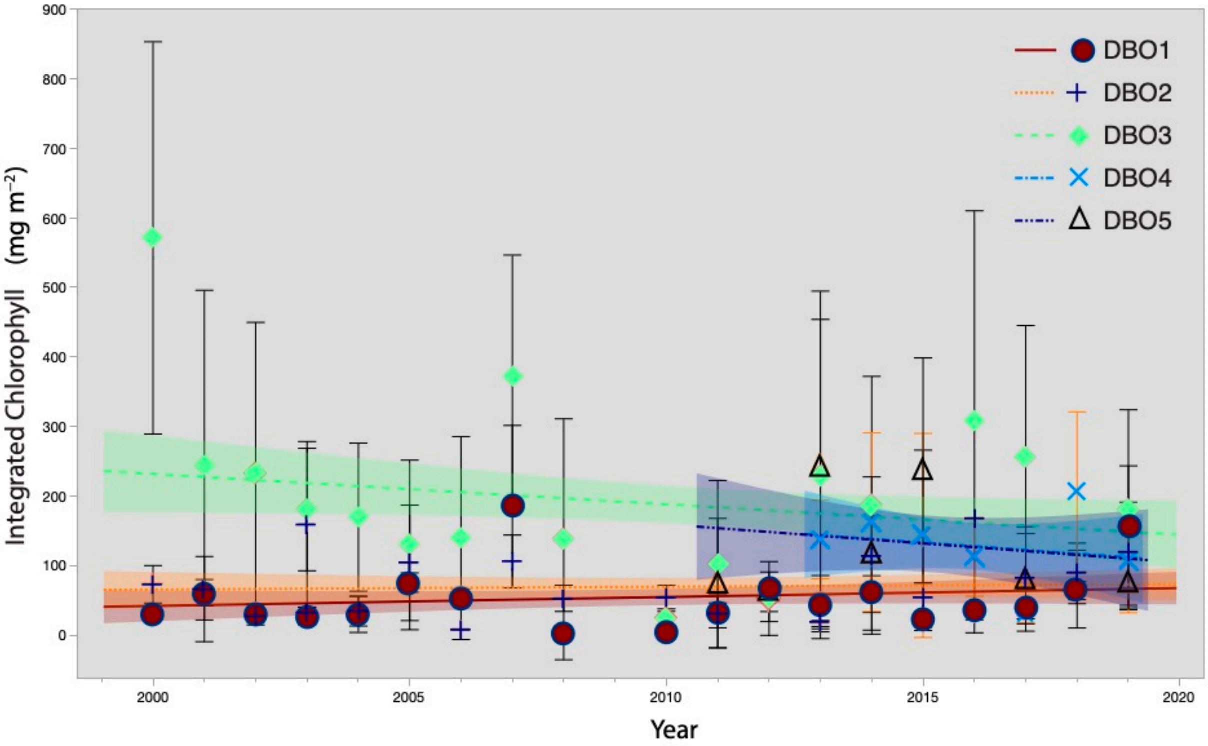

Figure 2. Variation in chlorophyll-a among all DBO stations sampled, integrated over the whole water column. Error bars shown are standard deviations from the mean in each year for each DBO region with shading representing the best linear fit for each regression line.

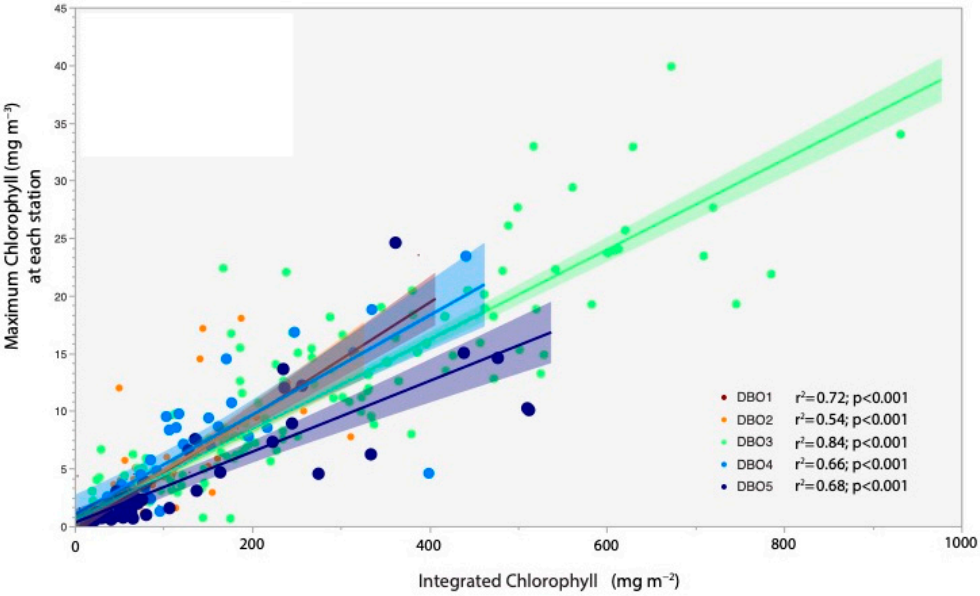

Figure 3. Correlations between integrated chlorophyll over whole water column relative to maximum chlorophyll observed at any specific depth.

