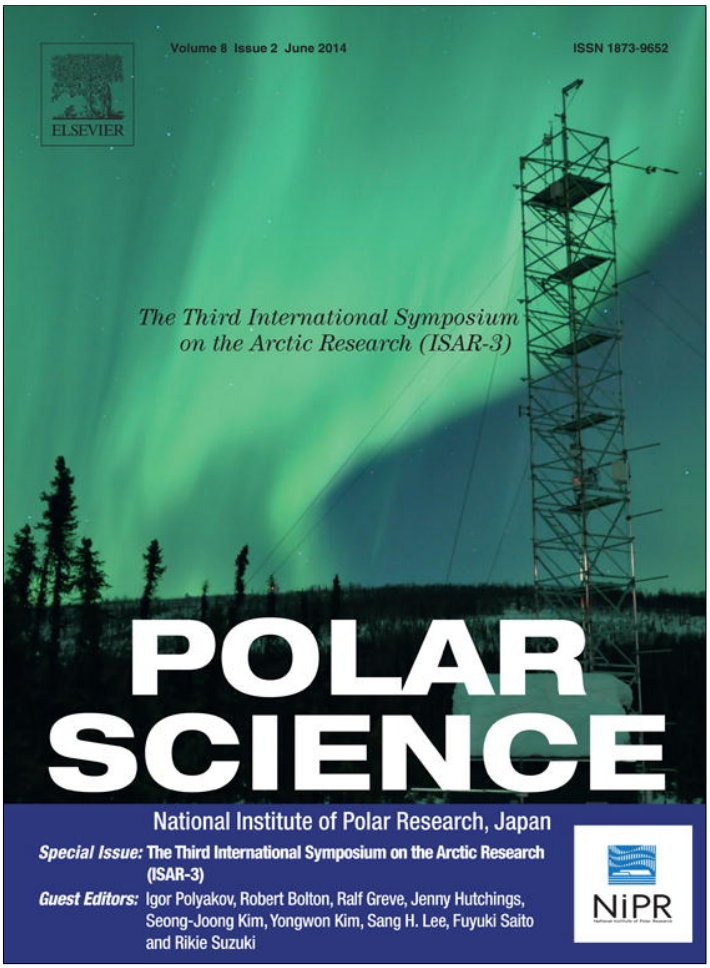

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Assessing algal biomass and bio-optical distributions in perennially ice-covered polar ocean ecosystems

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Abstract

Under-ice observations of algal biomass and seasonality are critical for understanding better how climate-driven changes affect polar ocean ecosystems. However, seasonal and interannual variability in algal biomass has been studied sparsely in perennially ice-covered polar ocean regions. To address this gap in polar ocean observing, bio-optical sensors for measuring chlorophyll fluorescence, optical scattering, dissolved organic matter fluorescence, and incident solar radiation were integrated into Ice-Tethered Profilers (ITPs). Eight such systems have been deployed in the Arctic Ocean, with five profilers completing their deployments to date including two that observed an entire annual cycle in the central Arctic Ocean and Beaufort Sea respectively. These time series revealed basic seasonal differences in the vertical distributions of algal biomass and related bio-optical properties in these two regions of the Arctic Ocean. Because they conduct profiles on daily or sub-daily scales, ITP bio-optical data allow more accurate assessments of the timing of changes in under-ice algal biomass such as the onset of the growing season in the water column, the subsequent export of particulate organic matter at the end, and the frequency of intermittent perturbations, which in the central Arctic Ocean were observed to have time scales of between one and two weeks.

Keywords: Phytoplankton; Bio-optics; Profiler; Arctic Ocean

1. Introduction

Pelagic ecosystems in polar oceans are expected to experience significant climate-driven changes in the upcoming decades, especially the high-latitude ocean regions that currently experience perennial ice cover. In regions of the Arctic Ocean that remain ice covered year-round, both the thickness and the areal extent of perennial, multi-year ice are decreasing (Kwok and Rothrock, 2009; Laxon et al., 2013; Tucker et al., 2001). Decreasing thickness of sea ice allows more sunlight into the under-ice environment, deepening the ocean's euphotic zone and increasing the amount of light energy available for photosynthesis and primary production (Zhang et al., 2010). Decreases in the areal extent of perennial ice cover exposes more of the upper Arctic ocean to wind forcing during summer (Rainville et al., 2011), increasing the flux of kinetic energy into the surface ocean and potentially altering the nutrient supply to the euphotic zone during the time of year when light levels are sufficient to support

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photosynthesis (Carmack et al., 2004; Yang et al., 2004). These two phenomena represent significant alterations to the current photosynthetic environment in perennially ice-covered ecosystems, where the extant algal assemblages have evolved to survive in relatively quiescent, low-light conditions.

The impact of future loss and thinning of perennial ice cover on polar algae and primary production is difficult to predict. Uncertainties are exacerbated by the lack of a synoptic, comprehensive climatology showing the present spatial, seasonal, and interannual variability of phytoplankton in those Arctic marine ecosystems that currently experience year-round ice cover. Not having the observational capability for generating this much-needed climatology of under-ice algal biomass and related biogeochemical properties represents a critical gap in the nominally 'global' ocean observing infrastructure. Improved measurement of basic ecosystem parameters in perennially ice-covered ocean regions is one focus of the Arctic Observing Network (AON), whose objectives specifically include the development of autonomous systems capable of providing such observations in the central Arctic Ocean (National Science Foundation, 2007).

One of the most successful ocean observing programs developed for ice-covered regions of the Arctic Ocean is the Ice-Tethered Profiler (ITP), which since 2004 has conducted long-term, autonomous vertical sampling of the ocean's top 750 m across much of the central Arctic. The ITP was initially developed to measure basic physical properties of the water column including ocean temperature and salinity (Toole et al., 2006, 2011), and over 70 such ITPs have been deployed to date. ITP-enabled observations of the physical structure of the upper water column have considerably advanced our understanding of heat and salinity variations in the central Arctic Ocean (Timmermans et al., 2010, 2011), the distribution and seasonality of dissolved oxygen (Timmermans et al., 2010), and Arctic ice–ocean interactions, especially with respect to the role of ocean heat content on sea ice (Toole et al., 2010). ITPs are often deployed in conjunction with other autonomous systems including those that monitor ice mass (e.g., Ice Mass Balance buoys, Richter-Menge et al., 2006), atmospheric chemistry (e.g., O-buoy, Knepp et al., 2010), and ocean current structure under the ice (e.g., Autonomous Ocean Flux Buoys, Shaw et al., 2008). Such multi-platform 'Ice-Based Observatories' (IBOs, see Proshutinsky et al., 2004) are a source of vital data for building a better understanding of the Arctic climate system. *In situ* profilers like the ITP and the Polar Ocean Profiling System (Kikuchi et al., 2007) provide the necessary observations of ocean physical properties in the top half kilometer of ocean directly below.