3.7. Chlorophyll-a Concentrations from October 2020 Cruise

The observations of chlorophyll-a in the water column during the October 2020 cruise vary from the annual July observations. Overall, integrated chlorophyll-a in October 2020 (Figure 4) was not as high as the example from July 2018 (Figure 5). However, some stations in October, particularly in shallow water (<40 m) such as UTN1 and on the eastern side of the Bering Strait, had higher integrated chlorophyll-a than in July.

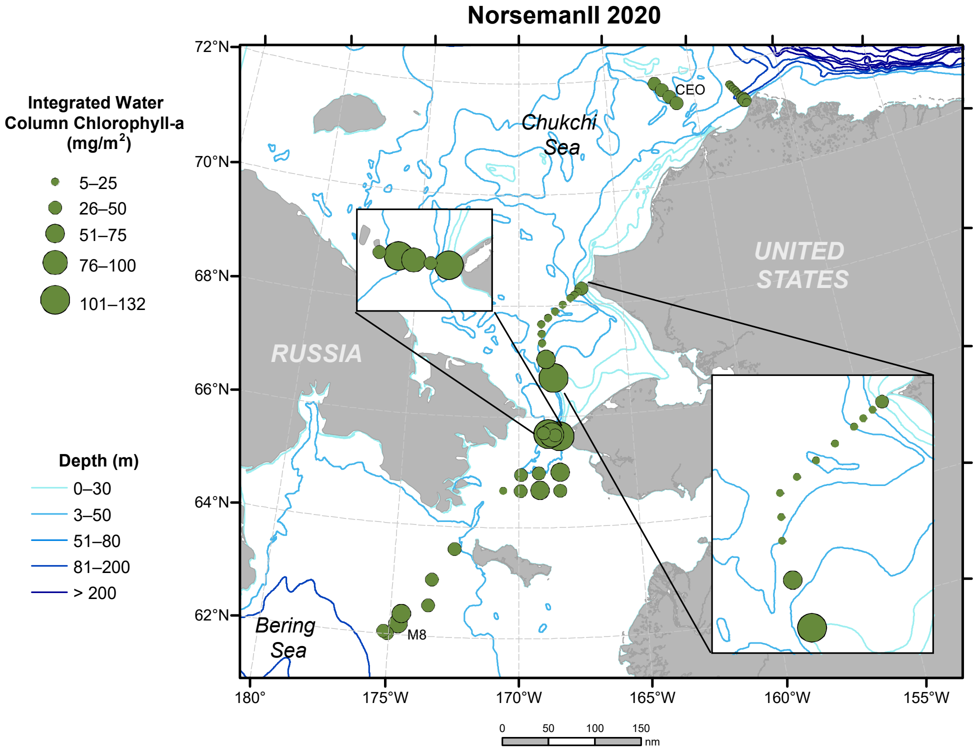

Figure 4. Spatial variation in integrated chlorophyll over whole water column during October 2020 RV Norseman II cruise.