Motivated by the ITP's contribution to understanding the spatial, seasonal, and interannual variability in the physical structure of upper Arctic Ocean, and motivated by progress in long-term use of bio-optical sensors on open-ocean profilers at lower latitudes (Bishop and Wood, 2009; Boss et al., 2008a), an effort was begun in 2009 to add bio-optical capabilities to the Arctic ITP network. The primary goal of this effort was to collect the first-ever daily and sub-daily observations of the vertical distributions of algal biomass, related bio-optical properties, and underwater irradiance in the top few hundred meters of the Arctic Ocean. These observations would provide better quantification of the spatial, seasonal, and interannual variability that algal assemblages exhibit in perennially ice-covered ecosystems in central Arctic Ocean. Ecological phenomena of interest included the timing of the onset and the end of the summer growing season, and the temporal dynamics of algal biomass under ice cover. Of equal interest was the subsequent export of organic matter to depth: its timing and magnitude during the summer growing season and also at the end of summer when photosynthetic rates are minimal. Bio-optical approaches for studying these phenomena have a long history of use in lower-latitude ocean ecosystems. Their successful integration into autonomous platforms such as the ITP could dramatically improve our understanding of seasonal and interannual variability in basic ecological properties of under-ice ecosystems in the Arctic.

2. Technology and methods: ITP-based bio-optical observations

A prototype bio-optical sensor suite was developed for use on Ice-Tethered Profilers to meet specific measurement criteria for ensuring high data quality over the expected year-plus deployments, and to meet specific operational criteria necessary for incorporating new sensors into the existing ITP system (refer to Krishfield et al., 2008 for a description of the base ITP technology). The bio-optical sensor suite included a customized 'triplet' fluorometer (*ECO* FLbb-CD, WETLabs Inc.) to measure chlorophyll fluorescence, dissolved organic matter fluorescence, and optical scatter (Table 1), as well as an irradiance detector (PAR-LOG, Satlantic Inc.) to measure the intensity of the photosynthetically active radiation (PAR) in the visible wavelengths in the water column. The

Table 1
Performance specifications for the combination fluorometer-backscatter sensor used in this study (WETLabs *ECO* FLbb-CD). Values for sensitivity reflect typical values reported in calibration data sheets supplied with the sensors.

ECO FLbb-CD parameter	Wavelengths (nm)	Range	Sensitivity	Units
Scattering	700/700	0–3	1.8×10^{-6}	$m^{-1}\ sr^{-1}$
Chlorophyll fluorescence	470/695	0–30	0.007	$\mu g\ l^{-1}$
CDOM fluorescence	370/460	0–375	0.09	ppb

fluorometer and radiometer were mounted on aluminum struts affixed to the top endcap of the ITP, oriented side-by-side in acetal clamps and looking upward (Fig. 1). These sensors were placed adjacent to the standard conductivity, temperature, and depth (CTD) sensor used on all ITP systems (SBE41CP, Sea-Bird Electronics Inc.), and all of the ITPs described in this study also included a SBE43I dissolved oxygen sensor. Placement of the bio-optical sensors at the very top of the ITP endcap is optimal because measurement self-shading of the irradiance sensor by the ITP is minimized. As well, the view orientation of the fluorometer (i.e., directly up) minimizes any possible reflection of the profiler itself into the sensor's field of view. Furthermore, locating the fluorometer adjacent to the irradiance sensor allows for the use of a single copper shutter plate to provide physical protection for both sensors and to help reduce potential biofouling by virtue of the toxic effects of copper (Manov et al., 2004). During an ITP profile, an electromechanical actuator (Bioshutter-II, Satlantic Inc.) rotates this shutter out of the sensors' sample volumes to enable measurement of the water volume close to the CTD intake (as depicted in Fig. 1). When the shutter is closed, this bio-optical sensor suite is compact enough so that the entire system can fit through the standard 28 cm (11″) diameter hole that is drilled through sea ice to deploy an ITP.

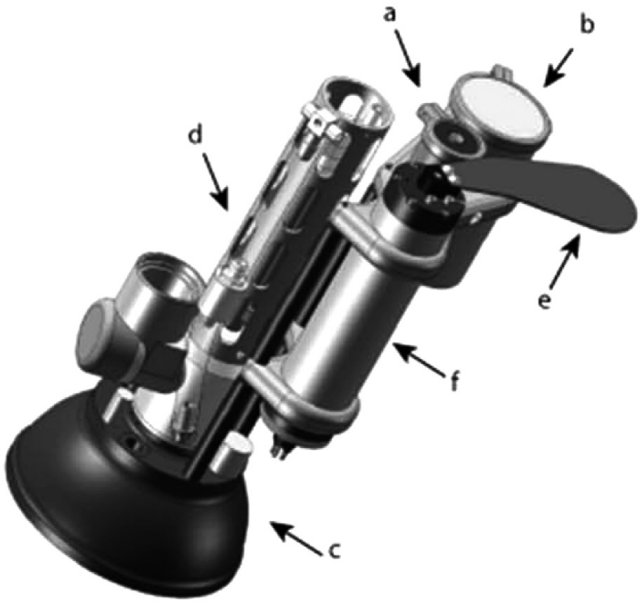

Fig. 1. A Satlantic PAR irradiance sensor (a) and a WETLabs FLbb-CD 'triplet' fluorometer (b) were mounted to the ITP's top endcap (c) adjacent to the Seabird SBE41CP CTD (d) with integrated SBE43I dissolved oxygen transducer. A copper shutter (e) protects the optical faces of both sensors and is rotated out of the way during profiling (as pictured) by an electromechanical actuator (f).

Engineering modifications at the factory were required to increase the manufacturers' pressure ratings of the fluorometer and the shutter actuator, to meet the ITP's depth requirements and payload limitations. A titanium housing on the irradiance sensor saved considerable weight compared to the previous stainless steel version, an important concern for ballasting ITPs and trimming their buoyancy. Custom low-power control electronics placed inside the ITP endcap interfaced these bio-optical sensors with the ITP host controller and provided special power-monitoring features that stretched bio-optical sampling to well over a year. These electronics sample and then report bio-optical data at 4 Hz, four times faster than the CTD, providing finer-scale vertical assessment of bio-optical structure in the water column. At an ITP's typical profiling speed of $\sim$0.25 ms^{-1} along the tether, this corresponds to $\sim$6 cm vertical resolution. Bio-optical data were merged with the physical and engineering ITP data streams and included in the daily ITP data transmissions over an Iridium satellite link.