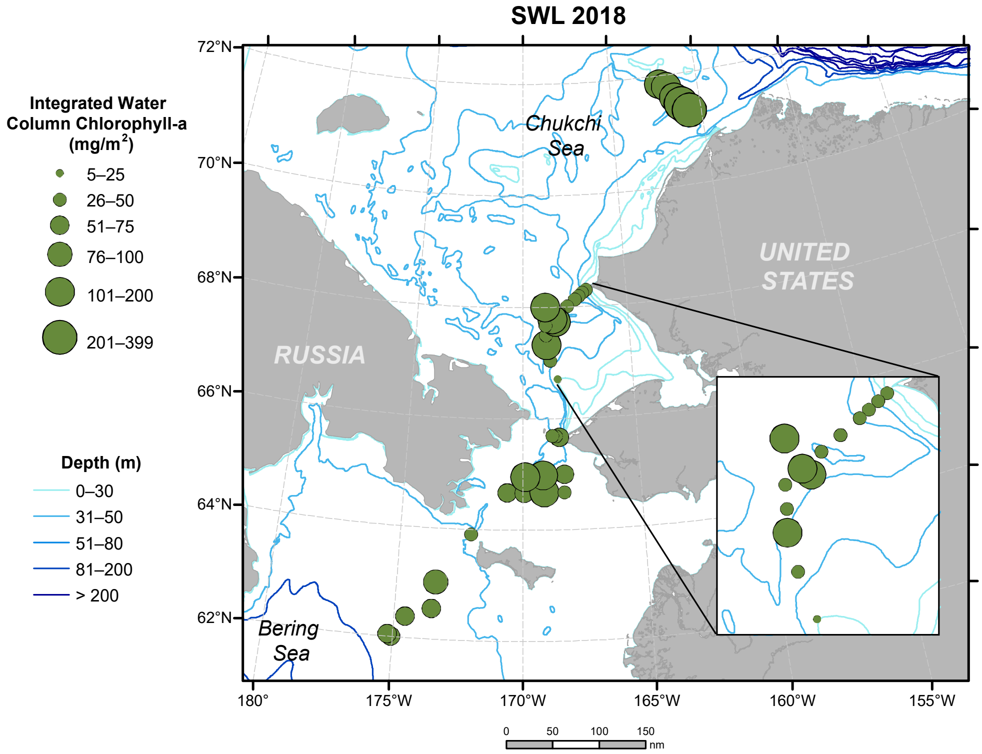

Figure 5. Spatial variation in integrated chlorophyll over whole water column during July 2018 CCGS Sir Wilfrid Laurier (SWL 2018) cruise.

Examination of the whole water column on a southeast to northwest transect of the UTN stations (Figure 6) shows that, in October 2020, nutrients, including silicate, nitrate + nitrite and total inorganic nitrogen were present in a less stratified water column at significant concentrations. By contrast, in a typical water column profile from July 2018 (Figure 7), water temperatures are higher at the surface and the water column is much more stratified. Macronutrients, including silicate, nitrate + nitrite and total inorganic nitrogen are present at lower concentrations, and primarily near the seafloor.

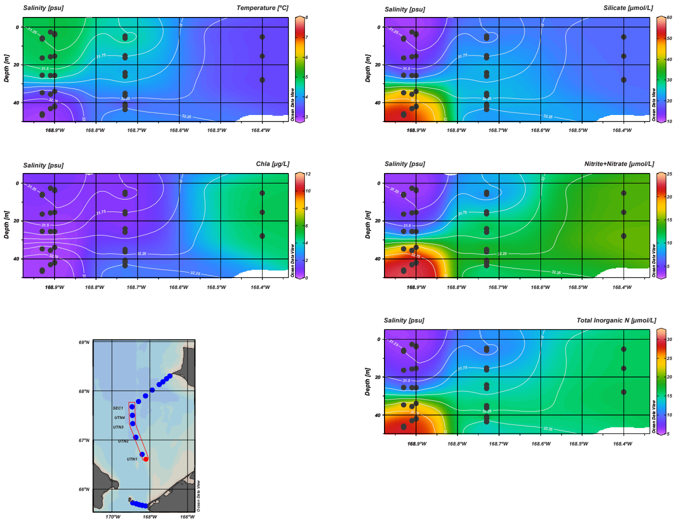

Figure 6. Distributions of water column properties on a southeast to northwest transect of the UTN stations that are part of DBO 3 from the October 2020 Norseman II cruise. Salinities are shown as white isolines and colors correspond to nutrient concentrations matching the color bars to the right.

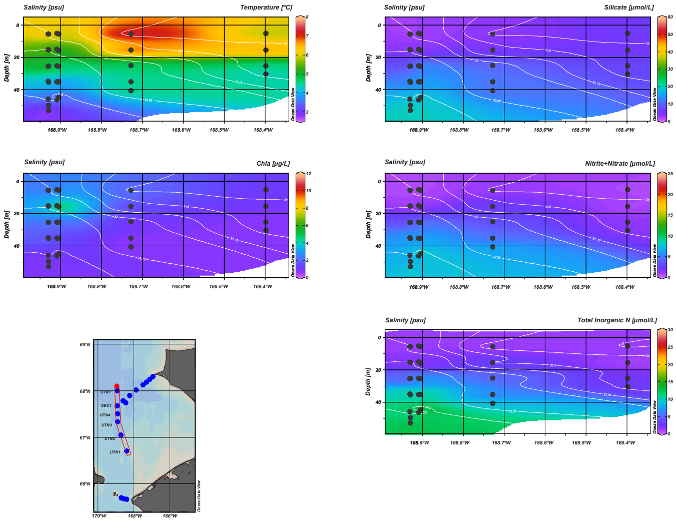

Figure 7. Distributions of water column properties on a southeast to northwest transect of the UTN stations that are part of DBO 3 from the July 2018 Sir Wilfrid Laurier cruise. Salinities are shown as white isolines and colors correspond to nutrients matching the color bars to the right.