The triplet fluorometers used on these ITPs were calibrated by the manufacturer following factory protocols. The scale factor for chlorophyll fluorescence was determined using a monoculture of phytoplankton (*Thalassiosira weissflogii*), calibrated against chlorophyll concentrations as determined by the absorption method. The scattering scale factor was determined using suspensions of proprietary microspheres. The CDOM fluorescence scale factor was determined by calibrating against solutions of quinine sulfate dihydrate. The manufacturer also determined the 'dark' offsets of each optical measurement in the absence of any sample, by recording apparent fluorescence and scatter while the triplet's windows were blocked with black electrical tape. Additional efforts to refine these calibrations further were deemed impractical, given the environmental variability in optical properties that these sensors were expected to encounter during long-

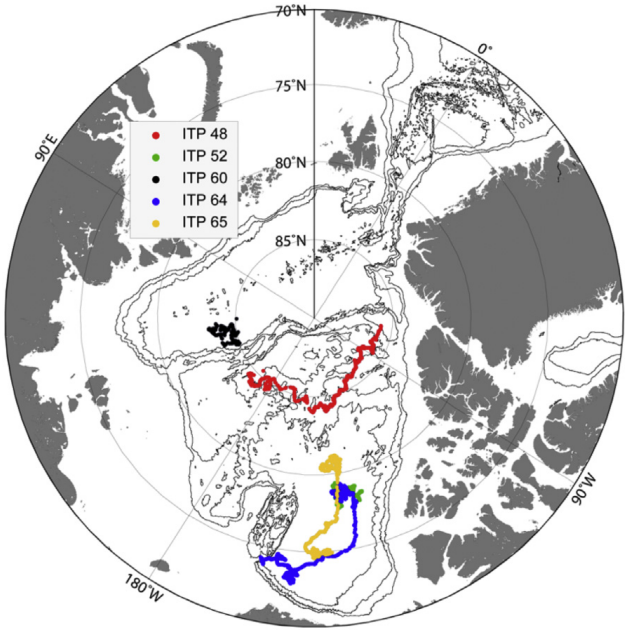

Fig. 2. Drift tracks of the five bio-optical ITPs described in this study. The two in the Transpolar Drift (ITP48 & 60) are drifting counterclockwise in this view. The remaining three in the Beaufort Sea are drifting generally southward.

term deployments through various regions of the Arctic Ocean. More accurate estimates of chlorophyll concentration from *in vivo* fluorescence would require knowledge of algal taxonomic composition and photophysiology, which is impossible to predict with confidence for an ITP traveling hundreds of kilometers over a seasonal period. Similarly, spectral properties of marine CDOM differ considerably across the Arctic Ocean (Stedmon et al., 2011), precluding more refined calibrations given that the excitation and emission maxima of environmental CDOM varies in an unpredictable manner. Optical scattering also involves similar challenges for more refined calibration given expected environmental variability in composition and size distribution of particles. For these reasons, ITP measurements of chlorophyll fluorescence, CDOM fluorescence, and scattering intensity should each be considered as operational estimates of the concentration of chlorophyll, CDOM, and scattering respectively, not as direct measurements of these properties in a strict sense.

3. Observations: bio-optical distributions and seasonality under perennial sea ice

3.1. Deployments

Five ITPs were outfitted with this prototype bio-optical sensor suite and were deployed in late summer of 2011 and 2012 as part of the Arctic Observing Network (Fig. 2, Table 2). The 2011 deployments were located in the Transpolar Drift above 84° N (ITP48) and in the Beaufort Sea around 78° N (ITP52). The primary profiling mode of these particular ITPs was to complete two excursions to ~200 m before conducting a third excursion to ~760 m, resulting in a 'deep' pair of profiles (down, then up) every third cycle. The interval between each down- or up-profile was set at 6 h in the months between March and October inclusive, but from November through February the time spent at depth between profiles was increased to 18 h to conserve battery power and extend operational lifetime. During this winter period the profiling pattern was also altered so that every second pair of profiles went to ~750 m. All ITPs were programmed to stop upward motion at ~7 m to avoid contact with the overlying sea ice. Bio-optical data from ITPs are therefore not collected in the very top of the water column, immediately under ice cover.

Of the two profilers deployed in 2011, ITP52 operated for approximately 110 days and traveled a total of 925 km along-track in the Beaufort Sea before all transmissions ceased, presumably due to destruction of the ice floe containing the system (other buoys deployed on the same floe ceased functioning around the same time). In contrast ITP48 in the Transpolar Drift continued to operate for over 14 months, performing 1370 vertical profiles and traveling approximately 3085 km cumulatively. ITP48's bio-optical time

Table 2
Deployment specifics for 5 bio-optically equipped Ice-Tethered Profilers described in this study. The final column indicates how many usable profiles of bio-optical data were collected from the total number of profiles of each unit. ITP locations with abbreviations 'TPD' were deployed initially in the Transpolar Drift; those with 'BEA' were deployed in the Beaufort Sea.

ITP	Dates operational	Deployment location	Ice thickness	Distance covered	Profiles	Bio-optical profiles
48	9/12/2011–11/19/2012	84° 48.8 N, 166° 12.9 E (TPD)	1.2 m	3085 km	1370	1299
52	8/5/2011–11/23/2011	78° 0.4 N, 139° 55.5 W (BEA)	4.2 m	925 km	377	373
60	9/8/2012–12/23/2012	85° 3.4 N, 122° 43.0 E (TPD)	1.5 m	1200 km	260	131
64	8/28/2012–8/24/2013	78° 46.5 N, 136° 39.8 W (BEA)	Open water	3324 km	1124	1057
65	8/27/2012–6/29/2013	80° 53.4 N, 137° 25.8 W (BEA)	1.5 m	2671 km	904	871

series captured the end of the 2011 growing season as well as the entire growing season of 2012. This profiler would likely have continued to operate longer had the drifting surface ice not brought it to waters shallower than its 790 m long tether, which likely grounded the anchor and destroyed the tether. The three additional ITPs in 2012 were also deployed in these same general areas of the Transpolar Drift (ITP60) and the Beaufort Sea (ITP64 and ITP65). One of these 2012 systems (ITP64) also operated for nearly a year, traveling over 3300 km during its 12 month operation in the Beaufort Sea and collecting 1124 vertical profiles. Note that ITP64 was deployed in open-water conditions, freely floating, because no ice floes were found at that time on which an ITP could be safely installed. Newer ITPs in 2012 incorporated a tapered, more buoyant surface package that allows for open-water deployments and which provide a means to survive fall freeze-up of sea ice.

3.2. Bio-optical vertical structure and seasonality

The periodic 'deep' profiles to ~750 m provided important information regarding the behavior of the optical signals measured by the triplet, especially the measurements of chlorophyll fluorescence. The average apparent chlorophyll concentration ranged between ~0.20 and 0.29 μg l^{-1} at 700 m depth for these five ITPs, even in mid-winter. This likely represents an elevated instrument offset rather than an actual chlorophyll biomass of those magnitudes, given that mid-winter algal biomass at such depths is expected to be very low if not below the level of detection of these fluorometers (0.015 μg l^{-1}). Consequently all chlorophyll fluorescence data presented in this study include a correction that subtracts an empirically determined instrument offset, calculated as the average apparent chlorophyll measured between 690 and 710 m. For all subsequent plots presented in here, data from the interleaving 'shallow' profiles between 7 and 200 m or vice-versa are omitted in order to eliminate any bias that might arise from correcting profiles of fluorescence data with 'deep' offsets computed from an earlier or later profile. Some degree of offset may also occur in the CDOM and scatter data but this is more difficult to assess empirically. With respect to CDOM fluorescence, concentrations of CDOM can reasonably be expected to be nonzero in deep Arctic waters (Stedmon et al., 2011) and thus no analogous 'deep' background measurement is available. For optical scattering, it may similarly be inappropriate to assume low or no scattering at depth during midwinter from which an empirically derived offset could be computed. Consequently, the CDOM fluorescence and the scattering data are presented here as reported by the sensor, converted from raw counts to the relevant physical units but uncorrected for any offset beyond that determined during factory calibration.

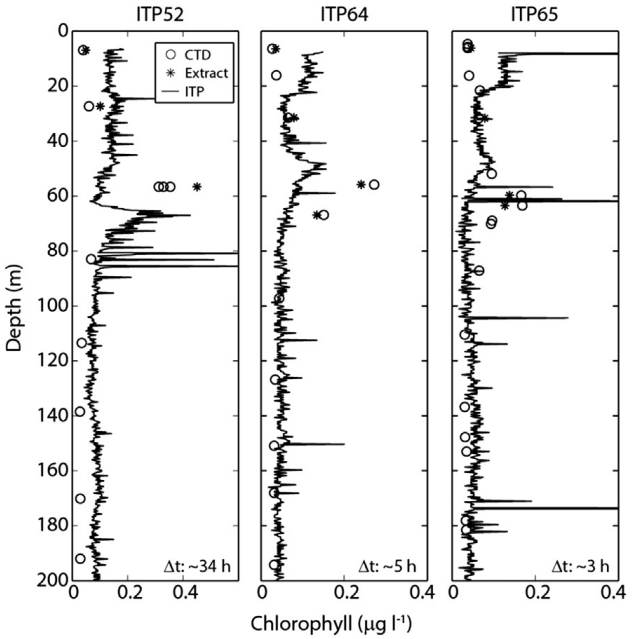

Fig. 3. Vertical distributions of chlorophyll in the top 200 m near the three ITP deployment sites in the Beaufort Sea (ITPs 52, 64, and 65). Traces indicate the *in vivo* fluorescence reported by each ITP for its first full profile. Symbols indicate extracted chlorophyll measurements from bottle samples from hydrocasts taken nearby (asterisks), with the corresponding *in vivo* chlorophyll fluorescence measurements from a rosette-mounted fluorometer (open circles). The difference in time (in hours) between the hydrocast and the subsequent first full ITP profile is noted at the bottom of each panel.

For the three ITPs deployed in the Beaufort Sea, independent chlorophyll measurements were available from hydrocasts performed near to the ITP deployment location, roughly within one day prior to the first full-depth ITP profile. Chlorophyll concentrations on discrete bottle samples taken during these hydrocasts, as determined by the extraction method (Fig. 3, asterisk symbols), were not uniformly greater or less than the chlorophyll concentration estimated by the *in situ* fluorometer used on the rosette (open circles). Discrepancies between these two standard approaches ranged between 12% and 40%. Once corrected for the empirically determined deep offset, chlorophyll measurements from these ITPs (Fig. 3, traces) compared favorably with those from hydrocasts, capturing vertical structure in the top 100 m (e.g., elevated concentrations between 60 and 80 m for ITP52) and closely matching the low levels seen deeper in the water

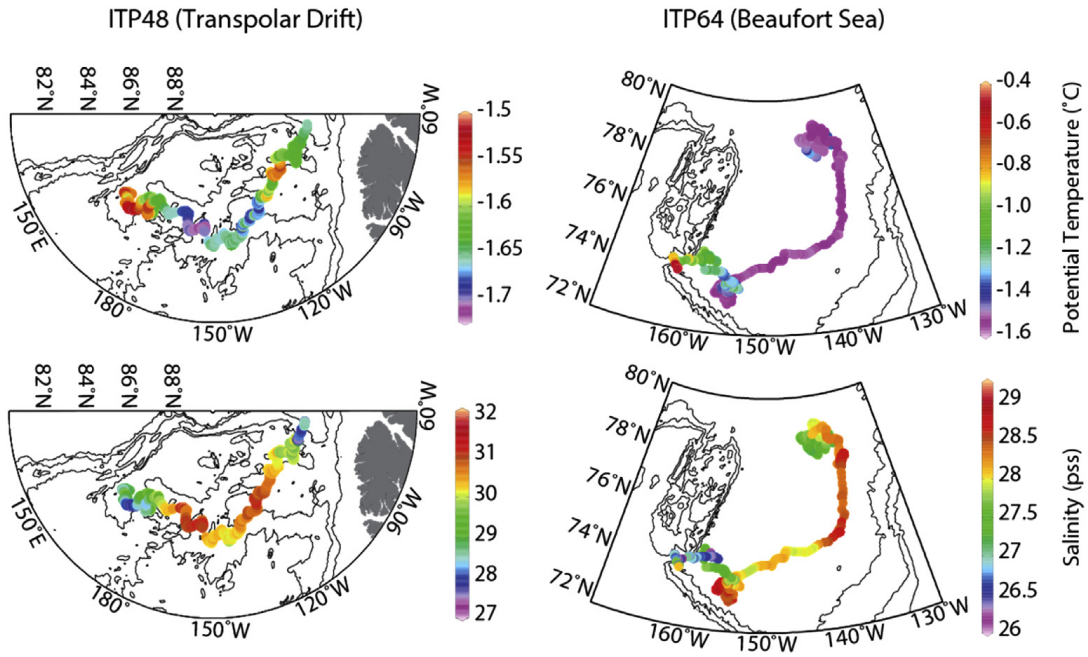

Fig. 4. Potential temperature (top) and salinity (bottom) at 15 m depth along the drift tracks of ITP48 (left column) and ITP64 (right column).

column. Differences in the time and location of these hydrocasts and the subsequent first full ITP profile preclude an exact comparison of vertical distributions.