4. Discussion

The time-series results do not indicate a significant trend towards increasing chlorophyll biomass in the DBO stations over the time period of observations, as was expected. This is a surprising result in light of satellite remote sensing analysis of chlorophyll biomass. For example, Lewis et al. [19] report a significant upward trend in chlorophyll-a biomass, particularly over the past decade in the Chukchi Sea, but other remotely sensed and in situ observations have also not identified strong positive trends in chlorophyll biomass [10,11]. Our results do not invalidate the assumption that thinning seasonal sea ice will result in higher production and higher chlorophyll biomass, but it may indicate a change in the timing of blooms, which are associated with sea ice break-up [13]. Our sampling was consistently in July, so increases in phytoplankton production observed from satellite platforms may reflect growth as sea ice breaks up earlier or returns later. Another challenge is that satellite remote sensing of chlorophyll requires chlorophyll biomass to be near the sea surface, but in many of the DBO stations, and particularly in DBO 1 (Table 1) and DBO 4 (Table 4), by the time of sampling in July, the maximum chlorophyll-a biomass is well below the sea surface (>25 m) and cannot be observed from satellite platforms. DBO 2 and some stations in DBO 3 are, on the other hand, regions where at least some stations have well-mixed water columns with maximum chlorophyll biomass close enough to the surface (Tables 2 and 3) to be more suitable for satellite- based comparisons. Even where satellite sensed data indicates changes, other complexities can arise. For example, due to earlier recent ice break up in the Gulf of Anadyr in the northern Bering Sea, there may be a trend towards lower productivity in the western Bering Strait in June, when previously there was a stronger bloom associated with melting sea ice advected through the Strait [11]. On the other hand, the expansion of blooms into shoulder months such as October [7] is consistent with our own observations of a modest bloom in October 2020 in the Bering Strait region. Wind mixing in the absence of sea ice appears to have brought nutrients higher into the water column and may have also mobilized phytoplankton cells from at or near the sea floor, so it uncertain whether this October bloom represents new cell division or simply viable cells being brought into sufficient light in the presence of inorganic nutrients. Moreover, since the DBO stations were located specifically in areas known to have high production, it is also possible that the increased production observed from satellite platforms represents production in areas outside of the DBO station grid, where conditions may have become more favorable to promote higher production. Recent, as yet unpublished work [16] indicates that, in the month of July in the past couple of decades, there are no trends in satellite-based estimates of chlorophyll within most of the

DBO areas, although increases outside the DBO areas are present in the Pacific-influenced Arctic. These results are consistent with the results we present here that do not indicate any enhanced chlorophyll biomass in the already productive DBO regions that have been identified. Thus, taken in this context, our data indicate that caution is advised in assuming that reductions in seasonal sea ice are directly related to significant increases in chlorophyll biomass in productive areas on Arctic shelves.

There are likely also biogeochemical factors at work. Increasing flow through the Bering Strait over the past several decades is associated with an increasingly freshened water flux [20,21]. This promotes stratification, which could limit inorganic nutrients from reaching surface waters once depleted, thus promoting biological production. In addition, fresher water flowing through the Bering Strait is most closely associated with the Alaska Coastal Water mass, which is nutrient depleted [15]. Nevertheless, the evidence provided in this study for water column mixing late in the season (October) suggests that there are mechanisms such as fall storms that can provide nutrients to surface water in the absence of sea ice, which used to be present at that time until recently. This is coupled with a break-up of the deep chlorophyll layer in the water column, which brings still viable phytoplankton cells from near or on the sea floor into the photic zone and potentially supports production over a longer seasonal scale.

These complexities indicate that scale-related, timing-related and depth-dependent sampling, whether from satellite or from in situ platforms, introduces challenges in identifying consistent trends in chlorophyll biomass and related biological productivity, which may be occurring due to declines in sea ice persistence in the Pacific-influenced Arctic. The ultimate resolution of whether sea ice declines unambiguously promote greater production requires additional sampling of chlorophyll and associated nutrients and water column structure. While satellite platforms provide a synoptic view of near-surface chlorophyll conditions, shipboard observations sustained over many years will also play a role in determining the future trajectory of biological production in the Pacific Arctic.

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Data Availability Statement: Data used in this study are available from the Arctic Data Center (https://arcticdata.io/catalog/edit/portals/DBO) and the Pacific Marine Arctic Regional Synthesis data archive (http://pacmars.eol.ucar.edu/).

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