Numerous 'spikes' can also be seen in the ITP-derived chlorophyll and scattering profiles that are not apparent in the hydrocasts. These presumably reflect algal aggregates or other larger particles, akin to what Boss et al. (2008b) inferred when using similar optical sensors on autonomous floats in the North Atlantic. Such features can be easily disturbed or erased when performing standard hydrocasts from ships and especially icebreakers, which can strongly alter local water column structure in the top tens of meters. Such features are less likely to be missed or disturbed when profiling with an ITP given its relatively slower vertical speed, smoother vertical profiling rate, smaller size, and fast (4 Hz) bio-optical sampling rate.

During its 14 month journey in the Transpolar Drift, ITP48 passed through several different water masses, as indicated by changes in the temperature–salinity relationships measured by its onboard CTD (Fig. 4, left column). For this initial analysis we used the physical properties at the 15 m depth horizon to discriminate roughly between water masses, in order to help determine if apparent days-scale changes in bio-optical profiles could be attributed to sampling different water masses. In the Beaufort Sea, ITP64 similarly experienced changes in the water masses it sampled over its twelve months of operation (Fig. 4, right column). With ITP48, movement of the overlying ice brought the profiler into a different water mass at the beginning of December 2011, which appears in the bio-optical time series as a baseline shift most clearly in the scattering and CDOM data (Fig. 5, left column). For ITP64, the sharp shift in CDOM seen around April 2013 (Fig. 5, right column) coincides with a freshening in salinity as the profiler encountered the southwest boundary of the Beaufort Gyre. These co-occurring changes in water column physical structure allow us to discount the hypothesis that the observed bio-optical discontinuities reflect a sudden change in sensor behavior.

Beyond these baseline changes in bio-optical distributions that can be attributed to encountering different water masses, the three bio-optical variables all show seasonal trends related to the growth of under-ice algal assemblages (Fig. 5). For ITP48 in the central Arctic above 85° N, chlorophyll and scattering maxima occurred high in the water column in the top ~20 m. Application of the offset correction resulted in peak summertime chlorophyll concentrations on the order of 0.45 μg l^{-1}, not the apparent ~0.7 μg l^{-1} that would be indicated by not accounting for this offset. For ITP64 in the Beaufort Sea, apparent chlorophyll was slightly lower in magnitude and chlorophyll and scattering maxima were found deeper in the water column, around 70 m during mid-season. This difference is likely due to the insolation that the Beaufort Sea receives compared to the deep central Arctic. Being at lower latitudes, the Beaufort experiences higher levels

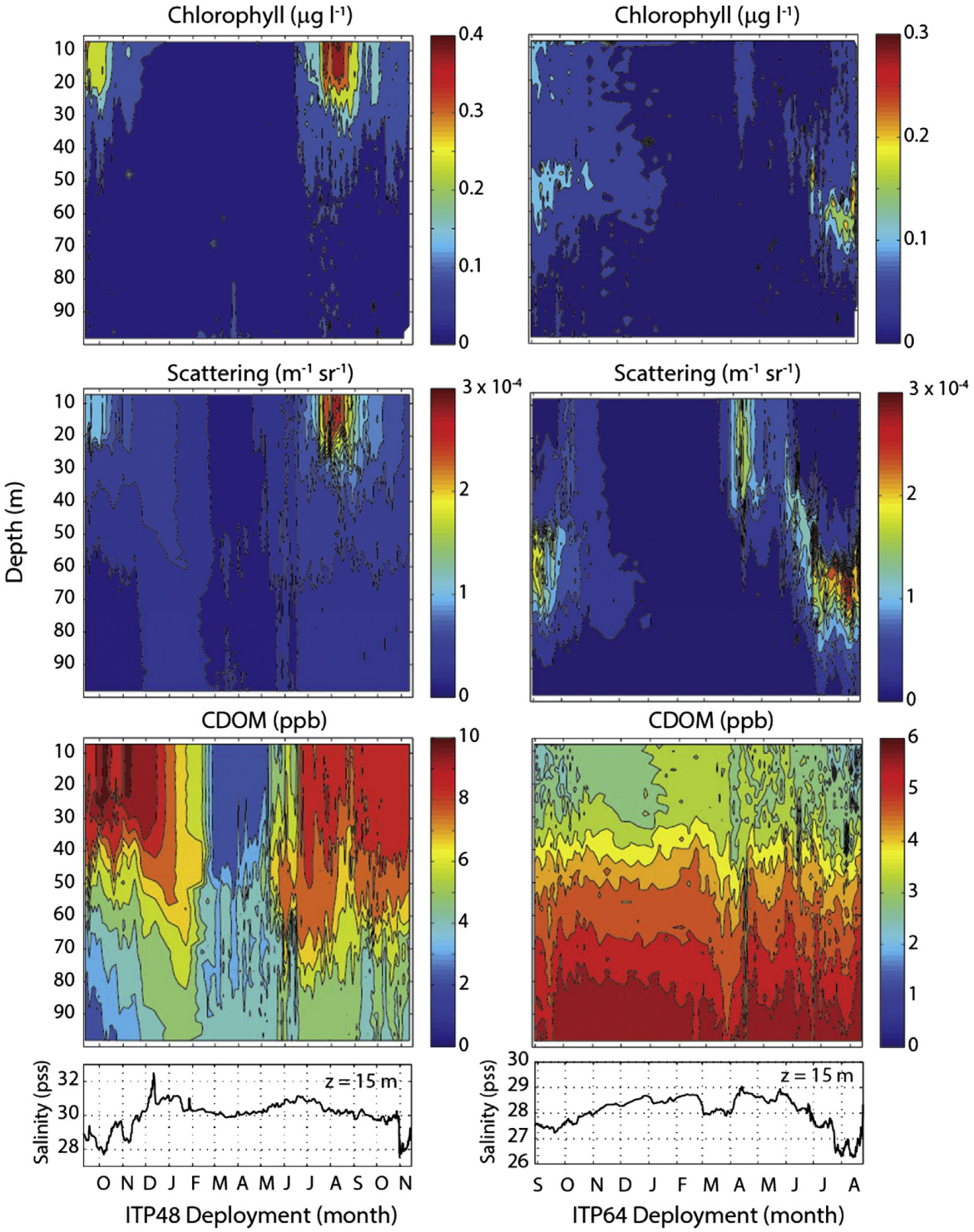

Fig. 5. Depth–property plots of chlorophyll fluorescence (top row), scattering (second row), and CDOM fluorescence (third row) for the top 100 m for the entire time series of ITP48 (left column, 14 months) and ITP64 (right column, 12 months). Before contouring, all profiles were smoothed with a running average corresponding to roughly 1 m in the vertical. Chlorophyll data were corrected for instrument offset as described in the text. Corresponding time series of salinity at 15 m depth are shown for each ITP.

of insolation in general, and receives more light earlier in the year. This basic difference in insolation would presumably lead to rising chlorophyll levels occurring earlier in the season in the Beaufort, which is in fact observed in the ITP64 time series: chlorophyll begins to increase noticeably in March and April, compared to June and July for ITP48. The higher surface insolation at lower latitudes would also allow chlorophyll to

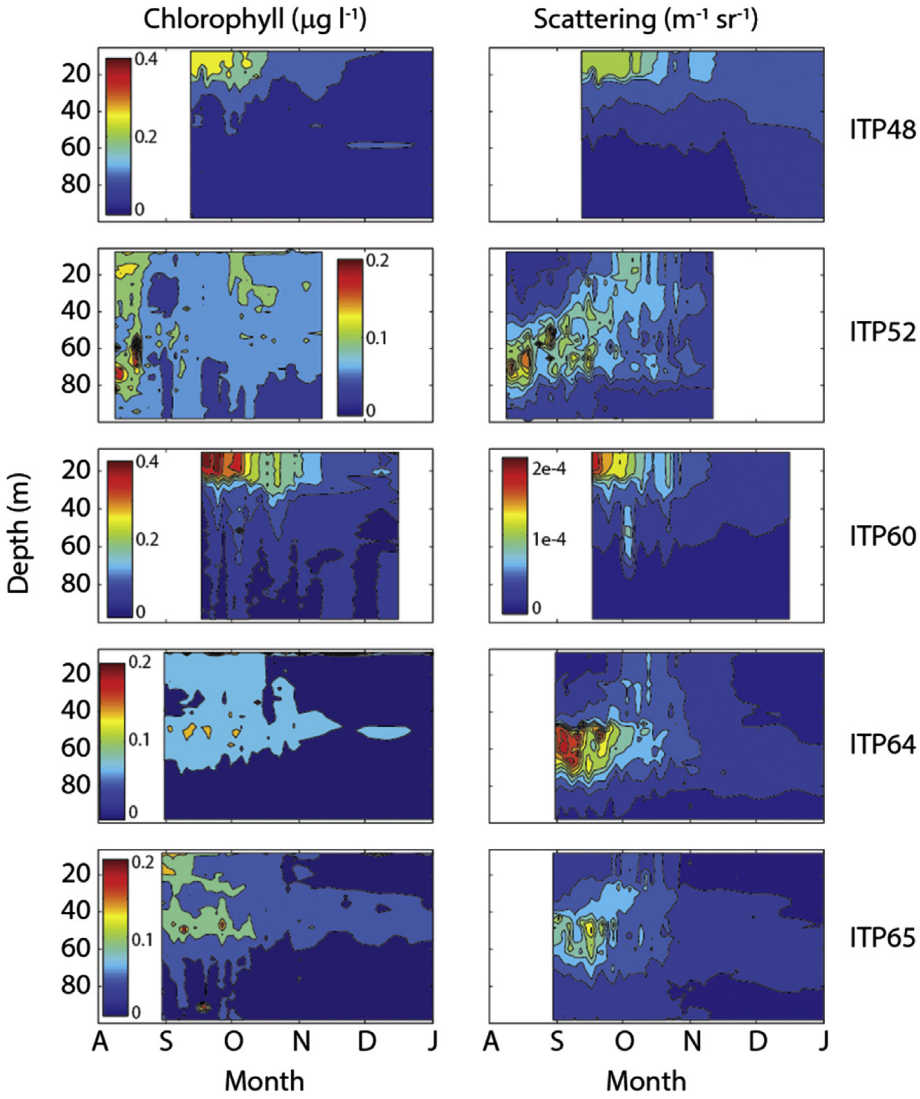

Fig. 6. Patterns in chlorophyll biomass (left column) and optical scattering (right column) in the vertical distributions measured by these five ITPs between August and the end of December of 2011 (ITPs 48 and 52; top two rows) and 2012 (ITPs 60, 64, and 65; bottom three rows). ITPs 48 and 60 were deployed in the Transpolar Drift; the other three were deployed in the Beaufort Sea.

survive deeper in the water column, which is seen in the Beaufort Sea where chlorophyll and scattering maxima progressively deepen between April and June. Observed concentrations of CDOM also reveal seasonal trends but its temporal evolution is more complex because only part of the CDOM signal is related to biological activity (bottom row). Refractory CDOM also contributes to this signal and so a non-seasonal component can be expected. In these two annual time series, vertical distributions of CDOM differ strongly between the Beaufort and the central Arctic, with the former showing a strong seasonal component and the latter showing highest concentrations deeper in the water column.

These broad regional differences between the central Arctic Ocean and the Beaufort Sea are more broadly confirmed with data from the remaining three profilers (Fig. 6). The two profilers deployed in the Transpolar Drift (ITP48 & 60) both indicate maxima in algal biomass closer to the ice cover, within the top 30 m. The three deployed in the Beaufort Sea all exhibit chlorophyll maximum levels deeper in the water column, around 50 m or below. The previously described effect of lower incident sunlight at higher latitudes could explain this general trend, all other factors being equal. Scattering magnitudes also show common trends at the end of the growing season in these different regions: in the Transpolar Drift scattering intensity decreases with depth in each, whereas in the Beaufort Sea the scattering layer at ~50 m (which corresponds with the chlorophyll layer) gradually shoals between October and November. Presumably this latter observation reflects an end-of-

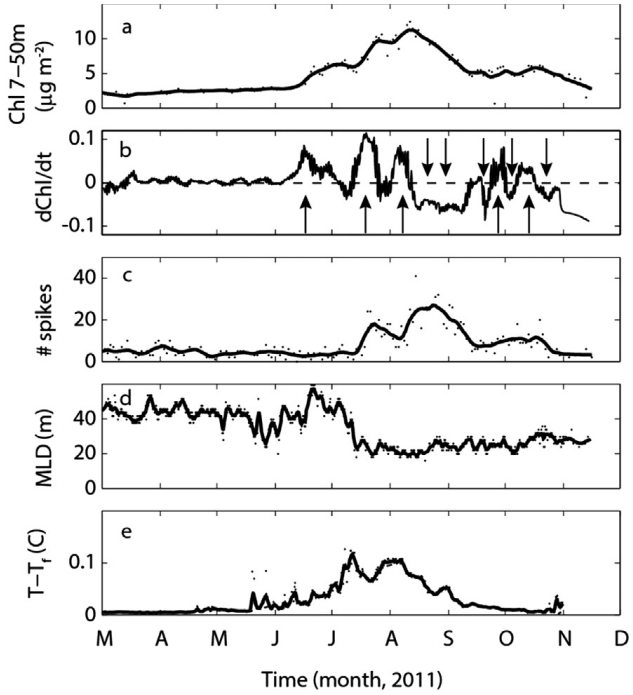

Fig. 7. The 2012 seasonal trends in (a) depth-integrated chlorophyll between ~7 and 50 m, (b) the time rate of change in depth-integrated chlorophyll, (c) the number of 'spikes' in chlorophyll detected between 750 and 220 m depth (see text for details), (d) the mixed-layer depth and (e) the difference from freezing temperature computed at 15 m depth, all observed in the ITP48 time series. Mixed-layer depth was defined as the critical density difference of 0.25 kg m^{-3} from the shallowest measurement. Arrows in (b) represent events indicated in the text. Solid lines in each panel represent a smoothed, ten-point running average to emphasize the overall trends.

season response to decreasing day lengths and diminishing light levels.

3.3. Short-term fluctuations in apparent algal biomass

A novel finding in these daily time series of bio-optical properties is the occurrence of short, weeks-scale fluctuations in under-ice algal biomass. For ITP48, the integrated, baseline-corrected chlorophyll in the top 50 m (i.e., ~7–50 m) along the ITP48 drift track began to increase around June and was still meaningfully above background in early November (Fig. 7a). The time-derivative of depth-integrated biomass – often used as a proxy for algal growth rate – showed distinct weeks-scale increases in biomass between June and early August (Fig. 7b, upward arrows). These fluctuations correlate, with a slight lag, with the difference in water temperature above freezing (Fig. 7e). This was followed later in the season by similarly distinct negative changes in biomass throughout August and September (downward arrows).

Export of ice algae into the water column from above might contribute to these fluctuations, as chlorophyll in ice algae cannot be discriminated from that in water column phytoplankton using this sensor suite. These fluctuations might also reflect *in situ* changes in algal biomass due to phytoplankton population growth and losses, due to changing irradiance or nutrient availabilities. Unfortunately during this period the irradiance sensor on ITP48 was experiencing intermittent faults, presumably due to a manufacturing flaw that the vendor identified in other PAR sensors produced at that time. Consequently these weeks-scale changes cannot be interpreted in the context of any change in underwater light levels resulting from fluctuations in cloud cover or changes in the transmissivity of the overlying ice that would alter the absolute intensity of the underwater light field on those several-day scales. Regardless of the ultimate cause of these short time-scale fluctuations, these changes indicate substantial alterations in apparent upper water column algal biomass. An ability to discriminate the ice algal contribution in these bio-optical signals would provide important insight into the ecological dynamics that underlie these fluctuations.

3.4. 'Spikes' and assessment of particle export

The so-called 'spikes' seen in these bio-optical data were also examined in more detail, to see if their frequency might provide a means to identify and quantify sedimentation and export events in these under-ice assemblages. Our approach is similar to the one described by Briggs et al. (2011) for bio-optical data measured on open-ocean profilers, except that we assessed spike dynamics in profiles of chlorophyll fluorescence alone. The spikes observed in the 4 Hz ITP bio-optical data stream typically represented individual chlorophyll fluorescence readings that were well above the local average and also not symmetric, i.e., very few spikes lower than the local average. Thus these individual readings could not be ascribed to random noise and were instead interpreted as particularly large aggregates of algal matter passing in front of the sensor's sample volume. Spikes were observed not only in the upper water column above 100 m but also well below the euphotic zone, where light levels were too low to sustain photosynthesis. Spikes observed at depth were therefore assumed to represent the chance sampling of large particle aggregates being exported out of the euphotic zone.

We developed an empirical metric for quantifying this phenomena that examined every datum in the

4 Hz chlorophyll fluorescence data stream and averaged the two prior and two subsequent samples. If the datum in question was over 10% greater than this local average it was considered a 'spike' (i.e., an observation of a large aggregate particle). Using this empirical definition we computed the total number of nominal spikes in chlorophyll in each upward profile between 750 m and 220 m, well below the euphotic zone. The trend in these spike counts suggested that particle export into these depths began in mid-July for ITP48, approximately 1.5 months after the start of the growing season (Fig. 7c). It is interesting to note that the onset of these spikes occurred concurrently with a distinct shoaling of the mixed layer (Fig. 7d) but also with the movement of this ITP into the cold halocline where there is little influence from Pacific water. It is possible that water mass differences may be responsible for at least part of this difference in spike frequency seen at this time. Spikes remained relatively frequent at these depths until the end of October, when counts returned to the levels seen in early spring 2012 before the growing season began. This bio-optical approach for estimating particulate export out of the euphotic zone is not quantitatively rigorous, partly because of its empirical nature but also because it depends strongly on the impulse response of this particular commercial fluorometer which itself has not been adequately described. Nonetheless, it does provide a useful qualitative metric for the timing of particle presence in waters below the euphotic zone, if not its magnitude.

4. Discussion and conclusions

4.1. Implications for assessing algal distributions in Arctic Ocean

Knowing how the vertical distribution of phytoplankton varies in different regions of the ice-covered Arctic Ocean is fundamental to understanding photosynthesis and primary production in Arctic marine ecosystems. Numerous field programs have examined algal distributions in the Arctic Ocean (e.g., Gosselin et al., 1997; Hill and Cota, 2005; Lee and Whitledge, 2005; Reigstad et al., 2002; Sherr et al., 2003; Tremblay et al., 2008), yet none have generated the detailed, daily-scale observations that autonomous profiling systems can provide when equipped with even a basic complement of bio-optical sensors. Measurements of optical and bio-optical properties in the upper water column beyond just chlorophyll fluorescence, such as scattering magnitudes, CDOM concentrations, and irradiance, are more scarce from the Arctic Ocean but remain an area of active interest (e.g., Guéguen et al., 2007; Stedmon et al., 2011). At present, bio-optically equipped ITPs represent an effective and tested approach for observing seasonality and interannual variability in algal biomass and these related bio-optical properties in under-ice Arctic Ocean ecosystems.

The preliminary observations we present here illustrate some important insights into these under-ice ecosystems that can be obtained using autonomous profilers. The time of year when under-ice phytoplankton assemblages begin growing in the summer in particular is a critical variable for modeling primary production and ecosystem dynamics under perennial sea ice (Ji et al., 2011; Jin et al., 2012; Popova et al., 2010; Zhang et al., 2010). The timing of when organic material begins falling out of the euphotic zone – both during and after the growing season – is similarly central to modeling carbon cycle dynamics in under-ice ecosystems. Few actual observations are available to help constrain estimates of these fundamental ecosystem events, and the under-ice environment is not readily sampled by traditional methods such as ships or satellites. This lack of observational capability has been the major impetus behind developing new autonomous approaches for assessing under-ice polar ecosystems such as the ITP, the POPS, and newer untethered profiler systems such as the Autonomous Polar Productivity Sampling System (APPSS; P. Matrai, pers. comm.).

It is important to reiterate that with these basic optical sensors it is impossible to determine directly what fraction of the water column chlorophyll biomass under ice cover represents phytoplankton *per se*, as opposed to sea ice algae that have been released from the overlying ice and are advecting vertically through the euphotic zone. Release events can introduce a significant contribution to algal biomass in the upper water column during its export to the deep ocean or benthos (Boetius et al., 2013; Pineault et al., 2013). At present we are unable to discriminate these events clearly in our time series, given the types of sensors used on these first-generation bio-optical ITPs. More sophisticated bio-optical measurements on future ITPs, which might incorporate hyperspectral radiometry for use with optical inversion algorithms (Moline et al., 2012), multispectral fluorometry to discern changes in assemblage composition (Proctor and Roesler, 2010), or variable fluorescence to probe photosynthetic state (Laney, 2011), may provide additional avenues for discriminating the different contributors to total water column algal biomass and their associated photosynthetic state. An ability to measure such

properties beyond biomass, over seasonal time scales, would dramatically advance our understanding of seasonality in algal ecology and primary production in perennially ice-covered regions.

Autonomous profilers can provide a unique perspective into pelagic water column ecosystems, even in perennially ice-covered regions of the Arctic as we show here with these bio-optically equipped ITPs. Under-ice profilers are only one part of a much broader larger Arctic environmental observing effort, and any synoptic assessment of bio-optical seasonality and interannual variability in the central Arctic Ocean will require considerably more data than have been or are being collected with these first eight systems. Three more bio-optical ITPs were deployed in summer 2013, again in the Beaufort Sea and in the Transpolar Drift, bringing to eight the total number operating in the Arctic Ocean in this three-year period. An eventual goal is to make assessments of chlorophyll fluorescence, irradiance, and other bio-optical properties a standard part of the ITP observational network.

4.2. *Long-term bio-optical measurements under perennial sea ice: challenges*

A major perceived limitation with integrating bio-optical sensors into autonomous systems is power demand, particularly for active sensors such as fluorometers. For modern fluorometers the use of light emitting diodes has largely mitigated this concern, and the profiling frequency or operational lifetime of these bio-optically equipped ITPs is not limited by the power requirements of its optical sensor suite. One important limitation that does remain is the inability of ITPs to collect observations from the top few meters under the ice. Often, considerable biomass of phytoplankton and/or hanging ice algae can occur in these first few meters (e.g., Gradinger, 1996) and by not sampling close to the ice bottom, ITP-based observations of the under-ice water column may likely miss a fraction of the total algal biomass. A more complete assessment of variability in under-ice algal biomass, and its subsequent impact on under-ice productivity in the Arctic Ocean, will require advances that allow measurement in this thin, near-surface layer.

The potential for biofouling was a concern when developing a bio-optical sensor suite for ITPs, even though very little biological accumulation has been observed in the few prior instances where ITPs have been recovered after many months of deployment in the Arctic Ocean. Autonomous floats in general typically include no active mechanism for protecting bio-optical sensors against biofouling (Bishop and Wood, 2009; Boss et al., 2008a,b), and the use of shutters in particular has been advised against. The International Ocean-Colour Coordinating Group (IOCCG, 2011), in noting that shutter use below 300 m had not yet been demonstrated, indicated that power consumption would make such an approach prohibitive in long-term autonomous profilers. Our shutter system represents an innovation in this respect, being adequate for use to depths of around 800 m with a power demand that does not limit an ITP's overall deployment lifetime. For ITP48, which provided the longest ITP bio-optical time series collected to date (1370 profiles over 14 months), none of the bio-optical parameters exhibited noticeable indications of biofouling over the entire deployment. This would likely have been evident as strong, monotonic changes over time in the 'deep' chlorophyll offset or in the scattering magnitudes at depth, neither of which was observed. We continue to explore additional approaches for minimizing the possible effect of biofouling on ITP bio-optical observations, e.g., by adding brushes to the shutter plates in order to wipe the optical surfaces of the irradiance sensor before and after each profile. We could not apply this approach to the WETLabs triplet fluorometer we used on these ITPs, unfortunately, because even soft brush bristles can scratch the low durometer optical resin that this sensor uses on its optical face.

The effect of sensor drift over time becomes important with autonomous systems such as the ITP, where subsequent recovery after long deployments is not envisioned. This is especially the case when using commercial bio-optical sensors, given that most are not rigorously assessed in terms of their performance and long-term stability in cold polar waters. Moreover, most commercial *in situ* oceanographic optical sensors do not incorporate built-in test and calibration hardware to track and report their own performance over time, which complicates their use in long-term observing scenarios where eventual shifts in sensitivity cannot be discounted *a priori*. The PAR irradiance sensor used on our prototype bio-optical ITPs is passive, involving a photodiode detector and associated amplifier circuitry whose temperature dependence and long term drift are relatively straightforward to characterize. In contrast, fluorometers and other active optical sensors employ light sources that to some degree age with time, and whose excitation intensities might be expected to decrease over the course of these deployments.

To address this issue our profilers, the shutter plates on these prototype bio-optical ITPs incorporated a formed rigid image conduit molded into the top side of the shutter. This conduit acted as an optical feedback

system such that when the shutter is closed and the sensors are on, excitation energy from the fluorometer's blue excitation source is relayed back to the irradiance sensor. This occurs for 2 min prior to the start of the profile, while the sensors warm up, and for a comparable period immediately after each profile is completed. Irradiance measurements during these pre- and post-profile self-monitoring periods can be examined day-to-day, with any change in this coupling over longer time scales potentially indicating biofouling on the optical faces, decreases in the sensitivity of the irradiance sensor, decreases in optical output of the fluorometer, or a combination of these factors. A comprehensive model for the combined effect of sensor drift and biofouling is difficult to develop when applying such an external approach to the commercial fluorometers we used on our prototype bio-optical ITPs (compared to how an internal, built-in test and calibration system might be devised). We continue to assess this optical feedback approach and explore improved ways to infer changes in drift and biofouling in the bio-optical data we continue to collect with our ongoing ITP program.

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